NCKRI SYMPOSIUM 3

Proceedings of the 20th National Cave and Karst Management Symposium

Edited by: Lewis Land and Mark Joop

National Cave and Karst Research Institute

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NATIONAL CAVE AND KARST RESEARCH INSTITUTE
SYMPOSIUM 3

NATIONAL CAVE AND KARST MANAGEMENT SYMPOSIUM

PROCEEDINGS OF THE TWENTIETH CONFERENCE

NCKMS: A CHANGING CLIMATE

November 4 through 8, 2013
Carlsbad, New Mexico

EDITORS:

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New Mexico Bureau of Geology and Mineral Resources
and National Cave and Karst Research Institute

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Cover Photo: A testimony to "A Changing Climate" frozen in time, the Witch's Broom, a column in the Papoose Room of Carlsbad Cavern, formed during two different climatic conditions on the surface: the drapery formed by a slow drip rate under drier conditions, perhaps during a glacial period when vast quantities of the water supply were locked in ice; and the stalagmite formed by a faster drip rate under wetter conditions, during an interglacial period when the ice caps were melting. Note the challenge of getting artificial lighting to the Witch's Broom on a flowstone-covered floor. Concealed electrical wiring is visible at the base of the stalagmite in the lower right corner of the image. Photo by Dianne Joop.

CONTENTS

Show Caves, Interpretation, and Biology

Cooperative Management and Implementation Strategies

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FOREWORD

Welcome to the Twentieth National Cave and Karst Management Symposium in Carlsbad, New Mexico. The theme of this year's conference is changes in climate, in the broadest sense, to include the impact of changes in our physical climate as well as changes in the political, technological, and social climate on cave and karst management. The setting will provide conference participants with a unique opportunity to view world-class caves and karst features that occur (for better or worse) within and adjacent to the giant oil fields of the Permian Basin region. Field trips will display a variety of issues related to karst resource management, including trips to an extremely popular and heavily visited show cave, a back country cave, and surface karst phenomena in gypsum karst terrain that is impacted by extractive industries such as oil and gas drilling. Conference participants may observe that drilling activity in southeastern New Mexico has increased significantly in recent years because of advances in drilling and well completion technologies, and a social environment in the Carlsbad area that has long accepted and welcomed the industry's presence in their community. These changes in the technological and social climate have a significant impact on the decisions made by cave and karst resource managers in southeastern New Mexico and west Texas.

Edited by:

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KEYNOTE SPEAKER

LONG-TERM UNDERSTANDING, PROTECTION, AND ENJOYMENT OF CAVE AND KARST RESOURCES

Dale Pate
Geologic Resources Division
National Park Service
Denver, Colorado

As we close in on the 20th National Cave & Karst Management Symposium (NCKMS), it is important to reflect on the many accomplishments made in the last four decades since the first National Cave Management Symposium (NCMS). Understanding the past and where we come from gives us the ability to move forward into a future where we will continue to build upon our understanding, protection, and enjoyment of cave and karst resources. The first NCMS was held in 1975 in Albuquerque, New Mexico. At that time there were few cave conservancies across the United States, there wasn't a Federal Cave Resources Protection Act. There were only a few "cave specialists" working in federal, state, and local agencies with cave properties. There was no National Cave & Karst Research Institute. And the word "karst" was not even part of the title of these symposia. But there was momentum building across the United States and the world. Called by some back in the 1970's as the "Golden Age of Caving", many things came together at about the same time that gave cavers and cave scientists the ability to travel to all corners of the world and the ability for these pioneers to safely enter, explore, and study remote and vast cave and karst systems. At the same time, in the US and other places, there were explosions in the building of housing and other infra-structure needs. In numerous areas, new sub-divisions were being built in significant cave and karst areas. During this time, many caves were destroyed simply due to lack of involvement by those in the know, namely cavers and cave scientists. In order to protect and preserve local cave and karst areas, the caving community had to become more involved and more politically active on all levels. With these and many other efforts over the last 40 years, there has been significant progress in many directions.

With a theme of "a changing climate", this year's National Cave and Karst Management Symposium promises to be a good one filled with excellent papers, field trips, and the ever-present camaraderie that enhances discussions and builds new friendships, partnerships, and new directions for cave and karst resources management.

So, in many ways we come full-circle. We are back in New Mexico where the NCMS started with this most recent symposium being organized by the National Cave and Karst Research Institute, a national organization that was created out the momentum of the last 40 years. Despite some of the negative connotations of "a changing climate", we have a lot to be thankful for and a bright and hopeful future that will continue to move cave and karst management in a positive direction. Providing these symposia as an outlet for the discussions on cave and karst management activities was a good proactive approach back in 1975 and is still an excellent and useful tool today as we fight for the long-term protection, conservation, and enjoyment of cave and karst resources across the US.

Biography

Dale L. Pate is the National Cave and Karst Program Coordinator for the National Park Service. Dale's career in the cave and karst field began as an avid caver in 1970 in Central Texas and the mountainous areas of Mexico including the Purificación area within the rugged Sierra Madre Oriental. Having received a BA in Geography from Texas State University in 1974, Dale began work in 1976 with the U.S. Geological Survey (USGS) in Austin, Texas. During the next few years, he augmented his education with a number of geology classes from the University of Texas. Dale remained with the USGS through June 1991 when he became the Cave Specialist for Carlsbad Caverns National Park. At the park, he served as a manager for 21 years with oversight of numerous cave and karst projects which included all activities within Lechuguilla Cave. Dale became the full-time National Cave and Karst Program Coordinator for the NPS in July 2012 after having served the position in a half-time capacity since May 2007.

BANQUET SPEAKER

CERTAINTY UNDERGROUND: WHY GEOLOGY IS MORE STABLE THAN SOCIETY

Abe Van Luik
Waste Isolation Pilot Plant (WIPP)
US Department of Energy
Carlsbad Field Office
Carlsbad, NM

An oft-expressed sentiment is: "why bury dangerous waste where it can't be seen and we won't know what it is doing? Why not store it in massive containers above ground so every generation can see it and see that it is OK?" The short answer? "Geology is more stable than society."

An oft-expressed fear is that an earthquake could do unimaginable things to a repository for dangerous wastes deep underground, and imaginations and memories jump their tracks to match a disaster flick's horrific images to the imagined repository.

Above-ground storage can be safe, it is practiced today, but for how long can it be relied on, a century or two, sure, but not thousands or tens of thousands of years. It is primarily this fear that fuels the fire for agitating for above-ground long-term storage that can be "watched." But watched by whom and for how long? Who will pay for someone to provide physical protection (safeguards)? Who is liable if at some point some maintenance is required?

Two issues with long-term storage are: Intergenerational equity: should future generations be made to deal with our messes? The answer is simply and emphatically no.

Are national/local governments stable for millennia and hence reliable partners making the repository area safe from inadvertent intrusions? The short answer is no, the longer answer is more complicated and contains the word "depends" –depends on the value to the local community.

This presentation will illustrate why, no matter what the inevitable longer term changes in governments, if there is local importance attached to a location or structure, it will be maintained and respected. The presentation will also underscore, using photos taken in various caves, that earthquake ground motion is more destructive at the surface than it is at depth.

Biography

Dr. Abraham (Abe) Van Luik is a Senior Physical Scientist and the Director of International Programs at the Carlsbad Field Office (CBFO) of the US Department of Energy. CBFO oversees and owns the Waste Isolation Pilot Plant (WIPP), currently the world's only operating deep geologic repository for radioactive waste.

Abe joined CBFO after several decades of working on the Yucca Mountain Project in Nevada, where he served as Senior Policy Advisor for Performance Assessment, the long term repository safety projections that went out to a million years. With CBFO, Abe works with other staff to set up cooperation between the U.S. repository program and other international agencies. Cooperative activities are formalized in a Memorandum of Understanding between the Department of Energy and its German counterpart, which is especially useful since the German repository program is also working in salt. Similar agreements are in place with the British and French nuclear waste management agencies.

Abe's nuclear-waste career began at Argonne National Laboratory in Illinois, continued at Rockwell Hanford Operations in Washington, with Roy F. Weston and Rogers Engineering in Washington, DC, with the Pacific Northwest National Laboratories (PNNL) in Washington State, and with Intera, Inc. in Las Vegas, Nevada. Finally, he joined the Department of Energy in Nevada, where he oversaw the science and engineering side of the proposed Yucca Mountain repository's license application to the Nuclear Regulatory Commission.

Van Luik has a bachelor's degree in chemistry from the University of California at Los Angeles and both a master's and doctorate from Utah State University. His dissertation involved studying the physical chemistry of Utah's Great Salt Lake.

Abe is pleased to be part of a working repository's science program: "Salt forms when the evaporation removes more water than is coming into the north arm of the Great Salt Lake. WIPP is located in salt formed in similarly evaporating sea waters 250 million years ago. The chemistry is the same. It seems only fitting that I've returned, during the final years of my career, to what I studied while obtaining my PhD."

GEOLOGY / HYDROLOGY
JOHANNA KOVARIK, CHAIR

HYDROGEOLOGIC CONTROLS ON THE OCCURRENCE AND MOVEMENT OF GROUNDWATER DISCHARGED AT MAGIC SPRING IN THE SPRING BRANCH CREEK DRAINAGE BASIN, SPRING BRANCH, TEXAS

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Abstract

The hydrogeologic controls, flow velocities, flow direction, groundwater delineation, and physical characteristics in a joint controlled dendritic conduit-spring system are characterized. The known conduit extends from Magic Spring to and past CM Cave with 4,475 m of measured passages and tributaries.

Four storm events were measured characterizing the system's hydrodynamics. The rise time and half flow period time ($t_{0.5}$) occur in less than a day. The volume of ground stored in conduits is approximately one half million m^3. Storm flows into the conduit-spring system drain within 3.7 to 7.5 days. This system is thermally ineffective with little radial heat flux into the conduit walls.

The field components of this study include a karst feature density survey, four dye traces, continuous monitoring of dynamic parameters, stage height, and discharge at Magic Spring.

Hydrographs and chemographs show patterns interpreted as pulses of water recharging through caves, sinkholes, and a stream sink. These pulses are superimposed on baseflow from the joint controlled dendritic conduit-spring system.

The dye tracing results identified groundwater piracy across surface water divides. The storm flow velocities at Magic Spring ranged between 8,700 and 15,120 m/d with baseflow characteristics below 3,000 m/d.

Introduction

The Spring Branch Creek drainage basin is located in the eastern part of the Edwards Plateau in Comal and Kendall counties, near the town of Spring Branch, Texas, USA. It was chosen as a study location based on history and previous work by Veni (1994). Veni completed his dissertation on the hydrogeology of the lower member of the Glen Rose formation (Lower Glen Rose) as a stratigraphic setting. Veni (1994) focused his research south of the Guadalupe River. This investigation was conducted north of the river in the same formational setting. Similar composition and texture occur in both areas.

Karst landscapes in limestone terrain, such as the Magic Spring drainage basin, are the result of bedrock dissolution where recharged water dissolves calcite and dolomite, enlarging fractures and joints, forming sinkholes and caves (Palmer, 2007). Surface streams interact complexly with karst groundwater systems. Locally at the research site, runoff is intercepted by karst features and drains through the conduit system to Magic Spring. The purpose of this study is to determine where the recharge points located, the interconnections of the flow paths, the flow dynamics of conduit flow and how it interacts with matrix flow, and if thermal signals exist that may help define conduit dynamics. Information gained from this study will be useful for improved management of this groundwater resource.

Techniques used to meet the goals of this study included dye tracing, and water quality and quantity monitoring. Water quality sondes, pressure transducers, and autosamplers were used during a test period from January 29, 2012 until August 22, 2012.

Study Area and Hydrogeologic Setting

This Spring Branch Creek watershed is bounded by the Guadalupe River to the south and the Twin Sisters hills and related highlands to the north (Figure 1). The local topography of the study site is a gently rolling landscape

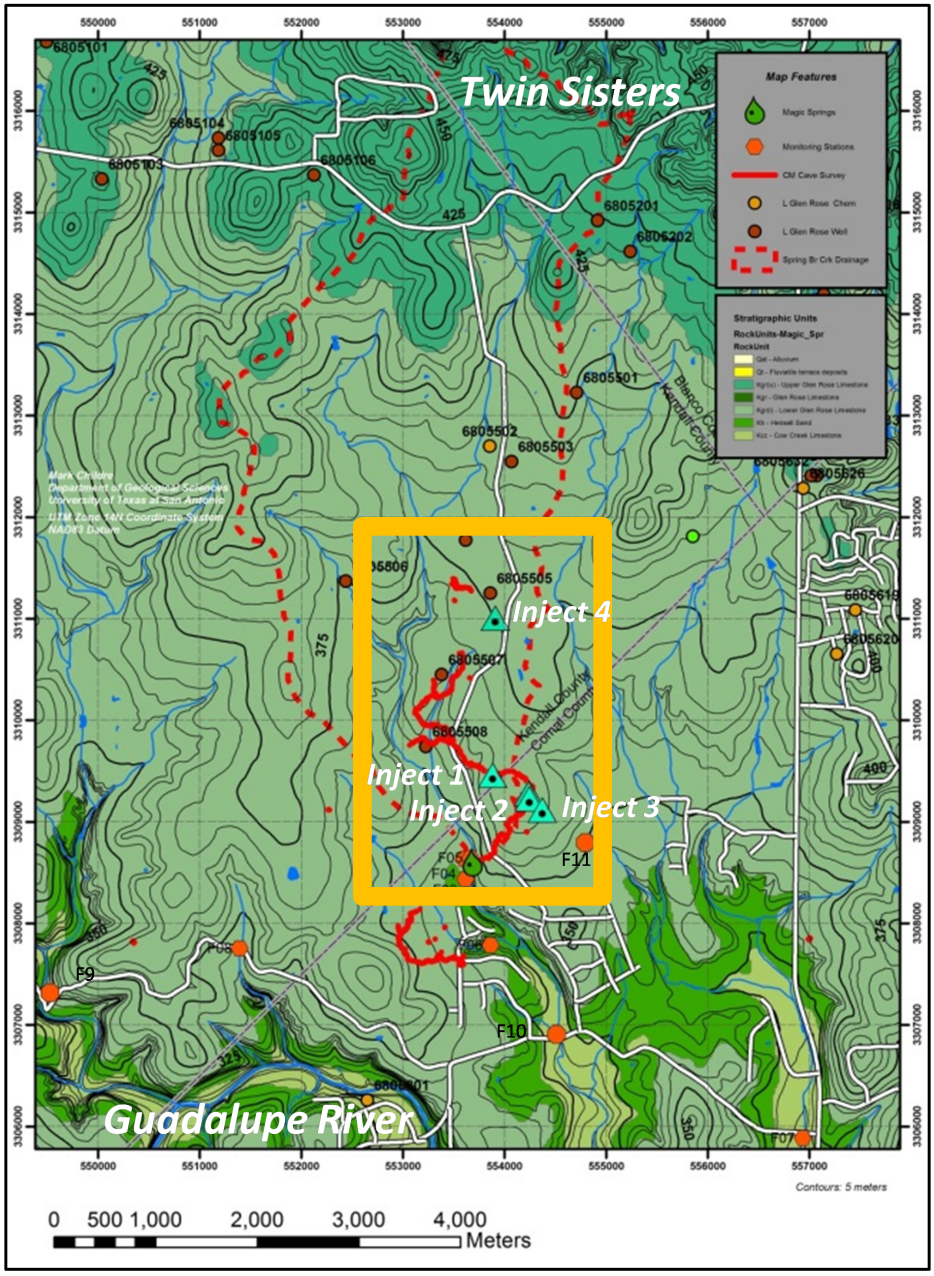

Figure 1. *Spring Branch Creek drainage basin and research site.*

that is dissected by steep and narrow drainages over karstified fractured rock. Spring Branch Creek is composed of eight tributary watersheds covering the surface drainage. Its main channel is a 14.4 km long limestone-bedded waterway that drains north to south.

Originally covered by juniper-oak savanna and mesquite-oak savanna, most of the drainage basin is used for grazing beef cattle, sheep, goats, and wildlife. Hunting leases are a major source of income. Erosion and the environmental climate in the Spring Branch area resulted in thin stony soils. Residential development is becoming much more common.

Hydrogeology

This study site is stratigraphically in the lower member of Glen Rose Limestone (Lower Glen Rose) atop the contact with the Hensel Member of the Pearsall Formation. The Hensel acts as a local hydraulically confining unit in the Spring Branch area (Hammond, 1984). The bedding dips approximately 0.5° and strikes 130° along the contact of the Lower Glen Rose and Hensel, as calculated using

previously released stratigraphic mapping and the three-point method.

Spring Branch Creek dissects the upper and lower members of the Glen Rose Limestone and the underlying Hensel and Cow Creek members of the Pearsall Formation. Groundwater development of the Lower Glen Rose Aquifer began about 1.2 Ma when the Lower Glen Rose was sufficiently exposed in the Guadalupe River drainage basin. Spring Branch is a tributary to the Guadalupe near the downstream limit of the Lower Glen Rose outcrop (Veni, 1994). Since 1.2 Ma to the present, the water level in the aquifer has declined because of the incising of the Guadalupe River.

Cave Systems

The Magic Spring-CM Cave system is the primary conduit system in the study area. Magic Spring has been known for decades but could not be explored until recently with diving equipment. Rambo (1990) discussed cave exploration north of the Guadalupe River and when a sinkhole was excavated in 1989 to reveal the entrance pit of CM Cave. A second short pit followed and at a depth of 27.2 m below the surface led into a small, nearly water-filled passage named "Oh My God" (OMG). This 16-m long passage is a tributary to Echo River, the main conduit that feeds Magic Spring about 1.3 km downstream; upstream Echo River has been explored over 2.4 km. Additionally, 720 m of tributary passages, have been surveyed to date. The main stream ends in a sump; exploration continues by divers.

The Magic Spring-CM Cave system is hydrologically perched on the Hensel. It passages are typically guided by joints. Recharge mostly occurs through overlying sinkholes and caves that have not yet been physically connected into the larger cave system. The conduit network has a dendritic pattern, although this is only subtly seen in map view due to limited exploration of most tributary passages.

Methods

Karst Density Survey

A karst density survey was performed in order to identify the distribution of significant recharge features. The survey was completed after a 200 x 200 meter grid system was established around the CM Cave entrance, and 49 sinkholes and 43 smaller caves were recorded.

Rainfall

Rainfall data were also recorded at five-minute intervals at US Geological Survey station 08167347 Honey Creek Site 1C near Spring Branch, Texas. A daily record of rainfall was also documented at Magic Spring throughout the research period.

Magic Spring Discharge and Hydraulics

A rating curve was constructed by measuring the spring's flow under ten occurrences. A Marsh-McBirney flow meter and a wading staff were used. Multi-Parameter TROLL 9000 and YSI 556 MPS (Multi-Probe System) sondes were used to recorded specific conductance, pressure, and temperature.

Dye Tracing

Charcoal receptors and an Isco 6712 full-size portable auto-sampler were used to sample for dyes at the monitoring points. The methods and test procedures for tracing were adopted from Schindel & Johnson (2007).

Dye injection and monitoring

Four caves were chosen as dye injection locations to establish direct paths to the main groundwater conduit system. Sattler's Deep Pit is within the Spring Branch Creek surface drainage basin, as is Echo River in CM Cave. Cave Crack and No La Vie Cave are in the Cypress Creek drainage basin to the east. Table 1 identifies the injection locations, dye, dye quantity, when injected, and when recovered.

Monitoring for dye occurred at Magic Spring, with an ISCO 6712 automatic water sampler, and at 11 other locations along Spring Branch and bordering creeks to the east and west with activated charcoal packets. The fluorescence for dye in the samples was measured using a Perkin Elmer LS50B fluorescence spectrometer and the dye peaks were calculated using analytical software.

Results

Karst Density

Two areas with high densities of karst features were discovered. One is in the area targeted by this study around CM Cave. The second is about 1 km to the northeast and surveyed by a team of cavers led by Terry Holsinger. High karst feature densities were defined as at least 20 karst features/0.16 km^2. The combined survey area covered 3.52 km^2 and was found to have 146 sinkholes, pits, caves, and a stream sink.

Table 1. *Dye tracing results from Magic Spring-CM Cave.*

Test #	Injection Point	Injection Date	Dye	Dye Quantity grams	Dye Recovery Location	Arrival Time
1	CM Cave	6/3/2012 13:38	Uranine (10.85g)	10.85	Magic Springs	6/4/2012 4:19
2	No La Vi Cave	6/24/2012 12:10	Eosin (168g)	168	Magic Spr-MM3	6/25/2012 5:30
3	Cave Crack	6/30/2012 12:22	SRB (146g)	146	Marker Ca18	6/24 - 8/19/12
	Cave Crack	6/30/2012 12:22	SRB (146g)	146	Magic Springs	7/4 - 7/15/12
4	Sattler's Deep Pit	7/1/2012 13:06	Uranine (254g)	254	Marker vb1	6/24 - 8/19/12
	Sattler's Deep Pit	7/1/2012 13:06	Uranine (254g)	254	Magic Springs	7/4 - 7/15/12

Test #	Distance (apparent) meters (m)	Distance (actual) meters (m)	Travel Time from Inject to LOD days (d)	Apparent Velocity (m/d)	Actual Velocity (m/d)	Sinuosity
1	893	1816	0.61	1441	2929	2.03
2	837	1391	0.745	1123	1865	1.66
3	829	1209	charcoal			1.46
	89	1209	charcoal			1.46
4	2410	5417	charcoal			2.25
	2410	5417	charcoal			2.25

The mapping of CM Cave revealed a joint controlled dendritic pattern bearing approximately 45° and 315° in the subsurface. The survey of karst surface features revealed that most bear approximately 300°.

Hydrogeologic Data

Four storm events were recorded between February and May 2012. The May storm event occurred after a dry period resulting in a logarithmic decline in discharge from evapotranspiration.

Dye Tracing Results

Hydrograph data and sampling results for each of the four traces were evaluated. Groundwater velocities, travel time, and flow direction were recorded, and hydraulic connectivity between different creek drainage basins is assessed. All four dyes were detected at Magic Spring, two dyes showed up in water samples from the auto-sampler and the other two dyes from the charcoal packets.

Dye injected in Echo River flowed directly through that conduit to Magic Spring. Dye injected at the three surrounding caves entered Echo River as follows. Dye from Sattler's Deep Pit was detected in the furthest upstream sampled location at survey marker VB1, about 600 m upstream of the CM Cave entrance. No La Vie Cave and Cave Crack are located east of Echo River, respectively about 100 m and 200 m downdip in the Cypress Creek surface water drainage basin. Dye from No La Vie Cave was detected from a tributary passage at survey marker MM5, located 68 m upstream of the CM Cave entrance, and dye from Cave Crack was first detected in Echo River from a tributary conduit at survey marker CA18, over 300 m downstream of the CM Cave entrance (Figure 2).

Discussion

Hydrodynamic Response: Two Pulse Recharge Event

Magic Spring's hydrographs show bimodal behavior as the response transitions from baseflow to diffuse flow (Figure 3). In contrast, dye tracing from within Echo River and from No La Vie Cave indicate a unimodal response.

This bimodal behavior indicates at least two distinct recharge paths upstream of the entrance to CM Cave. This behavioral response supports the hypothesis that recharge enters the groundwater system at multiple focused locations.

The shape of the specific conductance (SpC) response curve to a storm event reflects multiple focused recharge

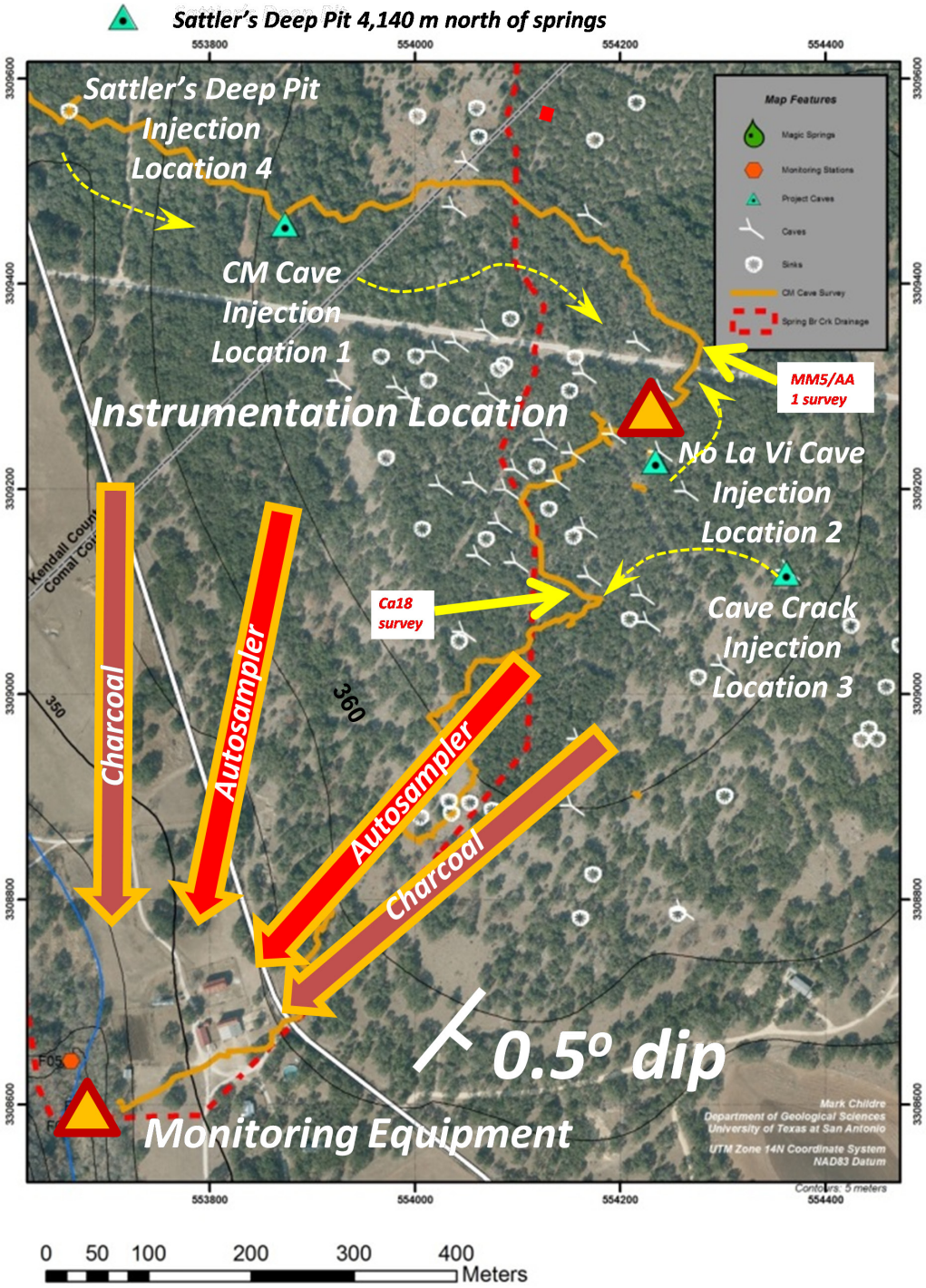

Figure 2. *Magic Spring-CM Cave dye injection and monitoring locations.*

sites (Figure 4). The primary recharge source for the second pulse is from Cool Creek Cave, a stream sink about 1.3 km upstream of Magic Spring that takes water from Spring Branch Creek. That reach of the creek is normally dry and the entire flow of the creek during a storm event was observed to enter Cool Creek Cave until it overflowed and the creek flowed downstream toward the spring.

Hydrodynamics

The timing between pulses or overall storm flow velocities ranged between 8,400 m/d and 15,120 m/d

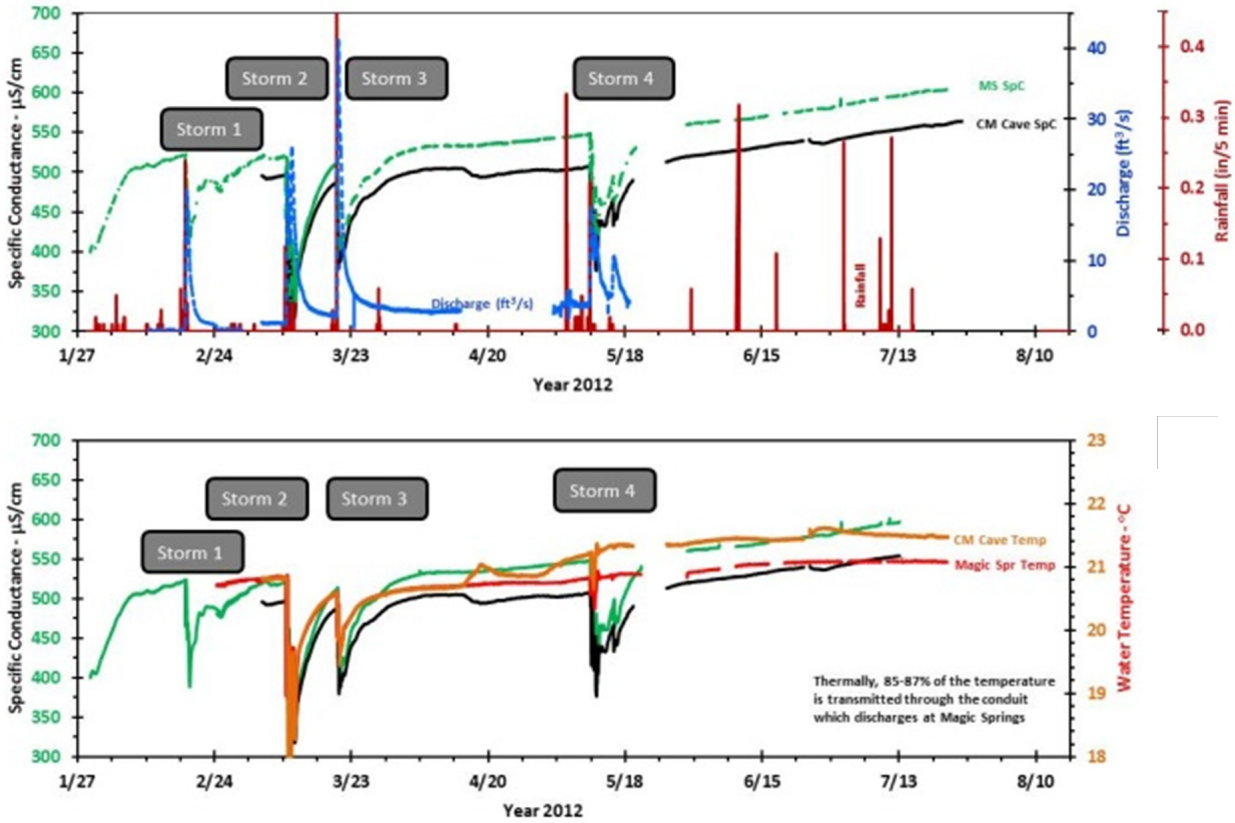

Figure 3. *Four storm event hydrographs and chemographs: Magic Spring, 2012.*

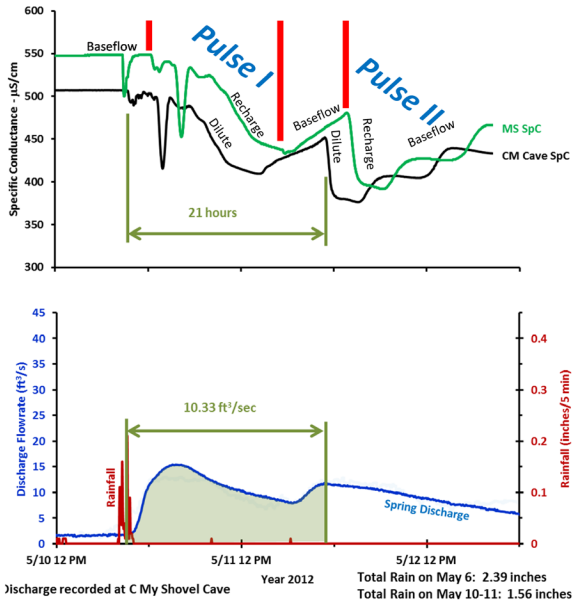

Figure 4. *Response of SpC exhibiting two-pulse behavior.*

(Figure 5). The sources of the pulses were identified as three recharge points: the two high density karst areas and Cool Creek Cave (Figure 6).

The karstic terrain, stream sink, topography, and conduit characteristics are the primary controls on the rapid bimodal response. Magic Spring's hydrologic response is characterized based on its hydrograph's rising limb, falling limb, recession coefficient, and maximum discharge. Any hydraulic events that happen within this rise time period would be the same and invariant with maximum discharge. With the rise time defined, the location for maximum flow and maximum diffusivity are known and will be the same for all four events. Historically, there is a 50% ratio for diffuse and recharge flow (Atkinson, 1977). An analysis of the four storm events monitored for this study shows the ratio between the focused karst areas and the stream sink ranges from about 30-83% during maximum discharges that respectively range from about 425-1,160 L/s.

The thermodynamic response of the cave system is ineffective during storm events, such that 85-87% of the temperature change is transmitted over 1.3 km.

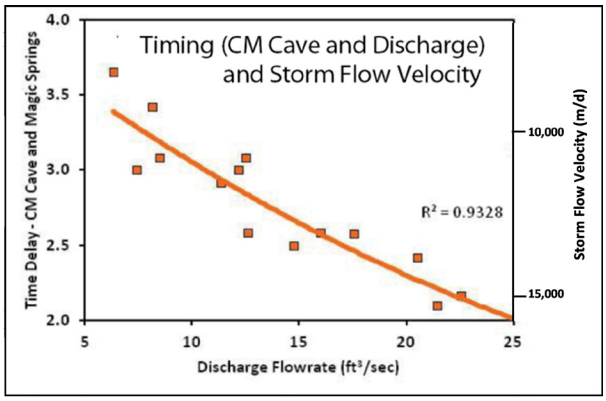

Figure 5. *Conduit flow velocity at Magic Spring-CM Cave, and time delay between recharge and discharge.*

Shape and Characteristics of Hydrologic Response Using Discharge

The rate of withdrawal of water from storage, from the springs, or from pumping; is indicated by the slope of the subsequent recession coefficient (α). The discharge of a spring is a function of the volume of water held in storage and that the half-flow period (t0.5). If e-α = β then the flow recession has the relationship:

$$Q_t = Q_0 e^{-\alpha t} = Q_0 \beta^t$$

where β is the recession constant.

A $t_{0.5}$ is defined as the time required for the maximum discharge. Substitution into previous equation gives:

$$Q_t = 2Q_{t_{0.5}} \beta^{t_{0.5}}$$

where $$t_{0.5} = \frac{constant}{log\, \beta}$$

The parameter $t_{0.5}$ is independent of flows, sensitive to change, and is a direct measure of the rate of recession and therefore can be used as a means of characterizing exponential baseflow recession (Ford & Williams, 2007).

There is a linear relationship between hydraulic head and flow rate (commonly found in karst at baseflow conditions), and the curve can be expressed as a straight line with slope -α if plotted as a semi-logarithmic graph. It can be represented in logarithmic form from which α in Table 2 may be determined from:

$$\alpha = \frac{\log Q_1 - \log Q_2}{0.4343(t_1 - t_2)}$$

For each storm event in Table 2, the dynamics for both the rising limb and the recession limb may be calculated. The response at Magic Spring is defined by the $t_{0.5}$, rising time, recession curve, and baseflow. The rising rate defines the initial dynamic response to a storm event and is invariant with values around 6 hours while the $t_{0.5}$ ranges between 12.9 to 15.7 hours depending on total discharge. The storm events are superimposed and plotted in Figure 7 for comparison. The sum of the rise time and half flow time is less than one day. Flows from the storm events were depleted back to baseflow within 3.8 to 7.5 days.

Surface drainage from Cypress Creek basin is partially pirated by the groundwater discharged at Magic Spring. As has been well established in the literature, karst groundwater drainage basins cannot be reliably delineated based on surface water drainage boundaries. Dye tracing, karst feature surveys, and spring hydrograph data should also be considered. In this study, two of the four dye injection points were in the Cypress Creek surface drainage basin. Their detection in CM Cave and Magic Spring demonstrates groundwater piracy from the Cypress Creek area, increasing the size of the spring's groundwater drainage basin to the east. Additionally, the sinking of Spring Branch Creek into Cool Creek Cave was found to significantly impact groundwater flow in the conduit system and suggests a possible decrease in groundwater basin size between Cool Creek Cave and Magic Spring (Figure 8). However, north of Cool Creek Cave the groundwater drainage was greatly increased to the west because of the flow from Cool Creek Cave.

Aquifer Volume and Mass Balance

Tracer studies used in determining subsurface flow conditions in karst terrains are greatly influenced by subsurface flow patterns the inflow and outflow points of the aquifer.

Tracer mass recovery at Magic Spring was measured for a rough estimate of the maximum conduit volume. If a single discharge value is used as a mean spring discharge then the volume of groundwater stored in conduits at the time of the tracer test may be estimated by:

$$V = \int_0^{T_t} Q dt = QT_t$$

where Q is mean spring discharge and V is the groundwater volume. Integrating the flow rate [Q(t)] for

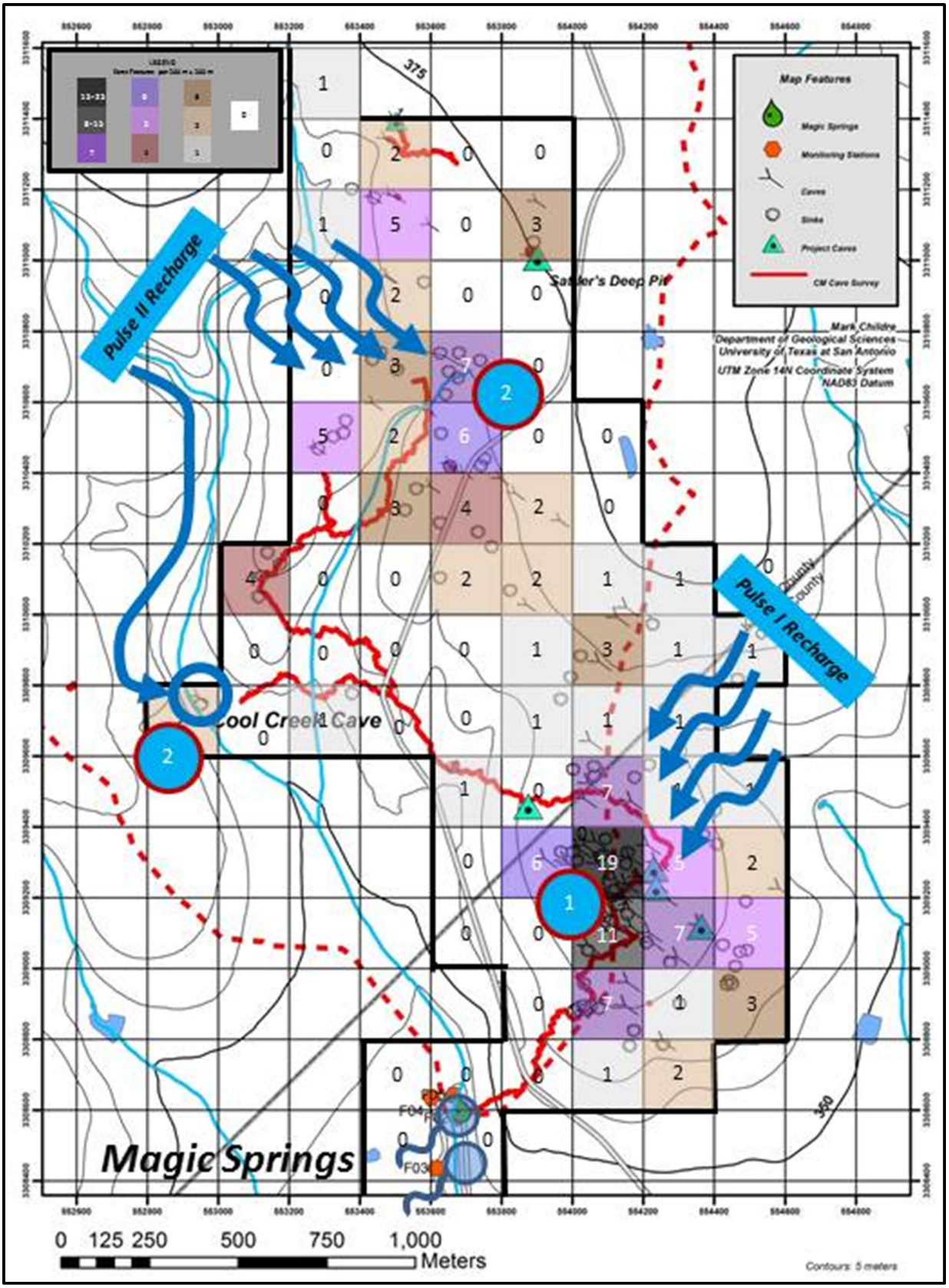

Figure 6. *Two pulse recharge system to CM Cave and Magic Spring.*

Storm Event			Rising Response		
Initial Response	Final Response	Time from baseflow (bf) to bf+1 cfs days	Average Flow Rise cfs	Rising Time hrs	Rising Rate cfm/m
2/18/2012 1:17	2/21/2012 19:57	3.78	14.08	6.33	2.93
3/9/2012 17:29	3/15/2012 0:54	5.31	14.31	6.00	2.58
3/20/2012 1:56	3/27/2012 12:53	7.46	26.30	6.50	2.74
5/10/2012 20:00	5/15/2012 0:22	4.18	7.77	6.08	1.71

Table 2. *Magic Spring discharge characteristics during peak flows.*

	Recession Flow Response				
Time bf to bf+1 cfs days	Time $t_{0.5}$ 1/2 flow hrs	Max flow cfs	Half flow cfs	Base flow cfs	α 1/hr
3.78	12.75	19.95	10.18	0.42	0.052
5.31	13.92	26.22	13.69	1.19	0.047
7.46	15.17	41.17	21.70	2.29	0.042
4.18	12.92	15.41	8.56	1.71	0.046

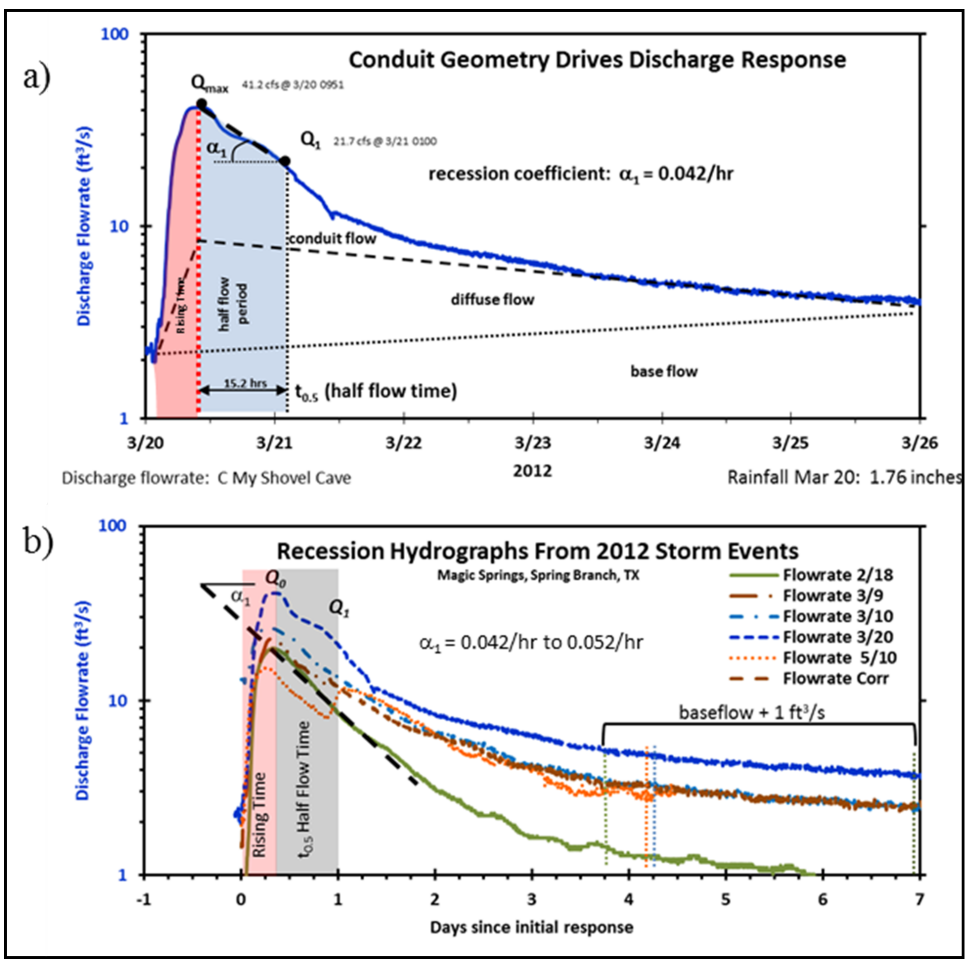

Figure 7. *Magic Spring combined storm flow recession hydrographs.*

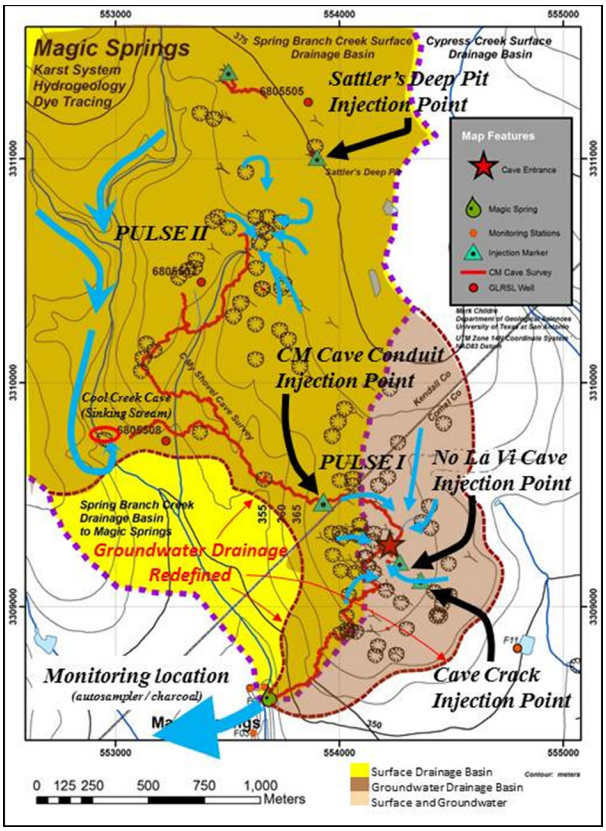

Figure 8. *Groundwater drainage basins for Magic Spring-CM Cave.*

each time period, 33.6% of the dye injected into Echo River was recovered (% $_R$) at Magic Spring. An estimate may be calculated:

$$V_t = \frac{100(V_s)}{\%_R} = \frac{100(163,815)}{33.6} = 487,544\ m^3$$

It is important to stress that this volume does not represent humanly accessible cave-size conduits but conduits of all size capable of sustaining turbulent flow. Simply dividing the calculated volume by the channel cross section shown in Figure 9 suggests similar size passages in excess of 97 km in length along the traced flow route. However, Veni (1994) at nearby Honey Creek Cave demonstrated exceptionally high storage volumes due to the honeycomb conduit porosity of basal Glen Rose, from which Magic Spring-CM Cave also flow.

Conclusions

The Magic Spring-CM Cave system has over 4.5 km of mapped joint controlled passages organized into a dendritic pattern. It is overlain by 146 known karst recharge features, many of which occur in the two high density areas. Their combined influence results in a two-pulse hydrologic response. The flow volumes for each pulse were calculated and the ratio between the pulses established. This ratio correlates best with the maximum discharge and shows the possibility of the stream sink at Cool Creek Cave dominating the second pulse as discharge increases.

The conduit system is thermally ineffective with 85% temperature retention over 1.3 km during the first hydrograph pulse following a storm event. It has a rise time between 6.0 to 6.5 hours and has a half flow period time ($t_{0.5}$) between 12.8 and 15.2 hours. The total time from storm event to $t_{0.5}$ is less than one day. The storm flows dissipated between 3.8 to 7.5 days. Groundwater velocities were measured between 8,400-15,120 m/d for storm flows and up to 3,000 m/d for baseflow conditions over 1.3 km of the cave stream.

The groundwater drainage basin was preliminarily defined based on the data retrieved. Modifications are expected as more tracer tests are completed under different flow conditions.

Recommendations

Presently, there is no groundwater management authority for this system. While much of its drainage basin is in Kendall County, which defines the boundaries of the Cow Creek Groundwater Conservation District, that district manages the Cow Creek Aquifer, not the Lower Glen Rose. A groundwater conservation district should be formed similar for the Lower Glen Rose Aquifer, but based on hydrogeologic boundaries otherwise

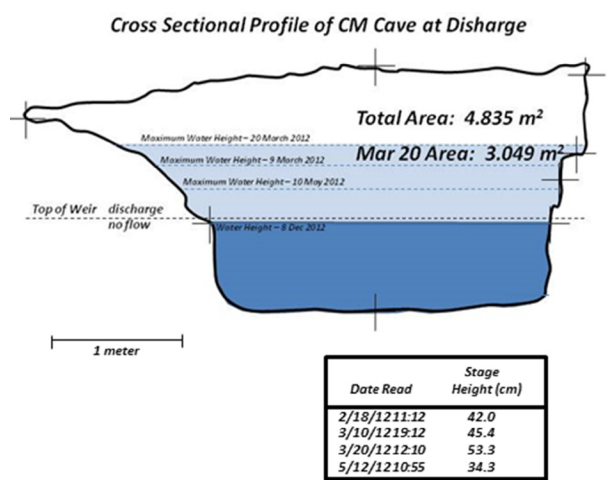

Figure 9. *Cross section of CM Cave passage at Magic Spring.*

management of this and other groundwater systems would be split between multiple agencies. A meeting of the property owners in the Magic Springs drainage basin from both counties should be held to discuss their mutual water resource.

The Magic Spring-CM Cave system requires additional tracing experiments under higher flow conditions for hydrodynamic and drainage area refinement. Additional monitoring locations and higher flow rates would bind the characteristics of this system, potentially giving evidence to other possible discharge points. That work should include Cool Creek Cave.

Although the regional dip has been established using the three point method on geologic surface maps, the local dip should be surveyed. Local variations in the dip and orientation may have impact on the overall recharge characteristics.

The passages at the junctions near survey markers AA1 and MM5 (Figure 2) should be closely investigated. Veni (1994) identified cave stream piracies in the Guadalupe River basin and these locations could reflect paleoflow paths and/or modern overflow routes that could cross current drainage basin boundaries.

Acknowledgements

Without the support, assistance, and access granted by the property owners, this study would not have been possible. I was granted access to Magic Spring by Will McAllister IV, who also provided rainfall data for the spring site. The entrance to CM Cave and unending support was given by Joe Eisenhauer. David Oden allowed dye injection at Sattler's Deep Pit. Special thanks must be offered to Wally Henderson who owns Cool Creek Cave.

Funding was provided by the South Texas Geological Society Jones-Amsbury Research Grant, and The University of Texas at San Antonio's Department of Geological Sciences and the Center for Water Research. The Edwards Aquifer Authority provided the dyes, lab support, and the lab for analysis of the traced water samples.

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SOLUTION MINING AND THE PROTECTION OF KARST GROUNDWATER SUPPLIES IN BURTON FLATS, SOUTHEAST NEW MEXICO, USA

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Abstract

The Bureau of Land Management (BLM) is an agency of the United States of America Department of Interior and responsible for stewardship of public lands. It is committed to manage, protect and improve these lands in a manner to serve the needs of the American people. Management is based upon the principles of multiple use and sustained yield of our nation's resources within a framework of environmental responsibility and scientific technology. These resources include recreation, rangelands, timber, minerals, watershed, fish and wildlife habitat, wilderness, air and scenic quality, as well as scientific and cultural values.

The BLM received a potash solution mining proposal to inject sodium chloride rich water into old mine workings which still contain valuable potassium in the walls and the large pillars that hold up the roof. There, the sodium chloride solution, through an ion exchange with potassium chloride, will become rich with potassium and then be pumped out and allowed to evaporate in large solar ponds on the surface. The potassium chloride will then be collected and refined. The water source for the project is from a shallow karst aquifer with limited recharge. The amount of water needed for the project will require approximately 10,886 kiloliters (2.88 million gallons) of water per day for the first 7 years and 5,443 kiloliters (1.44 million gallons) per day for the next 13 years.

The recharge area for the karst aquifer is in the Burton Flats karst plain. The geology is interbedded gypsum, anhydrite, and dolomite with the occasional gypsum outcroppings at the surface. There are 79 known caves in the project area and hundreds of dolines. Several of the caves go down to the water table, which is located in the dolomite members. Rainfall in the area is approximately 23 centimeters per year.

The large amount of water proposed for extraction from the karst aquifer brought concern that it may dewater the aquifer or draw the groundwater levels down to potentially critical levels. The water is vital to support the areas' cattle ranching industry. Further, a biological inventory had not been conducted in the caves or in the karst aquifer. Therefore, it was unclear if there were any aquatic troglobitic species that would be affected.

The Bureau of Land Management required a complete biological inventory be conducted to understand more about the effected environment. As a result of that inventory two new aquatic troglobitic species were discovered. The agency in conjunction with the mining company developed a groundwater monitoring plan to track the water levels and detect any significant drops in the aquifer levels. The BLM initiated an adaptive management strategy that set trigger points beyond which alternate water sources would be used for the project.

The Proposal

A proposal for a solution mining project in southeast New Mexico, USA was received by the United States Department of the Interior, Bureau of Land Management (BLM) from the Intrepid Mining Corporation. The proposal is to inject a NaCl brine solution into previously mined workings through injection wells. The injected NaCl brine will fill the lower elevations of the workings and replace the potassium chloride (KCl) from the remaining pillars and edges of the workings via ion replacement. The potash and sodium chloride concentrated solution will then be recovered via extraction wells and pumped through pipelines to solar evaporation ponds covering approximately 230 hectares (570 acres). The KCl/NaCl concentrate will then be harvested from the solar evaporation ponds and processed at a flotation plant (DOI, 2012).

The water needed for the project will require that approximately 10,886 kiloliters (2.88 million gallons) of water per day be pumped for the first 7 years and 5,443 kiloliters (1.44 million gallons) per day for the next 13 years (DOI, 2012). The water source for the proposed project is targeted for a shallow karst aquifer. Sodium chloride will be added to the water.

The Environment

Geology

The Burton Flats area contains Permian age evaporites of the Rustler Formation being primarily made up of interbedded gypsum, dolomite and anhydrite. The gypsum members occasionally crop out on the surface, which is largely composed of gypsum soils. From the top to the bottom the members are the Forty-niner, the Magenta Dolomite, the Tamarisk, the Culebra Dolomite, and the Los Medaños (Figure 1).

The Forty-niner member is composed of gypsum, anhydrite, siltstone, shale, and clay. The Magenta Dolomite member is 6 to 9 m (20 to 30 feet) thick and identified by its color, weathering to colors from pink to red to purple. It contains open voids and high porosity. The Tamarisk member is largely composed of massive anhydrite. The Culebra Dolomite is a thin-bedded crystalline dolomite that also has high porosity. Below the Culebra is the Los Medaños member. It is composed of siltstone, gypsum, and fine-grained sandstone (Hill, 1996). Both the Magenta and the Culebra dolomite formations are aquifers.

Climate

The area has an arid to semiarid climate. The average rainfall is between 25 to 35 centimeters per year. The average monthly maximum temperatures in July range from 34 to 37ºC (94 to 98°F) with average monthly minimums of -1 to -2 ºC (28 to 30°F) in December and January. Average annual potential evaporation rates far exceed average annual precipitation. Evaporation rates approach 180 centimeters per year in this area, resulting in a large moisture deficit.

Caves and Karst

The gypsum karst plain of the Burton Flats area has 79 known caves (Figure 2) and hundreds of dolines in the vicinity of the project. It is estimated to have 50 karst features per square kilometer in this dense karst area. Several of the caves are large and go down to the local water table approximately 26 meters deep. The length of the caves varies from 30 meters to 200 meters. The cave systems and dolines provide for rapid recharge of groundwater during rain events. The caves are formed in the 49er member of the Rustler formation and may terminate in the Magenta dolomite member where they encounter the water table. The caves may go much deeper but no diving has been conducted in any of the caves. Due to significant fracturing there is a high probability that the Magenta and Culebra aquifers are connected.

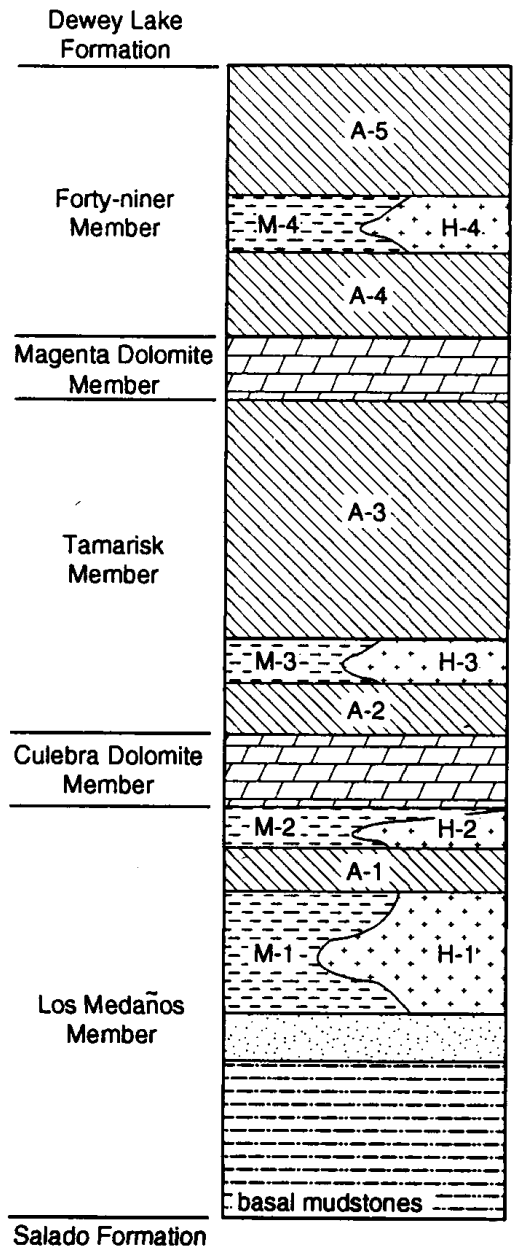

Figure 1. *Stratigraphic cross section of the Rustler Formation. A=anhydrite, M=mudstone, H=halite. After Powers and Holt, 2000.*

Figure 2. *Entrance to Skylite cave with water monitoring well being drilled in background.*

The Concern

The primary concern regarding cave and karst resources was that the amount of water proposed to be pumped from the karst aquifer is greater than the limited recharge that the area can sustain and the aquifer may be pumped dry. This would severely stress the ranching community, which relies on the water for their cattle. Additionally, there had not been a biological inventory conducted in the caves to determine what types of troglobitic species might be present that may be affected by significant lowering of the water levels.

The Solution

To address the concerns of impacts to potential biological communities the Bureau of Land Management required the proponent to hire a company to conduct a biological inventory on three of the caves in the project area located in Burton Flat. In this way it could be determined what species were present and if there were any aquatic invertebrate species that could possibly be impacted by the drawdown of the aquifer. The caves to be studied were located at the boundaries of the potentially affected area of the aquifer drawdown. Two of the caves, Banded Pit and Skylight, went down to the local water table at depths of approximately 27 meters. An environmental company, ZARA, was hired to conduct the biological inventory. The inventory was conducted over the course of several months and included the baiting of traps and aquatic areas. Three visits were made to each cave. ZARA Environmental conducted inventories of terrestrial and aquatic subterranean fauna in the three gypsum caves. All three caves showed a broad array of terrestrial invertebrate fauna, including typical cave fauna such as *Ceuthophilus* crickets, *Rhadine* ground beetles, *Cicurina* spiders, and *Speorthus* millipedes. Groundwater sampling for fauna revealed undescribed new species of *Parabogidiella* amphipod known only from Skylite Cave (Figure 3), and a new species of copepods. Also identified were ostracods. Terrestrial fauna include an undescribed species of *Rhadine* beetle that may be a new species or one that is only known from gypsum caves nearby (ZARA Environmental, 2012).

Knowing that unique species may be affected by aquifer drawdown and that the ranching communities depend on the water supplies, it was determined that a very specific groundwater monitoring plan should be developed to track any drops in the aquifer in the Burton Flats karst plain and develop a water monitoring plan to track any critical changes in the aquifer' stable levels.

The monitoring plan involved the installation of several groundwater monitoring wells as part of the solution mining project. These wells would further define the Magenta Aquifer unit and associated potentiometric surface across the project area. Additionally, they would be used to document and analyze drawdown from the project pumping wells screened in the Rustler Formation (Magenta and Culebra Dolomite Members). An "early warning" water monitoring well was installed between the pumping wells and the monitoring wells in the Burton Flats karst plain.

Six of the new monitoring wells in the Burton Flats karst plain network would be used to evaluate potential

Figure 3. *Undescribed new species of Parabogidiella amphipod known only from Skylite Cave.*

impacts to the aquifer associated with the three caves: Skylight Cave, Banded Pit Cave and Macha Cave. These wells were installed as pairs adjacent to the 3 caves. One well was completed to the bottom of the Magenta dolomite and a second well was completed to the bottom of the Culebra dolomite. (Figure 4)

The wells were completed in the Magenta and Culebra aquifers using perforated casing in an open hole to allow aquatic wildlife to enter and provide an opportunity for biologic sampling. Each well was equipped with a submersible water pump and a 4 centimeter tube attached to the inside of the well casing, in which an electronic datalogger is installed. The datalogger records stage height, temperature, ph, dissolved oxygen, and conductivity. The monitoring wells are sampled every three months for basic water chemistry and water levels. High volume pump tests will be conducted in the Culebra formation with monitoring in the Magenta to detect drawdown. This will provide information necessary to determine if the two aquifers are connected.

In addition to the requirements for the mining company the BLM installed rain gauges near the cave entrances to collect that data and analyze the correlation of rainfall data to the water levels in the caves. The BLM has also installed data loggers in the lakes within the caves. These data loggers record water height and temperature. This information will be correlated with the monitoring well data to help analyze the reaction of rain events to the water heights in the caves and in turn in the local water tables.

The Bureau of Land Management has initiated an adaptive management strategy for the extraction of water from the Rustler formation. The water level monitoring being conducted before the project pumping wells go into operation will provide baseline data to determine if excessive drawdown is occurring. Water monitoring wells will be logged approximately two years before project pumping begins. A water monitoring plan has been developed identifying a drawdown trigger point. If water levels in the Burton Flats karst plain drop 5 feet (1.5 m) the pumping will stop and the solution mining project will get their water from a different source until the water levels return to baseline levels. Additional biologic samples will be taken in the water wells to look for further evidence of amphipods and other species. This will help to define and establish a range for the new species that were discovered.

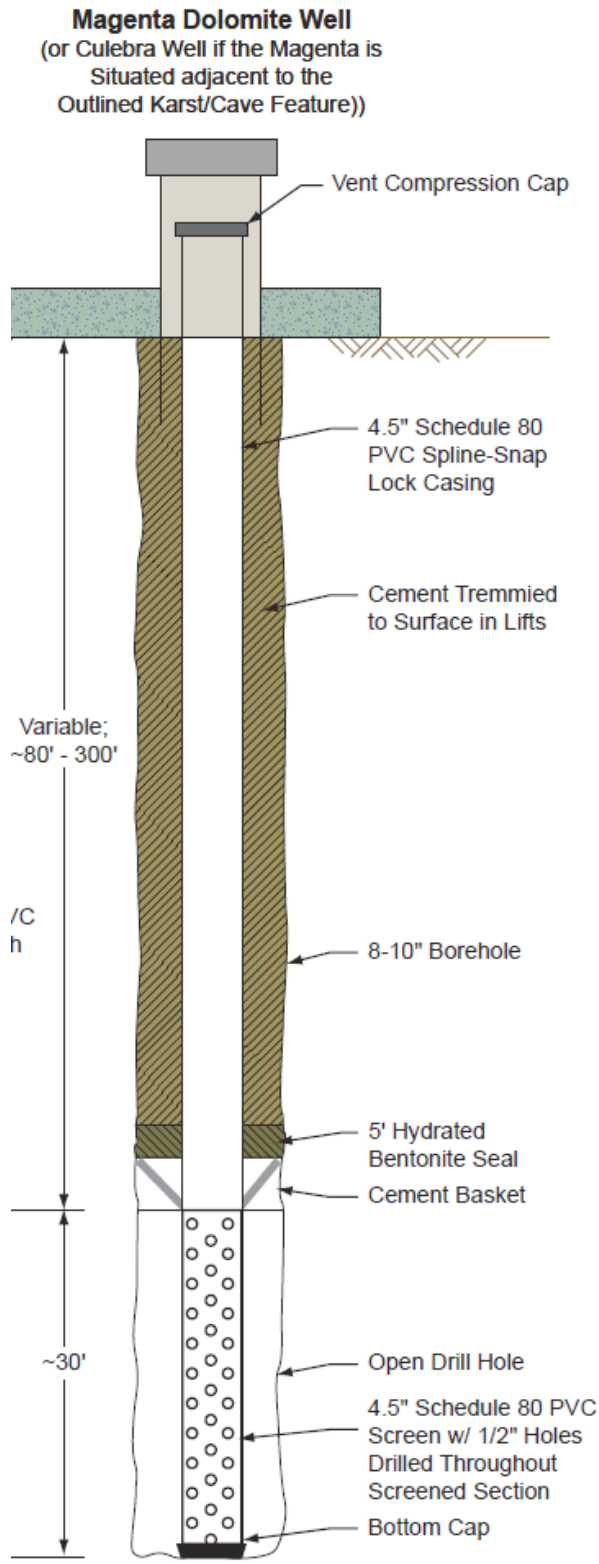

Figure 4. *Schemeatic of water monitoring well in karst aquifer.*

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Biography

Jim began caving at 9 years old with his parents and two sisters in central Texas where the "bug" bit him and he was infected with a lifelong desire to explore, understand, and protect underground resources. Much of his 33+ year career with the Bureau of Land Management has been developing their national Cave and Karst Management Program where he currently serves as the Senior Cave and Karst Specialist for the Washington Office. He assisted in writing the Federal Cave Resources Protection Act, their regulations, and implementation procedures and was instrumental in developing their national cave and karst management policies, manual and handbook, cave management training courses, national and local agreements, national cave safety standards, and guidelines for oil & gas drilling in karst areas. Jim is an Honorary Life Member, Fellow, and past board member of the National Speleological Society, a Fellow of the Cave Research Foundation, and a Charter Life Member of the American Cave Conservation Association. His interests, education, and career have led him into all aspects of cave exploration, science, and karst management. Caving and cave management have taken Jim to 16 foreign countries. Jim has authored over 25 publications on cave and karst management and geology. He earned his BS in Park and Recreation Management from Texas A&M University and conducted his graduate studies in Cave/Karst Geology/Geomorphology at Western Kentucky University in 1979-81.

POSTGLACIAL FAUNAL RECORDS FROM CAVE DEPOSITS IN JASPER NATIONAL PARK, ALBERTA, CANADA

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Abstract

In 2009, we initiated an on-going, long term research project that focuses on exploration of fossil-bearing cave deposits in Jasper National Park. Specifically, we were interested in understanding patterns of mammalian re-colonization of mountainous regions following late Pleistocene deglaciation. Our work has focused on the identification of fossil-bearing cave deposits, excavation and sampling of those deposits, and radiocarbon dating of recovered remains. Examined sites have at least an age of 9600 years BP. Research at four cave sites, located in relatively close proximity to one another, is contributing to an improved understanding of the late Quaternary record of Jasper National Park. This project is an example of a cooperating partnership between institutions (museum, national park and technical college) and assistance from a speleological society.

Introduction

Previous studies concerning Quaternary faunal remains from the Canadian Rocky Mountains highlighted the potential for recovery of rich vertebrate assemblages in cave deposits (Burns 1982, 1989, 1991, 2004). Despite those studies, relatively few caves in the mountainous interior of western Canada have been systematically explored and evaluated for paleontological remains. In 2009, we initiated a research project that focused on exploration of fossil-bearing cave deposits in Jasper National Park.

At the outset of the project our objectives were to better understand prehistoric resources preserved within park boundaries and to explore research questions surrounding the Quaternary record of animals in western Alberta. Specifically, we were interested in understanding patterns of recolonization in mountainous regions of Alberta following recession of Cordilleran Ice in the late Pleistocene. Here we summarize the results of fieldwork at four cave localities situated within Jasper National Park and discuss the implications of that work for understanding Quaternary vertebrate biogeography at northern latitudes.

Discussion

Disaster Point Cave

Disaster Point Cave is located in the front ranges (eastern side) of the Canadian Rocky Mountains at 1082 m. The cave entrances occur at the base of a rather steep natural depression. Because of the position and structure of the cave entrances, the cave acts as a funnel for sediments, drifting snow and debris deposited upslope of the entrances. The cave also serves as a natural trap for many animals because of near-vertical aspects of its two entrances.

Fieldwork took place in 2009 and 2010, and included floor surface collection throughout the cave and systematic excavation of stratified sediments in an area known as the Terminal Dig. A working summary of identified fauna from Disaster Point Cave is presented in Table 1. Remains of mammals and anurans are the most common components of the assemblage, and a surprisingly rich assemblage of land snails was recovered.

AMS radiocarbon dates of 1700 ± 30 yr BP and 2650 ± 30 yr BP on charcoal collected from stratified sediments in the Terminal Dig suggest that the sequence of late Holocene faunal remains is relatively continuous. A slightly older AMS radiocarbon date (6090 ± 40 yr BP) on bone collagen from a pelvis of *Ursus americanus* provides the current known maximum age for fauna preserved in the cave.

Table 1. *Summary of identified faunal remains from Disaster Point Cave (DPC), Procrastination Pot and Ice Trap. X = present, cf. = tentative identification.*

TAXON	DPC - Terminal Dig	DPC – Surface Survey	Procrastination Pot	Ice Trap
Osteichthyes				
Osteichthyes indet.	X	-	-	-
Serpentes				
Serpentes indet.	X	-	-	-
Amphibia				
Anura indet.	X	-	-	-
Bufo sp.	X	-	-	-
Caudata indet.	X	-	-	-
Mammalia				
Chiroptera indet.	X	X	X	-
Sorex sp.	X	-	-	-
Heteromyidae	X	-	-	-
Erithizon dorsatum	-	X	X	-
Tamiasciurus hudsonicus	-	X	X	-
Marmota sp.	-	-	X	X
Muridae	X	-	-	-
Arvicolinae indet.	X	-	-	-
Neotoma sp.	-	X	X	X
Lepus sp.	-	X	-	-
Lynx sp.	-	X	-	-
Mustela sp.	X	X	-	-
Gulo gulo	-	X	X	-
Ursus americanus	-	X	-	-
Ursus sp.	-	X	X	-
Ovis canadensis	-	X	cf.	-
Oreamnos americanus	-	-	-	cf.

Procrastination Pot

Procrastination Pot is a cave located on a ridge below tree line at 1650 m along the front ranges of the Canadian Rocky Mountains. Like Disaster Point Cave, the triple pit entrances of Procrastination Pot act as natural funnels or traps. Living inhabitants of the cave include bushy-tailed wood rats (*Neotoma cinerea*) and little brown myotis (*Myotis lucifugus*). The most recent winter census (2011) recorded 700 bats using the cave as a hibernaculum. Vast quantities of bat bones (some calcified) occur in the cave, suggesting long-term use of this cave. A radiocarbon date of 5780 ± 110 yr BP on a sample of bear (*Ursus*) bone indicates a mid-Holocene age for portions of the cave.

Ice Trap

Ice Trap is a high elevation cave, situated above tree line at 2183 m. The vast majority of the cave environment remains at subzero Celsius temperatures throughout the year and houses impressive ice formations. With a total surveyed length of over 3 kilometres and a depth of –347 m, it is Jasper's longest and deepest cave. Surface skeletal remains and dung of woodrats (*Neotoma* sp.) and marmots (*Marmota* sp.) are abundant near the entrance. Woodrat droppings are found more than 500 m from the single known entrance. Indurated woodrat middens occur in at least two areas of the cave. Radiocarbon dating of individual dung pellets from one of the middens resulted in an early post-glacial age assignment (9600 ± 40 yr BP) for at least one area of the cave. That record is significant because it represents a rare, direct date on Quaternary microfauna from western Canada. Another radiocarbon date (4620 ± 40 yr BP), based on a bulk sample from a second indurated midden, suggests a mid-Holocene age for use of the entrance areas of the cave.

Anticline Arch Cave

Anticline Arch Cave is situated near Ice Trap at a similar elevation. Environmentally and structurally, Anticline Arch Cave is significantly different from Ice Trap. This cave is only 28 metres long and -13 metres deep. However, a radiocarbon date on an ungulate tibia (9000 ± 40 yr BP) indicates that faunal material from the site is of comparable age to the oldest remains sampled from Ice Trap Cave.

Conclusion

Caves of the Canadian Rocky Mountains, for the most part, are relic fossil passages left over from before the most recent glacial periods. The known caves often are found in alpine plateaus, ridges, or steep slopes. Glacial and fluvial sediment infilling have made valley bottom cave entrances a rare phenomenon. Recovered remains provide insight into the post-glacial recolonization of the Canadian Rocky Mountains following deglaciation. AMS radiocarbon dates on woodrat dung from Ice Trap indicate the presence of small mammals at high elevations of the Canadian Rocky Mountains by 9600 yr BP and even some ungulates by 9000 yr BP (Anticline Arch Cave). Faunal remains from Procrastination Pot and Disaster Point Cave suggest that much of the modern biota of Jasper National Park was present by the mid-Holocene at the latest.

The large quantities of bat bones accumulated on the floor of Procrastination Pot, resembling a bed of pine needles, implores more investigation. Although the current residents are little brown myotis (*Myotis lucifugus*), examination of skulls could be undertaken to determine if there has been any shift in species use of this cave.

This research project is an example of a cooperating partnership between institutions (museum, national park and technical college) and assistance from a speleological society. The Royal Alberta Museum has the paleontological expertise, Jasper National Park provides the local area knowledge and logistic support, Northern Alberta Institute of Technology brings field study and travel skills and the Alberta Speleological Society travel skills and logistic support. Three of the four caves require single rope technique to access the cave environment.

Acknowledgements

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UNDERSTANDING A GLOBALLY UNIQUE NEXUS OF ACID MINE DRAINAGE, KARST AND WORLD HERITAGE SITE

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ABSTRACT

The Cradle of Humankind World Heritage Site (COH WHS), South Africa, is the only UNESCO-protected karst landscape in the world that is under threat from acid mine drainage (AMD). This has generated wide and considerable concern for the preservation of the fossil sites and karst ecosystems of the WHS. A recent assessment of the water resources environment and continued water resources monitoring has better informed this situation, providing support for management efforts to protect the aquatic environment and outstanding universal value of the site. Allogenic recharge of AMD (salinity >300 mS/m, pH <4, Mn ~30 mg/l) at ~18 megalitres/d and of municipal wastewater effluent (salinity ~100 mS/m, pH >7, PO4-P ~4 mg/l, *E. coli* ~240 000 cfu/100 ml) at ~3 megalitres/d on average from losing surface drainages, combined with a mean autogenic recharge of ~30 megalitres/d from natural precipitation, define the principal inputs to the karst hydrosystem. Their combined impact on the hydrophysical environment is manifested as a rise in groundwater levels of as much as 6 m in the space of a few years. Each input adds a characteristic hydrochemical signature to the associated recharge component that imprints itself variedly on the karst groundwater chemistry. The association of an observed ~3 m rise in Sterkfontein Caves water level with an AMD impact, however, is contradicted by a weak mine water signature in the cave water chemistry (salinity ~60 mS/m, pH ~8). The paper explores the new understanding that informs these circumstances and a hydrovulnerability assessment of each fossil site.

Biography

In a career that spans more than 30 years across both the public and private sectors, Phil is a registered Professional Natural Scientist currently employed by the Council for Scientific and Industrial Research as a Senior Research Hydrogeologist. His experience covers a wide range of groundwater studies across a broad spectrum of geological and hydrogeological environments. The studies include the exploration and development of groundwater resources for water supply purposes on a local (domestic) and municipal (bulk) scale, the evaluation and assessment of land use activities, such as waste disposal, industry, mining, and residential development, on the groundwater environment, and the mapping of groundwater resources on a regional scale. His principal professional interest is karst hydrogeology and speleogenesis. He served on the Team of Experts advising the Inter-Ministerial Committee on acid mine drainage, and is a member of the Inter-Governmental Task Team on AMD with an individual focus on water resources monitoring.

UNDERSTANDING AND MANAGING KARST WATER RESOURCES IN BELIZE: CASE STUDIES OF BOTH PAST AND PRESENT IN A CHANGING CLIMATE

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Abstract

Belize is a developing country that faces water resource issues in the forms of both quality and quantity, stemming from a long history of environmental stress and population threats, from the ancient Maya to present. Belize's karst landscape, which comprises a large part of the country from the coast to the Maya Mountains, is characterized by springs, caves, sinkholes, and aquifers systems formed from the dissolution of carbonate (limestone, dolomite) rock. This research presents several different case studies, spanning from the ancient Maya and issues with drought to modern communities that rely on groundwater resources quickly being depleted. Past drought patterns may recur, and their effects on population and the environment in areas like Orange Walk in the north to Gales Point in the south, where villages and towns surrounded by karst remnants have limited access to fresh, clean water. Part of this research used cave sediments to examine past vegetation change and the impacts of the Maya on the landscape on the Vaca Plateau to provide a history of socio-environmental interactions. We also examined the modern water resource issues for Belize, and have several pilot projects underway throughout the region to study and resolve these issues and compare the modern population to that of the Maya to better understand issues from future drought and climate change.

Introduction

Belize is a developing country that faces water resource issues in the forms of both quality and quantity. Part of this stems from a long history of drought and climatic change resulting in environmental stress and threats to populations, from the ancient Maya to present. Belize's karst landscape, which comprises a large part of the country from the coast to the Maya Mountains in the west, is characterized by springs, caves, sinkholes, and aquifers systems formed from the dissolution of

carbonate (limestone, dolomite) rock (Figure 1). This environment provides substantial groundwater resources. These significant karst landscapes are susceptible to development, pollution, and agricultural impacts, as well as overpopulation. The country has 39 watersheds, 18 of which are considered to be major watersheds such as rivers, streams and groundwater aquifers. The country's major economic drivers are tourism and agriculture, both of which rely heavily on Belize's natural resources (Barnett et al. 2011). Although agriculture is second to tourism economically, the government of Belize has identified the improvement and expansion of agriculture as one of the principal aims of national development planning. This research presents several different case studies, spanning from the ancient Maya and examining past drought issues and their effects on population and the environment, to modern Belize, in areas like Orange Walk in the north and Gales Point in the south. These communities subsist on agricultural and community wells that are going dry, and suffer from water quality issues. In Gales Point, where a village of 500 people live on a peninsula in a lagoon surrounded by karst remnants and whose access to fresh, clean water is limited by several environmental and social issues, this is especially problematic. There is also a need for improved water quality monitoring and testing, as the karst landscape provides little filtration in most areas, and the rural communities in particular rely on wells or springs for their water supply, which often are contaminated by agricultural pollutants, or when they are unusable cause people to turn to inadequate water sources to survive.

Figure 1. *Map of study area.*

Study Area

Belize, a subtropical country, experiences a dry season from December to May and a wet season from June to November. The mainland's topography consists of a mountainous, forested southern region and a flat northern region. In the peak rainfall month of July Southern Belize receives on average 70 cm of rain while for the same month the northern part of the country receives on average less than 25 cm. The Maya mountains found in the southern part of the country are composed of unmetamorphosed to slightly metamorphosed late Palaeozoic sedimentary rocks and granitic intrusions, while the northern, western and southern flanks of the mountains are flat-lying Cretaceous limestones. The northern part of Belize is a complex of Tertiary limestones and marls with many shallow closed-depressions, and Quaternary alluvial deposits, and swamps (James and Ginsburg 1979; Miller 1996) underlain by the flat lying carbonate deposits of Cenozoic age.

Methods

Recent studies have sought to better understand the socio-environmental dynamics of the Maya civilization in Belize, and since 2004 research in the north Vaca Plateau has focused on using geological proxies for reconstructing local and regional paleoenvironmental conditions. Since 2007, studies using cave deposits from the Vaca Plateau have proven to be effective in delineating periods of climatic and land use change sequences that help explain the waning of the Maya population in the area (Polk et al. 2007). To further refine the paleoenvironmental information that is already known about the study area, several lines of investigation were initiated in 2010 involving geoarchaeological field reconnaissance, and sampling of cave sediments and carbonate deposits to compliment the developing archaeological record. The primary research area focuses on the Minanha and Lower Dover archaeological sites. During two field seasons (2010, 2012), eight sediment core samples from caves in the study area near the Lower Dover and Minanha sites were collected (Figure 2, 3). Currently, processing of the new sediment cores is underway for radiocarbon dating, with a focus on establishing a chronology of up to 3000 years. Work

Figure 2. *Collecting sediment cores from Box Tunich Cave (photo by Jason Polk).*

on these core samples involves analyzing the sediments for $\delta^{13}C$ data to understand land use change from past human-environmental interactions. A driving hypothesis is that the location of these Maya population centers were the first to be susceptible to increasing drought and environmental degradation because of the nature of the highly-drained, thinly mantled karst topography, leading to issues with access to water for agricultural purposes.

Similarly, many other modern communities living upon the fragile karst aquifers of the country are also currently suffering problems due to these same types of climate change and water issues. The community of Gales Point, existing on a small karst peninsula (Figure 4), has struggled with water access for decades, relying on a small well and pumping system, and sometimes from a spring-fed stream during the wet season. In the past decade, the well was drilled and a pump installed a few miles from the village and water is pumped to a storage tower. In recent years, flooding, hurricanes, and equipment issues have caused continued problems with the water supply, and water quality remains an issue.

In Gales Point, as well as in Orange Walk and Corozal in the north, we are working to study the effects of these climatic changes and karst groundwater issues on the community and their perception of water treatment efforts and availability. This is being completed using participatory needs assessments, water quality studies monitoring fecal coliform bacteria on a monthly basis, and an isotope hydrology study to determine storm variability, recharge characteristics, and groundwater flow patterns. The research includes community assessments regarding water resources, karst landscapes, and sustainability knowledge. It also entails methods to survey, delineate, and assess karst groundwater

Figure 3. *Cutting and processing of sediment cores for carbon isotope analysis (photo by Jason Polk).*

sources, as well as developing water quality monitoring and outreach programs with partners to develop a comprehensive plan to address these issues.

Results and Discussion

As requested from the CARICOM Heads of Government, the Caribbean Community Climate Change Centre produced an Implementation Plan to guide the delivery of the 'Regional Framework to Achieving Development Resilient to Climate Change.' This plan identifies the regional strategies for coping with climate change and requires strategic action for the quantification and mapping of groundwater resources in the CARICOM Member States (Caribbean Community Climate Change Centre 2011). Throughout the wider Caribbean region, Global Climate Model-based rainfall projections under a 1° to 2°C increase in temperature are indicating a decline in annual rainfall and annual rainy days throughout the region (Nurse and Sem 2001; Solomon et al. 2007). The magnitude and extent of impact this will have on

Figure 4. *Map of Gales Point, Manatee, a small karst peninsula jutting out into the lagoon (map modified from Google Maps).*

Belize's water resources is currently unknown. This lack of knowledge is detrimental to the development of Belize as groundwater is the main source of water for irrigation and serves as potable water in many rural areas of Belize. Just as with the ancient Maya in the past, the future is unknown as to how coping with a degrading environment, population growth, and water resource issues in the face of climate change will play out. With the country's vision of increasing agricultural earnings by increasing productivity, there is a projected increase in the consumption of water for agricultural purposes. This, coupled with the additional demand for water resources by a rapidly increasing population and the clearing of forested areas, will, with no doubt, diminish the country's available water resources per capita, much as it may have done to the ancient Maya civilization in the past (Figure 5).

The vulnerability of groundwater resources from climate change is of primary concern to developing countries, such as Belize, and is difficult to evaluate because technology, expertise, and data are currently lacking to accurately assess this climatic and socioeconomic threat (FAO 2000). The rapid increase in population and demographic spread, recent changes of land use, and the lurking threat of climate change are factors that can exacerbate the water deficit situation already being experienced in the northern portion of Belize (BEST 2008; BEST 2009). When groundwater abstraction rates exceed its sustainable yield, it can result in saltwater intrusion and drought; both are outcomes that can be further exacerbated by the potential impacts of climate change. With increased agricultural practices in Northern Belize and unknown aquifer recharge areas there is also a high risk in the contamination of groundwater resources by agrochemicals that can have human health implications.

The government of Belize has identified the expansion and improvement of agriculture as one of the principal aims of national development planning. In northern Belize, agriculture is a vital sector with 43% of all farms

Table 1: Physical description of the Box Tunich sediment core.

Depth (cm)	Color	Description
0-1	7.5YR 5/4	silty, poorly sorted
1-2	7.5YR 3/4	silty, poorly sorted
2-3	7.5YR 3/4	silty, poorly sorted, small quartz pebbles
3-4	7.5YR 3/4	silty, poorly sorted
4-5	7.5YR 3/4	silty, poorly sorted
5-6	7.5YR 5/3	silty, loose, some clay
6-7	7.5YR 5/3	silty, poorly sorted, some clay, small quartz pebbles
7-8	7.5YR 5/3	silty, loose, some clay, small bones fragments
8-9	7.5YR 5/3	silty, loose, some clay, small bones fragments
9-10	7.5YR 4/6	silty clay, some inclusions of 5YR 4/6 clay, tiny bone pieces
10-11	5YR 4/6	silty clay
11-12	5YR 4/6	poorly sorted, inclusions of 5YR 4/4, silty
12-13	5YR 4/6	silty clay, poorly sorted
13-14	5YR 4/6	poorly sorted silty clay
14-15	5YR 4/6	poorly sorted silty clay
15-16	5YR 3/6	some organics, silty clay
16-17	5YR 3/4	silty clay with some gravel
17-18	5YR 3/4	silty clay w/ Mg deposits
18-19	5YR 3/3	organic matter w/Mg deposits, charcoal rich
19-20	5YR 1/2	dark organic layer w/ Mg and Fe staining, thick calcite crystal deposit (flowstone?)
20-21	5YR 1/2	dark organic layer w/ Mg and Fe staining, thick calcite crystal deposit
21-22	5YR 1/2	dark organic layer w/ Mg and Fe staining, thick calcite crystal deposit
22-23	5YR 1/2	dark organic layer w/ Mg and Fe staining, thick calcite crystal deposit
23-24	5YR 1/2	dark organic matter, clay, bacterial residue
24-25	5YR 1/2	dark organic layer w/ Mg and Fe staining
25-26	5YR 1/2	dark organic layer w/ Mg and Fe staining
26-27	5YR 1/2	dark organic layer w/ Mg and Fe staining
27-28	5YR 1/2	dark organic layer w/ Mg and Fe staining
28-29	5YR 1/2	dark organic layer w/ Mg and Fe staining
29-30	5YR 1/2	dark organic layer w/ Mg and Fe staining
30-31	5YR 1/2	dark organic layer w/ Mg and Fe staining
31-32	5YR 4/6	clayey, some rounded quartz pebbles
32-33	5YR 4/6	sandy clay, some rounded quartz pebbles, clasts of 5YR 5/8
33-34	5YR 4/6	sandy clay, quartz pebbles, calcite flakes
34-35	7.5YR 5/6	sandy clay, quartz pebbles, calcite flakes
35-36	7.5YR 6/6	sandy clay, rounded, black quartz pebbles, limestone pieces
36-37	7.5YR 5/6	sandy clay, rounded, black quartz pebbles, limestone pieces
37-38	7.5YR 5/6	sand and quartz pebbles

Figure 5. *Example of sediment core variability, indicating changes in erosion and vegetation from climate change over time.*

located in that region of the country, and also one of the heaviest users of groundwater, while concurrently a potential source of pollution (Day 1996). Northern Belize experiences water deficit during the dry season, receiving approximately 130cm/year of rainfall, which is a third of the precipitation of southern Belize (Marfia 2004). This is a major concern as groundwater supplies about 95 percent of the rural population. Another major factor in water access and quality is the karst hydrogeology of this region, wherein water rapidly flows underground to aquifer systems, bringing with it possible contaminants, and even some sources disappear, as in the case of Five Blues Lake (Figure 6) (Day 1996; Day and Reynolds 2012). This also leads to a lack of surface water in the form of rivers or lakes, and creates problems in being able to easily and accurately predict groundwater recharge and flow patterns. Solutions to these challenges can be achieved through an improved understanding of groundwater system and recharge variability, an increased ability to manage water resources through planning, and an improvement in the capacity of local communities and the national University to maintain these efforts in the future. The project's main goal is therefore to ensure water security in the face of climate change through the capacity building of Belizeans and the generation of data necessary to produce a comprehensive water balance

Figure 6. *Five Blues Lake, located in central Belize, which is a karst feature that drained in a matter of days in 2012, and has done so several times. It serves as the nearby village's water supply (photo by Bill Reynolds).*

estimate for the vulnerable karst regions of the country of Belize. This can then be updated periodically as data are collected and technology and training are improved.

An example of successful outcomes is at Gales Point, where previous use of chlorination cause problems with locals misunderstanding the chemical taste and not wanting to use the water. Recently, thanks to support from the Merritt Island Rotary Club in Florida, a UV light filtration system was installed in the community school, which provides clean water continuously, with low-cost and maintenance, as a pilot project for the community (Figure 7).

In collaboration with the Belize Ministry of Health (water division) and Ministry of Rural Development, we are working on education programs and capacity building to implement this system in the community, as well as others in the country. We are also working with the University of Belize on a climate and water program related to this research, and with the CCCCC regarding a high-resolution climate model for Belize to better predict variability over the next century. Having a cultural understanding of past water issues facing populations like the Maya, and those living similar in regards to water access and quality, and natural resources, in the present, allows researchers to better address water resource problems in the country. This work involves cooperation with state and local governments, public officials, educators, and students to address these issues from a variety of angles, and help us learn about using the present and the past to live sustainably in karst regions.

Figure 7. *AJ Strenecky of the Goshen Rotary and Mr. Anthony Flowers of the Ministry of Health inspecting the newly installed UV water purification system (photo by Jason Polk).*

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Biography

Jason S. Polk, Ph.D. is the Associate Director of Science for the Hoffman Environmental Research Institute and an Assistant Professor of Geography and Geology at Western Kentucky University. He earned his doctorate degree from the University of South Florida in Geography and Environmental Science and Policy, where his research focused on karst speleogenesis, climate change, and water resources. Dr. Polk's current research investigates the geomorphology and hydrology (including water quality) of karst environments, isotope geochemistry, karst resource inventory and management, and the influence of climate change on paleohydrology. He has published over 30 peer-reviewed papers and abstracts, is a Fellow of the National Speleological Society, and is Secretary of The Karst Conservancy. He is also a member of the Geological Society of America, American Geophysical Union, International Association of Hydrogeologists, and Association of American Geographers.

PALEOHYDROLOGY AND THE ORIGIN OF JEWEL CAVE

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Abstract

With more than 270 km (168 miles) of mapped cave passages, Jewel Cave is the third longest cave in the world. The passages are beneath an area of 775 ha (3 mi^2), located almost entirely within the Hell Canyon drainage basin. The canyon itself is situated in the bottom of a south-plunging syncline and most of the cave passages are located within the east limb. A down-dip cross section shows the cave passages assuming the shape of an elongate lens, located just below the Pahasapa/Minnelusa contact. The lower boundary is a maximum of 75 m (250 feet) below the contact, but thins at each end, where the permeable, basal Minnelusa sandstone is exposed.

Based on these observations, a conceptual model has been created to portray cave development as the result of local groundwater movement in geologically recent time. The apparent recharge was in the Pass Creek and Lithograph Canyon areas, and the discharge was in Hell Canyon. Groundwater initially moved through a shallow confined aquifer comprised of the basal Minnelusa sandstone, which was initially confined by the underlying Pahasapa Limestone and an overlying Minnelusa limestone. Although Laramide fractures provided secondary porosity, there is no evidence of sufficient connectivity to provide landscape-scale permeability. As water from the sandstone circulated into the discontinuous fractures of the Pahasapa, dissolutional enlargement integrated them to form the system of interconnected cave passages known today. The model precludes the need for direct recharge from rainfall, hydrothermal waters rising from below, or prior development of a Mississippian karst.

Introduction

In 1908 Jewel Cave became the first National Monument established for protection of a cave. It became part of the National Park Service (NPS) in 1933.

The first comprehensive geological study of Jewel Cave was conducted by Dwight Deal (Deal, 1962). In personal communication (c. 1980) he suggested that the Minnelusa sandstone might have something to do with the origin of the cave. The author has subsequently confirmed Deal's speculation and discovered new relationships – some of which are quite unexpected and don't fit what is commonly reported in geological literature. The relationships are compelling, and must be adequately addressed by any theory proposing an explanation of the origin of Jewel Cave. This paper presents the new concepts and attempts to integrate them into a broad framework to encourage and facilitate future research.

The ultimate goal is to develop a clear understanding of the nature of Jewel Cave. This will ensure a better interpretive story for the visiting public and provide a compelling justification for decisions that address external land issues. It improves the knowledge base necessary for better cave management.

Stratigraphy

Over the last 15 years, Jewel Cave National Monument has supported several projects to produce detailed geological maps of the Jewel Cave quadrangle and surrounding areas. These efforts have documented six distinct subunits within the Minnelusa Formation (Table 1), with a variety of lithologies, including limestone (LS), dolomite (DS), and sandstone (SS).

Table 1. _Subunits I through VI, within the Minnelusa Formation. Top of subunit VI is not present within the Jewel Cave quadrangle. Adapted from Davis (2003)._

Minnelusa Formation		Thickness
VI	brecciated SS, anhydrite	?
V	varicolored sandstones	37 m (120 feet)
IV	interbedded DS and SS	37 m (120 feet)
III	SS with LS cap	37 m (120 feet)
II	thin bedded cherty LS	15 m (50 feet)
I	cross-bedded SS	12 m (40 feet)

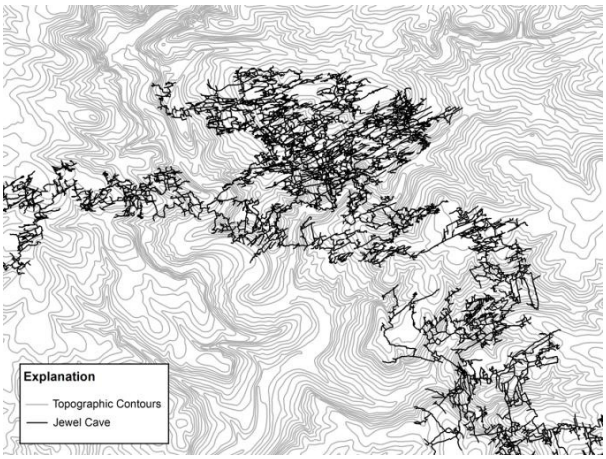

Figure 1. *Relationship between Jewel Cave and the surface topography.*

The remarkably consistent thicknesses enabled the mapping of subtle geologic structures that were previously unknown. Wiles (1992) identified the high permeability of the subunit I sandstone.

Spatial Relationships

In previous work, Wiles, Ohms, and Pflitsch (2009) demonstrated a close relationship between Jewel Cave and many modern day features, including topography, geologic structure, and stratigraphic contacts.

1. Topography

Most of Jewel Cave's passages are found beneath the hillsides. Extensive mazes of larger passages bottle down to just a few crawlways where the cave approaches Hell Canyon and Lithograph Canyon. Only a few passages actually cross beneath the surface canyons. The lack of surface fill material clearly shows that the cave has not been dissected by the canyons, after the fact. Thus, it appears that the cave formed concurrently with the canyons, and that its development was controlled by their hydrology.

2. Structure

Jewel Cave's passages correlate with Laramide structures, particularly in their relationship with faults and folds (Figure 2). Individual joint-controlled cave passages tend to terminate (or originate) at normal faults, with up to 12 m (40 feet) of vertical displacement. In some cases, small passages with atypical patterns cross a fault zone and connect with joint-controlled passages on

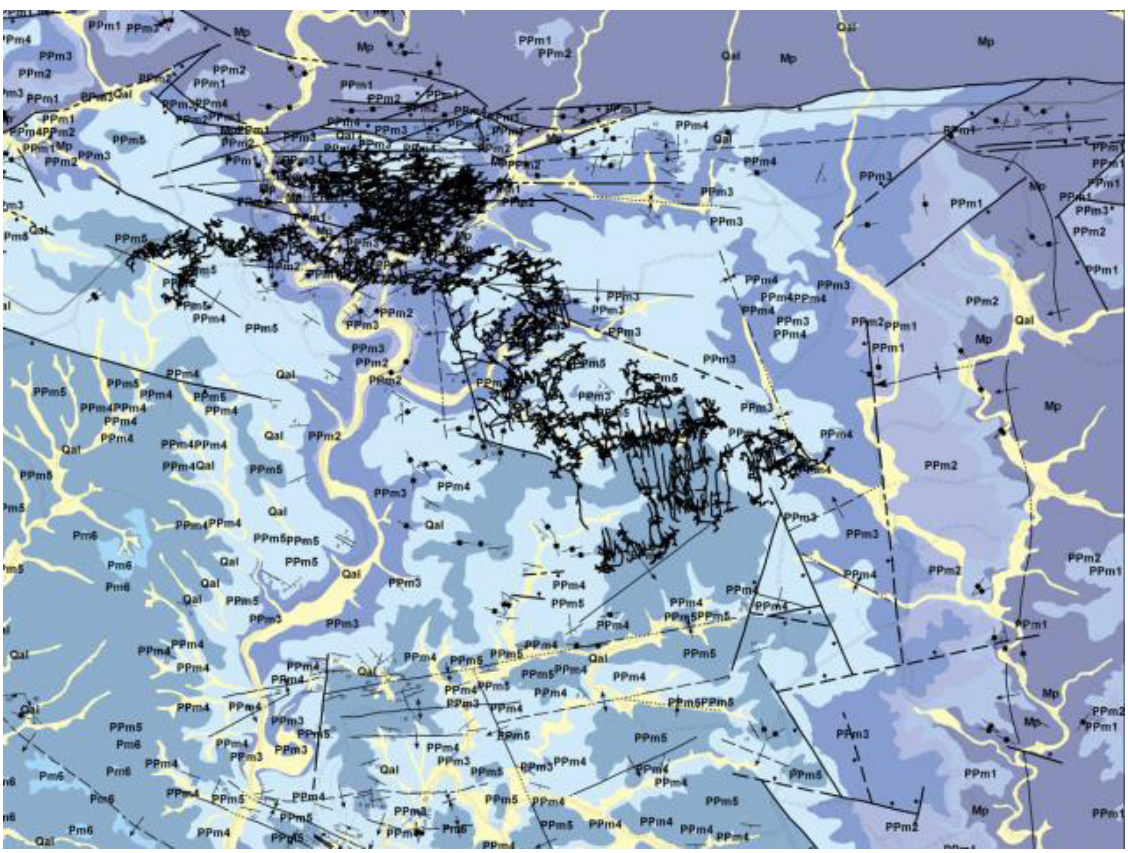

Figure 2. *Relationship between cave and geology. Adapted from Fagnan (2009).*

the far side, but there is no evidence of fault displacement cross-cutting pre-existing passages. All faults appear to pre-date the cave, and may even have played a role in directing phreatic groundwater flow and influencing the final distribution and character of cave passages.

Furthermore, Hell Canyon formed in the bottom of a broad, south-plunging syncline. The cave itself is congruent with this structural feature (Figure 3). It follows a curved geologic strike, and – with one exception, at the far southeastern extent of the known cave – dips toward the synclinal trough.

3. Geologic Contacts

All the large caves in the southern Black Hills exist beneath the Minnelusa cap, as it is configured today (Figure 4). Cave entrances are located at the contact, and the bulk of the passages are beneath the cap.

Currently, Jewel Cave has 270 km (168 miles) and Wind Cave has 227 km (141 miles) – over 500 km (300 miles) total. In sharp contrast, no cave over 150 m (500 feet) long is known to exist within the uncapped limestone.

This spatial relationship is compelling evidence that the Minnelusa was in some way responsible for the development of large cave systems. But, if this statement is true, two important questions naturally arise: Why didn't large caves form throughout the history of its erosional regression? Why are they only found where the cap remains today?

Considering the aforementioned relationships of the cave with modern topography and post-Laramide structure, a logical answer is that extensive cave development did not occur until around the time the Minnelusa had eroded to its present configuration. If this is correct, an additional question immediately presents itself: Could the present geomorphology have supported a cave-forming hydrologic system in the geologically recent past?

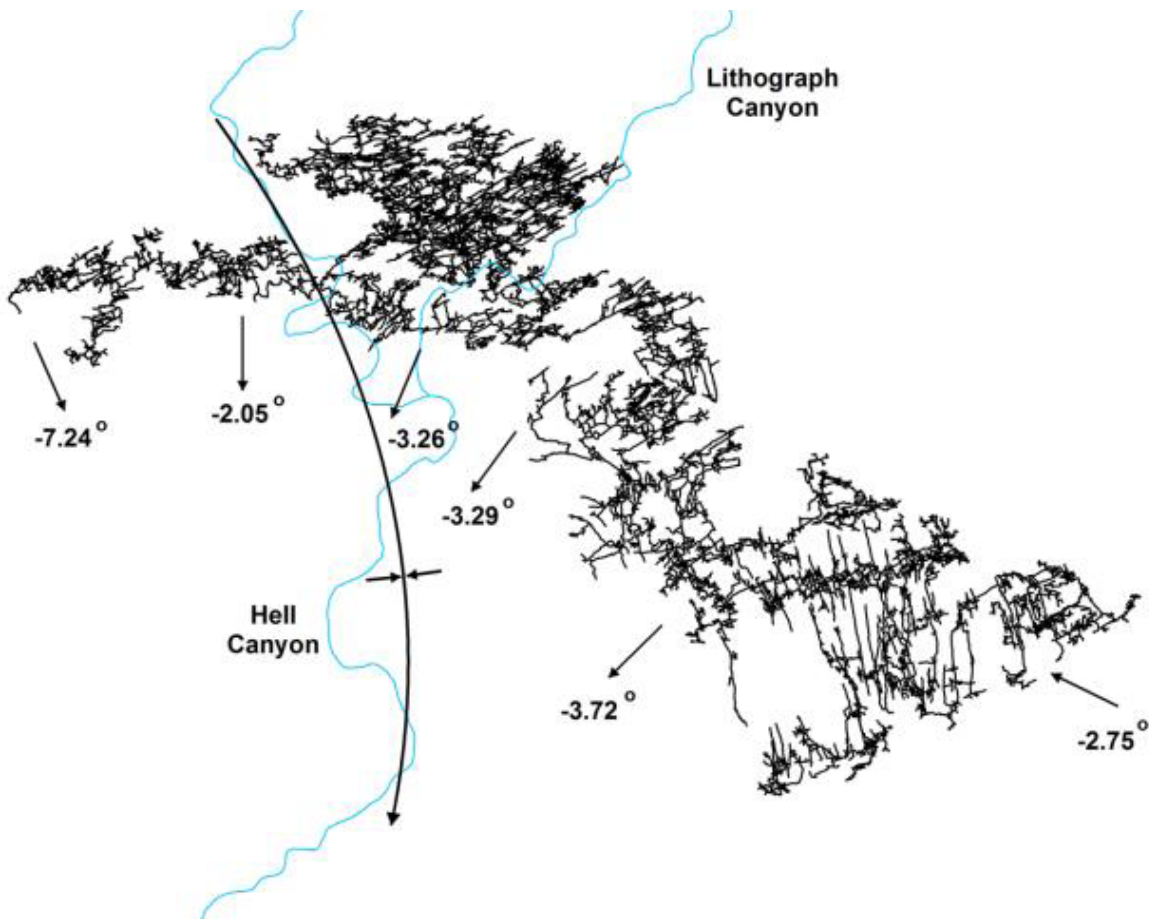

Figure 3. *Relationship between the variable dip of the cave and Hell Canyon.*

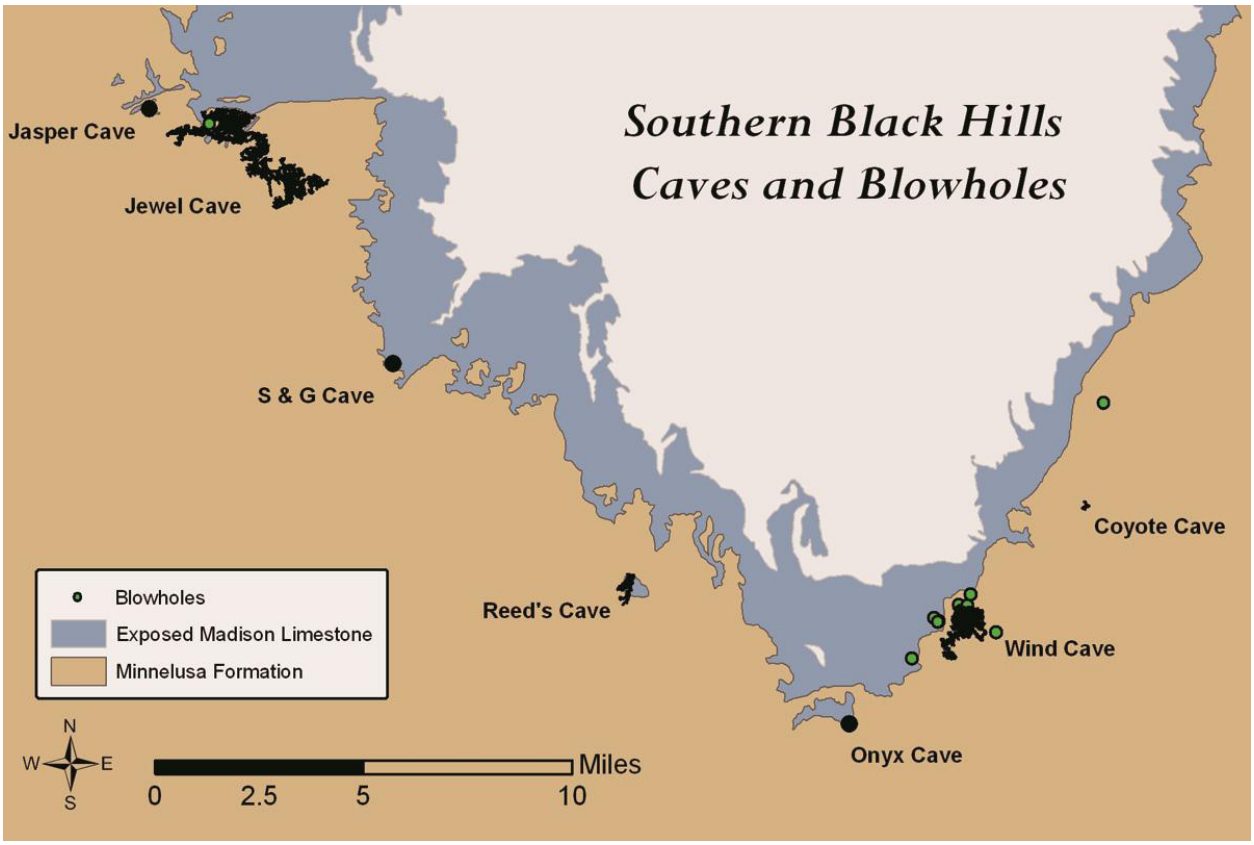

Figure 4. *Relationship between large caves and the Minnelusa cap.*

Hydrologic Setting

In simplest terms, dissolutional cave development is a mass transfer process, whereby water (the solvent) removes soluble rock (the solute). For this to happen, there must be 1) a recharge area, 2) a discharge area, 3) a gradient between recharge and discharge areas, and 4) initial connectivity between recharge and discharge areas.

At Jewel Cave, the recharge could not have been meteoric water entering directly from above, because of intervening impermeable layers – particularly a 10-foot layer of silica-cemented sandstone, located near the base of subunit III. Even today, direct infiltration occurs in less than 1% of the known passages, where erosion has breached the impermeable layers. In the remaining 99%, there is no evidence of dripping (such as the presence of dripstone), even in the distant past.

It is unlikely that recharge could have come from below, because the Pahasapa Limestone is underlain by the Englewood Limestone which, despite its name, contains enough basal shale to confine the underlying Deadwood aquifer with an average hydraulic head of 30 m (100 feet), based on reports by Dyer (1962) and Davis, Valder, and Sarratt (2006). It functions as an aquiclude, preventing the flow of water from below.

If the recharge didn't come from above or below, then it must have been introduced laterally from a more distant location. For purposes of this discussion, the subunit I sandstone is considered to have provided the primary initial connectivity between recharge and discharge areas.

The reason for this assumption is that, even with the secondary porosity afforded by fractured limestone, there is no evidence of landscape-scale *connectivity* within the Pahasapa Limestone. Even today, after the maximum enlargement of limestone fractures has occurred, there is an obvious sense of *discontinuity*, with large cave passages extending hundreds of feet before coming to an abrupt end; at which point there might be a small constriction that veers to a side passage or a different level.

Without initial connectivity, there could be no throughflow, and therefore, no mass transfer. However, throughflow *could* occur within the subunit I sandstone if

it had a sufficiently high initial permeability. Sandwiched between two relatively impermeable limestones (the underlying Pahasapa Limestone and the overlying Minnelusa subunit II limestone), it could function as a confined aquifer.

In the immediate Jewel Cave area, subunit I outcrops only in Teepee Canyon, Hell Canyon, Lithograph Canyon, and upper Pass Creek; all of which coincide with modern drainages. The highest elevations in Teepee Canyon and Pass Creek represent viable recharge areas. The outcrops in Hell Canyon and lower Lithograph Canyon are down-gradient, and represent obvious locations for discharge.

In the Figure 5, the upper contacts of subunit I are extrapolated across Hell Canyon and Lithograph Canyon to approximate the exposures prior to the final incision into the underlying Pahasapa Limestone. In Pass Creek, the lower contact was similarly extended to the east. In each case, the upper contact remains as it is seen today.

The sandstone exposures are shown in red and the blue arrows represent the most direct paths that could be taken by water moving from recharge areas to discharge areas. The fact that Jewel Cave's known passages are directly in line with the proposed flow paths appears to be more than mere coincidence. Although this is a rough estimation of what might have occurred, it is consistent with the other considerations just presented.

All things considered, the modern configuration *does* fulfill the requirements for recharge and discharge areas, gradient, and initial connectivity.

Cross-sectional Relationships

Figure 6 is a cross-section A-A' (yellow line in Figure 5) taken along a west-plunging anticlinal axis (superimposed on the broader south-plunging syncline), which coincides with the cave's only known natural entrance – as well as its only known paleontological fill, located just inside the entrance.

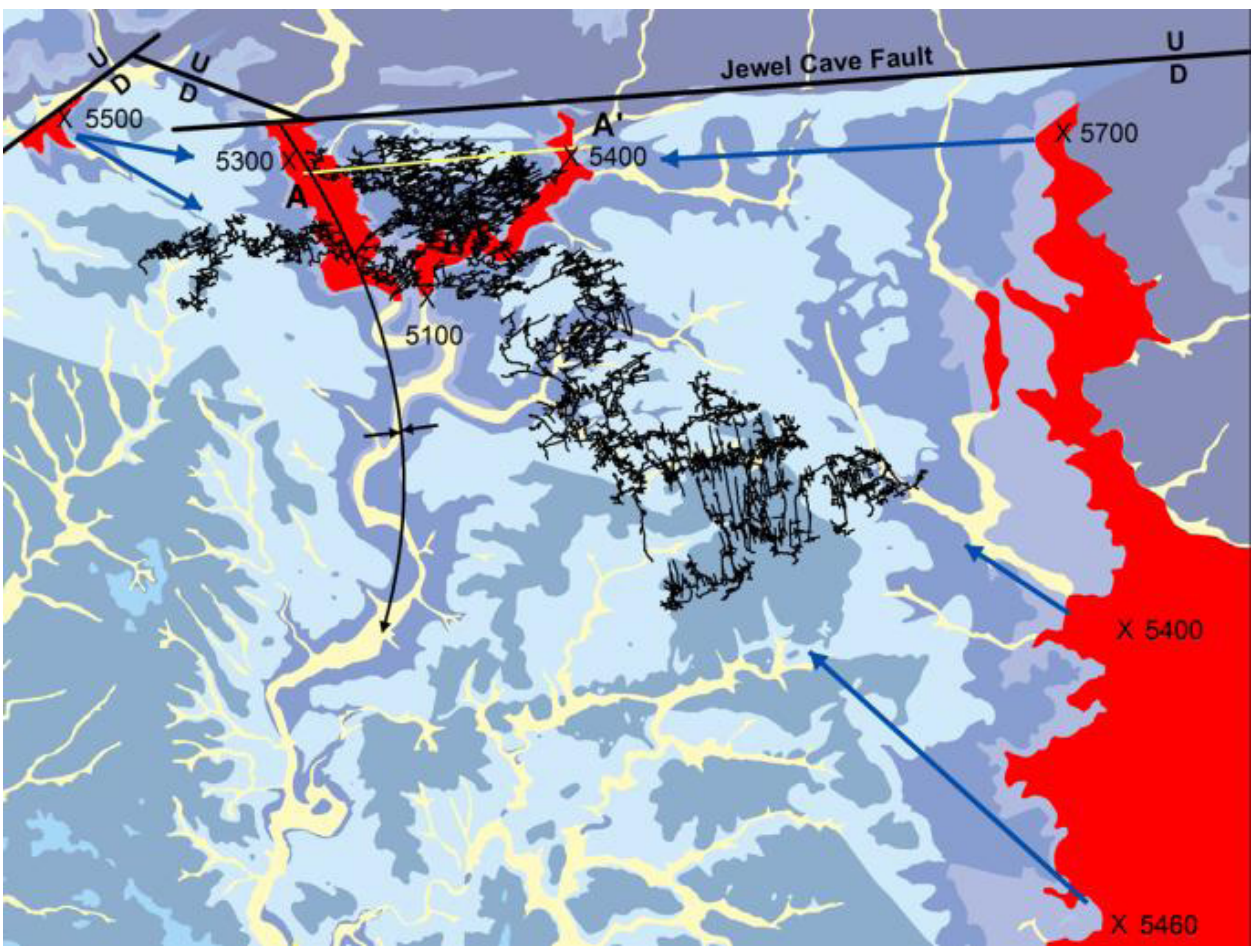

Figure 5. *Relationship between cave passages and exposures of basal Minnelusa sandstone.*

Near *A*, the subunit I sandstone is exposed at Hell Canyon; at *A'*, it is exposed in a tributary of Lithograph Canyon. Surprisingly, the cave has an obvious lens shape, which thins and rises up near Hell Canyon and the natural entrance. This is evidence that the primary dissolution event didn't occur prior to the uplift and erosion of the Hills or before Hell Canyon formed.

Regardless of what might have happened in the late Mississippian, it is clear that any paleocave development would have little bearing on what is seen here. The much-more-recent Hell Canyon clearly controlled the water flow that formed the cave.

It is also noteworthy that cave development consistently remains in the upper 75 m (250 feet) of the limestone, and that this relationship holds true even at Wind Cave, where the limestone is 25 m (80 feet) thinner.

Proposed Sequence of Events

Taking all these observations into account, a simple, straightforward sequence of events is proposed. The following description is based on the area represented by Figure 6, and ignores the possible hydrological influence of the Jewel Cave Fault.

1. Laramide uplift, and subsequent fracturing and erosion, brought the landscape close to its present-day morphology.
2. The Lithograph Canyon tributary (and upper Pass Creek) became losing streams and served as recharge areas. Hell Canyon became a gaining stream in the discharge area.
3. Initially, water flowed primarily through the sandstone (Figure 7), confined by the underlying and overlying limestones. This created a "blanket" of water that could reach all parts of the developing cave in a non-point manner.
4. Water circulated down from the sandstone, through isolated areas of fracture-enhanced permeability, and began to dissolve the cave in isolated "cells." Water in the sandstone would maintain nearly full capacity of CO_2 while the water dissolving the fractures would deplete CO_2, and there would always be active dissolutional mixing where the two waters met.
5. The enlarged cells eventually coalesced, integrating the voids in the limestone and taking on a greater proportion of the flow (Figure 8).
6. The basal Minnelusa sandstone contemporaneously collapsed into the still-forming cave (red spots in Figure 8), creating localized "neo-fill" (Wiles, 2012). The material is Pennsylvanian in age, but it was emplaced approximately 300 million years later.
7. Eventually, Hell Canyon was cut deeper, the climate dried, and the recharge ceased (Figure 9). There was no longer any through-flow, nor a fresh source of acidic water. Lack of flow caused the water to warm and reduced hydrostatic head caused the pressure to drop, resulting in the precipitation of calcite spar. This was followed by precipitation of manganese minerals (not shown).
8. After Hell Canyon had been cut 30 m (100 feet) into the limestone, perennial flow ceased and the cave slowly drained. Without buoyancy from the water, large cave passages collapsed (Figure 10).
9. Evaporative speleothems formed. Limited dripstone formed.

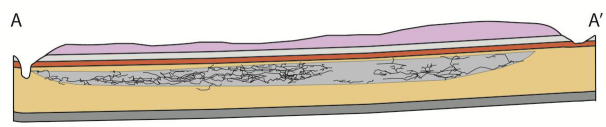

Figure 6. *Lens shape of cave passages.*

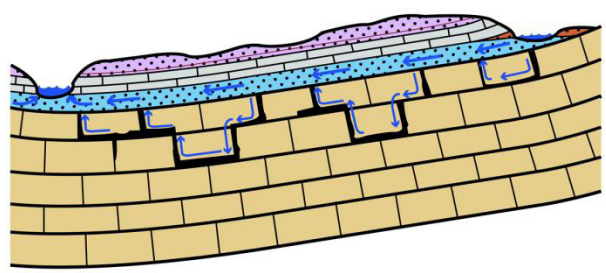

Figure 7. *Initial flow moves primarily through subunit I sandstone.*

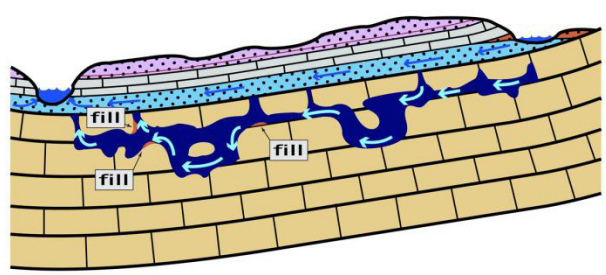

Figure 8. *Dissolution of fractured limestone.*

Conclusions

Several lines of evidence point to a geologically recent origin for Jewel Cave. Although the exact timing has not yet been pursued, it is reasonable to believe that cave development began just prior when the landscape reached its modern configuration. New information has been incorporated into a conceptual model that is simple and straightforward, and geomorphically compatible with the main surface and cave features. It precludes the need for direct recharge from rainfall, hydrothermal waters rising from below, or prior development of a Mississippian karst.

This conceptual model should not be viewed as a final answer, but as a challenge for future researchers to find answers that will adequately incorporate all the observations. It is a good starting point for addressing questions that, until recently, were not even known to exist.

The top two resources management goals identified in Jewel Cave's General Management Plan are: 1) to continue cave exploration and 2) to pursue methods of predicting where undiscovered passages will be found. This is especially important for a cave where nearly 50% of the known passages are located outside the park boundaries, and 97% remain undiscovered (Wiles, Ohms, and Pflitsch, 2009).

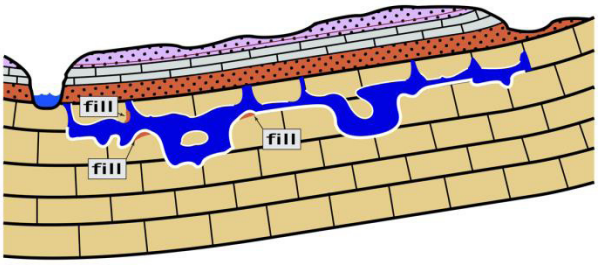

Figure 9. *Deposition of calcite spar.*

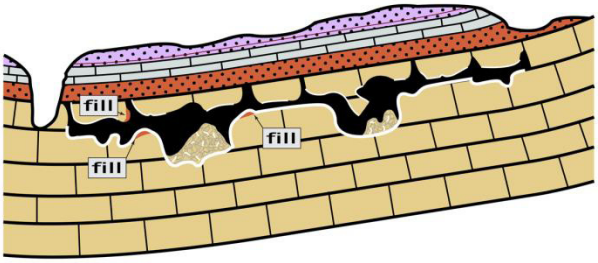

Figure 10. *Cave drains and large rooms collapse.*

Building on previous work, the model is the next logical step toward predicting the location of undiscovered passages. It bolsters the park's ability to justify external protection actions, such as mineral withdrawals and land exchanges. The early research has already been used to justify mineral withdrawals 1990 and 2008, totaling 2,825 ha (6,983 acres); and a land exchange in 2000, that converted 148 ha (366 acres) from private to Forest Service Land.

The NPS is mandated to make science-based management decisions. The better the science, the more meaningful the decisions will be.

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Biography

Mike Wiles was born in Huron, S.D. He was introduced to caving at the age of 20, by members of the Paha Sapa Grotto, of the National Speleological Society, then a student grotto at South Dakota School of Mines and

Technology. Since then, he has volunteered more than 7,000 hours toward the exploration of Jewel Cave and has helped discover more than 70 miles of passages. Mike has earned a B.S. in Chemical Engineering and an M.S. in Geological Engineering, both from SDSM&T. His 1992 Master's thesis is entitled, "Infiltration [of groundwater] at Wind and Jewel Caves, Black Hills, South Dakota. Mike has worked at Jewel Cave National Monument for over 30 years, first as an Interpretive park ranger, then as a Cave Specialist, and is currently the Chief of Resource Management for the park.

WATER COLUMN VARIABILITY IN A COASTAL TOURIST CAVE IN MALLORCA, SPAIN

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Abstract

Coves del Drac is visited by more than 1 million tourists annually and has been a tourist destination in the western Mediterranean for over 100 years. All areas of the cave are developed with historic or current tour route infrastructure, including walkways, handrails, and electric lighting. This study compares one vertical water profile collected along the current tour path with two other profiles from historic tour route locations. Differences in freshwater and organic inputs, as well as direct anthropogenic impacts, are clearly observed in the aquatic parameters and stable isotopes collected in the profiles. Anthropogenically-driven undersaturation in the cave pools, as well as rising sea level, may threaten the unique speleothem encrustations that are formed at the air-water interface within the cave.

Introduction

Mallorca, the largest island of the Balearic Archipelago, is located in the western Mediterranean. Tourists enjoy Mallorca's natural beauty; five show caves currently operate in Mallorca (Ginés and Ginés, 2011). Coves del Drac (Drac) is the most visited show cave in Mallorca, documented by over 1 million annual ticket sales, making it the most visited cave in Europe (Robledo and Durán, 2010).

Recent and ongoing research focus on the unique speleothem encrustations within Drac and other littoral caves in Mallorca. These phreatic overgrowths on speleothems (POS) are carbonate encrustations on pre-existing carbonate supports, and form at the air-water interface in brackish phreatic pools. Since the water table is coincident with sea level, POS are strong proxies for sea level reconstruction (Dorale et al., 2010; Ginés et al., 2012).

Both calcite and aragonite POS are observed in Mallorca's caves. Some caves contain POS bands of both minerals, where bands at different elevations correspond to different sea level elevations. The mineralogy of a POS band does not change for any given sea level stand, suggesting a relatively stable geochemical environment during each sea level stand. To date, only calcite POS have been documented in Drac.

Previous work on Mallorca's POS by Csoma et al. (2006) found that proximity to the surface of the water promotes degassing of CO_2, which in turn controls the precipitation of POS.

This study compares aquatic parameters and stable isotopes in a vertical water profile from the current tour route with two profiles collected proximal to the historic

trail in Drac. The objective of this study is to delineate variations in geochemistry throughout Drac in an effort to further understand the dynamic of POS precipitation at the air-water interface.

Study Area

Drac is located in the village of Porto Cristo, on the eastern coast of Mallorca (Figure 1). The land above the cave is developed to support the cave's tourism, including parking lots, cafes, and shops, surrounded by scrub vegetation. Drac is a typical mixing-zone cave, reflected by its large, randomly oriented rooms connected by small breakdown passages (Ginés and Ginés, 2007). The cave is developed in Upper Miocene reef carbonates and the current survey documents a mapped extent of over 2,300 m (Fornós et al., 2012), though ongoing cave diving expeditions add previously unexplored flooded passages to the known cave size.

Tourists enter the cave through an artificial entrance and observe the numerous speleothems as they descend to the water table at Llac Martel (Martel). Once seated in a large room that can hold tour groups of several hundred people, tourists listen to a short narrative about the cave, and then enjoy a short classical music concert, played from three rowboats that enter and exit the gallery from out of sight. When the concert is finished, tourists may continue the remainder of the tour route entirely on foot, or by boarding a rowboat for a portion of the exit path. One profile was collected in the area where tourists disembark from the boats on Martel (Figure 2).

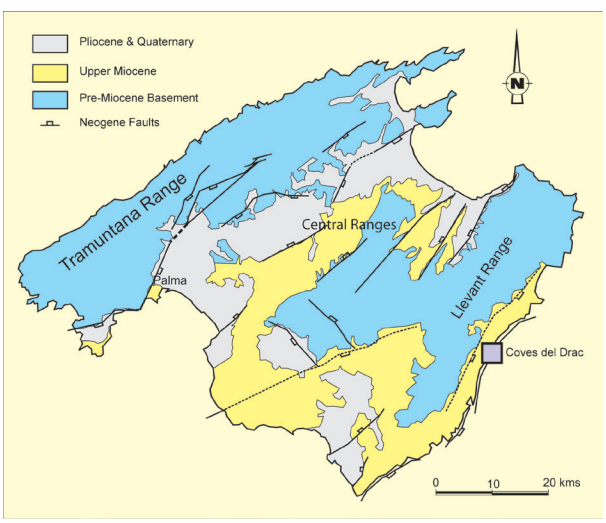

Figure 1. *Geologic map of Mallorca. Coves del Drac is developed in Upper Miocene limestone on the eastern coast of Mallorca.*

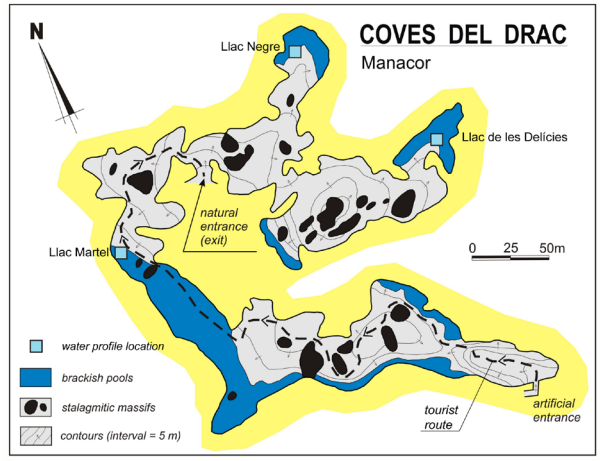

Figure 2. *Map of Coves del Drac with the current tour route, entrances, and water profile locations.*

All tourists exit the cave through its natural entrance, an obvious collapse feature.

The other portions of Drac are historic tour routes, and are similarly developed with concrete walkways (in various stages of disrepair), metal railings, and electric lights. The entrance and exit for the historic pathway is at the current tour route exit. Profiles collected at Llac Negre (Negre) and Llac de les Delícies (Delícies) are located in separate rooms. Negre represents the most distal expression of the water table with regard to the coast of the Mediterranean Sea, and is also the location of ongoing cave diving exploration. Calcite rafts float at the surface of both Negre and Delícies. POS are present at the air-water interface at all three sample sites (Figure 3).

Methods

In March 2013, vertical water column profiles were collected starting from the surface and ending at depths of 2.8, 2.6 and 2.6 m in Martel, Negre, and Delícies, respectively. Using a recently calibrated Hanna Instruments® 9828 Multiparameter Meter that was slowly lowered through the water column, temperature, pH, oxidative-reductive potential, dissolved oxygen, specific conductivity, total dissolved solids, and salinity were collected at 20-cm increments from the surface to the bottom at each profile location. Water samples for stable isotope analyses were collected at 50-cm increments using a 1-liter capacity LaMotte® Water Sampler. $\delta^{18}O$ and $\delta^{13}C$ were analyzed at the University of South Florida Department of Geology Stable Isotope Lab using a Thermo Fisher Scientific (Finnigan) Delta V Isotope Ratio Mass Spectrometer; results are reported

Figure 3. *The current calcite POS band, just below the water level, viewed from the tourist path at the Llac Martel sampling site. Width of photo is approximately 3 m.*

with respect to international standards VSMOW and VPDB, respectively, and analytical error is ±0.1‰.

Results and Discussion

Aquatic parameters show the greatest variability in Negre, and the least variability in the pool proximal to the tourist route, Martel. The profiles appear to trend toward convergence at depths exceeding 2 m (Figure 4).

The most consistent (least variability) values in all parameters are observed at Martel. This profile was collected at the location where tourists exit the boats, so homogenization is expected in at least the shallower depths. The warmest temperatures were observed at Martel.

Delícies had slightly lower temperatures than Martel, and similar consistency throughout the profile. Decreasing pH was observed with depth in the profile, and dissolved oxygen had an overall increasing trend with depth, but

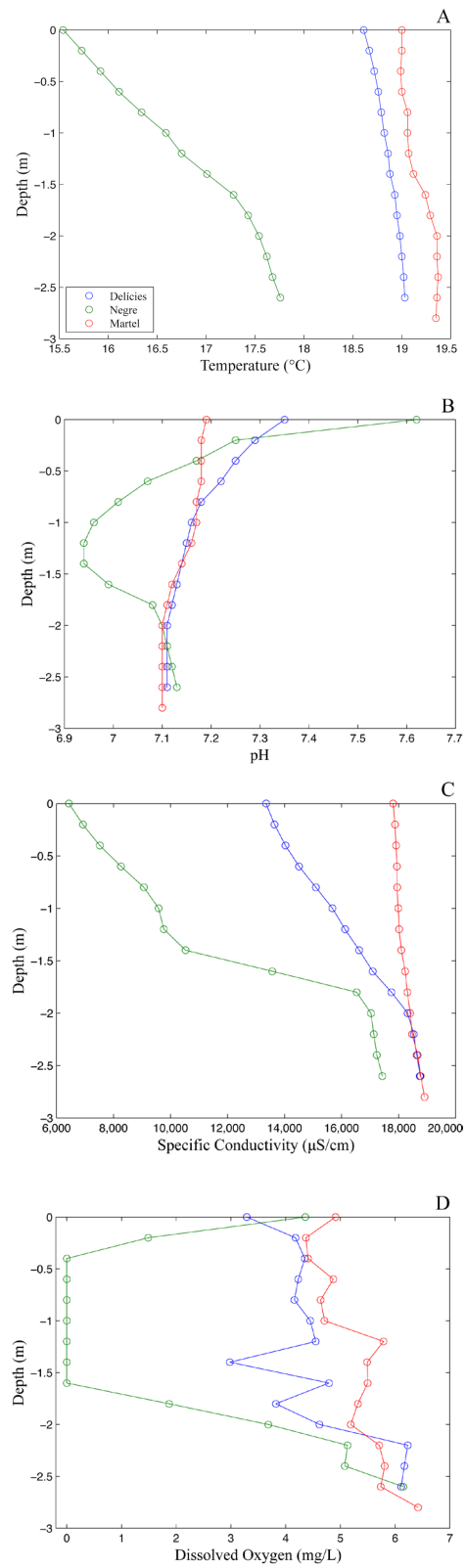

Figure 4. *Vertical profiles of (A) water temperature (°C), (B) pH, (C) specific conductivity (µS/cm), and (D) dissolved oxygen (mg/L).*

included negative excursions. The specific conductivity values increased with depth and converged with those of Martel at depths exceeding 2 m.

Negre is the most distal profile from the Mediterranean Sea. Water temperature and specific conductivity are considerably lower at Negre compared to the other two locations, suggesting an input of cooler freshwater to this location. The specific conductivity increases from 10,530 µS/cm at -1.4 m to 16,530 µS/cm at -1.8 m. The dissolved oxygen decreases from the surface value of 4.36 to 0 mg/L at -0.4 m, returning to oxic conditions at -1.8 m. It is likely that organic matter enters Negre with the cooler, fresher water, and is trapped by a density difference as exhibited in the specific conductivity profile. pH is highest at the surface (7.62), decreases to a minimum of 6.94 at -1.2 and -1.4 m, and converges with the other profiles at -2 m. The lowest pH values were recorded within the anoxic zone, attesting to respiration of the organic matter.

$\delta^{18}O$ values in Negre show an excursion toward more negative values in this anoxic zone as well, further supporting microbial respiration at the density difference indicated by specific conductivity (Figure 5A). $\delta^{13}C$ (Figure 5B) is similar to pH, with more positive values observed in the surface of Delícies and Negre. These more positive values are the result of CO_2 degassing, leaving the heavier isotope in the water. Combined, pH and $\delta^{13}C$ confirm that these pools act as a CO_2 source.

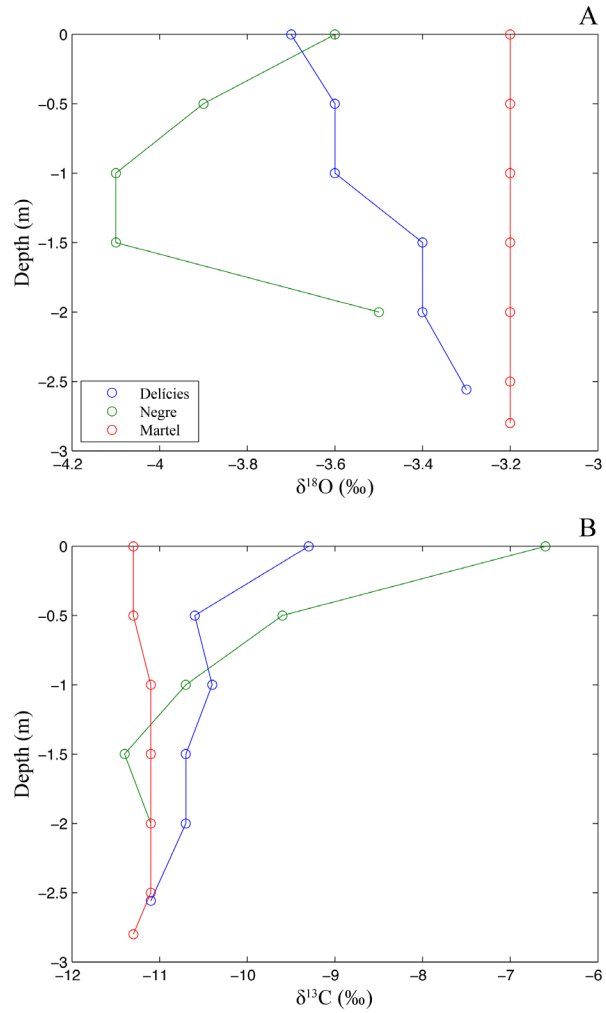

Figure 5. *Vertical profiles of (A) $\delta^{18}O$ (‰) and (B) $\delta^{13}C$ (‰).*

Future Directions

Recently, a POS from the current precipitation band in Delícies was recovered. This speleothem featured well-developed calcite crystals at the top of the encrustation, grading to corroded crystals at its bottom, attesting to undersaturated conditions existing immediately below a supersaturated horizon.

Carey et al. (2001) and Martínez-Taberner et al. (2000) report depleted dissolved oxygen concentrations at the halocline in caves closer to Mallorca's coast due to microbial respiration of organic material. Several authors report that the bottoms of Mallorca's brackish littoral cave pools are undersaturated with respect to carbonate minerals, causing the recycling of rafts that grow too large to be supported by surface tension (Ginés et al., 1981; Csoma et al., 2006). Thus, a saturation index gradient may exist where supersaturation and precipitation of POS is controlled by degassing of CO_2 from the surface of the water, whereas undersaturation exists deeper within the water column, possibly facilitated by microbial processes. In the context of a changing climate, the current POS band may be jeopardized by rising sea levels elevating the undersaturated portion of the water column.

Acknowledgements

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Biography

Liana M. Boop is a doctoral candidate at the University of South Florida in Tampa, Florida. Liana received her BS in Environmental Science from the University of Connecticut in 2007. Liana's dissertation research focuses on the geochemistry of brackish pools that precipitate phreatic overgrowths on speleothems within Mallorca's caves. Her professional and personal interests are inspired by her passion for caves and karst.

A PRELIMINARY ASSESSMENT OF SPELEOTHEM SAMPLING METHODS FOR PALEOCLIMATE RESEARCH

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Abstract

Speleothems are incomparable archives of paleoclimate information. However, most methods to extract past climate information from speleothems are destructive, because sampling must occur along the growth axis. Development of sustainable methods for sampling these nonrenewable resources, whereby the needs of science and cave conservation are balanced, ought to be a priority of the paleoclimate community. Ergo, I am studying currently practiced field methods in speleothem paleoclimatology. Part 1 of this two-part study entails surveying paleoclimatology labs working on speleothems nationally and internationally. The results of this portion of the survey were converted to an anonymous list of current methods. These data will be written into a second survey in which stakeholders, including cave managers, will be asked which method(s) aligns best with their cave use and goals. The final output will be a peer-reviewed assessment of methodology, including "best practice" guidelines, which will improve sampling and field methodology in the community as a whole. Additional outputs (e.g., interpretive educational products, brochures, or a speleothem sample archive, etc.) could be produced through collaboration with speleothem paleoclimate labs and cave and karst managers worldwide.

Introduction & Background

Cave formations (speleothems), in addition to being aesthetically pleasing, are also sources of past climate (paleoclimate) information. The mineral and chemical structure of speleothems record changes in past climate because as meteoric water falls above a cave, infiltrates into the ground, and drips onto stalagmites, the original isotopic composition of the rainfall is maintained. Because speleothems can be dated absolutely using small quantities of uranium and thorium in their mineral structure, paleoclimate records from caves can be related to other climate changes anywhere worldwide. Speleothems can be particularly useful in arid areas, where few other sources of paleoclimate information preserve well (e.g., Wagner et al. 2010). Understanding past climate variability will allow us to comprehend how the climate system functions and better prepare us to address future climate change.

Sampling speleothems in the lab for paleoclimate research is somewhat destructive; sampling must occur along the growth axis (generally down the center of the stalagmite) to be meaningful. For this reason, many scientists prefer to remove stalagmites entirely, so they have access to the most material possible and can produce robust science (for more information on this see Gregory Springer's publications in the January and June 2012 issues of the *NSS News*). Others prefer coring of stalagmites as a less invasive technique (Spotl and Mattey 2012), but this method is not yet commonly used. Development and adoption of new methods to sample speleothems for paleoclimate research is necessary to improve both cave conservation and sampling efficiency.

Some scientists have paid attention to conservation when sampling and have published on the topic. For example, it is not uncommon to see phrases such as "it must also be emphasized that great care must be paid to sampling strategy and to other conservation issues so that vandalism is avoided" (Lauritzen and Lundberg 1999). A few researchers have actively discussed sampling efficiency and conservation, by outlining a strategy to select stalagmites that are directly responsive to a relevant climate variable (Frappier 2008). Similarly, some scientists have outlined other approaches, including careful site selection using prescreening approaches, cautious sample removal, and creative replacement using replicas (Truebe et al. 2011). Other researchers suggest treating speleothems more like archeological materials rather than simply as rocks – Fairchild and Baker (2012) point out "Most geologists have regarded speleothems

simply as a type of rock sample and have been slow to grasp the necessity for conservation through archiving." However, it is equally common to see mention of multiple (sometimes more than 10) stalagmites taken out of a cave for a paleoclimate reconstruction. Clearly the dialogue must deepen between cave managers and cave paleoclimate scientists about cave conservation.

To facilitate this dialogue, I am developing a two-part cave stakeholder survey, which includes one survey of current cave paleoclimate scientists and a second survey of other cave stakeholders such as cave managers, cave conservancies, recreational cavers, etc. (hereafter: "cave managers"). The objective of this project is to develop mutually agreeable "best practice" guidelines for speleothem sampling for paleoclimate research.

Methods

"Best practice" guidelines will be developed using a suite of methods currently in practice by paleoclimate scientists and opinions/feedback collected from cave managers. Scientists were asked the following questions via email:

(1) Field methodology

(a) How do you select a cave to sample in?
For example: ease of access, size of cave, remoteness of site, etc.

(b) How do you select a speleothem within that cave?
For example: site characteristics, speleothem size/shape, distance from entrance, pre-damaged, etc.

(c) Describe how you sample a speleothem from the cave you have selected:
For example: removal, removal/reassembly/replacement, coring, etc.

(i) Is this your ideal sampling strategy? (Yes/No)

(ii) If yes, why do you prefer this method? If no, please describe how you would ideally sample and why you cannot sample that way.

(2) Cave ownership

(a) Of the caves you have worked in at any point in the past 10 years, how many are on public lands?

(b) Of the caves you have worked in at any point in the past 10 years, how many are on private lands?

(c) Who controls access to the caves you work in (or recently worked in)?

(3) Other

(a) Is there anything else you would like to add?

(b) Is there anyone else I should contact for information on field methods in speleothem paleoclimatology?

(c) May I follow up with you if I have further questions? (Yes/No)

Their answers have been collated into a survey for cave managers. The second survey will be online, allowing cave managers worldwide to participate. Results of both surveys will be presented in a peer-reviewed format and made available to cave managers and scientists around the world. This publication will include "best practice" guidelines for speleothem sampling, which will improve sampling efficiency and cave conservation in the paleoclimate community as a whole.

Preliminary Results & Discussion

Some preliminary data have already been compiled from part 1 of the survey. The data show that paleoclimate scientists use a variety of metrics for selecting a cave to sample from: whether a cave is in a scientifically valuable location for their specific research question, is easy to access, and contains many speleothems. Selection of a speleothem within that cave depends on: speleothem morphology, distance into the cave, whether the speleothem is out of sight or otherwise visually uninteresting, whether the sample is already broken or damaged, and the mineralogy of the speleothem. When selecting caves and sampling locations, scientists point out the usefulness of having "pre-screened" the site using dripwater analysis, microclimate monitoring, or preliminary uranium-thorium dates. Many scientists recognize that such strategies increase their own sampling efficiency while conserving nonrenewable cave resources. Some scientists are even developing new methods, including using MRI-scanning (Magnetic Resonance Imaging – a tool from the medical industry) to identify the best speleothems to sample for their research. Finally, a number of scientists have identified the need to archive samples in one location, rather than at individual labs, making those materials available for future researchers. This procedure will minimize future impact on caves because it means scientists can work directly from samples in the archive rather than from new speleothems from new caves.

Although the responses to the survey are likely from the subgroup of paleoclimate scientists who are already

thinking about cave conservation issues, this study holds great promise to produce a "best practice" set of guidelines for paleoclimate sampling in caves.

Recommendations for Cave Managers

As the study progresses, cave managers can help in a number of ways. Initially, they can fill out the survey (the second part of the methods assessment for speleothem paleoclimatology), and send it to their contacts and constituents to complete. Secondarily, when approached by paleoclimate scientists, cave managers could proactively recommend "best practice" methods and/or work with scientists to develop interpretive educational products for explaining to the public why paleoclimate research from caves is useful. Additionally, cave managers can provide creative new suggestions about how best to sample for paleoclimate research while protecting cave resources; sharing that information with scientists will be critical to advancing new sampling methods.

Conclusions

Speleothems are a good source of paleoclimate information, and are often the only source of such critical information in some areas of the world. Paleoclimate information from speleothems is increasingly useful to understanding our climate system and preparing for modern and future climate change. This paper outlines a project to develop more sustainable methods to sample speleothems for paleoclimate studies by surveying speleothem paleoclimate labs and cave managers, cave conservancies, recreational cavers, and other cave stakeholders.

Many cave paleoclimate scientists are actively working to reduce the impacts of their research. Others know that cave conservation is an important issue, but also recognize that there is little funding or community support for developing and publishing low-impact methods. This project aims to overcome that barrier by increasing transparency of the methods that are currently in use, as well as producing guidelines for how to sample speleothems more sustainably. The goal of this research is to encourage responsible sampling that reconciles cave conservation with paleoclimate science. It is an opportunity for cave managers and cave paleoclimate scientists to work together to improve sampling, while maximizing the scientific and cave aesthetic benefits to society.

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Biography

Sarah Truebe (NSS #61563) is a PhD Candidate at the University of Arizona. Sarah grew up caving under southern Arizona, but since becoming an adult, she has also caved in more than seven states and six foreign countries. She spent a brief period in California, at Stanford University, to obtain Bachelor's and Master's degrees in Earth Systems, an interdisciplinary program

in earth and environmental science and policy. As a PhD student, Sarah is reconstructing past rainfall variability in southern Arizona using speleothems, understanding drip water geochemistry and calcite precipitation in a modern cave monitoring project, and working on an assessment of current speleothem climatology methods. She hopes to find a cavey post-doc or job after she finishes her PhD next year. In her spare time, Sarah volunteers with the Southern Arizona Rescue Association and plays piccolo with the University of Arizona Wind Ensemble.

IMPACT OF CLIMATE CHANGE ON HUMAN AND ECOLOGICAL USE OF KARST GROUNDWATER RESOURCES: A CASE STUDY FROM THE SOUTHWESTERN USA

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Abstract

Climate change models for the arid southwestern USA predict increasing temperatures and declines in precipitation. These changes will have multiple adverse impacts on water and ecological resources and pose diverse challenges on their management. The San Solomon Spring system of west Texas discharges from the western edge of the karstic Edward-Trinity Plateau Aquifer. It consists of six springs in Jeff Davis and Reeves counties, is one of the largest spring groups in the state, and provides water for agricultural use and habitat to two federally listed endangered species and three species proposed for listing. It serves in this paper as a case study for the impact and management of climate change on springs in the American southwest.

Water and ecosystem management can be driven by market and/or ecological forces. Market considerations can guide water management if there are no ecological or other considerations that depend on aquifer levels or flowing surface water, and if total water use is sustainable for the climatic conditions. Where endangered species are involved, ecological factors dominate management, but require greater levels of information and understanding of the relationship between aquifer conditions and ecological health. Computer software, such as ADAPT, are starting to become available to assist with local climate change evaluations and decision-making processes.

Introduction

Climate change is frequently in the news. It has become a common topic of discussion and debate as to whether changes in the weather, major storms, and small rises in sea level are the result of changes in global climate. While reports of new record high temperatures and graphs showing near-exponential increases in atmospheric carbon dioxide become more familiar, the direct impact on people's daily lives and the ecosystems surrounding us remain somewhat abstract. Computer models continually improve and provide better estimates of global shifts in climate and weather patterns. Studies of their impacts at the local level are starting to emerge. This is such a study.

Friedman (2008) aptly described climate change as "global weirding," as opposed to the more familiar "global warming." While average global temperature is increasing, the changes are not uniform between regions or always intuitive. Consequently, a paper of this scope cannot address the impacts of climate change on karst groundwater resources globally or even across the United States. Instead, this paper examines a region in west Texas as potentially representative of karst groundwater needs by humans and endangered species in the arid American southwest. It begins with a review of one karst spring system, then compares it to another nearby to examine different response models for predicted groundwater availability.

Site Description

The San Solomon Spring system is located at the western edge of the Edwards Plateau in Jeff Davis and Reeves counties, Texas. The springs occur in and near the City of Balmorhea (population approximately 500) and the community of Toyahvale and Balmorhea State Park (Figure 1). San Solomon Spring is the largest of six springs (East Sandia Spring, Giffin Spring, Phantom Lake Spring Cave, San Solomon Spring, Saragosa Spring, and West Sandia Spring) distributed over a 13-km long by 2-km wide northeast-southwest trending area, and is the featured attraction of Balmorhea State Park.

The springs were used by Native Americans since prehistoric time. Their irrigation canals were visible as late as 1898 (Hutson, 1898). In 1583 Spanish explorer Antonio de Espejo made the first documented discovery of San Solomon Spring (Castaneda, 1936), and possibly the other springs, although modern settlement of the area

didn't begin until the mid-1800s with the establishment of Balmorhea (Miller and Nored, 1993). Modern irrigation canals carrying flow from the springs were dug as early as 1853 (Brune, 1975).

From 1961-1990, the San Solomon area had a mean annual maximum temperature of 23.9 ºC and average annual precipitation of 30.8 cm (Anaya and Jones, 2009). The springs are situated at an average elevation of 1,000 m above mean sea level. The area consists predominantly of nearly horizontal Quaternary alluvial plains that slope and drain to the east. Limestone hills skirt the western edge of the area at Phantom Lake Spring Cave, and small Tertiary igneous hills associated with the Davis Mountains delimit its southern and eastern margins. Most of the area is rural pasture and farm land.

The San Solomon Spring system is often described as discharging from the Edwards-Trinity Aquifer, which is comprised of Lower Cretaceous age carbonates of the Washita and Fredericksburg groups, and the carbonates and clastics of the underlying Trinity group. However, at this western edge of the aquifer the Buda Limestone is mapped by Barnes (1982) as separate from the Washita (the Buda is generally considered a part of the Washita Group) but is it recognized as hydrologically continuous with and a part of the Edwards-Trinity.

Phantom Lake Spring Cave discharges from the Buda Limestone, which north and east of the cave dips and is down-faulted under the alluvial plain. Well data from White et al. (1938) show the limestone extends below the other San Solomon system springs which flow from the overlying alluvium. Although that early report suggests the source of Saragosa, East Sandia, and West Sandia springs was the local alluvial aquifer (the southwest edge of the Cenozoic Pecos Alluvium Aquifer), Chowdhury et al. (2004) demonstrated geochemically that East Sandia flows from the Edwards-Trinity (their study did not include Saragosa and West Sandia springs).

In January 2013, Veni and Land (in prep.) injected uranine dye into the downgradient section of Phantom Lake Spring Cave, which does not discharge from the cave's entrance. The dye arrived at San Solomon Spring six days later, having traveled at a minimum average rate of 1 km/day. Dye was not detected at any of the other springs or at any of four monitored wells. Their results suggest little inflow from other sources into the cave stream between the dye injection point and San Solomon Spring.

LaFave (1987) and LaFave and Sharp (1987) determined the cave and San Solomon Spring were fed by two sources of waters. Using hydrograph and geochemical evidence, they identified a local source of recharge in the Cretaceous limestones immediately west of the springs. These data also identified the Permian carbonates of the Apache Mountains, 40-80 km northwest of the cave, as a more distant recharge area that sustains much of the springs' baseflow. Their results were confirmed through more extensive geochemical analyses by Uliana (2000) and Chowdhury et al. (2004). Figure 1 shows the recharge area for the springs as roughly estimated by Veni and Land (in prep.). Sharp (2001) provided potentiometric and geochemical evidence which indicates that much of the groundwater flowing through the Apache Mountains is fed by an extensive system of alluvial bolson aquifers on the west side of the mountains; this potential recharge area is not considered in Figure 1.

Groundwater in the Apache Mountains is hypothesized to flow into the Cretaceous limestones where they are juxtaposed with the Permian units in the subsurface by the Stocks Fault near the mountains' east end. From there, the groundwater flows southeast along the fault, and then past the fault further southeast down the Rounsaville Syncline, until it is seen at Phantom Lake Spring Cave followed by the other San Solomon springs (LaFave, 1987; LaFave and Sharp, 1987). Upstream exploration of the cave by divers supports this hypothesis, having extended the survey of the cave 1.4 km northwest of the entrance along the east flank of the syncline. The cave has a total surveyed length of 3,075 m and is the deepest underwater cave in the US with a depth of 140.8 m at the current limit of exploration (ADM Exploration Foundation, 2013).

Local Water Resource and Ecological Challenges

In 1986, the Texas Water Commission proposed the locale of the San Solomon Spring system as part of a "critical area" that "is experiencing or is expected to have ground-water problems resulting from ground-water overdrafts from an aquifer" (Ground Water Protection Unit, 1989). Ashworth et al. (1997) cursorily examined the declines in San Solomon system spring flows and concluded they resulted from decreased rainfall since

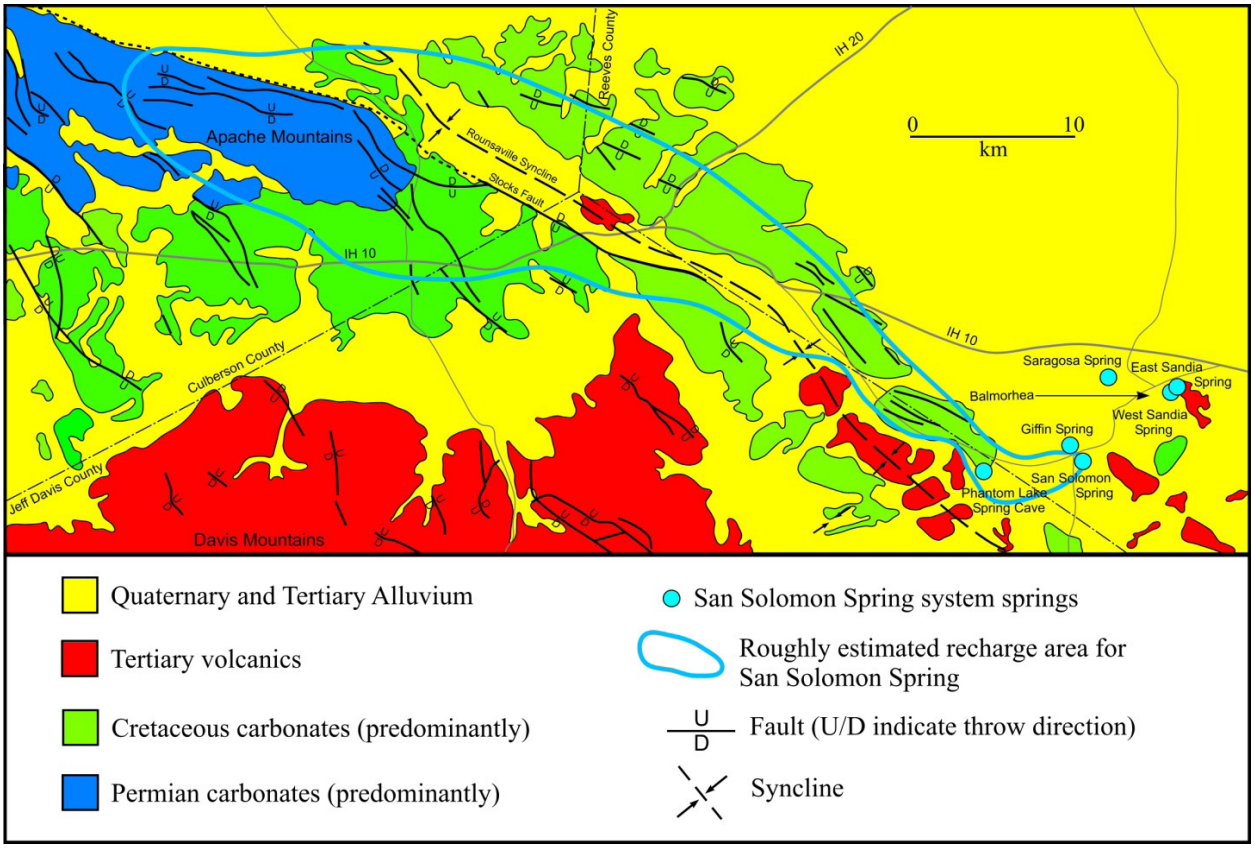

Figure 1. *Simplified hydrogeologic map of the San Solomon Spring system region (based on Barnes, 1975, 1976, 1979, 1982; LaFave and Sharp, 1987). Balmorhea State Park surrounds at San Solomon Spring and Toyahvale is next to Giffin Spring.*

1992 to the date of their study. However, Brune (1981) showed that the drought of record in the 1950s had no measurable effect on flow from Phantom Lake Spring Cave, the second largest and most upgradient spring. Further, Brune (1981) documented generally sustained declines in flow from East Sandia Spring, Phantom Lake Spring Cave, San Solomon Spring, and Saragosa Spring since 1945, when irrigation pumping began to greatly increase and major declines in water levels occurred in the adjacent Cenozoic Pecos Alluvium Aquifer (Texas Water Development Board, 1986; Sharp, 2001). The potential impact of significant groundwater declines in the Cenozoic Pecos Alluvium Aquifer on the springs' flows has not been studied.

Whatever the cause, the effect of diminished spring flows has been most noticed at Phantom Lake Spring Cave. Observing this decline, the cave was purchased by the US Bureau of Reclamation, in cooperation with the US Fish and Wildlife Service (USFWS). They built a refugium canal and pool in 1993 (Figure 2) and constructed a wetland in Balmorhea State Park in 1996 (Edwards, 2001) to protect the populations of the Comanche Springs pupfish (*Cyprinodon elegans*) and Pecos gambusia (*Gambusia nobilis*), which are federally listed as endangered species. These fish are also present at East Sandia, Giffin, and San Solomon springs (Figure 1).

In 1999, flow ceased from the entrance of Phantom Lake Spring Cave and from May 2000 (Edwards, 2001) to the present, the US Bureau of Reclamation has pumped water from inside the cave to the refugium pool, which flows over a small dam back into the cave, to sustain the species at that location. In addition to these fish, USFWS (2012) has proposed federal endangered listing and establishing critical habitat for three aquatic invertebrates: Phantom Cave snail (*Pyrgulopsis texana*), Phantom springsnail (*Tryonia cheatumi*), and a diminutive amphipod (*Gammarus hyalleloides*). They are only known from the same four springs of the San Solomon Spring system that contain the listed species of fish.

Figure 2. *Entrance of Phantom Lake Spring Cave with the edge of the refugium pool and canal in the foreground.*

Climate Change Models, Impacts, and Water Management for the Southwestern USA

Computer programs have been created and improved, especially over the past two decades, to model the behavior of Earth's climates and predict how those climates may change under different conditions. Most models to date have focused on global climate. As computer memory and computational power has increased, the precision of the global climate models has improved and regional climate models have developed.

Widely considered the most authoritative study of global climate change, the 4th Assessment by the Inter-governmental Panel on Climate Change predicts a 3-3.5ºC mean annual increase in temperature for the southwestern USA from 1980-1999 to 2080-2099, and a 5-10% decrease in mean annual precipitation over that same period (Solomon et al., 2007). A similar in-depth and acclaimed, but more recent study focused on climate change in the USA (Karl et al., 2009). It projected slightly lower annual temperature increases for the area where San Solomon is located, 2.2-2.8 ºC, and the same annual decreases in precipitation of 5-10% by about 2090. However, those values assume low rates of emission of greenhouse gases. Their projections under a high emission rate scenario for the same area and period showed temperature increases of 5-5.5 ºC and 25-30% decreases in annual precipitation.

Many climate studies (e.g. Karl et al., 2009) have postulated several likely impacts on water resources for human and ecological use as a result of the modeled changes in climate. Those related to karst and the San Solomon area include:

- **Decreased water availability:** Increased potential for drought and diminishment and cessation of stream and spring flows, lower groundwater levels in wells and lakes, decreased rainfall and snowpack, increased water loss by evaporation, less water for use in drinking, agriculture, industry, and energy production, increased demands on water supplies for domestic, agricultural, industrial, and energy production needs, and decreased capacities for water systems to dilute pollutants.
- **Increases in water pollution:** As mean air temperature increases, surface water will become warmer, making it able to hold less dissolved oxygen which will increase the occurrence of harmful algal blooms, change the toxicity of some pollutants, increase the risk of waterborne diseases, and degrade the quality of aquatic ecosystems.
- **Changes in aquatic biology:** Aquatic species will be replaced by species better adapted to the warmer water, and temperature, rainfall, and flow changes over the next 50 years may result in the significant deterioration of the health of some aquatic ecosystems; wetlands, especially those dependent on spring flows, will be the most vulnerable.

These projected changes will require actions and alterations in water and ecosystem management that include, but are not limited to:

- **Water and ecosystem planning:** Review all existing local to regional water and ecosystem management plans, regulations, and documents related to uses that impact either water or ecosystems,

and revise them to provide sustainable water yield and habitat under the new climatic conditions.

- **Investments in water supply infrastructure:** Installation of metering gauges and low water use fixtures, fix leaks in water distribution systems, construction of water recycling and reuse facilities and pipelines.
- **Water conservation regulations and incentives:** Establish water use limits, water use allocation, tiered pricing with greater per unit costs for higher water use, community rules on when or if lawns may be watered, requirements for low-water systems on new construction, and tax incentives and rebates for converting existing equipment to low-water use systems.
- **Water pollution prevention regulations, incentives, and infrastructure:** Create or revise rules and discharge permits for maximum pollutant and nutrient loading, develop requirements for new construction to include pollution prevention and mitigation facilities, and tax incentives and rebates to provide existing construction with new or upgraded prevention and mitigation facilities.
- **Ecosystem management:** Establish or revise land use, game, and non-game regulations, recovery plans, refugia, and tax incentives and rebates for enhancing, restoring, and creating habitat, and increasing monitoring, removal of exotic species, and mitigation of other threats.

Climate Change and the San Solomon Spring System

In many ways, the San Solomon Spring system is typical of many karst systems in the western part of the USA. While it is technically within a large karst region, the Edwards Plateau, the location of its drainage area on the fringe of the plateau make it more like many western karst regions which are small and hydrogeologically isolated. Consequently, many of the ecosystems they support are small, isolated and thus more vulnerable to impact. Such isolated desert springs are often called *cienegas* in the US southwest.

The term *cienegas* is especially used by biologists to identify springs and associated wetlands whose flow dries before reaching a perennial stream, thus isolating the aquatic populations depending on those flows to the water volume, velocity, depth, chemistry, temperature, and other conditions associated with that spring. Even during flood events, when flows may reach perennial streams, the cienega species remain within the cienega having adapted to its conditions, including food sources and predators. They often cannot survive in other aquatic systems. If the flow of the springs, or other conditions, threaten the survival of its species, they may be listed as threatened or endangered by the USFWS, as at the San Solomon Spring system.

Like many western areas with small human populations, groundwater pumping in the San Solomon area is potentially the primary reason for declining aquifer levels and associated spring and stream flows. Perhaps the best known example of a spring that ceased flowing due to over-pumping of groundwater in Texas is Comanche Spring in Fort Stockton, 85 km to the east of San Solomon Spring. One of the larger springs in Texas, Comanche Spring was the type locality for the Comanche Spring pupfish found at San Solomon (USFWS, 1980).

At the time of this writing, May 2013, the effect of climate change in the southwestern USA is not readily distinguishable from a long-term drought. NOAA (2013) shows the San Solomon area as in a "severe" drought and predicts the drought currently occurring throughout the southwestern USA will persist or intensify at least through the summer of 2013. For the time being, the decreased spring flows can be argued as the result of pumping and the drought, not climate change. However, assuming the drought or at least prolonged periods of lower than average precipitation continue, climate change will establish a new normal for average rainfall. What effect will that have on water and ecosystem management in the southern USA? One of two scenarios is likely: market-driven and ecology-driven.

Comanche Spring is a likely example of future market-driven solutions to climate change stresses. Although it is the type locality of an endangered species, the spring went dry in 1962 (Brune, 1981) and the listed fish were lost in that location several years before they were listed. Audsley (1956) observed a direct correlation between groundwater pumping and declines in spring flow, but without ecological mandates to consider, pumping continued until the springs dried (Figure 3).

No subsequent detailed hydrogeologic study for the Comanche Spring area could be located for this report, but various personal communications suggest that groundwater declines may have stabilized since the

springs dried. Pumping is believed by some to be at a rate that is sustainable for agricultural, domestic, and industrial use, but not to maintain spring flow. While groundwater levels are lower, the increased energy cost of raising the water to the surface is currently affordable for market needs. Assuming climate change results in declines in precipitation similar to the San Solomon area, and simplistically results in similar percentages of lost aquifer recharge, then the Fort Stockton community would likely be able to decrease groundwater use by 5-10% through conservation and other non-drastic measures to maintain sustainable water use under Karl et al.'s (2009) low emissions scenario by 2090. However, decreasing water use by 25-30% under the high emissions scenario would likely force market economics to determine if expensive water savings and production infrastructure will be developed or agricultural water use substantially reduced. This general scenario will probably play out across the American southwest as climate changes progresses.

The San Solomon Spring system serves as a probable example of future ecology-driven responses to the modeled climate change. While it is relatively close to Comanche Spring, there is a wide regulatory distance between the spring groups due to the Endangered Species Act of 1973. This Act provides the legal authority for the USFWS to require management of an aquifer to preserve spring flows for endangered species preservation. When that authority was questioned in the San Antonio, Texas, area, a federal judge ruled that either the state could take control of the Edwards (Balcones Fault Zone) Aquifer to protect endangered species depending on its spring flows, or the federal government would take control. This decision resulted in the state's creation of the Edwards Aquifer Authority to establish and enforce pumping limits and other means to limit excessive groundwater withdrawal (Texas Senate, 1993).

Figure 3. *Presently dry Comanche Spring. The circular culvert is about 70 cm in diameter. It opens to a cave which is the source of the spring.*

Currently, declines in aquifer levels in the San Solomon area have resulted in the drying of only Phantom Lake Spring Cave, where a temporary solution has been applied by pumping water from the cave into a pool to sustain the listed fish and then letting it flow back in. No legal restrictions on water use or management have yet been applied. However, such restrictions may be imposed if conservation and other voluntary water saving methods are insufficient to keep the other springs in the San Solomon system from going dry. Yet before any major legal action can be taken, substantial hydrogeological research should be conducted first. The resulting data would serve as a foundation for assessing the areas and volumes of groundwater lost to pumping and climate change in order to accurately predict declines in aquifer levels that would threaten additional spring flows.

Anaya and Jones (2009) provided the most recent and detailed hydrogeologic study of the Edwards-Trinity Aquifer. They described how limited data compromised the precision of their model in some areas. This is especially true for the San Solomon Spring system area. Despite the presence of major springs that have been well known for decades, their model shows the aquifer in that area as dry or of an uncertain saturated thickness. As noted previously in this report, divers have explored Phantom Lake Spring Cave to a depth of 140.8 m, demonstrating a substantial saturated aquifer thickness. Other data on the area are also not available for their model, arguably making their results unreliable for the San Solomon Spring system.

The additional relevance of Anaya and Jones's (2009) study is that it is typical of the state of knowledge of many aquifers in the southwestern part of the USA. The region is sparsely populated, few wells and springs are available for monitoring and from which to construct accurate groundwater availability models, and local economic resources are often insufficient to fund the installation of multi-year monitoring networks, analysis of their data, and related appropriate hydrogeological research. The expense and complexity of such a project substantially increases when the aquifer is karstic.

Consequently, the ecology-driven response to climate change at the San Solomon system will likely be, as demonstrated in many endangered species recovery plans, for the USFWS to take action based on the best available data and address uncertainties by erring on the side of species protection. However, erring to protect the species is no assurance of adequate protection where the uncertainties are great or undefined. As spring flows continue to across the southwestern USA and climate changes threaten ecosystems around the country, USFWS will almost certainly receive increasing numbers of petitions to list additional species. Research funds may be lost to administrative costs for listing and the seemingly endless legal challenges that accompany many listings and management actions.

Regardless of whether management is driven by market or ecological forces, computer-based tools are becoming available to assist support the decision-making process. Following are two examples; neither has yet been applied to the San Solomon area.

The US Environmental Protection Agency (2013) released the BASINS climate assessment tool in 2007. This environmental analysis software package combines geographical information system and national watershed data with watershed modeling tools to facilitate watershed-based assessments of the potential implications of climate variability and change on surface water systems. It allows users to create climate change scenarios to quickly assess a wide range of potential situations on how weather and climate could affect their water resources, and guide the creation of effective management strategies.

Complimenting BASINS, ICLEI-Local Governments for Sustainability (2013) offers ADAPT (Adaptation Database and Planning Tool) as a management tool specifically for community governments. It is based on-line where users input data and evaluate their community's vulnerabilities, select preparedness goals, and create and prioritize responses.

Conclusions

If today's climate change models prove correct, the impacts of climate change will severely tax the resourcefulness and resources of water and ecosystem managers. Karst aquifers will prove especially problematic. They are far more difficult to accurately model than other aquifers. Effective study of karst systems requires more techniques, research, and data.

Effective management of karst aquifers is often comprised by poor understanding of those systems. The general public, as well as resource managers not trained in karst water and ecosystem management, often suffer from misconceptions that underestimate adverse environmental impacts. For example, wells that discharge large volumes of water do not necessarily reflect aquifer-full conditions when they tap high-permeability conduits. Also, karst springs without rare species may not seem to reflect ecological threats if rare but unknown groundwater faunas occur within the conduits feeding those springs and are adversely impacted by climatic changes. This is seen at the San Solomon Spring system, where listed and non-listed rare species occur in surface flows, but it was only by diving into Phantom Lake Spring Cave that Krejca (2005) found three stygobites in the aquifer, one of which is likely a new species.

Market conditions can serve as an effective water management tool if ecology is not a consideration, as well as recreation and other uses of potentially lost surface flows. However, water withdrawal must be demonstrated as sustainable in perpetuity and in consideration of climatic conditions and changes.

Ecosystem preservation can be used to manage water resources for human and ecological purposes. It requires a more in-depth understanding of aquifer hydrogeology and how it affects ecosystem health. The production of water resource modeling tools should continue to grow and assist managers in their planning process, whether it is driven by market or ecosystem forces.

There is insufficient information currently available on the hydrogeology of the San Solomon Spring system to predict if additional springs, besides Phantom Lake Spring Cave, will dry or decline to unsustainably low levels for their populations of endangered species under the current climate change scenarios for that region. Additional study is certainly warranted. However, the study of water and ecosystem management at the San Solomon Spring system can serve as an example for other springs in the southwestern USA, especially those flowing from karst aquifers.

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Biography

Dr. George Veni is the Executive Director of the National Cave and Karst Research Institute (NCKRI) and an internationally recognized hydrogeologist specializing in caves and karst terrains. Prior to NCKRI, he owned and served as principal investigator of George Veni and Associates for more than 20 years and has conducted extensive karst research throughout the United States and in several other countries. Since 2009, he has served as the Vice President of Administration for the International Union of Speleology. He has been as a committee advisor for geological, geographical, and biological dissertations and theses for three universities, taught karst geoscience courses for Western Kentucky University for 11 years, and taught karst science and management workshops internationally for NCKRI since 2011. Three cave-dwelling species have been named in his honor. He has published and presented nearly 200 papers, including four books, on hydrogeology, biology, and environmental management in karst terrains.

PRELIMINARY SUMMARY OF WATER RESOURCE INVESTIGATIONS DURING 2012 AT TIMPANOGOS CAVE NATIONAL MONUMENT, UTAH

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Abstract

This manuscript considers the hydrology and geochemistry of water resources within Timpanogos Cave National Monument in American Fork, Utah. In particular, data are presented for five cave pools within the Monument and the American Fork River that flows through the Monument. Two independent dye trace attempts in this study have not established a connection between the surface near the canyon rim at the south border of the Monument and the cave pools or the river. Ion chemistry of the pools reveals elevated sulfate concentrations. Analysis of sulfate and other reaction products suggests the possibility of combined carbonic and sulfuric acids as speleogenetic agents. Enrichment of ^{13}C in dissolved inorganic carbon above expected values provides initial support of this hypothesis.

The enrichment of sulfate in the cave pools when coupled with higher concentrations of fluorine, suggest increased interaction with bedrock influenced in the past by hydrothermal activity. This is especially relevant in pools with muted water-level fluctuations during the course of the study. Other pools have greater water-level variation and unexpectedly have a very consistent chemical composition. One hypothesis is that the source waters for the pools with stable geochemical character are from the talus near the canyon rim. Evidence from the stable isotopes of oxygen and hydrogen within water samples support this hypothesis— cave pools with constant water levels are more enriched in heavier isotopes and thus derived from lower elevations compared to cave pools with variable water level and depletion in the heavier isotopes.

Introduction

Ball State University (BSU), in cooperation with the National Park Service (NPS), conducted a study in 2012 of groundwater in Timpanogos Cave National Monument (TICA) in American Fork, Utah. This investigation focused upon the pools of water within the series of three connected caves, and sought to determine the source of the water in the pools and the chemical changes that occur within the pools during the course of a typical year. Of particular interest to the NPS is the size of the watershed that contributes to these pools and whether that watershed extends beyond the boundaries of the Monument into adjoining multi-use lands of the Uinta National Forest.

In conjunction with the studies of cave pools in TICA, a parallel investigation of the American Fork River in the Monument served as a basis of comparison between groundwater in the caves and surface water in the canyon. Spot samples east of TICA from nearby Cascade Springs, a large karst spring in the Uinta National Forest mantled with glacial till, and two hydrothermal springs, the Homestead 'Craters' near the city of Midway, provided context and comparison with active groundwater flow systems. This manuscript reports only on sites in TICA, the methods utilized in this study, and some preliminary results from our investigations.

Geology and Hydrology

TICA consists of 100 hectares located on the rugged, north-facing slope of the American Fork Canyon in the Wasatch Range; just 50 km from the major metropolitan

area of Salt Lake City, Utah (TICA, 2006). The caves of TICA, including Timpanogos, Hansen, and Middle Caves (together the 'Timpanogos Cave System' – Figure 1), are positioned half way up the canyon wall some 350 m above the American Fork River. The river has a near-continuous gradient of 0.045, captures all surface runoff within the Monument, and has headwaters in the higher peaks of the Wasatch Mountains north east of the Monument. The cave system is viewed on a popular cave tour accessed by a steep, winding trail up the canyon wall. Two man-made tunnels join the three caves.

The Monument is located primarily on the northern slope of 3,851-m Mount Timpanogos and surrounded by the Uinta-Wasatch-Cache National Forest. To the north and west of Mount Timpanogos and comprising the southern border of the Monument, a major plateau surface at 2,450 m, known as Sagebrush flats, interrupts the descent of the land into the canyon (White and Van Gundy, 1974).

The cave system has formed within the Mississippian-age Deseret Limestone at an elevation range between 2,020–2,075 m. The Deseret is a massive to medium–bedded, dark blue-black limestone and dolomite that weathers to a dark gray. The caves run parallel to the Timpanogos Fault that is oriented roughly perpendicular to, and 3.8 km east of the Wasatch Fault (Mayo et al., 2000). The caves are linear and largely comprised of a series of fissure-like chambers with a narrow and tall morphology. Calcite flowstone, stalactites, stalagmites, helictites, aragonite bushes, frostwork, and hydromagnesite 'moonmilk' are just some of the natural mineral deposits that decorate the walls of several chambers (TICA, 2006).

Drip waters collect within several pools that occupy low areas in the caves. Three of the most prominent pools, Middle Cave Lake, Cavern of Sleep, and Hidden Lake occur alongside the primary tourist trail (Figure 1). Whereas Cavern of Sleep and Hidden Lake, in Timpanogos Cave have near consistent in water levels, Middle Cave Lake is seasonally variable to the extent that a pump is utilized to draw down the water level at the beginning of the tourist season.

Hansen Cave Lake, a significant pool on the southwestern edge of the cave system in Hansen Cave (Figure 1), has a highly variable water level similar to Middle Cave Lake. During the early spring snowmelt, water levels in this lake are elevated and slowly lower during the summer dry season. Tranel et al. (1991) determined that both Hansen and Middle Cave Lakes are more sensitive to the rate of snowmelt and the occurrence of storm events than either Cavern of Sleep or Hidden Lake; for the same precipitation event, peak drip rates in Timpanogos Cave occurred six months later than in Hansen and Middle caves.

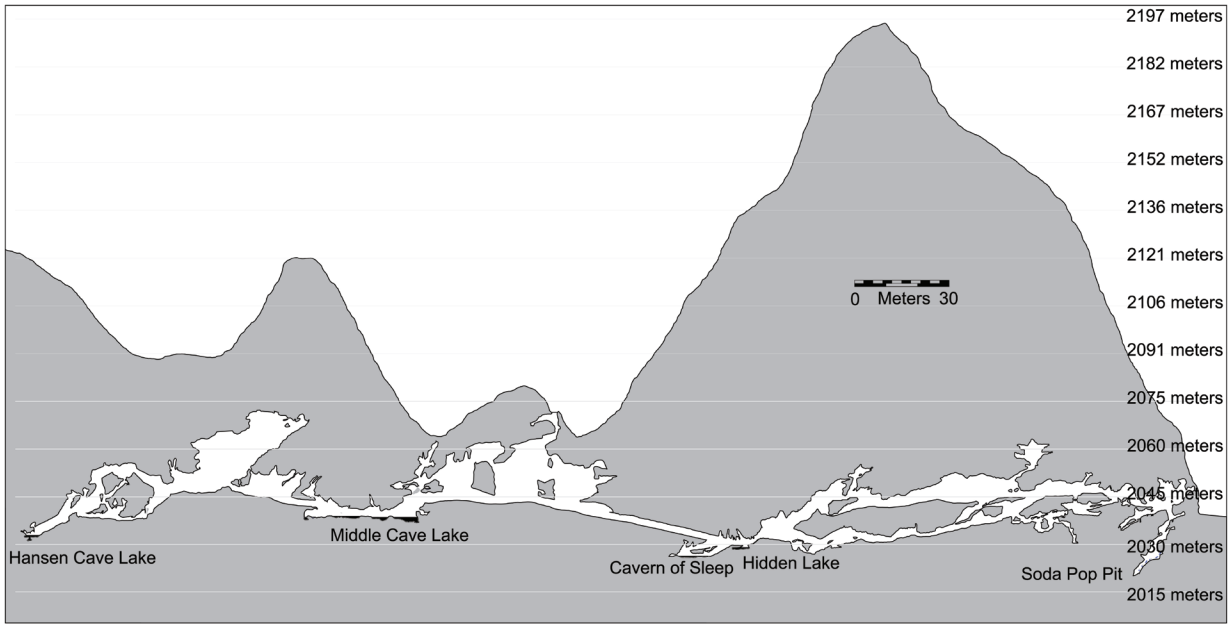

Figure 1. *Longitudinal profile of the Timpanogos Cave System with sampled pools identified and overlying topography included (modified from Kowallis, 2003).*

Soda Pop Pit, a seasonal pool on the northeast edge of the cave system in Timpanogos Cave (Figure 1), also has a highly variable water level to the point that it largely disappears in the summer and fall. This pool is located at the base of a series of vertical pitches and is accessible only by rope. During spring snowmelt, water enters this section of cave as a small stream and collects at the base of the drop. Later in the season, during the dry season, the stream and pool are absent and water enters the cave as a series of slow drips.

To date, the source and fate of water in these pools is largely unknown. Tranel et al. (1991) associated the slow drip rates and water-level changes in Cavern of Sleep and Hidden Lake to 'bedding-plane' flow as opposed to the 'fracture' flow associated with the fast drip rates and water-level changes in Hansen and Middle Cave Lakes. Horrocks and Aley (personal communication) attempted a dye trace from the collection pit in the outside restroom to the river below. No dye was ever recovered from that trace. This current research expands on these earlier studies and will ultimately present a more comprehensive picture of the hydrogeologic framework of TICA.

Methods

Dye Tracing

One technique used in this investigation was dye tracing. In this method, non-toxic fluorescent dyes were dissolved in water and injected into the ground on the mountainside above the caves. During each trace small packets of activated charcoal were used as 'receptors' to collect any dye that made it to the pool from the site where the dye was deployed. All receptors were analyzed at the Kentucky Geological Survey.

The rugged terrain of TICA required novel techniques to deploy the dye—the first attempt in April 2012 dropped dye frozen in blocks of ice from a helicopter. These 'dye bombs' were deployed near the canyon rim and into the remaining snow pack. This effort utilized three dye types: fluorescein, eosin, and rhodamine WT. The fluorescein was deployed near the top of the chute near Soda Pop Pit and the east exit for the caves. Eosin was deployed at the top of the chute that crosses over the entrance to Middle Cave. The rhodamine WT was dropped into the talus at the top of the chute that passes just west of Hansen Cave. The vertical distance between the deployment sites and the cave pools were approximately 350 m for the fluorescein and rhodamine WT and 250 m for the eosin. Horizontal distances between deployment site and the cave pools were less than 350 m in all cases. Receptors were placed in the five principle pools in the cave system as well as the American Fork River. These receptors were changed weekly until mid-July 2012.

The second, more focused attempt occurred during October 2012 when 'water balloons' of fluorescein concentrate were launched from the cliffs on the rim of the Sagebrush flats overlying the Monument to a site on the talus slope below the cliffs and overlying Hansen and Middle caves. As with the first trace attempt the vertical and horizontal distances were both on the order of 350 m. In this second trace attempt, receptors were changed weekly in Hansen and Middle Cave lakes as well as the American Fork River until mid-December when snowfall presented a significant avalanche risk.

Ion Chemistry

Weekly samples and field measurements of water chemistry between May and August of 2012 were collected for the five cave pools and the American Fork River. An additional sample set in October 2012 provided information on changes in water chemistry toward the end of the dry season. Samples from Cascade Springs and the Homestead Craters in August and October of 2012 provide a comparison between the cave pools at TICA with the longer and deeper flow systems of other regional carbonate aquifers. Only the data from TICA are presented in this paper.

A YSI Pro Plus was used for on site measurements of temperature (T), pH, oxygen reduction potential (ORP), specific conductance (SpC), and dissolved oxygen (DO). HACH digital titration kits were used for measurement of alkalinity and total hardness. Measurements of alkalinity were conducted using an end-point titration using a 1.6 N sulfuric acid titrant with Phenolphthalein and Bromcresol Green-Methyl Red indicators and a calibrated pH meter. Values of alkalinity were computed using the online U.S. Geological Survey alkalinity calculator (http://or.water.usgs.gov/alk/). Alkalinity values are reported as mg/L of bicarbonate (HCO3-), which at the pH values observed was the dominant alkalinity species. Hardness was determined by using a two-step titration using Sodium EDTA as the titrant and CalVer2 and ManVer2 as indicators.

Ion analyses were completed at BSU in the Department of Geological Sciences for cations (NH_4, Ca, Li, Mg, Na, and K) and the Department of Biology for anions (CL, Fl, Br, NO_3, SO_4, and PO_4) using ion chromatography. All samples were collected in two 250 mL HDPE bottles and filtered using a 0.45 µm membrane. The samples for cation analysis were preserved with 2 mL of 6 N HNO_3. All samples were stored at 4°C until time of analysis.

Stable Isotope Geochemistry

For each filtered sample for ion analysis, along with additional samples in April and December of 2012, a split was stored in a 30-mL glass bottle, treated with $CuSO_4$ as an anti-microbial agent, and stored at 4°C with a parafilm seal until analysis for $\delta^{13}C_{DIC}$. A similar set of split samples were analyzed for $\delta^{18}O$ and $\delta^{2}H$. Composite samples of precipitation were also analyzed for $\delta^{18}O$ and $\delta^{2}H$ and were collected near the entrance to Timpanogos Cave using a carboy, a funnel with tube, and a layer of mineral oil to prevent evaporation. The composite precipitation only comprises two samples from August and October of 2012. Very little rainfall occurred outside of these two collection periods.

Measurements of the stable isotopes of oxygen, hydrogen, and carbon were conducted at the Stable Isotope Laboratory at the University of South Florida with calibration to the VSMOW and VPDB standards for oxygen-hydrogen and carbon, respectively. Measurements of $\delta^{13}C_{DIC}$, $\delta^{18}O$, and $\delta^{2}H$ are accurate to within ±0.1‰ for C and O, and ±0.5‰ for H.

Results and Discussion

As of the last receptor analyzed from December of 2012, no dye has been detected in the cave pools or the American Fork River from either attempt. These results do not suggest that there is no connection between the deployment sites and the cave pools or the river, rather they re-confirm the challenges experienced by Horrocks and Aley (personal communication) and demonstrate the complex considerations for dye tracing at this location. Despite the volume of dye used (approximately 0.4 kg for each dye in the first trace and 1 kg of fluorescein in the second trace) and the relative proximity of the deployment and receptor sites (approximately 0.5 km for the cave sites and 1.5 km for the river site), the dyes were not 'injected' into a specific karst feature and may have become 'trapped' within the talus near the canyon rim and may be stored within the epikarst or channeled into a groundwater flow path that may bypass the caves and river altogether. In both cases, there was sufficient snowfall either before or immediately after the deployment to cover the dye and prevent UV degradation. Snowmelt would help convey the dye into the soil, but very limited precipitation during the summer and fall was perhaps not enough to flush the dye into the epikarst and cave pools.

Despite the challenges with the dye traces, measurements of water chemistry have helped identify both the potential sources of the water and the processes that occur in each pool during the course of a year. In all samples from all pools, the dominant chemical constituents are Ca^{2+}, Mg^{2+}, and HCO_3^-, which come from the dissolution of limestone and dolomite. Also common are SO_4^{2-}, Cl^-, K^+, and Na^+, which may come from aerosols in the atmosphere, or the oxidation of reduced sulfur in the bedrock surrounding the cave.

The sum of molar concentrations of Ca^{2+}, Mg^{2+} plotted against the sum of molar concentrations of HCO_{3-} and SO_4^{2-} reveals that, with the exception of Hidden Lake, the data cluster near a linear regression with a ratio of 3:5 (Figure 2). This ratio is the expected product from a reaction pathway that includes equal contributions from carbonic and sulfuric acids. $\delta^{13}C_{DIC}$ data generally support this possibility (Figure 3) with enrichment in ^{13}C, particularly in the April–June 2012 samples from

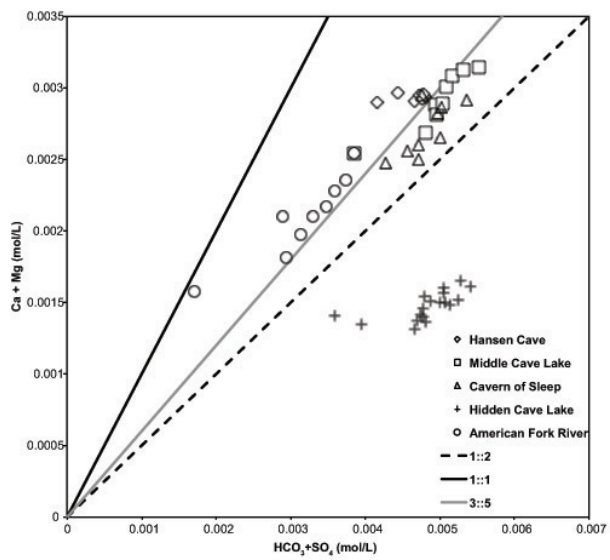

Figure 2. *Molar concentration of reaction products with cations and anions on the vertical and horizontal axes, respectively. Molar ratios of reaction pathways illustrated for carbonic acid (1:2), sulfuric acid (1:1) and equal proportions of carbonic and sulfuric acids (3:5).*

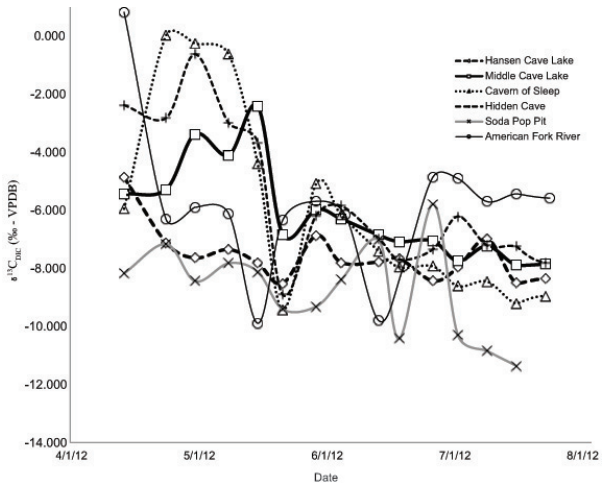

Figure 3. *Time-series plot of the values of the stable isotopes ratios of dissolved inorganic carbon.*

Cavern of Sleep and Hidden Lake, that is greater than can be explained by a simple reaction between soil CO_2 in this semi-arid landscape and the inorganic carbon in the bedrock.

In the ion data, SO_4^{2-} concentrations are particularly elevated in Cavern of Sleep; reaching concentrations in excess of 90 mg/L. Fl^- concentrations are significantly elevated in the samples from Cavern of Sleep and Hidden Lake with values that range between 0.6 and 1.1 mg/L (Figure 4). The combined presence of appreciable sulfate and fluorine in these waters suggest, at present, two potential interpretations: 1) The bedrock surrounding these pools is more enriched in sulfides or fluorides, and 2) the water in these cave pools has longer interaction with the bedrock.

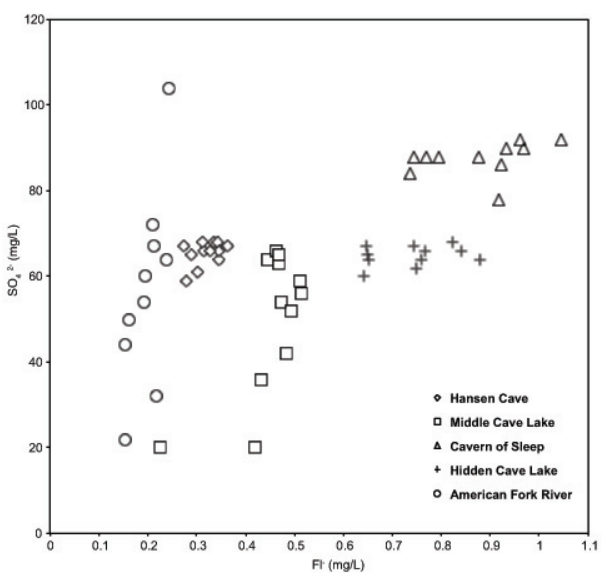

Figure 4. *Concentration of dissolved sulfate in water samples on the vertical axis compared to the concentration of dissolved fluorine on the horizontal axis.*

With regards to the first point above, enrichment of bedrock with sulfides or fluorides, the otherwise dark Deseret Limestone is laced with brilliant white calcite that fills fractures. That suggests influence from rising geothermal fluids that would certainly enrich the bedrock in sulfur- and fluorine-bearing minerals. Nearby deposits of ores such as copper and nickel support this process.

Regarding the second point, longer interaction time with bedrock, this is certainly plausible considering the slow response of these pools to storm events and snowmelt. However, average molar sums of Ca^{2+}+Mg^{2+} in Hansen Cave Lake and Middle Cave Lake are greater than average concentrations at Cavern of Sleep and Hidden Lake (Figure 5). In fact, Ca^{2+}+Mg^{2+} and Fl^- data from Hansen Cave Lake, despite having the greatest fluctuation in water level, are considerably more stable than from those sites that have stable water levels.

Why does Hansen Lake display a stable geochemical profile despite the large fluctuations in water level? For one possible answer we look to the stable isotopes of oxygen and hydrogen. Heavy water, with more than an

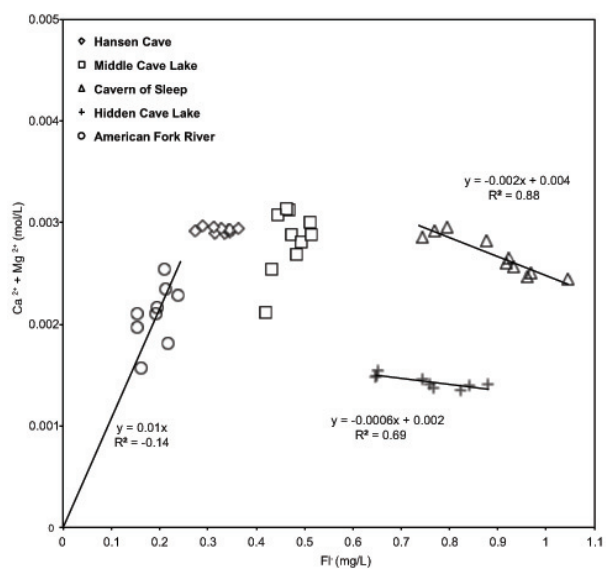

Figure 5. *Molar concentration of dissolved calcium and magnesium in water samples on the vertical axis compared to the concentration of dissolved fluorine on the horizontal axis. Regression lines are shown for the data from the American Fork River, Cavern of Sleep, and Hidden Lake.*

average number of the heavier isotope more frequently precipitates first from a cloud and evaporates last from a pool. The remaining water in the cloud or pool is thus 'fractionated'. This process is highly dependent upon temperature. Therefore, in a mountainous setting, such as along the Wasatch Front, rain or snow in lower elevations will be more enriched in the heavier isotope than the rain or snow on mountain peaks.

In the collection of samples from TICA, water in the American Fork River is the most depleted in the heavier isotopes, consistent with water derived from snowmelt at higher elevation (Figure 6). In the caves, Cavern of Sleep is the most enriched in the heavier isotope, suggesting water in this pool is derived from groundwater at the elevation of the cave. Hidden Cave Lake and Middle Cave Lake are somewhat 'lighter' in composition compared to Cavern of Sleep, perhaps from water infiltrating from the rugged land surface above the cave (Figure 1 – Kowallis, 2003). The two precipitation composites collected in this study bound the isotope data for Cavern of Sleep, Hidden Lake, and Middle Cave Lake.

Hansen Cave Lake, at nearly the same elevation as the other cave pools, is even more depleted in the heavy isotope, suggesting the source of this water is even higher than the land surface directly above the cave. One possible source is the talus near the canyon rim. Such a source could help also explain the stability of the geochemical data from this site. The large surface area provided by the rocks in the talus allows chemical reactions between the water and rock to occur rapidly, ensuring a constant product despite variations in residence time.

At all sites there is a clear 'early' behavior before early June where data are considerably more clustered and concentrated above the Global Meteoric Water Line (GMWL) and a 'late' behavior after early June where the isotopic composition of the samples trends toward depletion in ^2H and progresses below the GMWL (Figure 6). It is possible that these represent a change in reservoir characteristics from one dominated by melt waters to one significantly influenced by waters with significantly lower deuterium excess; perhaps waters that have been fractionated by evaporation.

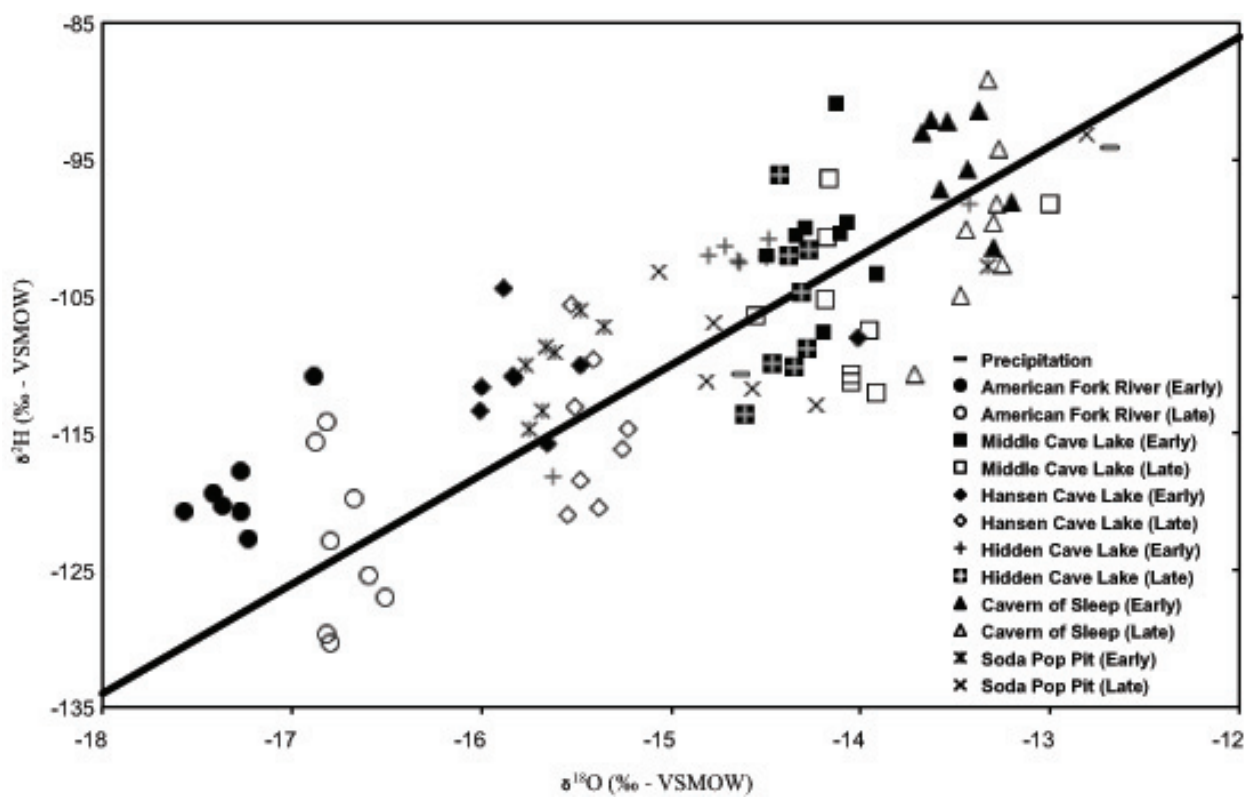

Figure 6. *Stable isotopes ratios of hydrogen on the vertical axis compared to the stable isotope ratios of oxygen on the horizontal axis. The solid line is the Global Meteoric Water Line (GMWL). Each site is divided in to an 'early' set before June 5 and a 'late' set after June 5.*

Interestingly, the isotope data from Soda Pop Pit have a dual behavior during the course of the study. Before early June the data are clustered near the composition of data from Hansen Cave Lake. After early June the sample composition migrates toward that of Middle Cave Lake. This implies a change in source-water elevation from melt near the canyon rim to groundwater in the rock immediately above the cave. In the case of both Hansen Cave Lake, and Soda Pop Pit, it is clear from the isotopic data that source waters may be derived from the canyon rim near the southern border of TICA. Consequently, management strategies for water quality should consider, at least in part, the portion of the National Forest on the Sagebrush flats adjacent to the Monument.

Summary Points

The hydrogeology and geochemistry of the pools within the caves of TICA suggests a range of behavior linked to rate of recharge, reaction pathway, and source-water elevation. Pools with near-constant water-level elevations may have complex geochemical behavior and significant reaction time with bedrock. Sulfate concentrations are elevated ^{13}C values are enriched. Considering these characteristics alongside the molar ratios of reaction products, it is possible that the dissolution of limestone occurs via equal contributions of carbonic and sulfuric acids. Source waters for these pools are near the elevation of the cave. In contrast, pools with large water-level changes can, in some cases, have very consistent geochemistry. This points to the potential for rapid reaction with a media that has a large surface area, such as the talus near the canyon rim. The depletion of the heavier isotope in these pools is consistent with a source water from at or near the canyon rim and supports the progressive management of the lands immediately adjacent to the southern border of TICA.

Acknowledgements

Data collected for this study was supported through a grant from the National Parks Foundation through the Great Basin CESU Network. Additional funds were provided through a STEP internship program at TICA. Generous support was provided from the Cave Research Foundation, the Cleveland Grotto Science Fund, and the BSU ASPiRE Program.

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SHOW CAVE, INTERPRETATION, BIOLOGY
DALE PATE, CHAIR

PRIORITIZING CAVES FOR KARST INVERTEBRATE RECOVERY IN CENTRAL TEXAS

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Abstract

Prioritizing caves known to contain endangered karst invertebrates in central Texas is more challenging than one may think. Here, we outline a strategy to achieve this goal while thinking of what is best for these species including addressing future impacts from climate change, and what works for landowners that are bound to permit restrictions. For example, there are two entities in the Austin, Texas area that hold regional Section 10(a)(1)(B) incidental take permits issued by the U.S. Fish and Wildlife Service. When developing the Habitat Conservation Plan for one of these permits several years ago, they listed several caves that they would either acquire or establish management agreements for. Since that time, they have acquired thousands of acres. Some of the caves listed on their permit occur on these lands. However, there are other newly discovered caves on these lands that contain endangered karst invertebrates that are not listed on their permit. Also, some of the caves that are listed on their permit are surrounded by development. This begs the question of which caves should they focus on for long-term preservation? Should they be limited to what their permit says or take a wider approach and look at what is best for the species while considering new cave discoveries? To answer this question from a species perspective, several aspects of these caves should be assessed including but not limited to the cave depth, cave size, species diversity and abundance, and the amount of development etc. around these preserves. Cave size and depth are important because deeper caves may provide more protection from ambient surface fluctuations in temperature and humidity. This approach should provide a more holistic pathway to long-term karst invertebrate conservation. By assessing what is best for the species and acknowledging new cave discoveries, perhaps minor amendments could be made to 10(a)(1)(B) permits that would provide higher species benefits.

CAVE AND CLIMATE CHANGE: EDUCATING THE PUBLIC AT RATS NEST CAVE, ALBERTA, CANADA

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Abstract

Rats Nest Cave is a Provincial Historic Site whose mandate is to present its natural history to the public. In addition to a suite of interpretive messages, and relevant to this conference's topic, we have addressed diverse climate change over the geological history of the cave. We start with the cave-hosting rock and the fossils it contains, to its origin along a thrust fault, ending with its enlargement and secondary mineralization during the Quaternary glaciations (the latter having been dated by radiometric methods). We have undertaken a program of speleothem remediation which, visible to the public, serves to reinforce the conservation and sustainability message emphasizing the importance of caves to society.

Introduction

Rats Nest Cave was protected as a Provincial Historic Site in 1987. Public tours began some years afterwards in 1995 supported by interpretive information gained via a number of studies at the cave by the authors and others (Yonge 2012, Yonge 1991 and e.g. Figure 1) and by provincial funding from the Science Alberta Foundation. The tours are wild in nature with horizontal and vertical caving being offered: (www.canmorecavetours.com).

A wide variety of the populace has been taken through the cave over the years, with 2012 numbers at 3,553 participants. Visitors were world-wide (with the female to male ratio at 45:55 %), but the majority have been Albertan (82%) in recent years (Figure 2).

Groups range from independent tourists, corporate, school, church, guide and scout and tertiary institutions. The cave generates considerable interest, with a high rating on Trip Advisor plus several media releases in the media, e.g. TV and radio.

Interpretive information related to climate change

For our public education (on climate change), we start outside (Figures 3 and 4) with the cave-hosting Mississippian limestone (the Livingstone-Mount Head Formation), which contains index fossils: brachiopods, horn corals, and crinoids. Our interpretation here focuses on the corals and therefore tropical paleoclimate of the time, and how that could have been considering that we now experience a Siberian-type climate. The out-of-place fossils give a good opportunity to talk about plate tectonics (especially looking across the valley to the classically folded and thrusted mountains that constitute the Canadian Rocky Mountains). It appears that during the Mississippian, these limestones were laid down just north of the equator along reefs aligned east-west (Gadd, 1995).

In discussing plate tectonics, we introduce mountain building and faults that occurred during the Cretaceous as the ancestral super continent of Pangea was breaking

Figure 1. *McMaster University sampling seepage water to study the systematics of speleothem formation under the present climate regime (temperature, drip rate, humidity and stable isotopes).*

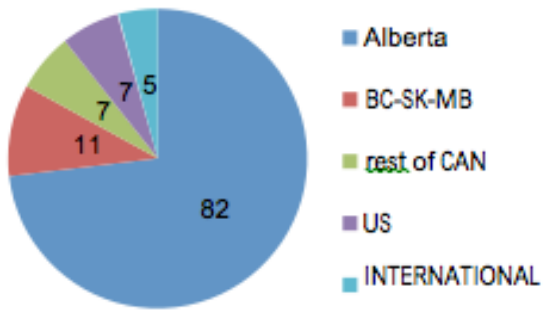

Figure 2. *Percentage of visitor types to Rats Nest Cave in 2012 (total visitors are 3,553).*

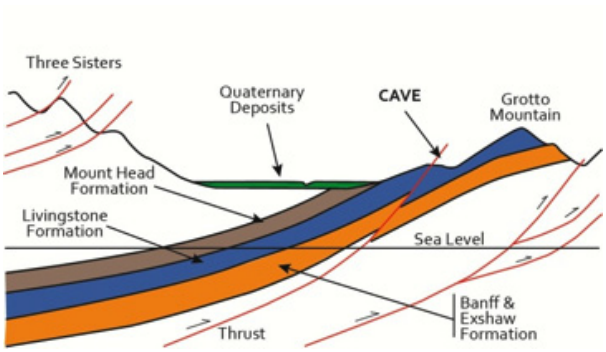

Figure 3. *The geological setting for Rats Nest Cave, which is developed along a thrust fault as indicated.*

Figure 4. *The geological setting for Rats Nest Cave, which is developed along a thrust fault as indicated.*

up and dinosaurs roamed in and around the ancestral Bears Paw Sea (the world-class Albertan Tyrell Dinosaur Museum exemplifies this era with stunning local exhibits). Specifically we refer to low-angle thrust faults along one of which the cave has formed (Figure 3) and which is readily seen underground (Figure 5).

The climate change story then moves into the multiple Quaternary Glaciations which, when ending at a given interglacial, result in the enlargement of the cave by extensive glacial meltwater (Canadian Rockies Caves are intimately coupled to glaciations leading to classic glaciokarsts in the region – Ford and Williams, 1989). At this stage the cave also experiences clastic sedimentation and secondary mineralization, which potentially give proxy paleoclimate records (Figures 6, 8 and 9).

Speleothem dates thus define interglacial periods (Fairchild and Baker, 2012; Ford and Williams, 1989) and at Rats Nest Cave, a number of U-Th dates of speleothems confirm this (Figures 7 and 8).

Calcite speleothem fabrics can yield information about past temperature (and vegetation cover) above the cave

Figure 5. *Inclined passage in Rats Nest directed along a thrust fault.*

(e.g. Figure 8). For example, one sample collected in the cave dates to the so-called Marine Isotope Stage 5e at 123ka, a warmer interglacial than today when sea levels were 5m higher (Figure 8).

We consider the outside, where repeated glaciations successively act to remove evidence of prior glaciations (Rutter et al. 2006). So while there is abundant recent glacial material (i.e. from the Wisconsinan Glaciation), little remains of previous glaciations (with the added difficulty that glacial sediments are notoriously difficult to date).

Caves however, being enclosed, tend to preserve all phases of sedimentation making them important archives of climate change, especially speleothems which can be dated by Uranium Series methods (principally ^{234}U-^{230}Th). An important adjunct to this is that in the Canadian Rockies, speleothems form during the interglacial stages, as caves are either flooded (if sub-glacial) or are deprived of seepage water (if in permafrost) during glacials.

In addition to the Pleistocene glaciations, the cave contains interesting material from the Holocene other than speleothems. Just inside the cave entrance, debris has accumulated in a 15m pit, of which bones are a significant component (Table 1 and Figures 10 and 11).

Carbon-14 dating of the bones has yielded a maximum of 7.2 ka, showing that all of the 34 mammals represented are of Holocene origin having fallen in after the last glaciation.

Two artifacts recovered from the pit have been dated back to 3.2 ka and identified as Pelican Lake Culture (Figure 11), a late stage bison-hunting group that arose and thrived during the warmer than today Holocene Hypsithermal period, 7.5-5.0 ka. The fact of this climatic optimum is supported by speleothem stable isotope studies at the cave (Figure 9). Pictographs at the cave entrance appear to be more recent, perhaps 500 years old.

While the prior discussion is somewhat technical for a lay audience, the interpretation can be tailored to suit needs; the audience might of course include climate scientists. At a less technical level, for example, we conduct an annual field trip from the grade 10's at our local high school: climate change forms part of the curriculum of their so-called Ascent Program.

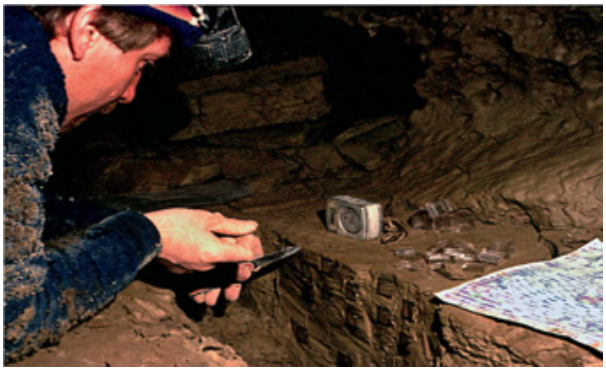

Figure 6. *Paleomagnetic sampling of clastic sediments in Rats Nest Cave.*

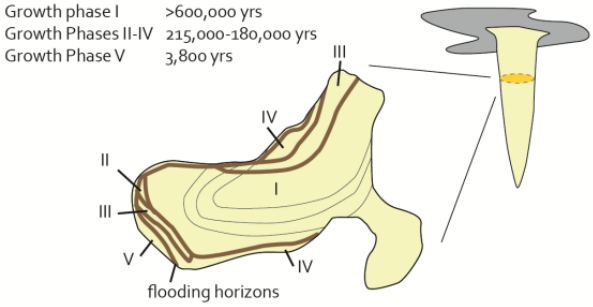

Figure 7. *A stalactite from Rats Nest Cave, showing growth during interglacial periods with evidence of cave flooding.*

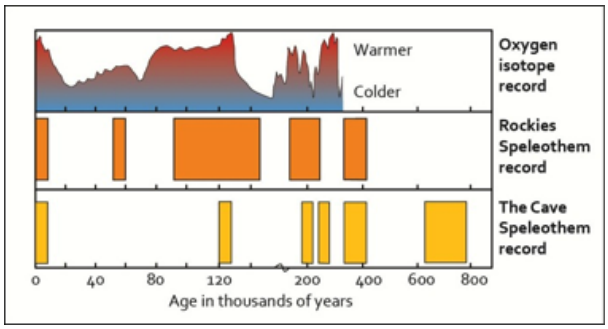

Figure 8. *Speleothem U-Series dates from caves in the Canadian Rockies compared to those from Rats Nest Cave and Oxygen isotope record of marine and ice cores.*

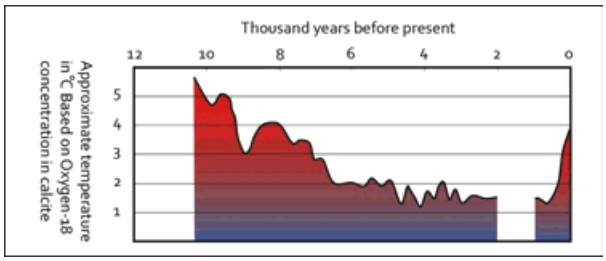

Figure 9. *Holocene stable isotope temperatures based on several speleothems from Rats Nest Cave.*

Table 1. *A preliminary list of species from Rats Nest Cave*

A Preliminary List of Species from Rats Nest Cave, especially from the Bone Bed Pit - Compiled by Dr. James Burns, 1986

AVES (birds)—includes passenger pigeon, crow and golden eagle

INSECTIVORA (shrews, etc.)
Sorex cf. S. arcticus (Arctic shrew)
Sorex sp. (shrew)
CHIROPTERA (bats)
Lasionycteris noctivagans (silver-haired bat)
Myotis lucifugus (little brown bat)
LAGOMORPHA (pikas, hares, etc.)
Ochotona princeps (pika)
Lepus americanus (hare)
RODENTIA (rodents)
Clethrionomys gapperi (red-backed vole)
Erethizon dorsatum (porcupine)
Eutamius sp. (chipmunk)
Marmota caligata (hoary marmot)
Microtus sp. (vole)
Neotoma cinerea (bushy-tailed wood rat)
Peromyscus maniculatus (deer mouse)
Phenacomys intermedius (heather vole)
Spermophilius columbianus (Columbian ground squirrel)
Tamiasciurus hudsonicus (red squirrel)

CARNIVORA (carnivores)
Canis latrans (coyote)
Canis lupus (gray wolf)
Gulo gulo (wolverine)
Lynx canadensis (lynx)
Martes americana (pine marten)
Mustela vison (mink)
Mustelidae sp. (weasel)
Taxidea taxus (badger)
Ursus americanus (black bear)
Vulpes velox (swift fox)

ARTIODACTYLA (even-toed ruminants)
Bison bison (plains bison)
Cervus elaphus (wapiti or elk)
Odocoileus sp. (deer)
Ovis canadensis (bighorn sheep)

PISCES (fish)

AMPHIBIA (frogs and salamanders)

REPTILIA (snakes)

Figure 10. *Debris spilled out from the base of the Bone Pit including skulls (Bighorn, sheep, cougar and bear) and bones.*

Speleothem Remediation at the Cave

Rats Nest Cave is a static cave in the sense that no vadose water currently flows through it as streams (Figure 12). The cave in fact is almost entirely phreatic and was completely flooded in glacial times (Yonge 1991, Palmer 2007). That vadose down-cutting is almost completely absent testifies to its glacially- coupled origin: rapidly melting ice sheets would have given little time for passage entrenchment.

Figure 11. *A schematic of the Bone Pit with inset dart tip circa 3,200 years old.*

Figure 12. *The Grotto in Rats Nest Cave containing copious speleothems and pool resulting from the accumulation of seepage water.*

Speleothems have accumulated after cave dewatering during the interglacial periods and, as argued above, are very important in determining past climates above the cave.

Because the cave is static, containing copious quantities of clastic glacial sediments, it has suffered as these have been spread around by careless cavers prior to its provincial designation.

The cave contains a great variety of calcite formations and these are of great interest to visitors (Table 2). The interpretation outlined above further adds to their value in the public eye. We have therefore embarked on a remediation plan, mainly tackling dirty and damaged formations (Figures 13, 14 and 15).

With the help of volunteers from the Alberta Speleological Society, the formations along well travelled pathways within the cave are being cleaned. The techniques used

to clean the muddied formations have been adapted from those described in Cave Conservation and Restoration (Hildreth-Werker and Werker 2006).

Preventing further damage to speleothems is intrinsically important to the remediation process: both the tools and water used to clean formations must be carefully selected. Tools chosen for formation restoration must be non-abrasive to the delicate outermost layers of calcium carbonate. As such, soft bristled tooth brushes nail brushes and plastic tooth picks are among the cleaning kits. Care is taken by the volunteers when using the cleaning tools to not apply excess pressure on the formations and extremely delicate speleothems are often not remediated to avoid causing further damage. The water required to clean the formations must be collected from a standing pool that self-replenishes from rain and surface water slowly percolating through the rocks above. This pool serves as a reliable source for the vital calcium bicarbonate rich water required to safely clean mud away from the formations without dissolving the outermost layer.

The results so far have varied from poor to outstanding. We have found that the formations that have been growing at a more rapid rate have already sealed the mud under several thin layers of calcium carbonate, while those growing more slowly have come almost entirely clean.

Educating the visitors to Rats Nest is a key factor in the continued conservation of this Provincial Historic Site. To assist in this goal, formations that have been remediated are marked off using flagging tape and signage has been placed to explain the restoration project and encourage visitors to stay on established trails and avoid touching the formations. A secondary benefit of this project is knowledge gained by our many volunteers regarding cave conservation and the spreading of that knowledge throughout the local caving community.

Table 2. Speleothem varieties and locations in Rats Nest Cave.

Calcite Mineral Formation	Location Where Good Examples are Found
Coatings and Crust	Birth Canal and above the Slimy Climb
Conulites	Chasm below the High Point, Grand Gallery
Coralloids	Grotto, Wedding Cake Passage, Rabbit Warren
Curtains	Grand Gallery, Coyote Descent
Flowstone	Many areas—Grotto, Great West Highway, Wedding Cake Passage
Helictites	Great West Highway, Wedding Cake Passage
Moonmilk	±8 m pitch near entrance, high dome above the Grand Gallery
Pearls	Pearly Way, Ranger Way
Rafts	Sucker Route, Mud Room
Rimstone Dams	Frozen River in the Wedding Cake Passage, Grotto
Spar	Above the Slimy Climb
Stalactites	Numerous areas—Ranger Way, Great North Highway, Grand Gallery, Grotto
Stalagmites	Numerous areas—Ranger Way, Great North Highway, Grand Gallery, Grotto

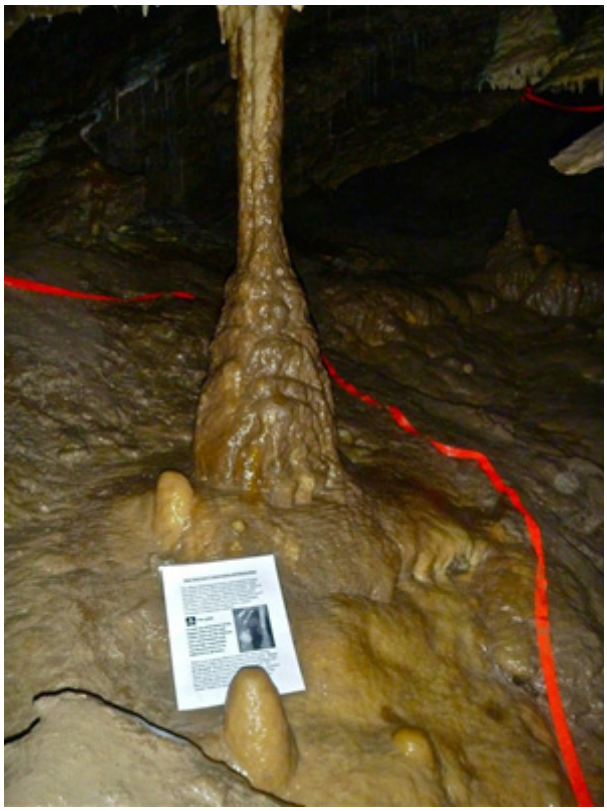

Figure 13. Work in progress on a column, taped off with a notice informing and educating self- guided cavers.

Figure 14. *Cleaning work on the column shown in Figure 13.*

Figure 15. *Results of speleothem cleaning: the inside, lower area is in its original dirty condition.*

Conclusions

The coupling of scientific studies to the natural history interpretation of this protected cave site has resulted in a successful management model, which has the added benefit of protecting the cave by a year-round presence. The alternative could have been to recognize the cave as a special scientific area and allow entry solely to researchers. However, with a city of over one million inhabitants within an hour's drive (Calgary) this strategy would have been a disaster. Without daily presence at the site, the gate would have been compromised and the cave severely vandalized. This has been the result at the more remote Cadomin Cave, which has suffered from spray paint, garbage and disturbance of its bat population.

The results of illuminating the cave's value as a record of geological history, paleontology, and climate change has been a flourishing business, with 3,533 visitors educated last year.

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USE OF IMPACT MAPPING FOR PLANNING THE INFRASTRUCTURE IN TOURIST CAVES - CASE STUDY: MAQUINÉ CAVE, BRAZIL

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Abstract

The main objective of this article is to show how mapping and environmental impact analysis can be used to support the management decisions in tourist caves, such as infrastructure planning and monitoring efforts.

Introduction

The Maquiné Cave has great historical, scientific and speleological value in the Brazilian context. Located in the central portion of Minas Gerais, Brazil (Figure 1), this limestone cave has chambers with significant volume, speleothems of great beauty, is home for rare troglobites, and hosts an archaeological site in the entrance zone.

Since 1908, a large area of the cave has been used for tourism; being the first Brazilian cave to receive artificial lighting, in 1967. In that same year, a pathway system was installed (with stairs, walkways, flooring) and around the cave entrance, was implanted parking areas, gardens and restaurants. In 1999 a new lighting system was installed. With some interference, these infrastructures remain today in the cave. In 2005 the Peter Lund Natural State Monument was created. It was an important step to protect the cave and its surrounding area. The management of the area is shared by the State Institute of Forestry from Minas Gerais and the City Hall of Cordisburgo, through Maquinetur Foundation.

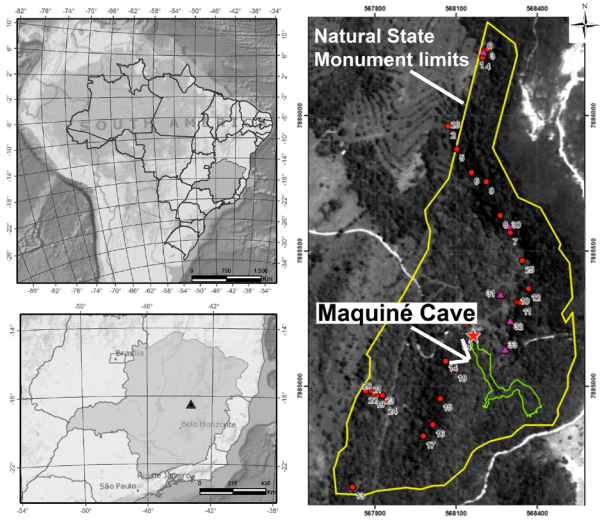


Figure 1. *Location map.*

In the first half of the nineteenth century the cave was studied and mapped by the Danish scientist and naturalist Peter Lund and his team, which revealed to the world the importance of this cave and its exceptional sedimentary deposits, where he found several specimens of extinct megafauna. Before that the saltpeter was explored in the cave. Today, about 50,000 people per year visit the cave, which has a significant socio-economic importance for the municipality of Cordisburgo, where it is located. In 2009 and 2010 was carried out the cave management plan, an important step towards the protection and control of environmental impacts.

The Peter Lund Natural State Monument is inserted in the Cerrado biome, one of 34 "Biodiversity Hotspots" on the global scale. The climate is mesothermal with dry mild summer (Cwb), with annual pluviometric average index of 1271.4 mm, characterized by a rainy season from October to March, and a dry season from April to September (IEF, 2010).

This article presents a summary of the impact assessment, briefly addressing the main anthropogenic interventions that cause environmental impacts, real and potential, inside and outside of Maquiné Cave. This assessment enabled the planning of management and monitoring actions in order to control, minimize and remediate the pressures on the cave, enhance existing assets and add quality to the cave tour.

The results presented below are part of a wider diagnostic, composed in different steps of speleological prospection; topographic and thematic mapping of Maquiné Cave,

establishment of Speleological Zoning, cave load capacity, management programs, and recommendations for emergency measures. This Diagnosis, in its turn, is part of an even broader set of environmental studies that includes the Management Plan for the Peter Lund Natural State Monument and the participation of a multidisciplinary team.

Methodology

The detailed topographic map of Maquiné Cave was the basis for the impact map (Figure 2). The topographic map was made using compass and sight clinometer (KB14 and PM5/ Suunto) and laser meter (DLE 50/ Bosch). This map was based on a highly detailed sketch, which used many topographic bases to delineate the deposits and internal features of the cave. The central axis of the topographic map was checked with a total station. In UIS classification, the work is between grades 5-4 and X-B-4-C. This map shows accuracy in galleries contour, and a faithful representation of chemical and clastic deposits.

Impact mapping was carried out throughout the cave by carefully observing surfaces, and recording the impacts identified in a map and by using photography, inspired in *Visitor impact point mapping* described in Bodenhamer (2006). Additionally, the lighting system and the water introduction system were mapped. Thus the electric cables and water piping, the position and orientation of the spotlights, the type of lamp used, and the location of pass and control boxes were mapped. The map of these systems was overlaid on the impact map in AutoCAD software, allowing correlation; for example, where the growth of lamp flora is observed and the type of lamp used.

The impact map is part of the thematic maps included in the management plan for Maquiné Cave. In this context, the cave attractions, weaknesses, conservation state, visitors flow, and risks to visitors were also mapped. The integrated analysis of thematic maps allowed the establishment of the Speleological Zoning.

It is noteworthy that the impact evaluation is focused on activities that arise directly or indirectly from tourist use. However, some impacts observed in the cave are due to events that occurred over the past 200 years, when large areas were excavated to extract saltpeter or fossils, causing permanent and irreversible impacts to the cave deposits. These impacts may currently be considered as historical remains and must be addressed during the cave tour.

Results and discussion

Caves are complex and fragile environments, with low resilience due to the presence of sensitive chemical and clastic deposits, endemic fauna, and aspects such as the absence of light, the limited resources supply and spatial confinement. On the other hand, caves provide educational, recreational and scientific opportunities for visitors and researchers. However, these uses, if not handled properly, can cause severe impact or even destroy the features that provide such opportunities (Pate, 2006).

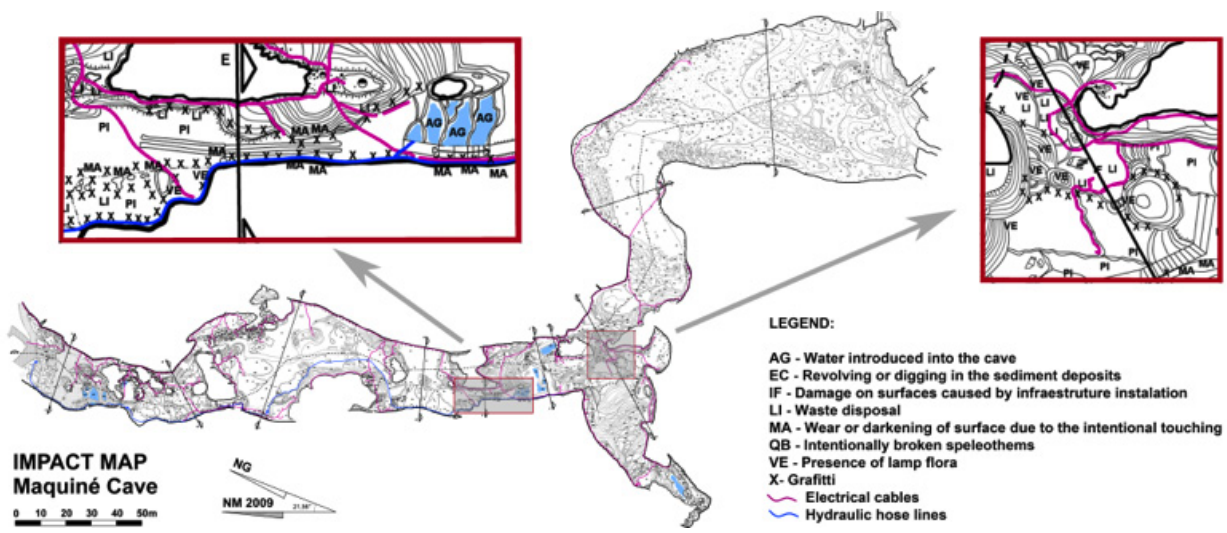


Figure 2. *Impact map*
Synthesis of the impacts and problems of the lighting system.

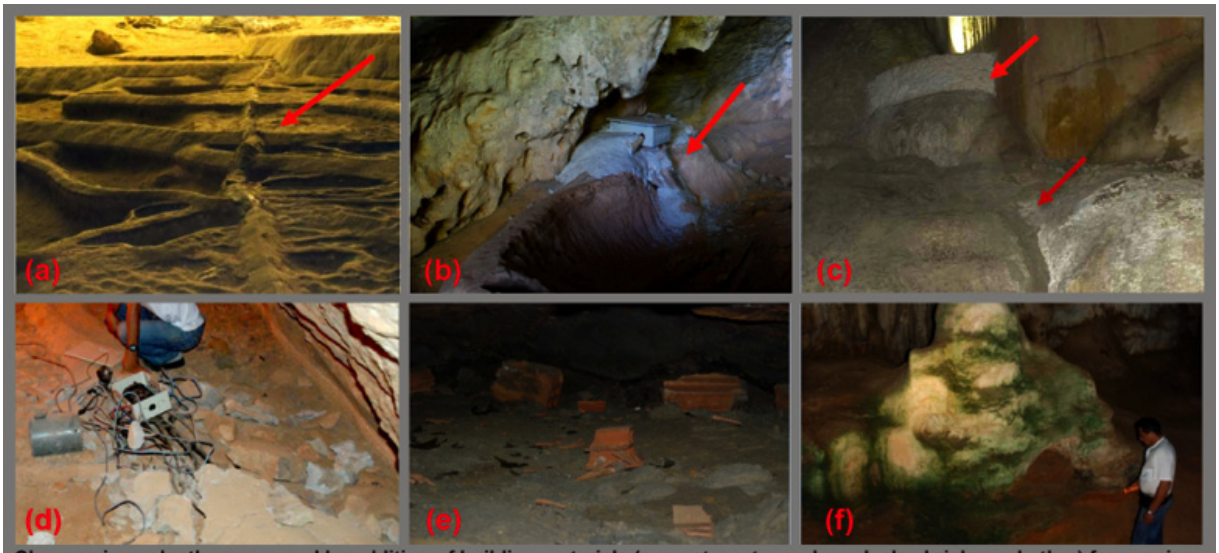
Among the main impacts noted in Maquiné Cave that stand out are serious damage to speleothems, sediments and rock surfaces, and possible impacts on fauna and microclimate. These impacts are the direct or indirect consequence of the installation, maintenance and operation of the existing infrastructure, as well as arising from problems of visitor flow management. As the caves are fragile and low resilience environments, the impactful activities, past and present, form a set of cumulative changes that must be mitigated and monitored.

In 2009 there were 115 active spotlights in Maquiné Cave, using 9 different types of lamps. Most of them have low efficiency, high power (500W) and high-energy consumption, such as halogen, metal halide, sodium vapor, mercury-vapor and mixed vapor lamps. The lighting system could be powered up in sequence, however, in days of great visitor flow, it was turned on about 8 straight hours. The use of high power lamps can cause microclimatic changes, such as temperature increase and relative humidity decrease, especially in caves of low energy flow such as Maquiné (Cabrol, 1997).

Through the Impact Map (Figure 2) it was found that the development of lamp flora occurred more intensively near high power lamps (halogen, metal halide and mixed vapor). In addition to the aesthetic impact of color change the presence of lamp flora (Figure 3-f) can induce surface corrosion in speleothems by biochemical and biophysical processes (Pulido-Bosch et al., 1997). The lamp flora represent an additional introduction of nutrients into the cave, which can affect the ecosystem dynamics.

Spotlights located near speleothems cause glare, make them unattractive and cause large variations in surface temperature and humidity, which contributes to the deterioration of speleothems (Veni, 1997). Furthermore, heterogeneous and insufficient lighting of the floor generates risk to visitors and contributes to the widespread stepping on speleothems.

The main cabling of the lighting system runs in one side of the cave, interspersed with passage boxes, from which are derived the secondary wiring to spotlights and control boxes. To hide the wiring cement mortar was applied over speleothems, sediment or rock surfaces and in some places the cabling was buried. To hide the spotlight low walls of masonry were built (Figure 3-a,b,c). At some points, it is clear that the speleothems were intentionally broken for the installation of the electrical system. Burying the cables disturbs the original sediment stratigraphy. Such changes are potentially harmful in archaeological or paleontological sites. The techniques used to hide wires and spotlights are also impactant, as the adhesion of the cement mortar can produce physical and chemical changes in speleothems and rock surfaces, besides volumetric changes that generate large visual impact, compromising the attractions.



Changes in speleothems caused by addition of building materials (cement mortar and sand, clay bricks and other) for passing electrical cables (A), installation of passage box (B), shields to hide spotlights (C). Photos (D) and (E) solid waste (broken lamps, mortar, masonry) generated in the installation and maintenance of the lighting system. Photo (F) Growth of Lamp flora over sediment and speleothem. Photos: L. Alt

Figure 3. *Examples of the impacts and problems of the lighting system.*

The lighting system demanded frequent maintenance, either for bulb replacement, revisions in the cabling and electrical contacts. The use of cement mortar cords made the maintenance process difficult or impossible (Figure 3-d). In some locations the installation of new mortar strings over the existing exceeds 30 cm in height, increasing the visual impact. In addition, the constant maintenance on the system causes stepping of fragile speleothems. Unfortunately, much waste from this activity was improperly abandoned in the cave (Figure 3-e). Some of these wastes, such as electric bulb fragments, represent an imminent environmental risk, apart from being sharp they may contain toxic heavy metals.

At several points there are electrical cable splices without proper connectors and tangled cables without support with friction points to speleothems and rocks. This disorganization offers risks for the electrical system and for the maintenance agents and visitors, since these points can create contacts with energized elements. Furthermore, when the lighting system is switched on, it generates constant noise and electromagnetic fields, which can potentially interfere with bat dynamics.

Synthesis of impacts and problems related to pathway system

The pathway system installed in 1967 in Maquiné Cave consists of flooring, walkways and stairways. This system was not deployed the whole way through the cave, so the visitor sometimes walks on built infrastructure, and sometimes directly on speleothems and sediment surfaces. There are no physical structures to control or to delimit the visitors' flow, stopping places and the room for groups to pass each other.

The lack of infrastructure associated with visitation control generates a large area of alteration, by trampling, that stretches for almost the entire cave. This causes soil compaction, loss of individuals due to crushing, speleothem damage, and waste spread in large areas (Figure 4-d). According to Ferreira and Souza (2012) the fauna were attracted to artificial food sources within the visiting area, causing ecosystem changes in Maquiné Cave. In other words, the irregularity of the natural surfaces causes discomfort and risk to the visitor. Trampling also causes the suspension of fine particulate material, which may in the long term, affect the guides health and lead to loss of attractiveness of speleothems by deposition of the particulate material. According to oral reports, in the past, several speleothems were washed with a high-pressure water system applying large volumes of water to remove dust and lamp flora.

The existing infrastructure was installed using different techniques and materials: (I) by removing materials - partial or total breaking of speleothems and sediment

Changes in speleothems by addition of building material (A) or breakage (B), Washing paving in the entrance zone archaeological site (C), Speleothems wear and aggregation of sediment loaded in shoes (D), Lack of handrails and irregularity in stair cause risk to visitor and induces touch in speleothem, causing darkening and surface wear (E), Compacting sediment around the pathway (F). Photos A to F: L. Alt, Photo B: V. Moura.

Figure 4. *Examples of impacts related to installation and operation of the pathway system.*

removal, (II) by adding materials (stone and cement mortar) over speleothems or sediment; (III) by the combination of these two techniques (Figure 4- a, b, c). These techniques in many instances caused irreversible damage, such as speleothem breakage, physical and chemical surface changes, visual impacts and the potential loss of visitors.

Stairways and walkways have irregular and/or slippery flooring which together with the lack of handrails and guardrails generates discomfort, walking difficulty, and imminent risk of falls and injuries to visitors. The risk increases when groups cross to each other in narrow walkways and stairways beside abrupt drops. Lack of handrails and guardrails induces the visitor to touch speleothems and other surfaces, causing darkening and in some cases surface wear (Figure 4-e).

To increase the adherence of stairs and walkways surfaces, a cement mortar mixed with sediment taken from inside the cave was applied. This practice causes sediment removal in sites with paleontological potential and can potentially destroy microhabitats for invertebrate fauna. Another practice commonly used is floor washing, which may cause changes in the fauna, relative humidity, and can stain speleothems and other surfaces (Figure 4-c).

In some areas of the cave, as in the entrance zone, there is an excess of infrastructure (wide sidewalk area, shop desks, turnstiles, gate) (Figure 4-c). However, this hall houses a prehistoric archaeological site. Flooring installation caused changes in sediment, possibly disrupting their original stratigraphy, which can cause irreversible damage to archaeological sites. The entrance flooring also changed the runoff water dynamics, probable causing suppression of vegetation and microhabitats to the epigeal fauna, which, according to Ferreira and Souza (2012), may have influenced the delicate ecosystem dynamics in the cave. This wide sidewalk area induces a dispersed flow of visitors, encouraging touch and interference on existing rock art panels.

Careful planning of the pathway system is decisive in a tourist cave and may reduce the diverse impacts in a cave, enhance visitors security, and help to protect sensitive or fragile resources (Hildreth-Werker et al, 2006). However poor planning of this may compromise the attractiveness of the cave. The Maquiné Cave is in a stage where a good review of the infrastructure (pathway and lighting system) and proper management of visitors, along with programs of restoration, conservation and monitoring, could mitigate many damages observed and promote a high quality tour.

Synthesis of the impacts and issues related to water introduction system

Most of the year, Maquiné Cave is dry; only in the rainy season some travertine dams fill naturally. In order to increase cave scenic beauty to attract more visitors, and to reduce the suspended particulate material in the air, a hydraulic system was installed to moisten the floor and fill some of the travertine dams. This system is comprised of plastic hoses, Polyvinyl Chloride tubes (PVC), and passage boxes. The system was deployed along one side of the cavern, which is opposed to the lighting system. For the installation of the system, components were buried in sediment or covered by mortar cords. The valves were installed in passage boxes, which were built of masonry over sediments, speleothems or rocks. The installation and maintenance of this system resulted in numerous impacts, similar to those identified for implementation and maintenance of the lighting system, due to the similarity of the techniques used.

Getting water inside a cave that possesses a small single entrance, low air circulation and low energy inputs, as Maquiné Cave, constitutes a risk of changing the original relative humidity level. Furthermore exogenous organism and chemical products, suspended or dissolved in the water, can be introduced. The water quality analysis performed by IEF (2010) identified the presence of cyanobacteria in the water. According to Cabrol (1997) the artificial introduction of water, in many cases, is not compatible with the cave environment and may erode, dissolve or degrade speleothems. Some guides reported that, before the water is introduced into the cavern, chlorine is added to it. This element is potentially harmful to cave fauna, due to its known biocide action, and may increase the corrosive power of water.

Synthesis of the impacts and issues related to visitor flow management

The visit to Maquiné Cave is guided, and the visitor does the same route to enter and leave the cave. One of the main problems observed in the cave are very large groups, sometimes with more than 50 visitors per guide

Part of a very large group, with more than 50 visitors per guide (A), Unsupervised visitation (B), Waste disposal (C), Graffiti (D), Attraction created by the interaction of guides with the cave (E), Some visitors uses the cave as a toilet (F), Wear and darkening of speleothems due to continuos touch over years (G), Unsuccessfully attempts to camouflage or remove existing graffiti (H). Photos: L. Alt.

Figure 5. *Examples of impacts and issues related to visitors flow management.*

(Figure 5-a), making it impossible to control the whole group, especially in the narrow section between the big chambers. In these places, where the guide loses visual contact with the group, there are large concentrations of graffiti over speleothems and rock surfaces.

Some attractions are created by the interaction of guides with the cave, when they beat speleothems, in order to produce sound, or jump hard on the floor, to show that the floor is "hollow" (Figure 5-e). This kind of action does not have educational value and encourages visitors to touch the speleothems - causing darkening and introduction of surface corrosion - and jump over several parts of the route - which generates sediment compaction, damage to speleothems and possible impacts on the cave fauna.

Another problem is that some guides complete their tours in the last visited chamber, allowing visitors to return unsupervised to the entrance of the cave (Figure 5-b). This favors the occurrence of many impacts like graffiti, broken speleothems, stepping or touching fragile features, using the cave as a toilet, and improper disposal of waste.

A significant portion of the more delicate speleothems in Maquiné Cave, like straws, draperies, stalactites, stalagmites or pearls were partially broken or removed. Many of these breakages seem to have happened in the distant past. It is noticeable today, in a small area of the cave, that some speleothems are beginning to grow over the broken ones, in a very slow process of natural regeneration.

A large part of the rock surfaces, including speleothems and rock art panels in Maquiné Cave, located within reach, have some graffiti, with dates ranging from 1887 to the year that the work was done (Figure 5-d). In some places the graffiti exist in high density, in others occur isolated. Some graffiti was made with material removal, by incisions, and others with the addition of various materials such as graphite, carbon, acrylic paint, clay, lipstick, among other things.

Numerous unsuccessful attempts to camouflage or remove existing graffiti by applying cement, artificial pigments, clay, sanding, and other techniques were observed. The use of these techniques caused even greater visual impact and physicochemical changes on cave surfaces (Figure 5-h).

Another potential problem is the amount of visitors per day in the cave, which is currently controlled by the guides. Long lasting microclimatic and CO_2 concentration monitoring was not performed in the cave. Therefore, it cannot be determined what the percentage of change in temperature and relative humidity is caused by visitors and/or by the existing lighting system. Changes in these parameters due to visitors or lighting system are widely described in the literature, especially in low energy caves, as Maquiné, since they generate impacts in speleothems and cave fauna (Villar, 1984; Cigna & Forti, 1988).

Synthesis of the impact assessment

The installation, maintenance and operation of the infrastructure (lighting, pathway, and water introduction systems) and the management of visitor flow generates impacts inside the cave, in their chemical and clastic deposits, on rock surfaces, fauna, microclimate, in paleontological and archaeological heritage. The interference conducted near the cave entrance for installation, maintenance and operation of the external infrastructure (parking areas, buildings and gardens), caused impacts on the karst landscape, vegetation, fauna, and soil. These changes, in their turn, can potentially result in impacts inside the cave, mainly in fauna dynamics and visual impact. The relationship between these impacts is summarized in Figure 6 below.

Throughout Maquiné Cave damage on speleothems and rock surfaces were observed that are caused by: (I) intentional breakage due to: installation and maintenance

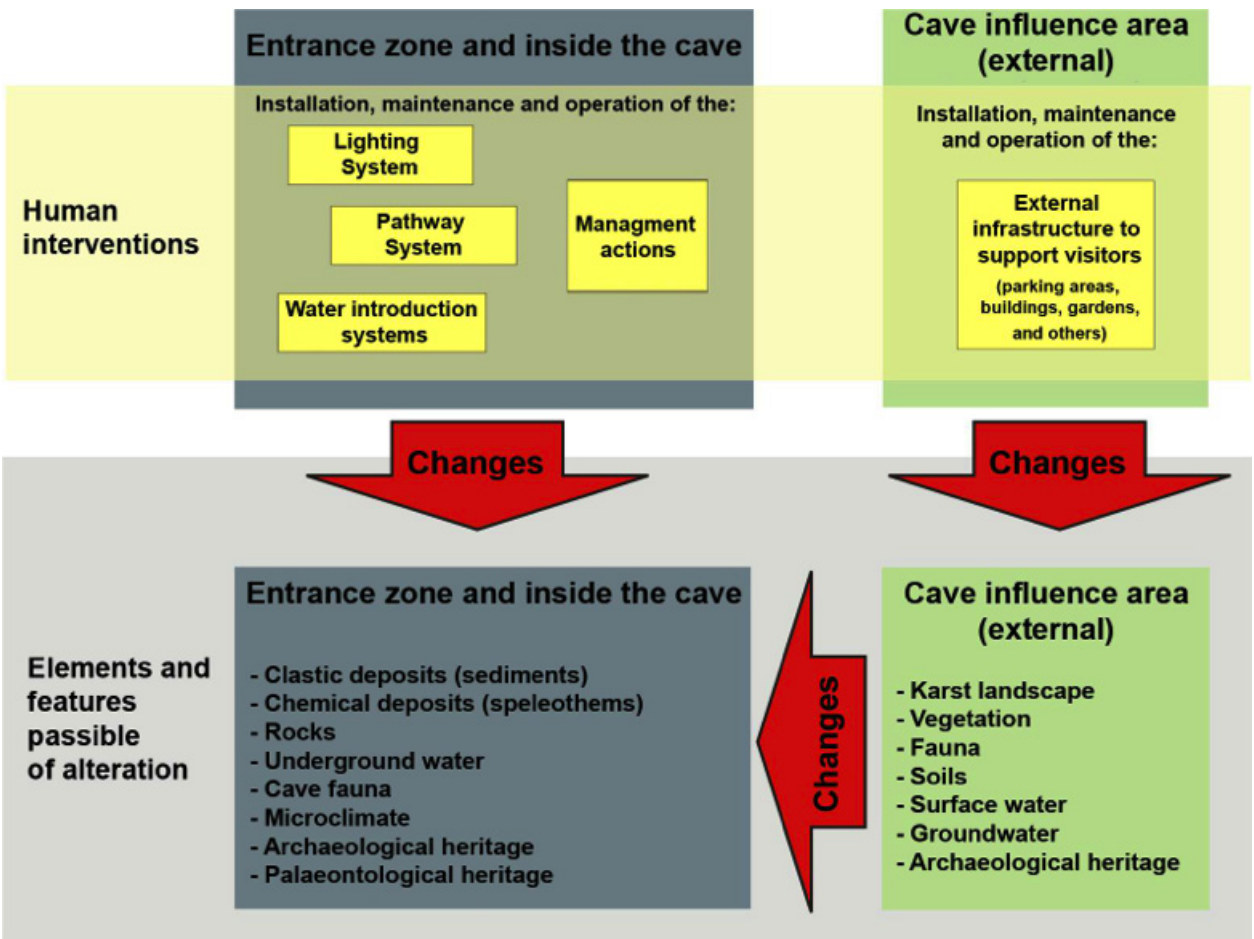


Figure 6. *Scheme of interaction between human interventions and cave environment in Maquiné Cave.*

of existing infrastructure, actions of vandalism, extraction of calcite, saltpeter or fossils; (II) speleothem surface wear due to trampling and intentional touching, (III) physical and physicochemical changes by adding building materials, by graffiti, by mistaken restoration attempts; (IV) possible biochemical and biophysical surfaces due to lamp flora growth; (V) ecosystem changes due to artificial introduction of nutrients and preventing bats entry (Use of gate with wire mesh for many years. This mesh was partially removed in 2009, allowing bats to return). Several of these damages are harmful to tourism activities.

Most of the damage to clastic deposits in the cave is caused by: (I) removal or revolving sediments for installation and maintenance of existing infrastructure, by historical activities such as the old digs for saltpeter or fossils extraction, (II) compaction, impermeabilization and modification of surface drainage due to trampling or the addition of materials.

Disperse waste can be observed throughout the cave, especially in spots that are not visible from local intensive visitors flow, such as high levels, low ceilings, or narrow passages between speleothems. The presence of two distinct types of waste can be clearly noted: those left by visitors - candies, chewing gum, batteries, flash bulbs, toys, toothpicks, matches, and others - and those from the installation and maintenance of existing infrastructure - such as scraps of building material (brick, cement, mortar, wood), remains of electrical material (wires, connectors, broken electric bulbs, electric bulb packs, damaged spotlights), and remains of hydraulic equipment . The table 1 below correlates the observed impacts with different impactant activities.

Synthesis of mitigation measures

We are defining programs and management recommendations to mitigate the impacts observed in Maquiné Cave. Each program has clear strategies to achieve its objectives and indicators that point to its effectiveness. For each management program there is an action plan, which includes: beginning and ending date for proposed actions, expected results, investment value, and who is responsible for implementation. Table 1 below shows the correlation between the main observed impacts and the main management programs that seek to mitigate these impacts. Below is a brief description of the proposed management programs and the recommendations they proposed.

Program for review of lighting system

This program aims to reduce the negative environmental impacts of the old lighting system, enhance the existing attractions, and provide security for visitors, guides and maintenance staff. The main activities under this program are the development of an executive electrical and lighting design project for the new lighting system, implementation of the new system, realization of photographic documentation, temperature/ relative humidity monitoring (before and after the intervention) and maintenance staff training.

These executive projects of the new lighting system shall be performed in accordance with current best practices, providing: (I) reduction of hotspots by the replacement of high power lamps with Light Emitting Diode (L.E.D); (II) reduction of the development of photosynthetic organisms in the aphotic zone, by using an appropriate wavelength according to Olson (2006), (III) removal of mortar cords and low walls that cause visual impact in attractions, with consequent restoration of these surfaces, (IV) removal of all the lighting infrastructure that will be deactivated and waste from the old system, (V) reduction of speleothem trampling in maintenance through the use of safe, high durability and low maintenance materials (tinned copper cables, waterproof fittings and spotlights), (VI) reduction in alterations in sediment, speleothems and rock surfaces by using apparent wiring and spotlight installed over removable bases made of inert materials. These projects should be harmonized with the walkway project, so that the main wiring can be installed with the walkway.

The new lighting system shall enhance the existing attractions, through the proper placement of the spotlights, showing the natural speleothem colors. The system should be trigger sequenced, illuminating only the chamber with visitors. Spotlights should not be focused on Primitive zones. The use of techniques that cause irreversible impacts on the cave, such as drilling, breaking, applying cement mortar and other products over speleothems and other surfaces should be avoided. To increase the safety of visitors, guides and maintenance staff an emergency lighting system should be installed, and the pathway and the narrow places should be properly lighted.

Program for pathway system revision

This program aims to reduce the negative environmental impacts caused by the current pathway system and

Table 1. *Correlation between management programs, impacts and environmental effects identified in Maquiné Cave and its influence area.*

IMPACTANT ACTIVITIES									ENVIRONMENTAL IMPACTS	MANAGEMENT PROGRAMS					
Lighting System		Pathway System		Water introduction systems		Management actions	External Infrastructure								
Installation and maintenance	Operation (Use)	Installation and maintenance	Operation (Use)	Installation and maintenance	Operation (Use)	Operation (Use)	Installation	Maintenance and operation	INTERNAL ENVIRONMENT AND CAVE ENTRANCE	Review of lighting infrastructure	Revision of pathway system	Guides continuous training	Revision of cave influence area	Conservation and restoration program	Monitoring program
■		■		■		■			Intentional speleothems breakage		■	■		■	■
■		■		■					Physico-chemical changes in speleothems and other surfaces due to the introduction of building materials	■	■			■	■
■		■		■		■			Improper disposal of solid waste	■	■	■		■	■
■		■	■	■		■			Changes in speleothems by trampling	■	■	■		■	■
■		■	■	■		■			Sediment disturbance (compaction, revolving, removal)	■	■	■			■
	■								Change in speleothems and other surfaces due to lamp flora	■				■	■
	■				■	■			Potential change in the microclimate	■		■			■
						■			Potential change of the CO2 concentration			■			■
	■								Changes in surface temperature of speleothems and others	■					■
	■					■	■	■	Noise generation	■		■			■
	■					■			Generation of electromagnetic fields	■					■
	■								Introduction of light in aphotic zones	■					■
■			■			■			Change in speleothems and others due to intentional touch	■	■	■		■	■
■	■	■	■	■	■	■	■	■	Potential change in cave fauna dynamics	■	■	■	■	■	■
■	■	■		■			■		Landscape changes or visual impact	■	■		■	■	■
		■							Changes in drainage and runoff water		■				■
		■				■			Alterations in speleothems and other surfaces by graffiti, and use of inappropriate techniques for graffiti removal		■	■		■	■
									CAVE INFLUENCE AREA (EXTERNAL)	■	■	■	■	■	■
						■	■		Topographic changes and removal of original vegetation cover				■		
						■	■	■	Introduction of exotic plant species				■	■	■
						■	■		Changes to the permeability of soil				■		
						■	■		Changes in landscape or visual impact				■		
						■		■	Inappropriate disposal and treatment of wastewater				■	■	■
						■		■	Improper disposal of solid waste				■	■	■

to improve the conditions for public use and safety, providing accessibility to individuals with special needs, until the second room of the cave. The main activities under this program are the development of an Executive Project for the new pathway system; implementation thereof; conducting photographic documentation (before and after implementation); and maintenance staff training.

These executive projects should specify inert and safe materials for the cave environment, according to Werker (2006) and other references, with design and construction techniques that cause minimal visual and physical impact to the cave, which should be demonstrated through 3D modeling, sketches and / or photo inserts. The materials and techniques used must be highly durable, providing ease and low maintenance cost. The use of techniques that cause irreversible impacts on the cave should be avoided. Where possible, the old stairs should be removed and speleothems restored. This project shall comply with cave zoning and the places established for the pathway.

The delineation of the pathway will concentrate the impacts of visitation in a restricted area, reducing problems such as trampling over speleothems, sediments and fauna, graffiti, intentional touching or speleothems breaking and other impacts in the cave.

Program for guides continuous training

The objectives of this program are to train the guides continuously, seeking quality service to visitors, the quality and relevance of the information provided and the educational practices, awareness of the cave fragility, and the need to respect the established load capacity and the optimal number of visitants per group.

The main activities under this program are the revision of the programmatic content of the visit, realization of semester courses for instruction and training, and development of educational materials.

Conservation and restoration program

The objectives of this program are to reduce negative environmental impacts and effects on Maquiné Cave. The following brief descriptions are the main actions foreseen in the program.

Restoration of damaged surfaces including: (I) restoration of the main surfaces with graffiti, marks of trampling or unsuccessful attempts at camouflaging graffiti; (II) restoration of speleothems and other surfaces after removal of infrastructure such as stairs, bulkheads, and cement mortar cords.

Re-naturalization of the First Hall including: (I) removal of existing infrastructure (desks, tables, roulette wheels, grills, benches, low walls, paved floor, gate), (II) Compatibility with pathway system and lighting system revisions.

Project to deactivate and remove the water piping system. Implementation of waste removal project, coordinated by a biospeleologist, including the removal of the waste from the installation and maintenance of existing infrastructure and waste from visitation.

Program for monitoring changes in speleological heritage

This program aims to monitor, continuously, some environmental indicators in Maquiné Cave, generating subsidies for the dynamic adjustment in the load capacity, for future revisions for the Cave Management Plan, and to assess the effectiveness of the proposed actions. Monitoring lets you check whether the expected results are being achieved, and if not, lets you see where the problems are occurring, and act correctively, according to the logic of adaptive management.

The main activities of this program are:

1. Continuous visitor flow monitoring
2. Continuous climatic monitoring inside and outside Maquiné Cave, with temperature, relative humidity and CO_2 concentration measurement.
3. Photosynthetic organisms monitoring in the aphotic zone of the cave.
4. Biological communities dynamics Monitoring.
5. Graffiti monitoring around the pathway system.

Conclusions

It is important to think about the concept of visitation desirable for Maquiné Cave. The model applied in the 1970s does not work fully, and causes irreversible damage to the speleological heritage by not providing a proper appraisal of the historic, cultural, educational and scientific potential available.

There are few places in Maquiné Cave where human impacts are not noted. Among the main effects observed

are serious damage to speleothems, sediments and rock surfaces, fauna and possible impacts to microclimate. These were caused by an interaction of problems in managing the visitor flow, infrastructure located in the interior of the cave and in the cave influence area.

A cave adapted for mass tourism can serve as a tool for education and awareness about the importance and fragility of caves and karst environments; contributing to the protection of speleological heritage as a whole. The Maquiné Cave has significant natural attractions that have made it one of the most visited caves in Brazil. These can be valued appropriately by a new lighting system, a new pathway system, by the reformulation of the programmatic content of the visit, by guides training, among other issues. The impact mapping gave support to the management decisions in Maquiné Cave, guiding the intervention strategies needed to protect the cave and to reduce impacts on this fragile environment, helping to plan a sustainable and secure public use of the cave.

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NATIONAL CAVE AND KARST MUSEUM

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Abstract

Caves are natural museums housing ancient relics, unusual life forms, and amazing discoveries- wrapped in a shell of geologic history. Karst landscapes are spectacular, their aquifers provide hundreds of millions of people worldwide with drinking water, yet few have ever heard the word. The importance and fragility of these resources make them both exciting and challenging to interpret.

An exhibition focusing on cave and karst resources can effectively communicate the scientific, environmental and stewardship messages to non-technical audiences. As a world leader in understanding caves and karst, and the effect of their resources on our health, economy, and future, NCKRI is embracing the opportunity to increase awareness and inspire stewardship of these complex systems by developing a state of the art museum.

The museum will consist of a series of cave and karst-related exhibits that will realistically convey an experience with caves and karst that will help visitors create intellectual and emotional connections to these resources. The exhibits will contain interpretive signs and dioramas, an in-cave theater, and interactive displays like a cave crawl. If the Institute's vision is successful, our visitors speleological knowledge will increase and they will be influenced to make responsible safety and ethical decisions in regards to cave and karst resources.

CAVER QUEST 3D VIRTUAL CAVE SIMULATION OF SNOWY RIVER IN FORT STANTON CAVE

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Abstract

Virtual worlds, or 3D simulations through which an avatar can travel, are becoming a common means to display products or provide training in new environments. This paper describes the steps in producing the 3D virtual simulation of Snowy River in Fort Stanton Cave, New Mexico. A traditional cave survey and map with cross sections was used to produce a 3D meshed surface of the cave walls using the *Blender* software package. Photographs were taken of the walls, ceiling, and floor and merged together. The merged montage was applied to the 3D mesh walls as a "texture". *Unity*3D was used to integrate an avatar into the scene to view the cave. *Unity*3D was also used to generate pop-up educational cave notes with relevant text and more detailed photos. A gaming element was added to engage the public and test what had been learned before allowing access further down the passage. The detailed steps in this overall process, and the photographic techniques developed including recent updates are described in this paper.

Introduction

Methods for portraying the underground structure and complexity of a cave have advanced over the years since the first hand sketches of early explorers. Perhaps the earliest computer word game, *Colossal Cave Adventure,* was developed by caver Will Crowther and others, finding its way to most of the computer mainframes in the 1970's. Survey tools allowed plan-view maps to be generated along with cross sections and vertical profiles. This enabled experienced cavers and cartographers to understand the nature of the cave, but those maps were not readily understandable to the general public. High quality photographs brought the beauty and majesty of the cave to the general public, and video cameras have extended that capability. Bill Franz created a virtual tour of Lava Beds caves a decade ago using Apple's QuickTime (Ingham, 2013, personal communication).

Recently 360° panoramas have enabled the public to view a cave room in great detail in all directions from a single location and zoom in to see the details of the walls (Four Chambers Studio, 2011, Bunnell, 2013, Burger, 2013). The *CAPS* program and website (Crowell, 2013) has combined such panoramas into an exploration program that jumps from panorama to panorama as you explore the cave.

This paper describes the next step in cave portrayals in which a 3D virtual world of the cave is generated where one can assume the role of a virtual caver as an avatar and walk through long extents of the cave, inspecting the entire passage as desired (Figure 1). In this world, an accurate model of the cave wall configuration is textured with actual cave photographs. The result simulates the feeling of caving because the viewer can explore as desired and become immersed in the experience.

The development of the Snowy River simulation in the Caver Quest software is used as an example (Lipinski et al, 2013). The software can be installed on a PC or a Mac with an OS X operating system. DirectX 9.0 video driving software (free download from Microsoft) would also be needed, but this is common software with most modern computers. K. Ingham's team is developing a similar portrayal of selected lava caves in El Malpais National Monument for the National Park Service. The simulation incorporates many educational outreach techniques (Ingham, 2013, personal communication; Northup, 2013).

Use for Scientific and Public Outreach

The 3D virtual cave can be used as a public outreach tool since it can be hosted on a cave management web site or distributed as desired. Once the 3D model is created, it can be loaded with numerous educational opportunities. In Caver Quest, there are a series of icons on the cave walls that the user can click on and see a pop-up cave note with a description of scientific, historical, or cave protection information relevant to that area, as well as more detailed pictures. To further engage and educate

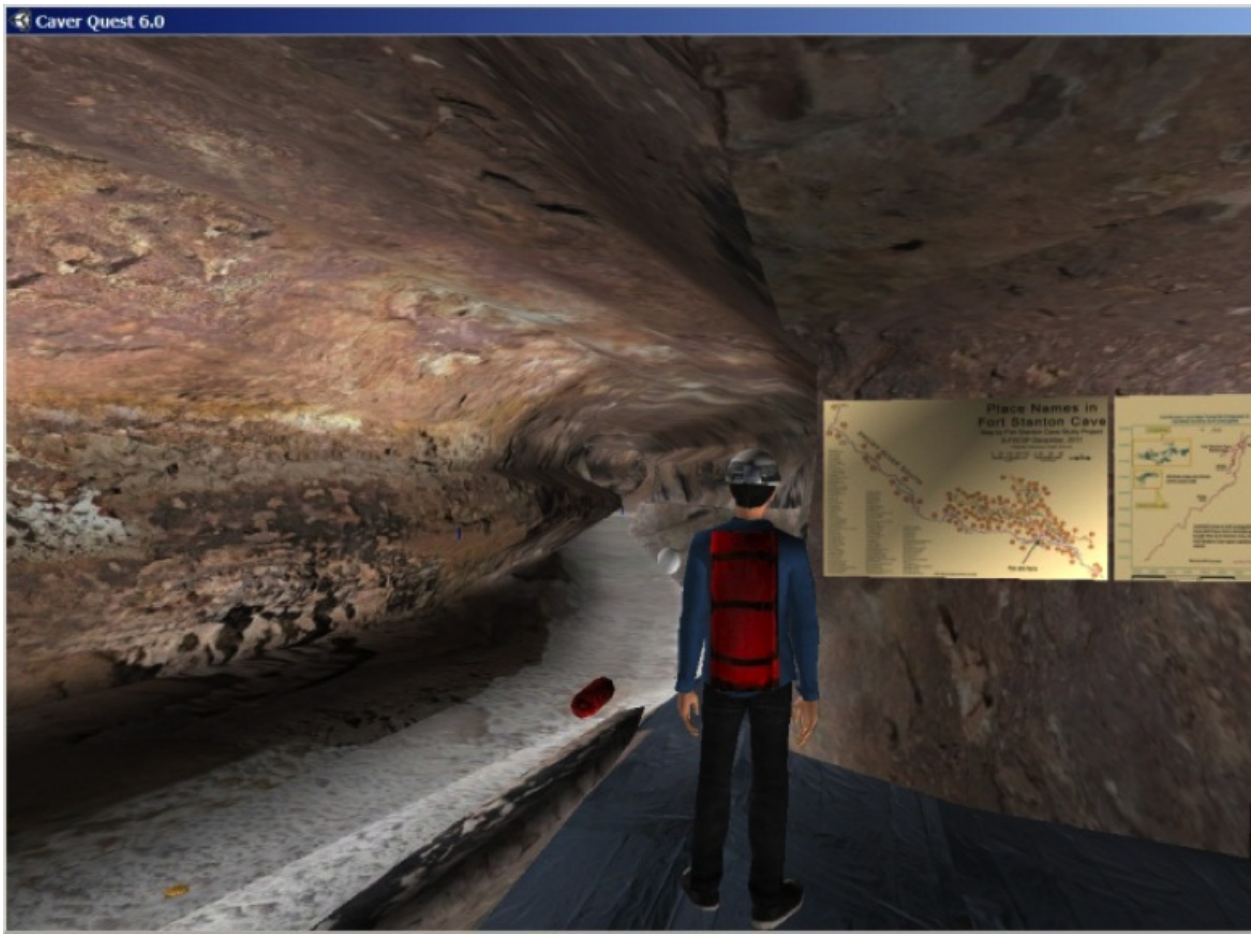

Figure 1. *Screen shot from Caver Quest near Turtle Junction with Snowy River in Fort Stanton Cave.*

youth, there are a series of barriers in the passages, which can only be passed when an exam that tests what has been learned is passed (Figure 2). There is also an overall challenge that the gamer is pursuing.

The 3D virtual cave portrayal has the potential to become a working scientific tool. The set of detailed photographs that are obtained for the wall texture can serve as a set of "before" pictures relative to any unforeseen event, whether it be floods, vandalism, general wear on the cave floor, mineral growth, or biological changes as the climate changes. Having the individual photographs assembled into a montage that is textured onto the cave wall makes it much easier to understand positional relationships among them.

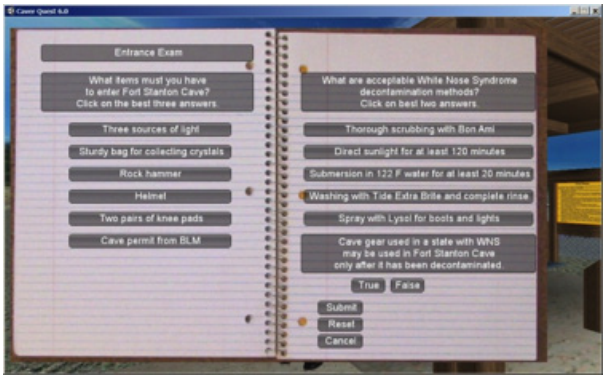

Figure 2. *Exam to enter the cave.*

The 3D simulation also allows scientists with diverse areas of expertise to walk through and examine the cave without needing to be there in person. This opens up the scientific investigation of the cave to a much larger range of experts, who might not otherwise be able to access the cave because of lack of funding, lack of time, handicaps, age, physical fitness, or limited access due to bat closures. The first step in the scientific method is observation, from which a hypothesis, experiment, and conclusion can follow. The cave simulation opens this first step to a very large audience, which can then be followed up with targeted research.

As an example, the observation of boxwork in the ceiling of Snowy River at Turtle Junction was first made (by J. Corcoran) in *Caver Quest* (Figure 3). The recognition that a spring-like feature in the Snowy River bed occurs below a major surface drainage was first made in *Caver Quest*. Observations like these could lead to hypotheses about the origins of boxwork, or the role of surface drainages in water insurgence in the river bed. This could be followed by targeted mineralogical studies and radionuclide dating to establish the timelines for water transport and mineral buildup. An assessment of difficulty in obtaining specimens, or the tools needed to do so, could be had using the virtual cave simulation.

Method for Generating the Simulation

The steps in generating the simulation are as follows:

1. Obtain an accurate survey, map of the cave, (including plan view and cross sections), and survey line digital data
2. Use the map and data to generate 3D mesh of the cave walls, floor, and ceiling).
3. Obtain a complete set of overlapping photographs of the cave walls, ceiling, and floor in the areas of interest.
4. Merge the photographs into one or more montages, remove dark spots and boundary lines, and adjust scale as needed.
5. Apply the photo montages to the cave wall as texture.
6. Import the textured 3D set of cave walls into an avatar gaming engine.
7. Add a caver avatar with assorted camera views and animations, then add educational cave notes, challenges, tests, etc.
8. Export to the desired platforms (PC, Mac, iPad, etc.)
9. Deploy as desired (museums, visitor centers, web sites, universities, etc.)

Obtain Survey and Map of Cave

There are several options for obtaining a good cave survey file and map. For this project we obtained the data set and maps that were generated by J. Corcoran using *Compass* software by Fountainware (Fish, 2013). This step is essential for establishing dimensional control for the simulation.

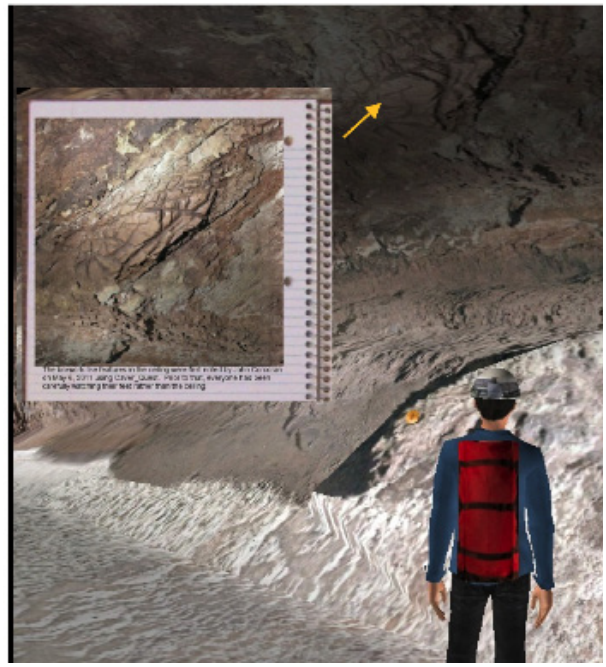

Figure 3. *Box work in Snowy River ceiling in Caver Quest.*

Generate 3D Mesh of Cave Walls

There are numerous 3D modeling tools to choose from, such as *Blender* (Blender Foundation, 2013), *Maya* or *3DS Max* by Autodesk (Autodesk, 2013). For this project, we used *Blender*. *Compass* has an option to export the survey line and the cave walls in DXF format, which can be imported by *Blender* (and other 3D software). The walls are based on left, up, right, and down measurements at each survey station, so this portrayal is very approximate. But it does give a rapid portrayal of the full cave.

For public or scientific outreach, a more accurate portrayal is needed. For this work we used the following process:

1. Import the survey line as a DXF file into *Blender* to serve as a proper scale for the maps and to serve as a control on the floor elevation.
2. Create a multi-point closed ring in *Blender* and oriented it vertically to serve as a cross section; we used 32 points, but using more points yields greater fidelity.
3. Import a scanned image of the cave cross section map at a particular survey station into Blender and adjust it to the correct scale.
4. Adjust the cross section points so that they approximated the cross section map shape.

5. Import a scanned image of the cave plan view at that location and adjust the scale.
6. Extrude the ring of points a set distance (one or more passage diameters).
7. Adjust the end of the extrusion to match any changes in shape indicated by the plan view.
8. Make additional adjustments based on the next cross section or passage photos.
9. Add features indicated by the plan view map or passage photos.
10. Repeat extrusions and adjustments until the next station is reached.
11. Adjust the elevation of the last extrusion (and intermediate ones) as needed, based on the line survey.
12. Repeat steps 6-11 until you have a significant amount of passage modeled and are ready to apply the texture to the walls.

Figure 4 shows a *Blender* screen shot with a top view of the extruded cave walls superimposed on a plan view from the map. The insert shows an isometric view of the resulting passage walls.

Obtain a set of wall photos

This step can be done at any time. The goal is to obtain a set of photographs that can be assembled into a smooth collage and used as texture on the 3D cave walls. There are standard techniques for obtaining a 360° azimuth panorama from a single location, but a 360° panorama is not appropriate for this application. Photos looking down the cave passage will have very oblique views of the walls and will result in pixels that are extremely stretched horizontally when applied to the wall. The passage will look good when viewed from the original camera location, but will look smeared and bad from other locations. Experience has led to the following recommendations:

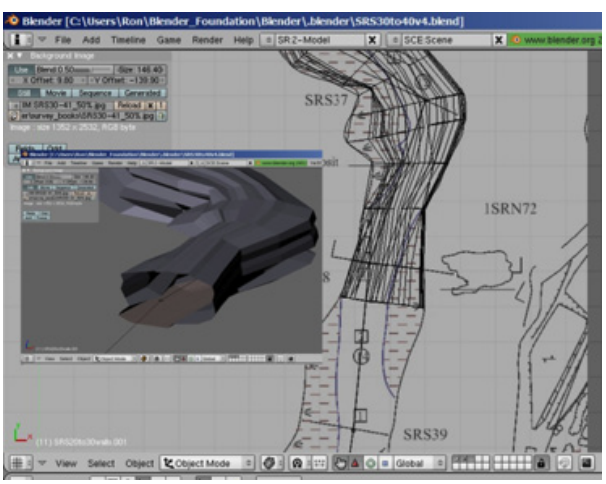

Figure 4. *Extruded passage walls overlaid on plan view map of Snowy River in Blender3D.*

1. Shoot the photos looking directly at the wall, not down the passage.
2. Shoot a cylinder of photos about the cave passage axis before moving to the next photo station.
3. Move the camera along the passage a distance that allows at least 20% overlap with the previous "cylinder" of photos. Use a tripod placing the lens at eye-height (~1.6 meters).
4. The phot-o line should be in the center of the passage horizontally.
5. Use a lens with at least a 90° field of view to minimize the number of photos at each station.
6. Use stitching software like Photoshop or Hugin, but do not expect it to work automatically. The near objects will move more than the far objects as you move the camera down the passage. You will need to manually merge photos using layers to smoothly blend them.
7. Provide uniform lighting across each individual photo to avoid dark blotchy areas. Currently we are using the compact Nikon SB-20 units, which have 5 levels of strobe power and a wide-angle lens setting. Two assistants hand-hold and point the strobes, one about 20 feet from each side of the camera. The resulting exposure is checked and improved as required.

Clearly, digital photographs are needed for this application, although one could use film and scan the result later if preferred. Five to ten megapixel cameras are sufficient for efficient blending. But high-resolution photos could be taken to serve as a database and then scaled to a smaller size for the 3D simulation as needed. Current work using a Nikon D-60 in RAW format requires a 1/4 reduction in JPEG file size for best final blending. Precision alignment of multiple frames simplifies stitching by reducing the need for rotation of each photo. There should be enough "bookkeeping" to properly relate the photos to the cave map.

Both near "projections" and far away "flat walls" must be included. Special fixtures such as the Nodal Ninja 3

(NN3) may be required so that camera rotation from a single viewpoint can be obtained to minimize parallax (Figure 5). Lighting uniformity and speed of operation will increase as the lighting team gains experience.

Both floor shots and ceiling shots must be included. The initial Snowy River work illustrated in this paper used a "4-around" cylinder at each tripod location. Recently teams implemented a "6-around" cylinder. This allowed a direct view of the left and right walls, and two oblique views of the floor and ceiling for each wall. The extra overlap for the six shots allowed a significant improvement of the post-processing time with little impact on the in-cave time. Care was taken to minimize shadows from the tripod legs on the white floor surface, but always expect post-processing adjustment of tripod effects.

Adequate photo coverage is a function of lens field of view, cave dimensions and tripod spacing. Initially this project used 3-meter increments down the passage, but recent work used a 1.5-meter spacing to achieve better overlap. We have found that using modern equipment in a "manual" instead of an "automatic" mode is faster because you can pre-set the focus. A 1-2 second shutter opening with hand control of a radio sync unit and no on-camera flash provides good results, as long as bright headlamps are not aimed at the target area.

Figure 5. *Our initial "light weight" tripod, NN3 fixture and CP-5000 camera were only chest high.*

The choice of proper lens is very important, but involves trading the number of photos at each station against the lens field of view, strobe coverage and post-processing distortion correction. Initial work used a WC-E68 converter lens on a Nikon Coolpix 5000 with an NN3 fixture. More recent work has been done with a 16 mm Nikkor (manual lens) on a Nikon D-60. We used *Lightroom* by Adobe (Adobe, 2013) to correct lens distortion and adjust the color and tone curves on the 16 mm fisheye photos.

Merge the wall photos

There are numerous programs for merging photos, such as *Photoshop* by Adobe (Adobe, 2013), *Hugin* (Hugin, 2013), and *ICE* by Microsoft (Microsoft, 2013). Such programs might work automatically for merging sections of flat walls. However, for sections where there is considerable relief, such as where the wall meets the floor, or there are large breakdown boulders in the foreground, the foreground will shift more than the background when the tripod is moved from the first position to the next position. For such cases the photos will need to be merged manually. Use of layers can help smooth the transition between photos. It helps if the lighting is fairly uniform in the original photos. The software can help flatten the lighting, but often there is still a visible mismatch.

Figure 6 shows a montage of 16 photos of the wall, ceiling, and floor of Snowy River between survey stations SRS12 and SRS13. The east wall has been inverted to make a continuous picture. This montage is ready to be wrapped onto the 3D meshed wall as a texture. Note that there are visible lines between the photos. This photo set was taken during the first trip for such photos in April 2011, and the techniques for good acquisition were still being developed. At that time we were using a compact CP-5000 with a wide-angle adapter and a NN3 panorama head. The original photos had dark shadows on each corner and required considerable pushing and processing. Due to White Nose Syndrome restrictions, we only recently had access to the cave to acquire better photos using the "6-around" process described above.

Figure 7 above shows a montage of 48 photos between SRS08 and SRS09 obtained recently using the improved

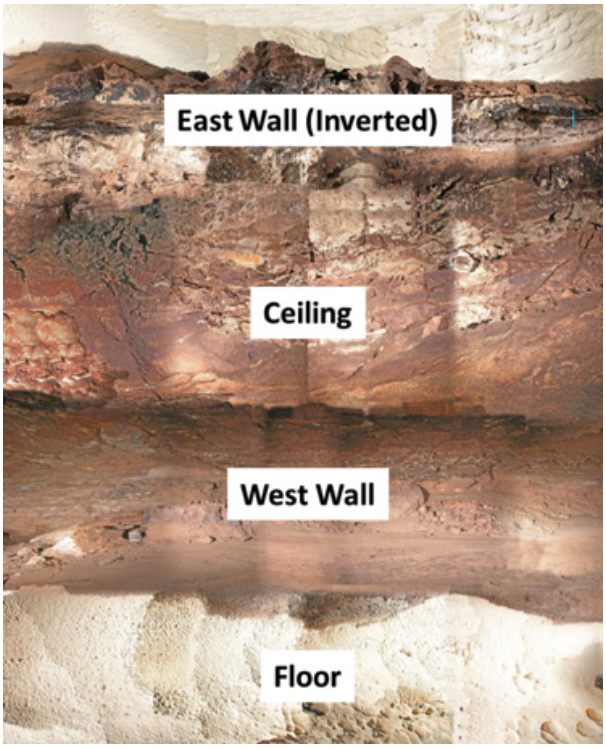

Figure 6. *Merged photos from Snowy River (SRS12-SRS13).*

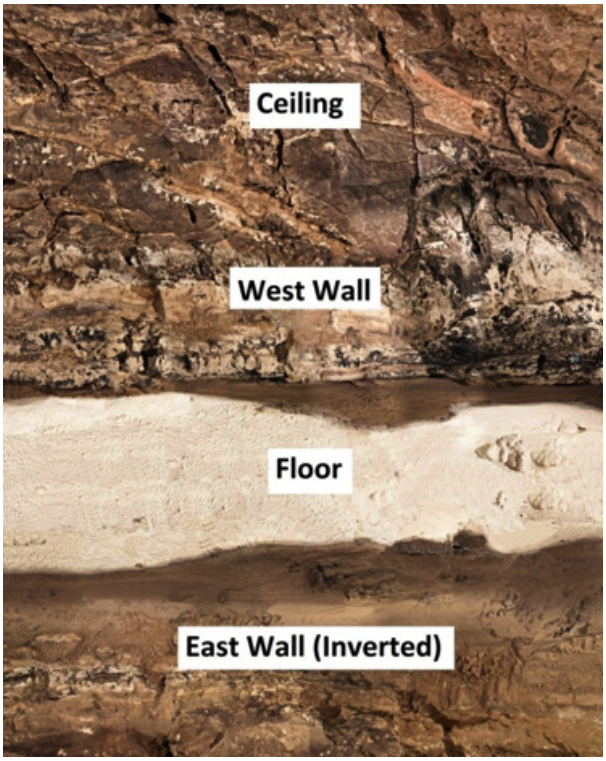

Figure 7. *Improved merged photos from Snowy River (SRS08-SRS09).*

techniques. The result is much more continuous and realistic. In addition, the use of a white card for color calibration resulted in a more accurate color rendition. Nonetheless, when the image in Figure 6 is applied to the 3D cave walls as a texture, the result looks fairly good and the interface lines are not as apparent.

Apply merged photos to 3D walls

The photo montages are applied to the 3D walls in the *Blender3D* program (Figure 8). It is important to preserve the proper orientation of the photo and any features such as layers. If there are ledges in the passage, the application will stretch the photo on the horizontal sections of the ledges. This is unavoidable unless direct shots are taken above and below the ledges and included in the montage.

Import textured 3D walls into game engine

Once the 3D walls are textured in *Blender*, they need to be imported into a game engine that allows generation of a full simulation, including an avatar. Blender can be used as a game engine to make avatars and games, if desired. But there are other options that may have features not available in *Blender* (Galuzin, 2012). We

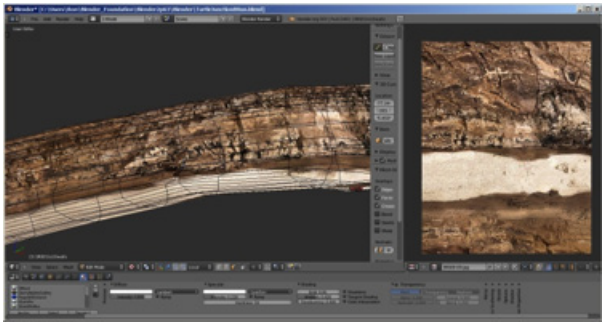

Figure 8. *Merged photos applied to 3D walls.*

initially used the *URU* game engine from Cyan Worlds (Cyan Worlds, 2013) (with gracious permission) to prove out the concepts, and then moved to *Unity3D* (Unity Technologies, 2013) to allow additional flexibility and deployability (Figure 9). Lighting can be adjusted as needed. It is important to select "mesh collider" for the cave walls and floor so that the avatar does not fall through them when imported.

Add caver avatar

An avatar can be built from scratch, with clothing, face, hair, and moving joints, and animations developed for it. But purchasing an avatar and importing it into Unity3D

can avoid this tedious process. The commercial market has developed many such options at reasonable prices, including animations. *Mixamo* (Mixamo, 2013) works directly with Unity3D, but there are also other options.

The avatar can be customized. For example, a caving helmet can be built in *Blender3D* and then attached to the avatar's head, where it will move smoothly with the head. A light source can be attached to the helmet if desired. A cave pack can be added similarly. All these are attached to the various body parts of the avatar via a parent-child relationship, which in *Unity3D* is a simple click and drag operation (Figure 10).

A standard third-person (synthetic) camera can be added to follow the avatar, using a camera-following script supplied by *Unity3D*. A first-person camera can be added by placing it inside the head of the avatar and adding a script to switch between the two. This is useful to allow closer inspection of the cave walls, both to enhance the experience, and for the benefit of scientists or cave managers wishing to view small details in a more natural manner.

Add educational cave notes and features

For educational outreach it is useful to have a means to provide pop-up information relevant to the area that the avatar is exploring. This is done in *Unity3D* with the standard graphical user interface (GUI) scripts and functions. In *Caver Quest* we use an icon on the cave wall to indicate the existence of such a cave note. When the icon is clicked, a notebook appears with relevant detailed pictures and text (Figure 11).

To enhance the appeal to youth, there is a game mode in *Caver Quest*. As the player moves down the cave passage, he encounters transportation devices that he can activate. Once activated, he can instantly teleport between them and save much time in exploring the cave. The ultimate goal is to activate all the transporter devices in the cave to make it ready for the next survey team that must survey the far reaches of Snowy River, over ten miles from the entrance. For management, there is an unlimited access option using these transporters.

There are also barriers in the cave passage obstructing progress in game mode. These barriers can be raised by passing an exam that tests the knowledge of the player. Answers to the exams can be found in the cave notes, so this motivates the player to stop and read each cave note, thereby increasing their knowledge of the cave.

Export to desired platforms

The nominal platform for the simulation is a personal computer with a large screen (or a projector, for large audiences). The free version of *Unity3D* can generate an executable and associated folder for a Windows-based PC, and an application package for a Mac OS-X. The purchased version of *Unity3D* has options for other platforms, such as Linux, Web based, iOS, Android, Xbox 360, PS3, and Wii. The small screens of some of the devices, (e.g. Android) may not display the cave to its full potential, but such devices are becoming very popular means for accessing information and will allow

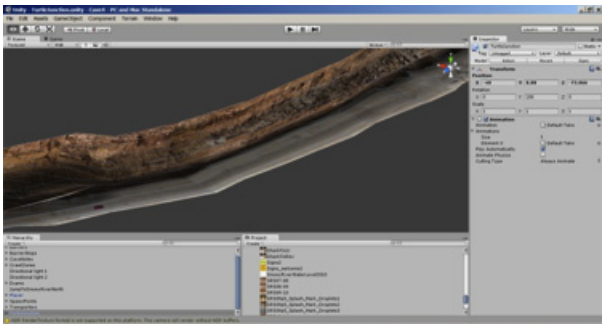

Figure 9. *Import to Unity3D via *.fbx file.*

Figure 10. *Cave avatar added.*

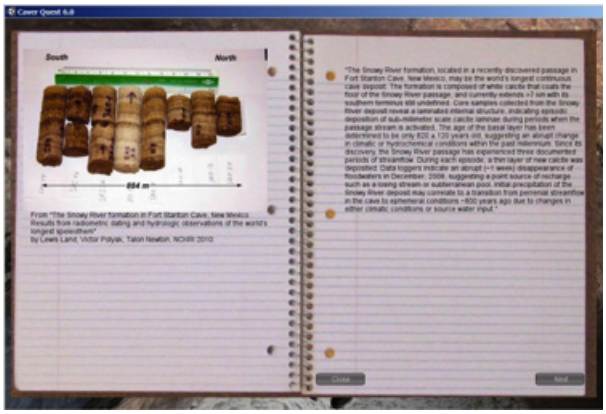

Figure 11. *Pop-up cave notebook.*

reaching a much broader audience. Nonetheless, in a dark room with a large screen, the 3D simulation can be a very good portrayal of the caving experience.

Deploy

Having a 3D virtual cave simulation opens up numerous options for its use. If there is a visitor's center associated with the cave, it can be displayed on computers at that location, or used as part of a presentation to an audience. It also can be placed on an agency web page, either as a web-based product that runs interactively directly from the web page, or as a stand-alone software package that can be downloaded. If the simulation is used for extensive outreach to the general public, some thought must be given to protection of the cave. The simulation is likely to encourage visits to the cave, which can be good for the community if there is a controlled access of the cave itself. The simulation is a good opportunity to instill proper cave ethics and conservation practices in those who use it. The simulation can also be made available to cave researchers via websites and conferences, or even as part of solicitations for research ideas.

Generation time and file size limitations

Much of the simulation generation effort is labor intensive. We started with a *Compass* file of Snowy River and a well-drawn map with cross sections in November 2010. After developing the appropriate techniques and skills with the requisite software packages, it took about 30 hours to extrude 300 m (1000 ft) of cave passages in *Blender* that matched the map. This included the varying width and depth of the river bed. Obtaining the photos took about 15 hours for 300 m of passage. Photo processing and stitching into a montage took about 10-15 minutes per photo, or about 60 hours for 300 m of cave passage (average diameter of about 5 m). From this we estimate that the time to extrude a mesh for the known 18 km of Snowy River could be about 2000 hours. Merging photo montages could take about 4000 hours. Acquiring the photos could take about 1000 hours. Adding cave notes and other features will add to the total, depending on the note density. These are substantial efforts, but not out of the realm of possibility. Shorter caves would take less time.

The full-resolution photographs in jpg format are about 1.5 MB each. The 18 km of Snowy River would require about 20,000 photos, or about 30 GB in jpg format. At full resolution, the simulation would convert those photos into images of about 4 MB each, increasing the simulation size to about 80 GB. But at about 1/16 resolution, it would still show good wall detail, and the simulation would be about 5 GB.

Photogrammetry and Lidar

All of this might get faster and easier, or more detailed and accurate, with the implementation of photogrammetry or lidar. Photogrammetry uses two or more images that fully overlap but are taken from a known distance apart. One option might be to use two identical tripods with quick detach heads to speed the process. A Disto (simple laser rangefinder) can be used for quick distance measurements. Computer software then generates a 3D picture of the image surface based on pattern recognition for each small section of the two photos, and considerable math. Commercial software can generate a 3D surface mesh that can be imported by *Blender3D* or *Unity3D*, and also apply the photographs themselves to the surface as a texture. One example is *PhotoModeler* by Eos Systems, Inc. (Eos Systems, Inc. 2013).

Another example is Autodesk's *Catch 123D* (Autodesk Catch123D, 2013). With *Catch 123D*, no measurement of the camera location is needed; with a four-shot overlap, the software will determine by itself where the camera was located relative to the wall. A trial run with a video camera aimed directly at the wall as the photographer (J. Cox) walked down the passage resulted in a fairly good 3-D mesh and stitched photo rendering, even with marginal lighting. With good lighting, this might be the recommended approach for photogrammetry in caves. Results of our photographic work in Fort Stanton Cave may be found on the fscsp.org web site and also in Figure 12. The figure shows that the software correctly identified the four locations of the camera used for the series of photos.

Lidar (distance mapping with a laser) is another option for generating the 3-D mesh of the cave walls. However, it tends to require heavier equipment and more electrical power in the cave. It also is more expensive than simple photography. Nonetheless, it should be kept in mind when planning a 3-D mapping project.

Summary

Computer software and digital photography have advanced to the point where is it possible to generate a 3D virtual cave simulation that can be explored by an

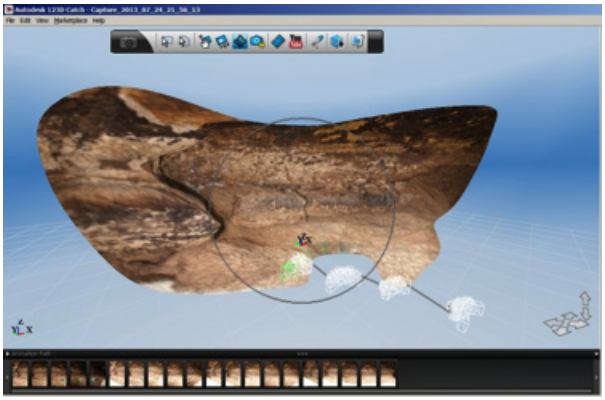

Figure 12. *Photogrammetry example using Catch 123D.*

individual through an avatar. The Fort Stanton Cave Study Project has generated such a simulation for Snowy River because of both the very limited access to that section of the cave and also the high level of interest in this unique resource. The effort was done entirely via volunteer hours using mostly free or low-cost software available on the internet and existing camera equipment. This suggests that cave managers and agencies might make this a tool for public and scientific outreach for sensitive caves or cave areas to reduce impact to those sections, and to allow participation by a greater audience, virtually.

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iCAVERNS: INTERPRETATION, THERE'S AN APP FOR THAT!

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Abstract

A quarter of a century ago, cave and karst resources were declared irreplaceable with the passing of the Federal Cave Resources Protection Act. Yet, today, few understand the importance or fragility of these resources. Human interactions in karst areas make these resources highly susceptible to damage. Nonpersonal interpretation digital media products could serve as an important tool to bridge this informational gap.

Worldwide, there are hundreds of parks or park-like attractions focusing on cave, spring, or sinkhole resources. Their visitors have a built-in curiosity about these places. Engaging this audience in interpretive programming could greatly increase their speleological knowledge. Paradoxically, the same attractions without accurate interpretive materials can also be responsible for promulgating cave and karst misconceptions. Digital media can be very effective tools for increasing awareness and stewardship of cave and karst resources.

Smart device applications (apps) present several advantages over traditional interpretation media including, engaging audiences outside of the attraction's boundaries, presenting interpretational messages to visitors in their native language, and maintaining content integrity. However, video and photography methods in cave environments present many challenges. Filming crews and gear requirements can cause irreparable damage to caves. This paper discusses the development of the iCaverns app, which was developed utilizing new green film making techniques as an educational and travel guide for Carlsbad Caverns National Park.

iCaverns enhances visitor experience by interpreting geologic resources at Carlsbad Caverns National Park. This app could also make park resources come to life, for more than 400 million people, in 155 countries and 38 languages.

Figure 1. *Screenshot of the iCaverns app user interface.*

Introduction

Twenty-five years ago, the United States Congress declared cave and karst resources as invaluable and irreplaceable parts of the Nation's natural heritage. Recognizing that urban spread, increased recreational demand, improper use, and a lack of statutory protection pose threats to cave resources, these leaders passed the Federal Cave Resources Protection Act of 1988. One purpose of this act calls for the securement, protection and preservation of caves for the benefit of all people to use and enjoy in perpetuity (16 U.S.C. § 16).

This purpose provides complex management challenges: preserving a resource while making it available for recreation. Perhaps the authors of this law gleaned from the wisdom of great naturalists like John Muir, Enos Mills, and Freeman Tilden to develop this seemingly paradoxical purpose. The work and accomplishments of these early conservationists illustrate the idea that one's

experience with nature influences them to conserve and protect it. John Muir is arguably the most important spokesperson for the conservation movement during the 1800's and he is remembered for his help founding the Sierra Club, as well as his role in the establishment of Yosemite National Park. Muir wrote, "I will interpret the rocks, learn the language of the flood, storm and tea valance. I'll acquaint myself with the glaciers and wild gardens, and get as near the heart of the world as I can" (Browning, 1998). Muir demonstrated the amazing power interpretation has to help people understand and care about the natural world.

Communication is the key in solving the perceived contradiction between land use and protection. As a planning directive, the Federal Cave Resources Protection Act calls for the Secretary to foster communication between land managers, those who utilize caves, and the public (16 U.S.C. § 16).

The first modern writer to identify an interpreter as someone who translates what is seen and experienced to others with less experience was Enos Mills (Brochu and Merriman, 2008). The National Association for Interpretation defines interpretation as "a mission-based communication process that forges emotional and intellectual connections between the interest of the audience and the meanings inherent in the resource."

Interpretation is generally broken down into two categories: personal- presented directly by a person and nonpersonal- media such as publications, signs, or products deliver the message. Interpretation is an effective communication tool for land managers because sound land management requires cooperation and input from all types of people including the general public. People have difficulty protecting something they do not understand (Guo and Jiang, 2011). Though the notion to increase the general public's understanding of caves and karst is widely accepted throughout the cave and karst community, there are very few examples in the literature identifying common misconceptions or effective instructional methodologies. However, there is an extensive body of knowledge within the realm of interpretation.

Utilizing effective interpretive methodologies, the iCaverns app is a nonpersonal interpretive tool serving as a travel guide for the natural resources at Carlsbad Caverns National Park and World Heritage Site. The main interpretive goals for iCaverns are to inform users about the speleogenesis, unique environments, and the impacts humans are having on the cave and karst resources inside this National Park. This app gives access to these resources through video and photographic images.

Cave and Karst Interpretation Trends

The exotic but beautiful appearance of karst landscapes, as well as the thrill of exploration and discovery draws millions of visitors to these features around the globe. The assumption is made that visitors to cave or karst-focused attractions have an interest in the resource. This built in interest primes the audience, making them more open and eager to learn about cave and karst resources. Therefore, cave and karst focused attractions are excellent venues to deliver cave and karst interpretation and education (North, 2011).

Indeed many of the cave or karst focused attractions have both personal and nonpersonal interpretive programs. Unfortunately, some of these programs have been responsible for passing forward misinformation about cave and/or karst resources (Kastning and Kastning,

Figure 2. *iCaverns app photo sample of the Left Hand Tunnel tour.*

1999; North, 2011). This same paradox exists when developing products like digital interpretive media. People purchasing cave or karst-centered media have an assumed interest in the subject. Because media products typically have a long shelf life, it is increasingly important to ensure the content is correct and in agreement with accepted scientific theories. Developing cave or karst focused for joint media engagement, like smart device apps would provide an effective interpretive experience for the whole family (Takeuchi and Stevens, 2011).

There are several advantages smart device apps have in comparison to traditional interpretation. Smart device apps engage the younger "plugged-in" generation as well as older generations. Apps bridge the generation gap, because they give generations the opportunity to experience them together. Apps virtually put the resource in the pockets and hands of those interested in it, whereas traditional interpretation requires an onsite visit. Lastly, app development teams have a higher level of control over the content. Both the developer as well as the end-user can easily update apps, making content maintenance somewhat effortless and seamless.

Conceptual Phase

The iCaverns project was born from the developer, Michael Hernandez, conceiving the notion to put Carlsbad Cavern into people's hands. The major conceptual theme for iCaverns is developing a comprehensive guide of Carlsbad Caverns National Park, which will entertain and educate visitors. This app is intended to enhance visitor experience and also to provide virtual experiences for people that do not have the ability or means to visit the park.

Users will have multiple choices available to move through the app. There is information provided about the town of Carlsbad, New Mexico as well as general information about Carlsbad Caverns National Park. The app includes an educational area, various animations, and nine virtual "ranger" guided tours.

iCaverns is targeted for Apple's smart device market, which reaches more than 450 million people in 155 countries / 38 Languages. The app will also be developed for Android devices; however, the two users vary greatly in expectations.

Development Phase

The major themes driving the design and development for the iCaverns app are information that is high quality, authentic, and engaging. All pieces for this application have been developed applying these qualities.

User Interface

Hernandez developed the user interface integrating the project design principals and usability data. The resulting interface is engaging and beautiful, yet it is simple to navigate. This was accomplished by keeping the interface design uncluttered.

The users can navigate away from the main screen by dialing up the portion of the app they would like to visit. Each sub-interface also carries the simple and uncluttered look. The interface for the cave tours is a replica of cave maps, so users will know where they are in relation to the item being discussed.

Animations

There are multiple animations on the iCaverns app, including one for modeling speleothem development and another modeling a Mexican Free-tailed bat in flight (Figure 3).

The animations were developed using Pixar Studios. While the methods are proprietary, one of the designs did include input from bat specialists, as well as the use of video and photographs to build the bat within the app with a high level of authenticity and quality. Users can view every angle of the bat and observe muscle movement during flight.

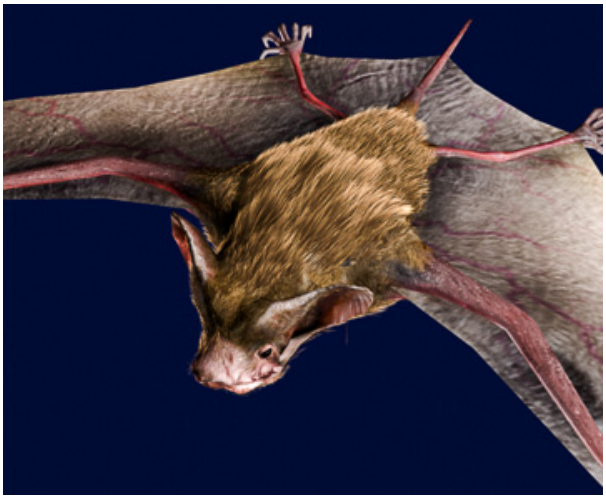

Figure 3. *Bat animation screen shot.*

Video Guided Tours

The "guided" tours section of the iCaverns app is patterned after the tours offered at Carlsbad Caverns National Park. Dianne Joop, a cave education and interpretation specialist and Mark Joop, a geologist and cave interpretation specialist, co-developed each of the nine tours around a central theme. With nearly five hours of video, the virtual ranger, Mark Joop, guides users through topics including the geologic setting, speleogenesis, cave biota, historic uses, human impacts, and various historical figures of the park.

Capturing high quality video in low-light situations is challenging, yet does not compare to capturing video in no-light settings. Cave environments are especially fragile and can be impossible to repair. Capturing the cave through video and photographs without damaging the environment was extremely important to the production crew. The iCaverns' Director, Dianne Joop, developed green film making guidelines, specific for cave environments. Green film making aims to make the film making process more sustainable by leaving as little environmental impact on the planet as possible while producing your project. Joop's production methods reduced impact on the cave environment by reducing crew size to two to four persons carrying minimal and necessary gear. The crew also lowered consumption by carrying reusable water bottles, using rechargeable batteries, and carpooling to shooting locations.

The iCaverns' photographer, Dianne Joop, worked within the boundaries of two photographic concepts, one, taking photographs to support the video component and two, capturing photographs to convey a story. Joop composed her shots to give users a sense of being in the caverns, traveling through passages, and making the discovery of the beauty that waits around the corner.

Figure 4. *Underground landscape in Lower Cave.*

Joop previewed photographs to small audiences to test the notion of people having the sense of being "there". In all instances, audience members affirmed this feeling.

Lastly, both visual elements are implemented to allow for immediate updates, accommodating for new discoveries.

Summary

When the iCaverns app hits the market, it will be the most comprehensive travel guide / educational app currently available. The app makes cave resources at Carlsbad Caverns National Park available to more than 400 million people, in 155 countries, as well as permitting users to engage in cave and karst educational and interpretive media in 38 languages.

Acknowledgments

We would like to express, the success in producing this project was greatly enhanced by the unwavering support of Carlsbad Caverns National Park; Chief of Interpretation and Education, Marie Marek, Fee Program Manager, Paul Cox, and Supervisory Park Ranger, Pam Cox. As well, we would like to thank Rolf Siegenthaler for his generous equipment donation.

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Introduction

Crumps Cave is located about one kilometer northeast of Smiths Grove, Kentucky (Figures 1, 2, and 3). The only known entrance was purchased by Western Kentucky University (WKU) in 2009 through a grant from the Kentucky Heritage Land Conservation Fund and the cave is managed as the focal point of a research and education preserve to study a wide range of environmental conditions and dynamics, and their interactions, using high-resolution electronic monitoring along with geochemical sampling, analysis and modeling. Crews from WKU's Hoffman Environmental Research Institute visit the cave weekly for sampling, data downloading, and equipment maintenance, with a major emphasis on high quality data collection and management. Groups of scientists and students from around the country and world visit the cave on a regular basis for educational activities. The purpose of this extended abstract is to summarize the major data collection programs underway at the cave.

Figure 1. *Pennyroyal Plateau sinkhole plain, south central Kentucky, typical of the area near Crumps Cave (photo by Chris Groves).*

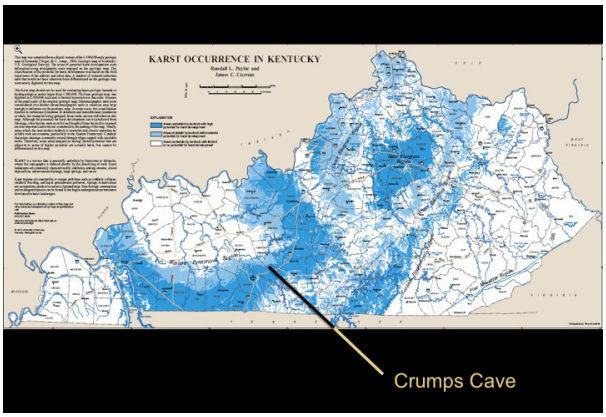

Figure 2. *Map of Kentucky's karst regions, and location of Crumps Cave. The Pennyroyal Plateau is the ring-shaped blue area in the western part of the state (map from Paylor and Currens, 2002).*

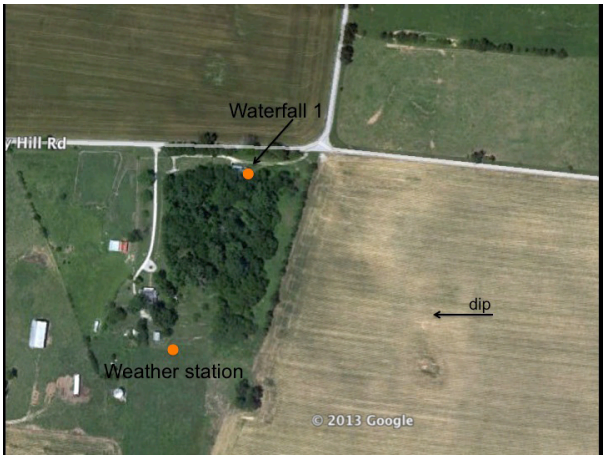

Figure 3. *Crumps Cave Preserve covers the ~one hectare area of the wooded sinkhole (image from Google Earth).*

The site is located at latitude 37.1oN with a surface altitude of 194 m above sea level. The climate here is humid subtropical (Köppen-Geiger Cfa) (Peel et al., 2007). Five long-term weather observation stations located with 35 km of the Preserve and all within less than 50 m elevation have a mean annual precipitation of 1,300 mm and temperature of 14.7oC (Kentucky Climate Center, 2012). Precipitation is spread approximately evenly across the year, though late spring tends to be a bit wetter, and fall a bit drier, than other times of the year. Hess (1974) estimated that mean-annual potential evaporation is 800 mm, varying from near zero to over 100 mm/mo.

The Preserve includes a roughly one hectare collapse sinkhole that contains the entrance to Crumps Cave (Figure 3), which from the entrance consists of a large, nearly horizontal passage typically 12 m tall by 18 m wide formed within the upper part of the St. Louis Limestone, which at this site dips about 2o towards the west. About 3 m of Baxter silt-loam soils overlie the bedrock on the flat surface surrounding the sink, with an additional 18 m of rock to the cave ceiling. The Lost River Chert, an interbedded, silicified limestone, lies between the surface and cave ceiling.

Water from epikarst drains form waterfalls that fall about 4 m from the cave ceiling at several locations, offering an opportunity to evaluate epikarst hydrology and hydrochemistry. Work here focuses on high-resolution data from measurement of the epikarst drain at Waterfall One (Figure 3), in a side alcove about 30 m from the cave entrance. As it falls from the cave ceiling and disappears into the cave floor making its way downward through the vadose zone, the water has entered the main body of the karst aquifer, where it reaches the water table about 40 meters below (during low flow conditions), then flows through large conduits to reach the Barren River at Wilkins Bluehole, 18 km to the southwest. Wilkins Bluehole is the second largest spring in Kentucky, with a minimum discharge of 0.56 m^3/s (Ray and Blair, 2005).

Monitoring Efforts

There are a number of interrelated efforts to collect high-resolution data, which include measurement of more than 20 parameters, most with ten-minute resolution using data loggers. These include 1) surface weather conditions above the cave, 2) measurement of water levels through wells into the epikarstic zone and the main water table,

3) measurement of flow and chemical conditions at the epikarst drain at Waterfall One, 4) collection of water in various parts of the system for evaluation of both carbonate and isotope geochemistry, and 5) monitoring of bat activity at several locations as they enter and leave the cave. These data support an ongoing series of experiments including study of epikarst groundwater flow with introduced tracers including fluorescent dyes and agricultural compounds from actual field-scale farming at the site, including both bacteria from animal waste and herbicides. Surface and cave biological and archeological surveys have also been completed at the preserve. Several of these efforts are described in more detail below.

Surface Monitoring

Weather/climate conditions are measured with an automated weather station above the cave (Figure 4) with ten-minute resolution, including rainfall, air temperature, relative humidity, solar radiation, wind speed and direction, and barometric pressure. Water leaving the rain gage is collected in a device that inhibits evaporation for weekly analysis of hydrogen and oxygen isotopes that provide information of precipitation source areas as well serving as a tracer that helps us to better understand mixing processes in the epikarstic zone, where they are also collected weekly in the cave.

Soil temperature data for 5, 10, 25, 50 and 100 cm depths are measured with 30 minute resolution at two nearby research-grade climate monitoring stations that make up part of the Kentucky Mesonet network, including the Warren County and Barren County stations that lie about 18 km west south west and 18 km east south east of the Preserve, respectively. Comparison of the data from the two sites indicates that over the one year of 30-minute resolution data the average difference between the 87,600 readings comparing paired measurements taken at the same depths and times was less than 1°C. Comparison of these data thus suggest that seasonal and diurnal variations between the two sites, and thus those in the soil at the preserve, are nearly identical, though timing of temperature variations on the scale of minutes to hours can be larger due to local conditions. Local differences between soil moisture conditions at the two Mesonet stations are greater, and our use of these data herein is limited to interpretation of relative changes (whether soil moisture is increasing or decreasing over some period, for example) when both stations are in agreement.

Figure 4. *Weather station above Crumps Cave (photo by Chris Groves).*

Soil water is collected weekly (when it is present) from two lysimeters above the cave.

Hydrologic Monitoring

In fall 2011, the City of Bowling Green very generously used its air-rotary drilling rig to drill two wells at the site just to the west the main trunk passage of Crumps Cave that allow us to monitor water levels (now with ten-minute resolution) in the main water table, which under dry conditions is down about 40 meters below the ground surface, and the top of the saturated part of the epikarstic zone, about 15 meters down, but above the cave. This is very instructive to see for folks who are just learning about concepts of how epikarst systems behave, with water table in two wells only about 20 m apart laterally, with a 25 meter difference in their elevations!

Below at Waterfall One, water leaving the epikarst drain on its way on to the main part of the aquifer (Figures 5 and 6) is directed into a large funnel-shaped tarp and into a 200-liter barrel-shaped compound weir with four circular, vertically arranged drainage holes, larger in ascending order to accommodate larger flows. Water

Figure 5. *Epikarst monitoring site at Crumps Cave (photo by Jason Polk).*

level is measured every ten minutes with a pressure transducer, and appropriate relationships are used to calculate discharge in liters per second as a function of water level. Water exiting the weir flows past duplicate temperature and specific conductance (spC) probes and triplicate pH electrodes. These observations are recorded every ten minutes on duplicate Campbell Scientific multichannel data loggers (that is, each logger records temperature, spC and a pH; one logger has a second pH probe and one has the weir pressure transducer). Multiple equipment design is used for three reasons: 1) redundancy minimizes data loss in case of any component failure, 2) comparison of independent, multiple readings provides a measure of data quality, and 3) in cases of potentially unexpected behavior of any parameter, multiple probes behaving in the same way ensure that the signals reflect actual flow system behavior rather than electronic artifacts. Water samples for lab analysis are taken by duplicate automatic water samplers each with 24 bottles, which when utilized are programmed with eight-hour resolution but staggered so one or the other sampler takes a one liter sample every four hours. This allows for four-hour resolution but lets the samplers run for eight days before filling all bottles, and also provides redundancy in case any component of the samplers malfunctions.

The site is visited every seven days for data measurement and downloads, probe maintenance and cleaning, and for lower flows discharge is also measured directly by timing flow into a bucket of fixed volume. The pH probe data are recorded as millivolts on the loggers during normal operation; each week the three pH probes were calibrated in pH 4, 7, and 10 buffers to develop current linear relations between voltage and pH, and these relations are later applied in the spreadsheets during data processing. During site visits pH, temperature and spC are also measured with a hand-held YSI multiparameter meter.

Water samples have been collected under a variety of flow conditions, and stored on ice until return to the laboratory and analyzed for alkalinity within 24 hours using the inflection point titration method. Species contributing to alkalinity other than bicarbonate are assumed to be negligible. Samples for cation analysis (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) are filtered and acidified and analyzed using Inductively Coupled Plasma-Optical Emissions Spectroscopy. Anions (Cl^{-}, PO_4^{3-}, NO_3^{-}) are measured by Ion Chromatography. Charge balance errors for all samples used in our analyses fall within 6%.

We have used least-squares regression analysis to relate specific conductivity data to calcium, magnesium,

Figure 6. *Barrel-shaped weir at Waterfall One in Crumps Cave for discharge measurements. Water level is measured with a pressure transducer in the barrel and the temperature, pH and spC probes are in the bucket below (photo by Jason Polk).*

and bicarbonate concentrations, respectively. These relationships, along with direct temperature and pH measurements, then allow calculation of several important components of carbonate system behavior with high resolution, including CO_2 pressures, saturation indices, dissolution rates, and total inorganic carbon (*TIC*) concentrations at the point where the water drains from the bottom of the epikarstic zone.

Bat Monitoring

One of the most critical cave management concerns at Crumps Cave is focused on the presence of a group of federally endangered Gray Bats (Myotis grisescens) that inhabit a large chamber of the cave about 400 meters from the entrance. To monitor their activity in a minimally invasive way, we have installed to BatLogger II ultrasound bat detectors, one near a constriction through which they must fly coming in or out of the cave, and one close to the entrance. Our data so far show both seasonal and diurnal changes in the activity of the bats, apparently related to air temperature.

Data and Interrelationships

Someone who has not thought a lot about caves, or else is not paying very close attention, could be excused for thinking that Crumps Cave is a rather static entity. Upon casual inspection, a few waterfalls notwithstanding, it is a large, rather dry trunk passage within which there does not seem to be all that much going on.

With very high-resolution, however, we are learning that the cave and the hydrologic/ecologic/atmospheric/biogeochemical systems of the environment within which it exists are tremendously dynamic, and the more we learn here the more it is revealed to us what the interesting questions really are.

This is especially so when the interrelationships become apparent. When various outside temperature thresholds are experienced, for example, not only do the bats seem to take notice, but we see in some cases that air temperature warming on a cool fall morning can cause (as we are starting to understand it) activity in the soil to change such that soil CO_2 concentrations quickly rise, which makes water entering the epikarst more acidic, the combination of these which results within a few hours at the epikarst drains that calcium and bicarbonate concentrations have significantly increased (from enhanced dissolution), dissolved CO_2 concentrations have jumped from 5 to more than 80 times atmospheric background, and the pH has dropped by more than a whole unit. That evening as it cools the whole processes is reversed!

What does this, in turn and for example, do to the microbial ecology of the epikarstic zone? We will see!

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MOVING THE NATIONAL PARK SERVICE CAVE AND KARST PROGRAM FORWARD - IDENTIFYING AND UNDERSTANDING PARK RESOURCES

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Abstract

On a national level within the National Park Service (NPS), basic knowledge of cave resources has increased significantly over the last 30 years. With karst resources, while there have been some advances, knowledge of these very complex and hidden resources remain fairly limited. In recent years, NPS park managers have increasingly been working with volunteers and scientists to complete studies including the physical exploration and documentation of cave and karst areas to obtain a better understanding of the resources that they manage. Efforts at the national level within the National Cave and Karst Program are being made to know more about these resources, identify missing areas of information and to develop projects and seek funding for studies that can help the NPS better understand these resources. This understanding will lead to the long-term conservation and protection of resources through appropriate management decisions and actions and through continued education and outreach for staff and visitors.

Current Knowledge and Activities

Physical Exploration and Inventories

A number of park units with significant cave and karst resources have been very active in trying to identify and understand their resources. This includes parks with some of the longest caves in the world like Mammoth Cave, Carlsbad Caverns, Jewel Cave, and Wind Cave. A quick review of active cave discoveries at a number of parks over the last five years finds that several hundred caves have been newly discovered and over 160 kilometers (>100 miles) of cave passages and rooms have been discovered, documented, and inventoried for basic resources. The collected data has been placed into databases within the park units and used, among a host of things, to understand the geographic distribution of these passages in relationship to surface features. These newly discovered 160 kilometers (>100 miles) of resources represents about 8-9% of all the known lengths of surveyed passages in caves of the NPS. While rough figures, this tremendous amount of work has been accomplished mostly by volunteers utilized by parks to help know and understand these very complex places. While some feel that total lengths of passages in a park unit are not critical in the overall management of those resources, these numbers do give us an interesting look at the amount of work being actively accomplished as park units seek a clearer understanding of what they manage.

The picture is far less certain when it comes to knowledge of significant karst flow regimes in park units. A few parks such as Mammoth Cave have a good handle on underground flow paths and how they relate to surface features and structures. Much of the groundwater that flows through Mammoth Cave and other cave systems in and near the park comes from a huge area outside the park boundaries. Efforts over the last 30 to 40 years have provided the park and surrounding communities a much better understanding of where waters in the park

Figure 1. *Natalia Kolk-Tennant reads survey instruments during a cave survey in Ozark National Scenic Riverways. (NPS photo by Scott House)*

originate and any contaminate sources that may provide pollutants. This knowledge has allowed the park to work with many neighbors to help prevent groundwater pollution in the entire area. This has also helped the park be much more prepared for catastrophic events that have the potential to endanger people and their health and the sensitive ecosystems that are found within the waters of Mammoth Cave and the surrounding areas.

Ozark National Scenic Riverways is another park unit that has seen quite a bit of work completed to understand its groundwater flow paths. The potential for lead mining in areas near park properties have spurred major interest in preventing lead contamination into the pristine springs of the park unit, particularly Big Spring. The US Geological Survey and Tom Aley, a karst consultant with cave and karst property nearby, have been leaders in this effort. In general for many other parks with significant karst resources, far less is known about these resources and the water that flows through them.

Scientific Studies

The facilitation of research within a number of park units with cave and karst resources has provided an extensive amount of knowledge to park databases. These studies extend over a number of disciplines and cover a range of resources including biological ecosystems from microbes to vertebrates, paleontological discoveries, paleo-climate conditions, geological and mineralogical studies, cave and karst system developments, water quantity and quality, meteorological conditions, and other important aspects of cave and karst resources.

One of the unfortunate areas of current and ongoing research has been associated with a disease that has been killing millions of bats that hibernate in the eastern United States including within National Park units with caves and mines. This disease, White-Nose Syndrome, is caused by a fungus, Geomyces destructans, and has spread rapidly from its starting point in one cave in New York and is now infecting bats across multiple states and into Canada.

Microbial studies are ongoing in a number of parks as more is learned about the role microbes play in the formation of crystal growth, the types of chemicals they produce that may have potential pharmaceutical use as anti-cancer, anti-fungal and anti-biotic drugs, and how microbial communities may act as analogs to potential microbial communities that may have or still do live on other planets such as Mars. Scientific discoveries continue to document new species and genera of invertebrates, most recently in park units such as Great Basin, Sequoia-Kings Canyon, and Grand Canyon-Parashant.

Scientific investigations continue to change the way we look at cave and karst development in park units and to utilize that information in new ways. Ideas and studies over the last 20 to 30 years have shown that caves within Carlsbad Caverns and other areas have been created by sulfuric acid dissolution. As well, the significant role that hypogenic speleogenesis has played in cave development is only now being fully recognized and appreciated. Significant advances in mineral dating of stalagmites have allowed paleo-climate studies to more precisely date past climatic events such as the drought periods that cause abandonment of cultural centers in the desert southwest over the last 1,000 years. Similar to tree rings, some stalagmites have yearly growth patterns that can be dated. Of particular importance has been the controversial redefining of the timeframe when down-cutting in the Grand Canyon occurred by dating mineral deposition within caves at various levels. Along similar lines, the use of cosmogenic isotopes has been used to pinpoint the dating of passage level development in caves such as Mammoth Cave and in the caves of Sequoia/Kings Canyon.

In recent years, scientific research has expanded greatly into the study of cave and karst resources and has become more main stream as the scientific world embraces these

Figure 2. *Drip water is collected in Wind Cave for a water-quality and chemical analysis project conducted by Dr. Andrew Long. (NPS Photo)*

once hidden and out-of-the way places. While much remains to be studied, National Park units and their incredible resources have been at the forefront of much of this new push to more fully understand the physical world. Much of this is directly due to the facilitation of research by park managers in their efforts to identify and understand the resources they manage.

Management of Infrastructure & Other Projects

In more recent years, park units with commercial cave operations have recognized the inherent problems faced due to infrastructure locations placed on top of and around major cave and karst systems. Mostly developed before there was a realistic understanding between the surface and caves, particularly in karst areas, early developments tended to focus on easy visitor access. Buildings, parking lots, maintenance yards, and other infrastructure in a number of cases were placed directly on top of the resources the park unit was created for. More recent planning documents for these park units have shown a great need to mitigate, or in some cases eliminate, the impacts and potential impacts to the cave passages and rooms below these structures.

Because of aging infrastructure, Wind Cave replaced its older buried sewer lines with new, double-line pipes. With most of the infrastructure built directly on top of the cave, Carlsbad Caverns through the development of the Carlsbad Cavern Protection Plan replaced old, buried outfall sewer lines with above ground lines, removed parking from most of the old Bat Cave Draw parking area, removed one set of Mission 66 housing, and installed oil/grit separators on visitor parking areas. Timpanogos Cave is also worth mentioning. They have recently taken steps to eliminate liquid wastes from being allowed to leak into surrounding limestone bedrock at their restrooms located near the cave entrance. This is no easy feat with the restrooms being located on an extremely steep rock slope over 305 meters (1,000 feet) above the Visitor Center area.

Because of the intense efforts that Mammoth Cave and the surrounding area has put into understanding its karst resources in recent years, they continue to lead the NPS in their attempt to limit contaminants that enter their cave and karst systems. The development of a Regional Sewer System starting in the 1980's has been a great success in limiting sewer releases in the entire region. Nearby cities including Park City and Cave City and other municipalities including Mammoth Cave National Park were included in this 30-year effort to reduce effluent releases into the karst systems surrounding Mammoth Cave. The park has done a tremendous job identifying problem areas and mitigating their effects such as capturing all water that runs off of their maintenance yard and running it through a special filtering system to virtually eliminate all chemical by-products from reaching the cave system below.

While there is still much more to be done in reducing and eliminating contaminants from reaching cave and karst areas within park units, numerous parks are beginning to understand their resources and take measures to effectively eliminate problems.

Database Development & Uses

For various reasons, it has been important for Natural Resource Stewardship and Science (NRSS) teams (including the National Cave and Karst Program and other teams within the Geologic Resources Division) to provide important information to parks for new NPS endeavors such as for the Foundation planning process and for the State of the Parks initiative. The need at the national level to have relevant and current information

Figure 3. *At Carlsbad Caverns National Park, Bat Draw parking lot is modified and returned to more natural conditions while retaining historical context for the area. (NPS photo by Dale Pate)*

of cave and karst resources within parks has necessitated that a database be developed that can help provide critical information for these programs and for other significant reasons. As important is our need to understand cave and karst resources on a local, regional, and national level so that we can help identify needs and information gaps which will lead to the identification and development of critical projects and the justification for allocation of funds to complete this projects. It is also important to make sure that park managers are aware of the resources they are asked to manage and that managers within the upper echelon of NPS regional and national levels are aware and informed of issues and other relevant activities associated with cave and karst resources.

The idea of maintaining a database is not to gather sensitive information, but rather to gather and maintain pertinent information that can help further the goals of identifying, understanding, and protecting these valuable resources while providing a variety of experiences for the visiting public.

Gathering Pertinent Information

In order to begin this important process of gathering information, the National Cave and Karst Program office has taken two critical steps to move this forward.

The first has been to contract the National Cave and Karst Research Institute (NCKRI) to develop a report on NPS park units that contain caves and karst that will help us understand which parks contain which resources and the extent of those resources as well as the amount and types of cave and karst educational programs that are available to the public. This report should also determine in a priority order, park units that are in need of more specific studies to better understand their resources. In order for NCKRI to provide the NPS with this information, it has provided a questionnaire to park units in its efforts to gain information on cave and karst resources. A final report is due in 2014.

A second effort is the development of Cave and Karst Summaries for NPS park units from information found from mostly internet searches. These searches are often augmented by NPS Natural Resource Stewardship & Science reports produced by various divisions such as the Geologic Resources Division, Water Resources Division, and others. These summaries provide the NPS Cave and Karst Program information on items such as numbers of caves, types of rock units and types of caves and also the age and distribution of limestone and other rock types that may form caves and/or karst. We are also attempting to determine if karst within a park unit is considered significant or minor. These summaries will be updated as needed and initially are being used to provide information to parks for the two national-level programs mentioned above.

Identifying Needed information

With knowledge of the extent of cave and karst resources found within NPS units, we can begin to recognize areas of missing data that are critical for the long-term protection and management of these resources. This is especially true for park units that are identified as having significant karst. Karst continues to be one of the most fascinating, and yet, least studied of American landscapes. Extremely sensitive to man-induced changes, its importance as freshwater aquifers and as habitat to numerous invertebrate and vertebrate endemic species cannot be over emphasized. Knowing groundwater flow paths as they enter, travel through, and exit park units is as important as is knowing where a surface river enters, travels through, and exits a park unit. A park manager that is unaware of the existence of a surface river flowing through his or her park would not be able to properly manage that river. The same goes for groundwater flow paths. Not knowing where groundwater comes from, travels through, or where it exits a park unit means that management of that flow is virtually non-existent. Will a catastrophic spill or chronic contamination affect drinking water for the park or a neighbor? Will a new subdivision on properties outside park boundaries affect groundwater within a park unit? Managing karst areas takes knowledge to manage properly. How many different groundwater flow paths are totally unknown at this time within NPS units with significant karst? There may be hundreds if not more. Even with park units with minor karst, are there significant elements of that karst that are critical to know for the protection and conservation of the resources of that park? By knowing what resources we do have, we have the opportunity to identify those areas where we are missing information.

Long-term Conservation and Protection

With the knowledge of what we don't know, we can work with staff from individual parks, regions, I&M networks, NRSS divisions, and outside organizations and individuals to develop specific projects that can

fill information gaps. With the NCKRI report in hand and a fresh look at parks and their amazing resources, we can provide justifications for a number of specific projects that will help us better understand the cave and karst resources the NPS manages. With the completion of more studies, we will know and understand more. With better understanding, the NPS can better conserve and protect resources that until recent years have been mostly unstudied and hidden from view. With better understanding, park, regional, and national management teams can make better decisions to conserve and protect these resources while still allowing visitor access. And with better understanding, NPS park units can provide more accurate and critical education and outreach to an ever-expanding public that will increasingly become more and more interested in cave and karst resources.

Biography

Dale L. Pate is the National Cave and Karst Program Coordinator for the National Park Service. Dale's career in the cave and karst field began as an avid caver in 1970 in Central Texas and the mountainous areas of Mexico including the Purificación area within the rugged Sierra Madre Oriental. Having received a BA in Geography from Texas State University in 1974, Dale began work in 1976 with the U.S. Geological Survey (USGS) in Austin, Texas. During the next few years, he augmented his education with a number of geology classes from the University of Texas. Dale remained with the USGS through June 1991 when he became the Cave Specialist for Carlsbad Caverns National Park. At the park, he served as a manager for 21 years with oversight of numerous cave and karst projects which included all activities within Lechuguilla Cave. Dale became the full-time National Cave and Karst Program Coordinator for the NPS in July 2012 after having served the position in a half-time capacity since May 2007.

NATIONAL PARK SERVICE CAVE ECOLOGY INVENTORY AND MONITORING FRAMEWORK

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Abstract

A team developed the *Cave Ecology Inventory and Monitoring Framework* for National Park Service (NPS) units. It contains information for NPS cave managers across the United States to determine how to inventory and monitor cave ecology. Due to the wide geographical scope of NPS caves and their many different types, the document does not prescribe exact protocols. Instead, it provides guidance for what types of inventory and monitoring are possible, a framework for deciding how to prioritize inventory and monitoring activities, and references to specific protocols that are already in place at NPS cave parks.

Introduction

In late 2008 a meeting was held in Lakewood, Colorado to discuss how national protocols could be written to

address a variety of National Park Service (NPS) units containing cave resources. It was decided to divide into smaller groups to focus on cave paleontology, cave inventory, cave air quality, cave water quality, and cave ecology. This document is the product of the cave ecology group, which has communicated intermittently by email and teleconference over the past five years.

Cave biological and ecological monitoring and inventory is a huge topic with great variety across the units of the National Park System. It may include studies on roots in lava tubes at Hawaii Volcanoes National Park, bats in talus caves at Pinnacles National Park, endemic microbes in Lechuguilla Cave at Carlsbad Caverns National Park, and Endangered Species Act-listed aquatic invertebrate species at Mammoth Cave National Park. Due to the large diversity of cave biological and ecological resources within the System, the project team determined that specific, one-size-fits-all protocols for all cave biological and ecological inventory and monitoring efforts were not practical or desirable. Rather, the team has worked to develop a decision-making tool that NPS units can use to determine their own local cave biology and ecology inventory and monitoring priorities and needs.

The *Cave Ecology Inventory and Monitoring (I&M) Framework* is intended to assist NPS cave managers to better understand what lives in the caves that they are responsible for managing. For many NPS units where cave resources have not emerged as a vital sign in their NPS Inventory and Monitoring (I&M) Network, additional guidance would be helpful. This guidance can aid managers in deciding what to inventory and monitor and ways that can be done. It also helps provide a national context, which may help parks conduct inventory and monitoring in a more cohesive manner.

Methods

The *Cave Ecology I&M Framework* was developed by a multidisciplinary group via conference calls and emails. Specialists led calls, during which notes were taken and then incorporated into the document. Numerous drafts were circulated with the authors clarifying and expounding on the document.

Results

A 100+ page document resulted from five years of work. Excerpts from the sections are presented below. At the time of submission, the *Cave Ecology I&M Framework* was still undergoing internal review prior to peer review. The final document may differ slightly from what is presented here.

NPS Cave Resources and Policies

NPS sites contain a wide variety of cave types, and not all are part of a karst system. Nonkarst caves include lava tubes, erosion caves, tectonic caves, talus caves, ice caves, and sea caves.

NPS Management Policies (2006) guide management of caves (Section 4.8.2.2):

> "As used here, the term "caves" includes karst (such as limestone and gypsum caves) and nonkarst caves (such as lava tubes, littoral caves, and talus caves). The Service will manage caves in accordance with approved cave management plans to perpetuate the natural systems associated with the caves, such as karst and other drainage patterns, air flows, mineral deposition, and plant and animal communities. Wilderness and cultural resources and values will also be protected."

Why Caves Are Important

Caves provide subterranean habitat for many species, some of which are wholly dependent on caves to survive. The unique characteristics of cave environments offer the specific conditions required by many animals, as well as some plants that utilize cave entrances. At first, these habitats may appear to be isolated from the outside world, with a layer of rock separating the underground from sunlight, precipitation, and wind. However, a closer look finds that the surface and subsurface are connected in a variety of ways.

Karst makes up about 40% of the land east of the Mississippi and 20% of land worldwide (White et al. 1995) and provides a critical source of water in many of these areas. Caves are found in many areas of the United States, with notable high concentrations in Kentucky, Indiana, Tennessee, Alabama, Georgia, Missouri, Arkansas, Pennsylvania, Florida, Texas, California, and New Mexico. Cave and karst resources occur in over 125 NPS units, most of which are within the contiguous U.S. (Figure 1). Only a small proportion of these units, though, are considered true "cave parks" in which caves and karst constitute the dominant resources. Caves and karst are also present in NPS units of Alaska, Hawaii, and the U.S. territories.

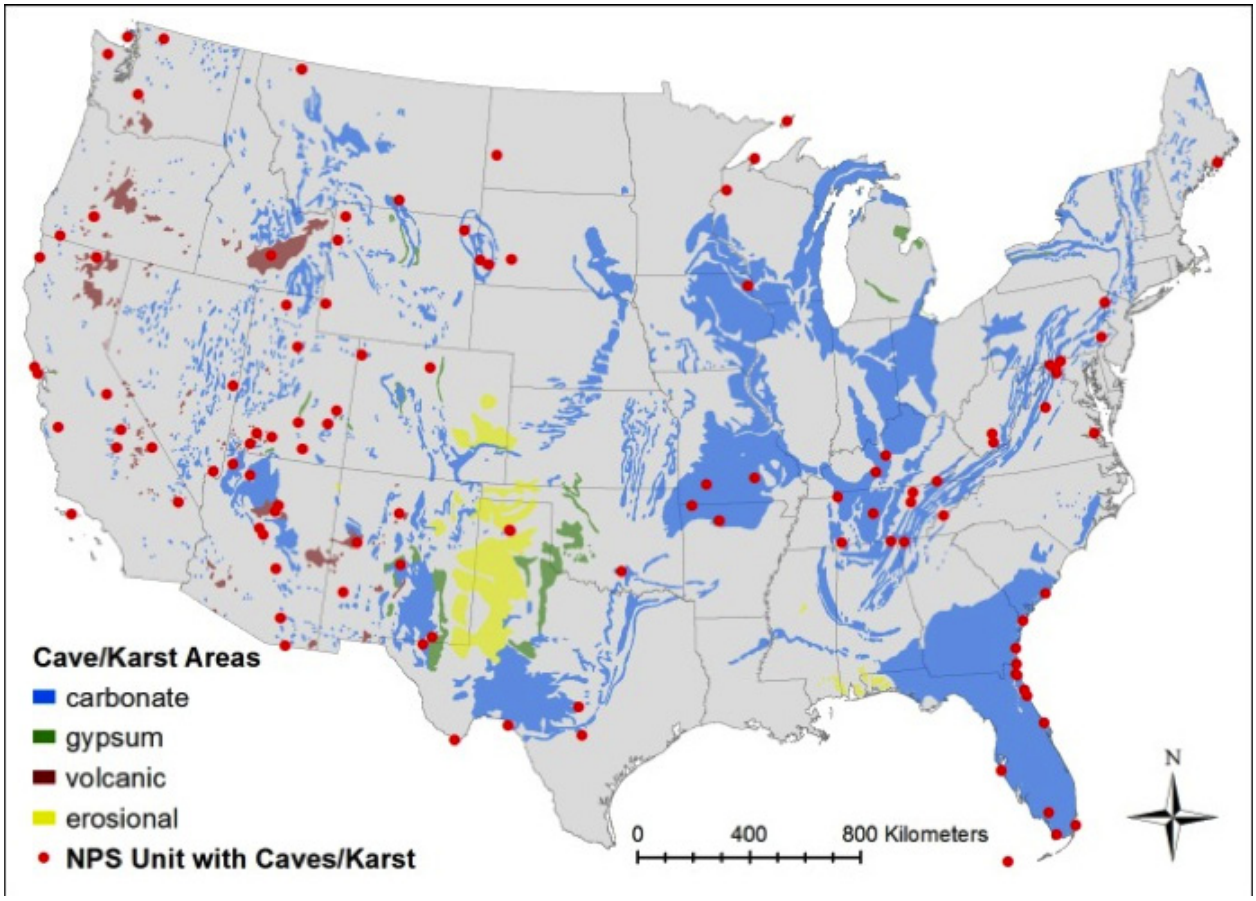


Figure 1. *Cave/karst areas and NPS units with cave/karst resources in the contiguous U.S. Adapted from Croskrey, 2012 and Tobin and Weary, 2004.*

Many of these caves contain cave-obligate biota, and without caves, these species would cease to exist. In North America there are over 1,100 known troglobites and stygobites (Culver et al. 2003), with many more likely present in other subterranean environments, like aquifers and the epikarst. Most cave species are largely unknown; they have small populations and low rates of reproduction, making field studies difficult, and few can be raised successfully in the lab.

Introduction to Cave Ecology

There are numerous systems that have been developed for classifying cave organisms. The most widespread system, and most familiar to natural resources managers, classifies organisms into four categories (Table 1).

Typical cave ecosystems are decomposer ecosystems (Figure 2). In the absence of solar energy, these ecosystems depend upon organic materials which fall, wash, wander, or are otherwise brought into caves. This plant and animal material dies (if it has not already), and a variety of fungi and bacteria begin the process of breaking down this material. Larger organisms – invertebrates – also may consume this surface-derived organic material, such as when a larger vertebrate falls into a pit entrance or is washed into a stream cave. The bacteria and fungi are fed upon by small invertebrates such as springtails and millipedes, which feed at the lowest trophic levels. These, in turn may fall prey to larger invertebrates – spiders, harvestmen, beetles, etc., and in situations where still larger predators – vertebrates such as cave fish or salamanders – are present, the various invertebrates can fall prey to these larger organisms. In most cave settings, larger animals that live exclusively in the caves to form still higher trophic levels do not exist. It should be emphasized that compared to surface habitats, caves have low biodiversity.

Table 1. *Cave Organism Classification from least cave adapted to most cave adapted.*

Accidentals	Accidentals are animals that find themselves in caves by accident. These include everything from a turtle being washed in during a spring flood to an unfortunate cow falling into a pit. They have no adaptations to the cave and usually die, contributing nutrients to the food base.
Trogloxenes	Trogloxenes (cave-foreigners or cave-guests) are species that use caves, but are also found in other locations. Common trogloxenes include bats and some cave crickets like Ceuthophilus that only use caves as a roost or to overwinter, and a frog or snake seeking the cool of an entrance on a hot summer day.
Troglophiles	Troglophiles are animals that use the cave for most parts of their life cycle, but have to return to the surface for some purpose, like feeding or reproduction. Some cave crickets, like Hadenoecus, are troglophiles. They reproduce entirely within the cave, but leave at night to feed on the surface.
Troglobites	Troglobites are limited to caves and similar environments. The most extreme forms show adaptations to the cave environment such as reduced eyes and pigmentation. They complete their entire life cycle within the cave. We sometimes separate terrestrial troglobites and aquatic stygobites.

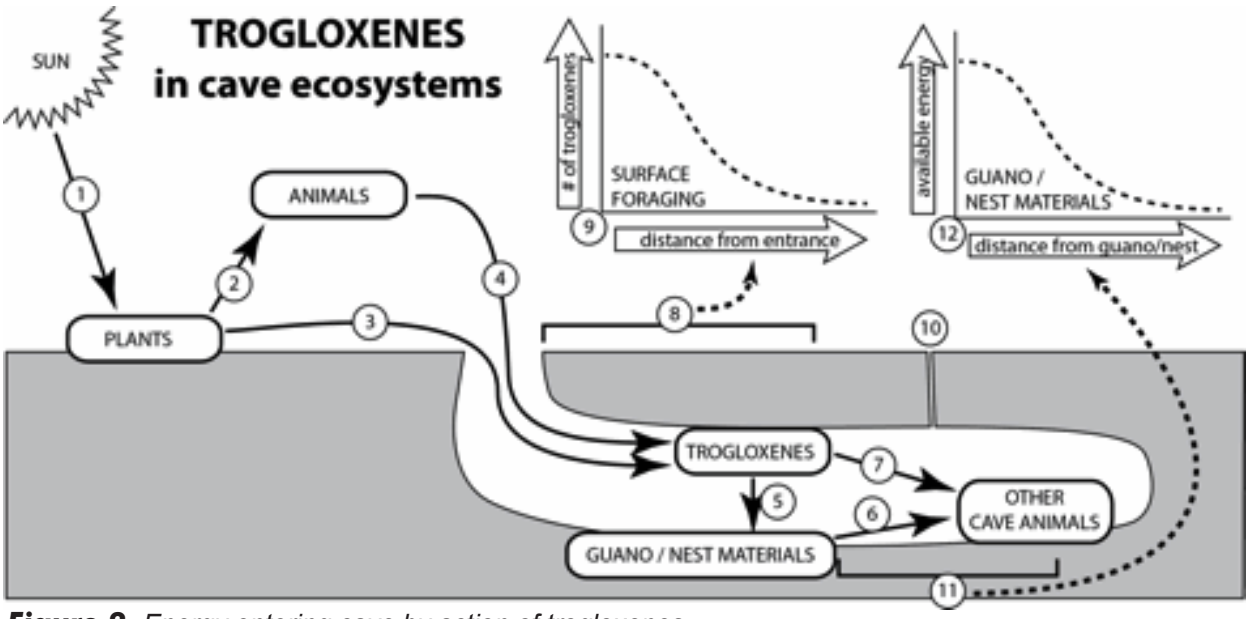


Figure 2. *Energy entering cave by action of trogloxenes.*
1. Energy from sunlight converts to plant biomass;
2. Energy transfer to above-ground animals as they eat plants;
3. Surface foraging trogloxenes feed on plants, organic debris;
4. Surface foraging animals feed on animals (such as bats feeding on flying insects);
5. Nesting material, feces (guano), &/or food stores or caches transfer nutrients to the cave;
6. Other animals in the caves feed on the organic material brought into the cave by trogloxenes, or on the fungi & bacteria growing on organic materials;
7. Bodies, eggs, & young of trogloxenes serve as energy for other cave animals;
8. Foraging range is how far trogloxenes travel from cave to feed;
9. We expect higher numbers of trogloxenes closer to cave entrances;
10. Sometimes cave entrances are too small for humans to notice, but these can be used by some trogloxenes (mice, crickets, etc.);
11. Abundance and diversity of cave animals drops with increasing distance from guano &/or nest materials;
12. High concentrations of guano, such as at bat roosts, provide lots of energy, but the available energy decreases with increasing distance from the source.

The above paragraph describes a typical trophic structure, but there are many variations. A few caves have very novel energy sources – for example, upwelling deep waters may contain high levels of sulfur, which can be broken down by certain microorganisms that oxidize sulfur compounds. In turn, aquatic invertebrates can graze upon these microbes as an energy source, forming an ecosystem based on an energy source other than sunlight.

General Considerations for Cave Inventory and Monitoring

Designing inventory and monitoring programs for cave ecosystems poses particular challenges: many cave species are rare and/or cryptic, and their distributions can be highly patchy and variable over time. Logistics of accessing sites can be complex, and observers must take unusual care to avoid damaging the ecosystems they are tasked with monitoring. Programs aimed at monitoring microbial species are particularly problematic, as the majority of microbial species found in caves (99.99%) cannot be studied using traditional culture techniques and instead require expensive and time-consuming molecular techniques.

In addition to cave-specific considerations, a good long-term monitoring program for any habitat:

- provides useful information to conservation managers;
- can track either communities or single species;
- doesn't neglect rare species that are not protected under endangered species legislation, but also considers prioritizing common species for monitoring;
- can focus on either charismatic species or inconspicuous-but-ecologically-critical biota;
- doesn't limit itself to tracking species that may become extirpated early or do not follow general trends;
- addresses questions that have management solutions;
- tracks metrics that are of interest to the general public; and,
- creates ground-breaking, publishable ecological data.

A primary objective of this *Cave Ecology Inventory and Monitoring Framework* (Framework) is to determine variability and long-term trends in cave biota using summaries of descriptive statistics for selected parameters. Additional objectives of the Framework include helping cave managers prioritize monitoring activities and providing guidance on conducting in-cave monitoring work by promoting safe and sustainable methods. Ultimately, the primary goal of the Framework is to encourage cave managers to understand as much as possible about local cave ecology and threats to the biota supported by caves in order to make informed decisions geared towards cave conservation and protection of cave ecological systems.

Deciding What to Monitor

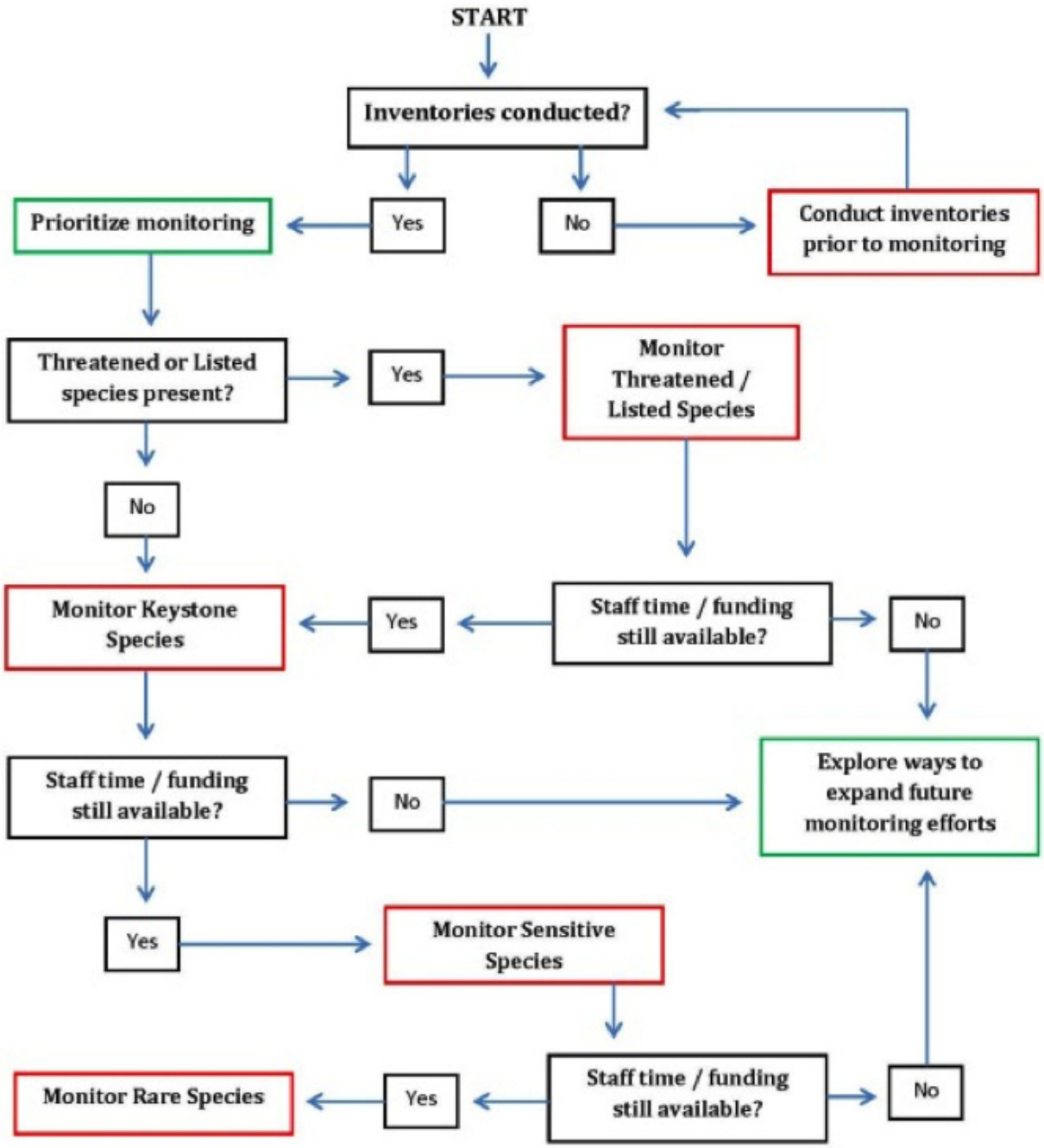
Park managers must decide what to monitor given a limited budget and limited staffing. In this section, a decision flowchart (Figure 3) with considerations about what to monitor is offered to help managers decide what cave habitats and communities are the highest priority to inventory and monitor.

Before monitoring can proceed, data mining and inventories must first be conducted. Data mining will help managers decipher past efforts and understand the current state of knowledge on potential monitoring targets. This is an important step for planning inventories and avoiding duplication of efforts. Basic inventories include specific biota, cave habitats, and threats to caves. Specific biota inventories may focus on something the park is known for, such as bats, or for more obscure biota, like microbes or springtails. Park managers need to know something about the cave habitats in their areas. Are the caves wet, dry, vertical, horizontal? Do they contain ice, bad air, or any other special features that could affect the cave ecology? A threats inventory can begin with the basic question: What do we know or suspect is altered from the natural condition that would have negative effects on cave life?

Following inventories, managers can prioritize monitoring. Several categories of biota to monitor may appear:

- Threatened and Endangered (T&E) Species - Often parks must meet goals for monitoring these species. They also have additional regulatory protections that go beyond those provided for other species. T&E species may not always reflect the overall health of the ecosystem. However, T&E species are generally more vulnerable to climatic changes or human disturbance, so a change in

Figure 3. *Decision Flowchart for Managers to Decide What Cave Ecology to Monitor. Black boxes indicate questions for managers, Green boxes indicate decision-making exercises, Red boxes indicate activity to be undertaken.*



their population levels could be an early indicator of a problem with overall ecosystem health.

- Keystone Species - Species which has a disproportionately large effect relative to its abundance. Plays a critical role in determining and maintaining community structure of an ecosystem.
- Representative Species - Species can be representative of all or a portion of a cave ecosystem and are cost-effective targets.
- Sensitive Species - Species sensitive to change, where monitoring might be most likely to detect changes. In part this requires an assessment of what likely/possible changes might occur, e.g., wildfires, climate change, changing vegetation structure, new construction, changing hydrological regimes, or oil and gas prospecting?
- Rare Species - Rare and unique species are vulnerable, and thus awareness of their condition is important.
- Indicator Species - Species that indicate a problem, for example, coliforms indicate fecal contamination of water supplies. An indicator species can represent the health of the entire ecosystem.

Special threats - Species which already have known potential/impending threats, such as White Nose Syndrome in bats, might be particularly appropriate monitoring targets.

Other considerations for what to monitor:

- What level of identification expertise is available in-house?
- Would it be feasible (time, money, personnel, resources) to obtain appropriate expertise?
- What would be the recurring, yearly cost incurred in monitoring?
- Will funding sources support long-term continuation of monitoring?
- How much time would it take to conduct the monitoring?
- How likely is it that the findings of the monitoring will have substantive impacts on management practices
- If change or a "problem" is detected, what procedures do we have in place to decide what actions will be taken? What is the potential for actions to improve the situation?
- Will monitoring produce data that are of sufficient quality and quantity to allow for statistical analyses?
- Is the monitoring capable of detecting actual change, as opposed to variation within confidence intervals of the methodology?
- To what extent will the life history of the organism impact results of the monitoring?
- Could the monitoring cause damage (to the cave, to the organisms being studied) which exceeds the benefits of monitoring?
- What kinds of baseline data (perhaps inventory data) are needed prior to beginning a monitoring program?
- What kinds of data are needed prior to determining what should be monitored?

Splitting up funding priorities can be done in multiple ways. Finding ways to monitor various categories would be advantageous. Otherwise, if a cave might have several T&E species, and all of the funding goes to those, the representative species would never be monitored. One solution could be to base funding on rough percentages, with the top category receiving X% of available funds, the second receiving Y%, and if additional funding can be found, rare species would be monitored.

Potential Monitoring Targets for Cave Ecology Inventory and Monitoring

This section provides cave managers with examples of what can be monitored, divided into four main areas: terrestrial cave ecosystems, aquatic cave ecosystems, plants, and microbes. Within each of these areas, potential targets are described and consideration is given to monitoring questions, focal species, techniques, sampling locations, and appropriate data analysis. In addition, references, related studies, and links to relevant monitoring protocols are provided.

Terrestrial Cave Ecosystems

A terrestrial cave ecosystem can vary widely from one cave to another, and even within a single cave. Included in this section are taxa that are likely to be encountered, including bats, woodrats, cave crickets, birds, and cave obligate invertebrates. We also consider other wildlife use of caves, detritivores and predators linked to keystone species, and listed or other special interest species.

Aquatic Cave Ecosystems

Aquatic cave ecosystems can vary considerably from one cave to the next. Some include one river that sinks into a cave and later reemerges. Others could include multiple inputs from numerous streams and sinkholes. Aquatic cave ecosystems are not limited to surface water. Groundwater can play a large part, with springs emerging in caves or water tables dropping to allow more access to deeper parts of the cave and then rising and restricting access.

Aquatic cave ecosystems are vulnerable to threats from sinkhole inputs up-gradient and from surface streams that can back-flood into cave streams through springs. They may also include threatened, endangered, or endemic species.

Plants

Plants are often not considered at first when thinking about monitoring cave ecology, but they can be an important part of the cave ecosystem. Vegetation near the cave entrance can influence what lives in the entrance and twilight zones. Ferns, mosses, and lichens are common within cave entrances, and the microclimate of some entrances may support rare and/or specialized plant species. In addition, the vegetation above the cave can have an impact on the cave environment via its roots, evapotranspiration, amendments to the soil, and more.

Lamp flora, or flora growing near artificial lights in the cave, often supports its own ecological communities. Since lamp flora is unnatural to the cave, eradication is usually the goal of cave managers, though short-term inventory and monitoring may be useful for quantifying impacts and determining mitigations.

Microbes

Microorganisms (microbes) are ubiquitous in caves, although their small size means they are often overlooked despite their important role in nutrient recycling, decomposition, and primary productivity. Microorganisms include bacteria, archaea, fungi, single-celled protozoa, and algae (although such photosynthetic species are limited to the entrance zone). Despite their small size, visible growth of bacteria can often be seen in the form of colonies, or in the case of fungi, reproductive structures (mushrooms and molds) may be seen. In some caves, the presence of microbes is displayed through geomicrobial processes that cause bedrock alteration (e.g., corrosion residue) or contribute to formation of secondary deposits (e.g., webulites, pool fingers). Routine monitoring of water quality by monitoring coliforms can indicate potential problems.

Data Management

We encourage cave managers to consider data management as an integral component of monitoring. Development of databases and data sheets should be tightly integrated with monitoring protocols to improve the efficiency and success of the monitoring program. This Framework is not mandating that any park or region must follow one specific data management plan. Although it would be advantageous in many ways to have a nationwide cave ecology database, at this time neither funding nor time is available for such an endeavor. However, if all parks conducting cave ecology projects consider the recommendations herein, the potential for assembling a large nationwide database in the future, if desired, will be improved. We refer readers to the Klamath I&M Network protocols (Krejca et al. 2013) for specifics in data management with regards to a cave ecology program.

Data Analysis

Analysis of cave ecology data can be varied. Before any data are collected it is recommended that a statistician or someone with a great deal of experience with statistics be contacted. This person can help ensure that the data gathering will result in meaningful data.

Pilot data, or data gathered during a short-term or small-area pilot testing period, can help inform whether the data being gathered are useful. It can also be used to help conduct a power analysis to determine the sample size needed to determine an effect of a given size with a specified level of confidence.

Many cave ecology projects target very rare species that are not conducive to data analysis used for surface ecology projects. This section touches on some of these considerations.

Roles and Responsibilities

Parks have the primary responsibilities for determining what the needs are for their parks in order to fulfill the NPS mission. This may include periodic inspections of their cave resources, awareness of incoming threats, management of cave watersheds, and more. Parks then

face the task of finding funding for the efforts they deem necessary. Fortunately, parks have many resources to turn to for assistance with cave and karst monitoring, including specialists at other cave parks and oversight from regional and national levels.

The NPS Cave and Karst Program is part of the Geological Resources Division based out of Lakewood, Colorado. This program offers support to all the NPS units with cave and karst resources. Information can be found on the program's website: http://nature.nps.gov/geology/caves/index.cfm. The program may provide advice or referrals for simple requests or may suggest routing requests through the Technical Assistance Call (TAC) if more complex support is required. More information about the TAC can be found on the NPS Natural Resource Stewardship and Science (NRSS) website: http://inside.nps.gov/waso/waso.cfm?prg=4&lv=1.

The National I&M Program is centered nearby in Fort Collins, Colorado. I&M regional and network offices are scattered throughout the country. Managers and ecologists have a great deal of knowledge about inventory and monitoring techniques. More information on I&M networks and programs, including reports and protocols, is available through the NPS I&M website: http://science.nature.nps.gov/im/.

NPS regions may have natural resource specialists, ecologists, geologists, and/or hydrologists who are able to assist with cave monitoring questions. Many regions also have funding available for park-sponsored projects.

Some caves extend beyond park boundaries, and certainly many karst watersheds do. There are many established precedents of the NPS working with adjoining land management agencies and/or private landowners in the management and monitoring of cave resources. Additionally, the NPS can seek help from other groups that specialize in cave-related work, including the National Cave and Karst Research Institute (NCKRI) and the National Speleological Society (NSS).

Operational Requirements

This Framework offers many ideas for managers of cave resources to pursue. However, it takes more than an idea and a framework to accomplish a project; it also takes funding and dedicated staff. The NPS Cave and Karst Program is currently conducting a data gaps analysis of cave and karst parks. This will help determine the greatest needs for additional cave ecology work and help direct funding to deserving parks.

Discussion

It has taken nearly five years to complete the Framework in preparation for peer review. It certainly could have been completed faster if it had a budget so that preparers could meet in person. However, given that no travel was expended on this project, it is remarkable what has been completed.

The ultimate product will be an NPS publication available to anyone.

The desire of the authors is that the Cave Ecology Inventory and Monitoring Framework will be a guiding document for those undertaking cave ecology studies at their management area.

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THE NPS CAVE VISITOR IMPACT VITAL SIGNS MONITORING PROTOCOL

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Abstract

The national Cave Visitor Impact Vital Signs Monitoring Protocol is an attempt to standardize visitor impact monitoring in all National Park Service managed caves. With standardized monitoring in place, it will be feasible for the first time to compare monitoring data from caves across the country. This cave monitoring protocol was initiated at the NPS Cave Vital Signs Workshop held in Lakewood, Colorado in 2008. That workshop identified the vital signs that were common to all caves, including cave visitor impact. A committee convened at that workshop decided that the cave visitor impact monitoring protocol would address four parameters of human impact on caves, which include: cave visitation, visitor touching, speleothem breakage, and cave visitor traffic. This protocol is now in draft form and is being presented to the wider cave management community for review purposes.

Background

It has been demonstrated many times by using photomonitoring techniques, that in low-energy cave environments, gradual change is almost imperceptible to humans. Because of this, long-term monitoring methods have been developed for caves. These changes, which have cumulative impact, can be caused by cave visitation. There have been a couple of important tools that have been developed to monitor cave visitor impact in caves, including photomonitoring and visitor impact mapping. Impact mapping is a better tool to determine impact over large areas, while photomonitoring is more capable of detecting small amounts of change in smaller areas. Although, these tools have often been used separately, when combined they can provide an effective method of documenting impacts in caves.

In 1995, Hans Bodenhamer first introduced the concept of cave visitor impact monitoring, which he described as the process of recording cumulative visitor impact on a static cave environment (Bodenhamer, 1995). Using this system requires the use of large scale cave maps 1:240 (2.5 m/cm or 20'/inch). Bodenhamer suggests that impact mapping is a viable alternative if the area to be monitored is expansive or if damages to resources need to be quantified. Bodenhamer developed two types of impact maps, one that locates and describes individual impacts points or sites and a second that classifies and locates impacted areas within a cave. The resulting maps provide a quantitative measure of impacts that can then be monitored.

Traditionally, photomonitoring in caves is conducted using a camera, tripod, compass, and plumb line. Photomonitoring is good at documenting a range of change over time. A special type of photomonitoring system was developed by Jim and Val Werker, from Southwest Composites and Photography (Hildreth-Werker, 2006). Their system establishes relatively unobtrusive, permanent stations that can be used to quickly repeat specific photos over time. Individual stations consist of a small stainless steel tube that is epoxied into a three-inch hole drilled in non-decorated rock surfaces. A specially designed camera mount and custom fabricated monorod are then used to take a series of photos that can be repeated at specified intervals. The disadvantage of this system is that there is some impact from installing the mounts. The disadvantage of all photomonitoring is that it is difficult to analyze the resulting photographs.

The cave management community has been using these two methods to monitor cave visitor impact for a long time. However, these efforts tended to be individual efforts developed for a single cave or park and usually did not include protocols or even Standard Operating Procedures (SOP's). Although individual efforts were occasionally reported in the National Cave and Karst Management Symposiums, no attempt was made to

develop national vital signs for caves until the Mammoth Cave Ecosystem Workshop of 2003.

This first attempt to develop cave vital signs, which was undertaken on May 1, 2003 by Mammoth Cave National Park and the Cumberland Piedmont Monitoring Network, involved a Cave Ecosystem Modeling Workshop at the Cave Research Foundation's Hamilton Valley facility. At that workshop, cave management specialists from throughout the National Park Service identified the major threats to cave and karst resources and the vital signs that should be monitored. However, cave visitor impact was not one of the six vital signs identified. The cave vital sign protocols developed from that effort were not applicable to caves across the National Park Service, but restricted to Mammoth Cave National Park.

The second attempt to develop vital sign monitoring protocols for cave and karst resources was initiated at the Cave Vital Signs Workshop held in Lakewood, Colorado on November 18-19, 2008 under the direction of Denis Davis, then Superintendent of Timpanogos Cave National Monument. This workshop was convened because the 32 Inventory and Monitoring Networks of the National Park Service, for the most part, did not fund protocol development for cave and karst resources, except for a few individual parks, including: Mammoth Cave National Park, Oregon Caves National Monument, and Lava Beds National Monument. However, these protocols were very site specific and not applicable to all NPS units with cave and karst resources. This workshop began by revisiting the vital signs that should be monitored for cave and karst resources in the National Park Service and identifying the vital signs that were common to all caves, including both developed and undeveloped caves. As a result, cave visitor impact was added to the list and chosen as one of the vital sign protocols that would be developed. Rod Horrocks, from Wind Cave National Park, volunteered to develop this protocol. His working group included Elizabeth Hale, from Oregon Caves National Monument and Lee-Gray Boze, from Jewel Cave National Monument.

Discussion

The National Park Service uses vital sign monitoring to track physical, biological, and chemical elements and processes in park ecosystems. These monitoring results are used to support management decision-making and to aid park planning, research, education, and public understanding of cave and karst resources. Monitoring helps managers determine patterns of impact and to develop measures to limit or stop future impact.

Monitoring techniques are an important tool for cave managers, as they allow them to determine the type and extent of impacts to cave resources. They are used to document imperceptible changes over time and thus justify mitigation measures. These monitoring efforts also provide baseline data, which can then be used for comparison purposes.

The parameters developed in this protocol apply to both developed and undeveloped caves and the tools used to quantify resource impacts are often the same for both types of caves. The four parameters discussed in this protocol are cave visitation, touching, speleothem breakage, and cave visitor traffic. For each individual parameter, sampling design, field methods, data management, and analysis and reporting are discussed within the protocol. Additionally, the associated indicators and stressors for these parameters are outlined and discussed.

Indicators are trigger points that when observed should provoke managers to implement mitigating measures, as their presence hints that impact to cave resources is occurring. The indicators included in this protocol include: trash, graffiti, polishing and staining of rock surfaces, broken speleothems, compacted floors, dust accumulations, lint accumulations, footprints, and damaged resources.

Stressors are the root cause of impact to cave resources and are first evidenced by the presence of the indicators previously outlined. The stressors used in this protocol include: unmarked trails, unauthorized use, or unregulated use for undeveloped caves and overbooked tours, lack of tour trailers, specimen collecting, touching, urinating, defecating, and wandering off trails for developed caves.

Cave visitation was chosen as a parameter because it can be used as an indicator of the condition or health of a cave ecosystem once the actual numbers of visitors using a particular cave is determined. Although, the cave visitation parameter could also incorporate the other three parameters, this parameter is differentiated from the others by our intention to only address the flow of people into and through a cave and not the impacts from their visits. The cave visitation section of the protocol

helps establish the tools used to define and quantify cave visitation, both in developed and undeveloped caves, so that cave visitation can be measured and evaluated. Many tools, such as cave registers, cave gates, zoning, traffic quantification, and sensors can be used so that cave visitation can be measured, managed, and evaluated. Another of the purposes of cave visitation monitoring is to demonstrate to management or managing agencies that mitigating actions are required and/or justified. Using cave visitation to understand visitation and trends will provide cave managers and the people using those caves with a rarely used, but effective tool. Cave visitation numbers can be used to predict the levels of impact from touching, vandalism, dust, lint, and hair and to maximize resource protection, safety, and visitor satisfaction (Jasper, 2005). For this reason, the cave visitation parameter is discussed first in this protocol, as it will help cave managers in developing monitoring frequencies for the other three parameters.

Visitor touching was chosen as a parameter because it can be used as an indicator of the condition or health of a cave ecosystem by demonstrating by its presence that the mitigating procedures and management policies currently in place are insufficient to protect cave resources. The touching parameter includes both intended and unintended impact from cave visitors touching cave surfaces. Visitors' touching the walls of a cave with their bare hands is a common problem in cave management as these actions lead to staining and polishing of cave surfaces. Many management plans and policies attempt to prevent this, but it remains a nearly ubiquitous part of cave visitation. Human-cave contact causes impact in caves that is not naturally reversed and is difficult to mitigate. Touching is a complicated issue because the impact from touching cave surfaces is cumulative and is not perceptible to periodic cave visitors, as it occurs over time and at very slow rates. As a result, convincing management or managing agencies that there is a problem can often be difficult. Once the impact from touching has been allowed to accumulate, there are no tested or approved methods to mitigate that impact; so prevention or arresting that impact should be the focus. Although caves have very little carrying capacity, entirely eliminating cave entry is not a feasible management policy, in both theory and practice. Therefore management must address the symptom itself. An important management tool to prevent unnecessary touching is education and interpretation (Foster, 1989). Educating the public of the value of natural resources helps reduce damage and vandalism by allowing people to feel a sense of ownership and responsibility for the non-renewable cave resources. However, there are other measures that can and should be used in conjunction with education in developed caves, including: adding handrails or handles, installing sacrificial touching rocks, and increasing light levels. In undeveloped caves, flagging trails and enforcing glove requirement policies can reduce impact from touching.

Speleothem breakage was chosen as a parameter because it can be used as an indicator of the condition or health of a cave ecosystem by demonstrating by its presence that the mitigating procedures and management policies currently in place are insufficient to protect cave resources. The speleothem breakage parameter includes both intended and unintended impacts from cave visitors breaking or collecting speleothems. Due to the nonrenewable nature of cave speleothems, at least as far as human life spans are concerned, any breakage or unauthorized collecting leaves permanent scars on a cave and can severely degrade the aesthetic quality of that cave and degrade the scientific value of its resources. Tools used to identify speleothem breakage include photomonitoring and invisible marking systems. This section of the protocol describes the monitoring tools used to determine if speleothem breakage is occurring. One of the purposes of speleothem breakage monitoring is to demonstrate to management or managing agencies that mitigating actions are required and justified. However, it is important that as soon as speleothem breakage is confirmed, mitigating measures are taken to address the issue. One should not wait to collect a preponderance of evidence before acting, as that would only lead to additional non-renewable resources being lost. Speleothem breakage monitoring goes hand in hand with speleothem inventories, which is baseline data that should be collected for every cave.

Cave visitor traffic was chosen as a parameter because it can be used as an indicator of the condition or health of a cave ecosystem by documenting the level of impact from cave visitors. The cave visitor traffic parameter includes the impact from cave visitors that is not covered by the other parameters. Tools used to quantify visitor traffic impact include photo monitoring, impact monitoring, and lint and dust monitoring. Visitor traffic impacts can diminish cave aesthetics, alter the cave ecosystem,

degrade the scientific value of cave resources, and even make traveling through a cave more hazardous. Some impacts are inevitable, some are unintentional, some result from carelessness, and others reflect what caving techniques are practiced and how groups are managed. Visitor traffic impacts include:

- Darkened, polished, discolored, and scratched rock surfaces
- Disturbed, broken, and trampled cave features, resources, and fauna
- Sediment and mineral tracking, compaction, erosion, and smearing
- Dust, lint, hair, and trash accumulation on cave surfaces and in pools
- Introduction of non-native organisms and substances to the cave environment

Summary

The cave visitor impact monitoring protocol discusses historical studies that were important in developing the monitoring procedures and the tools outlined in this protocol as well as the mitigating measures that can be implemented once impact to cave resources has been observed. Finally, it provides SOP's that cave managers can use to conduct the monitoring outlined in this protocol.

Once the draft of the protocol is completed, the Cave Visitor Impact Protocol Working Group will work with personnel from the NPS Midwest Regional Inventory & Monitoring Group, stationed in Rapid City, South Dakota, to produce a document that can then be peer reviewed by the winter of 2013. It is hoped that the Cave Visitor Impact Vital Signs Monitoring Protocol will be finalized by the spring of 2014.

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COOPERATIVE MANAGEMENT, IMPLEMENTATION STRATEGIES
JIM GOODBAR, CHAIR

COOPERATIVE CAVE MANAGEMENT IN THE ERA OF WNS

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Abstract

With declining budgets, less money than ever is available for meaningful cave management, including baseline inventories and monitoring. The spread of White Nose Syndrome (WNS) has made it even more difficult to effectively manage cave resources. In the region of the Ozark Plateau, Cave Research Foundation is continuing to provide these services, and more, by working within guidelines of various agencies and private landowners. These include Ozark National Scenic Riverways and Buffalo National River (NPS) Mark Twain National Forest (USFS) the Missouri Department of Conservation, Missouri Department of Natural Resources – Division of State Parks, U.S. Fish and Wildlife Service, and the privately-held Pioneer Forest. Most of this work is performed by unpaid volunteers from CRF and affiliated organizations. Rather than limiting the work done by volunteer workers, the agencies we work with are actually expanding the role of volunteers and are providing funds and facilities to facilitate this work. The conclusion is that good volunteer work is not only continuing but being encouraged in the face of adverse conditions.

Introduction

In previous papers (House, 1996, 2008) I have discussed the role of volunteers and pro-bono researchers in performing management activities on agency lands. Included in those activities are monitoring, inventory, data management, and cartographic survey. The value of cartographic survey for management uses has been previously described (House, 1985). Since the advent of White Nose Syndrome (WNS) there has been much uncertainty about the roles of researchers and volunteers in performing useful cave management activities on agency lands. Land managers have, in many instances, unfortunately reacted to WNS concerns by severely limiting the roles that non-agency personnel can perform. This has had a negative effect on performing useful and necessary management actions. The caves, in many instances, are now being managed less, rather than more. What follows is intended to be a series of nuts-and-bolts examples of how cave management activities can be facilitated through cooperative agreements and other arrangements with Cave Research Foundation (CRF). For purposes of understanding the karst regions involved, a good overview of Missouri caves and karst can be found in a previous paper (House, 2009).

Ozark National Scenic Riverways

The Ozark National Scenic Riverways (OZAR), a unit of the National Park Service, contains approximately 400 known caves along the Jacks Fork and Current Rivers in Missouri. Most of the caves within the park harbor bats, at least seasonally. Caves are of particular importance within the Riverways as they are noted as important features worth preserving in the park's enabling legislation.

The Cave Research Foundation has a history of working with the park since the 1980's. Some of the early projects were enabled by volunteer agreements. But as the need for better data rose, these agreements were superseded by cooperative cost-sharing projects and small contracts. Included in these were data synthesis, development of databases for inventory and monitoring, bat surveys, and baseline biological inventories.

A growing need for specialized cave management led to the present contractual agreement which covers a variety of cave management activities. A relatively small amount of funding pays for professional and volunteer services both. Included in these services are data management, cave monitoring, installation of signage, cartography, gate inspections and a host of other, smaller tasks. Specific gating projects are covered through other small contracts as money becomes available.

Signs of WNS were first detected in the park in 2010 when a small number of gray bats were noted to have wing damage consistent with WNS signs. Tissue samples confirmed the presence of the causative agent. At that

Figure 1. Cartographic Surveys.
A CRF member shoots instruments in an Ozark cave. Photo by Josh Hafner.

point, consistent with NPS policies, an emergency closure of all park caves was announced. At the same time, work began on a WNS plan that would take proactive steps to continue active cave management.

Within a period of three months, the WNS plan was written and approved. All park caves would be closed to visitation with the exception of Round Spring Cavern which is developed for lantern tours. Visitors to that cave would be screened to hopefully prevent inadvertent movement of spores.

The plan calls for continued management work on caves, specifically citing CRF as the park partner that will perform the work in conjunction with resource managers. Inventory, monitoring, mapping, and other useful activities continue under the WNS plan and a general agreement between the park and CRF. More than 100 monitoring trips to caves were taken in both 2011 and 2012. Cartographic surveys, which are highly important to proper cave management, are actively continuing. All survey trips also perform monitoring.

Figure 2. WNS Surveys.
CRF and NPS biologists inventory and swab bats. Photo by Scott House.

OZAR has provided research and volunteer housing at the Powder Mill Research Center. Full decontamination facilities are there (tubs, chemicals, washer, dryer, pressure hose, etc.) and the park has invested heavily in dedicated gear that does not leave the park.

Instead of just closing caves to all useful visitation, the Ozark National Scenic Riverways has taken the proactive approach of permitting, and contracting for, activities that greatly increase the ability of the park to manage its cave resources. In the Ozarks, OZAR has taken the lead in proactively balancing the concerns of spreading WNS with the realities of having to manage resources.

Buffalo National River

The Buffalo National River (BUFF) lies along the Buffalo River in northwestern Arkansas. Like the Ozark Riverways, the park has numerous caves, probably over 500, many of considerable length. Numerous bat caves lie within the park. As a precautionary measure, all caves have been administratively closed to visitation. CRF and BUFF have a cooperative agreement that includes monitoring, database management and cave survey. In addition, the work is facilitated through a research permit. This was felt to be the best vehicle for authorizing activities while maintaining closures for the general public. An active program of survey is supplemented by monitoring reports taken on every trip and entered into a database similar to OZAR's. Beginning in 2010, more than 130 monitoring trips have been taken to caves. All survey trips also include monitoring.

Like OZAR, BUFF provides volunteer housing, decontamination chemicals, washing machine, and dedicated cave equipment.

Missouri Department of Conservation

The Missouri Department of Conservation (MDC) manages state forest and conservation areas and has control over all state wildlife. Lands administered by MDC contain nearly 300 caves, many of which harbor bats. By their state WNS plan, created before the arrival of WNS, all caves are closed to visitation due to the appearance of WNS within the state. Actually the plan

called for a tiered response, slowly activating closures as WNS grew closer. However WNS "jumped" directly to Missouri, making much of the plan a moot discussion. Only research activities are permitted. Some volunteers are allowed to monitor specific caves, mostly the entrances only. All cartographic survey efforts on MDC lands have, at present, been halted. However, the MDC did recently cooperate in cooperative mapping project involving a privately-owned mine (described below) and that may set a precedent for renewing survey work.

Missouri State Parks

The Missouri Department of Natural Resources administers state parks through its Division of State Parks (DSP). Within its varied units, DSP lands contain more than 200 caves, including some spectacular karst resources. The DSP has a long history of cooperative work with cave groups. After the advent of WNS, DSP followed the lead of the MDC, the lead agency for wildlife management, in closing all caves to visitation. Only certain tour caves were exempted. However, the intent was to give resource managers time to formulate a more sensible policy. Since the 2010 closures, the DSP has worked with CRF and other groups to allow the continuation of beneficial activities at caves. For the past two years, CRF has received a grant to inventory, document, monitor, and survey certain DSP caves. Under this agreement, CRF works with park naturalists and resource managers to improve DSP knowledge of their cave resources. CRF volunteers have also installed new cave gates on at least a couple of DSP caves.

Mark Twain National Forest

Mark Twain National Forest (MTNF) of the US Forest Service has over 700 caves on lands it manages. MTNF caves include numerous bats and a number of their caves have been gated to protect them. CRF has been working under volunteer or cooperative agreements for over thirty years. For the last twenty years, challenge cost-share cooperative agreements have enabled biological inventory, survey, and monitoring work. WNS monitoring has been added to the work load as well as occasional archaeological monitoring and inventory. Due to WNS regulations MTNF archaeologists who enter caves would have to decontaminate their equipment and clothing the same as CRF does. The impracticality of that additional step has made it necessary for CRF, working with other groups, to accept more responsibilities.

Currently CRF operates on all districts of the MTNF. For several years MTNF has also used cooperative agreements to facilitate the gating of caves by CRF. Under the present multi-year agreement, gating is included in the same agreement as inventory, survey, monitoring, and assessments. CRF has been a one-stop shopping trip for cave management work on the MTNF.

United States Fish and Wildlife Service

The US Fish and Wildlife Service (FWS) manages only a few caves in the Ozarks. However, it is the lead federal agency for WNS studies and recommendations, particularly on federal lands such as OZAR, BUFF and MTNF. The Missouri field office has been a model of cooperation in permitting useful activities to continue on federal lands. All federal (and most state) management plans and activities covered by the National Environmental Protection Act (NEPA) must undergo a FWS review.

In one instance, a well-known mine was found, by a volunteer, to be containing large numbers of endangered bats. FWS through a grant to MDC funded CRF to map the mine in order to provide a useful baseline for performing a census of bat populations. Further, CRF surveyors provided a necessary guide service to biologists during winter bat counts (the mine is a complete maze).

Setting the tone for cooperative work in the Ozarks, the FWS has shown great common sense in working with agencies and CRF in permitting necessary work to continue.

Figure 3. Bat Cave Gating.
CRF, Bat Conservation International and AmeriCorps workers gate a cave on MTNF land. Photo by Scott House.

Pioneer Forest

Different from other agencies, Pioneer Forest is a private forest owned by a not-for-profit foundation, the L-A-D Foundation. The purpose of the forest is to manage native tree species on a sustainable basis while also providing for recreation and a natural ecosystem. On its lands, Pioneer administers nearly 200 caves. Pioneer Forest has worked with CRF and other groups to help manage its caves, for which it has no staff. Through informal letters of authorization and very limited funding, CRF has performed monitoring, gate management, inventory, and cartographic survey. Pioneer has not instituted mass closures of its caves. In this sense, its policies serve as a control for the experiment of seeing whether closures are effective in containing the spread of WNS.

Summary

No agency is aware of problems that occur in a cave that is never visited by staff or volunteers. Since virtually all publicly-owned caves are administratively closed to visitation, any visitor to a cave is extremely unlikely to report a problem and thus admit they have visited the cave illegally. Closing all caves to visitation, even to those qualified to monitor and research the cave, is, at best, a head-in-the-sand approach.

The intent of this discourse is to show how agencies may enable work to continue in a WNS-positive environment. By use of research permits, contracts, challenge cost-share agreements, and grants these agencies, public and private, have shown great foresight and flexibility in creating a cooperative attitude that fosters increased support from the cave community.

Far from the contentious relations that seem to exist in many areas of the eastern US, the Ozarks region sees agencies and cave researchers working together to meet the management needs necessary to effectively manage and protect these cave resources.

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GEOLOGIC MANAGEMENT OF CAVE AND KARST RESOURCES ON NATIONAL FOREST SYSTEM LANDS

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Abstract

The United States Department of Agriculture Forest Service (Forest Service) manages caves, karst systems, and associated resources on over 780,000 square kilometres of public land. The management of these resources is mandated by the Federal Cave Resources Protection Act (FCRPA) of 1988 and other federal acts, and is guided by the Code of Federal Regulations (CFR) and the Forest Service Manual (FSM). The FCRPA and its implementing regulations at 36 CFR Part 290 – Cave Resources Management provide the framework for management guidance in the FSM. Known caves and karst areas occur in over 100 National Forests and Grasslands, and over 2,200 significant caves have been identified to date, often with the assistance of partners such as the National Speleological Society and Cave Research Foundation.

The goal of the Forest Service National Cave and Karst Program is to protect and maintain the biological, geologic/mineralogical/paleontological, hydrological, cultural, educational, scientific and recreational values of caves and karst resources. Management actions such as timber harvest, mining, grazing, herbicide application, and development of infrastructure and recreation sites on National Forest System lands can impact cave and karst resources. Additionally, such actions in karst areas may exacerbate hazardous conditions related to karst. As per the National Environmental Policy Act of 1972, Environmental Assessments and Environmental Impact Statements may require a section on geology and specifically on cave and karst systems where these resources occur in project areas. This paper will outline the current status of geology program cave and karst management in the Forest Service.

Introduction

The United States Department of Agriculture Forest Service (Forest Service) manages a wide variety of natural resources, including caves and karst, across 780,000 square kilometers of land in the 48 contiguous United States (U.S.), Alaska, and Puerto Rico. The Forest Service has a unique and separate mission from other U.S. land management agencies, one of multiple uses and conservation as opposed to preservation, and allows for activities such as timber harvest, mining, grazing, and recreation with the proper environmental considerations. When considering a management activity on National Forest System (NFS) lands, the agency must take into account the needs of many user groups, as well as the best available science in terms of environmental conservation. In cases of proposed environmental disturbance, this is accomplished through evaluation of projects and management strategies through the National Environmental Policy Act (NEPA) process.

The Federal Cave Resources Protection Act (FCRPA) of 1988 defines caves and mandates protection of caves designated as significant. The Code of Federal Regulations (CFR) guides management of caves on federal lands. The Forest Service Manual (FSM) guides cave management in sections relating to recreation, geology, and prohibitions. In addition, cave and karst resources are also protected through approximately 40 additional federal acts addressing items such as watershed, groundwater, and threatened and endangered species protection.

In order to base management decisions on sufficient data, inventory of cave and karst resources is conducted by Forest Service field personnel and qualified volunteers through partnerships and memorandums of understanding (MOUs) with the National Speleological Society (NSS) and associated groups, Cave Research Foundation (CRF), and Geological Society of America (GSA). Areas with potential for cave and karst development are identified through field geologic mapping as well as work with remote sensing datasets. Once located in the field, caves are mapped and inventoried, and significant cave nomination forms are populated and approved by the proper authority. Data storage of cave and karst resources is highly sensitive, and significant cave locations are not subject to requests filed under the U.S. Freedom of

Information Act (FOIA) by the public, similar to federal archeological or "heritage" resources. These data are then utilized during the NEPA process to ensure consideration of land management action on cave and karst resources. Currently, cave and karst resource protection is carried out on a forest by forest and project by project basis depending on the type of project and the standards and guidelines incorporated into each forest plan. Future plans include standardization of cave and karst inventory and mapping, development of best practices and technical guides, unified national data storage, and increased cooperation with stakeholders. Finally, the Forest Service Office of International Programs offers assistance with cave and karst management in protected areas in other countries.

Cave and Karst Resources in the National Forest Service

NFS lands encompass a broad diversity of cave and karst resources across the 513,000 square kilometres (198,000 square miles) of potential cave and karst forming geologic units in the U.S (Figure 1). Karst is formed by the dissolution of soluble carbonate bedrock such as limestone, dolostone, and marble. Caves areoften classified by the parent material or speleogenic process, and are not only or always formed as a portion of the karst system. All types of caves such as volcanic, glacier, stream-cut, wave-cut, shelter, crevice, framework, as well as solution, occur on NFS lands. Figure 1 reflects the different units and areas in which they may occur.

The Forest Service is organized into nine regions, and within each region are individual forests and grasslands. In the eastern U.S., solution caves and karst systems occur in carbonate rock from Green Mountain and Finger Lakes National Forests in the northeastern states down the Appalachian chain through the Monongahela National Forest to the relatively young limestone in the Ocala National Forest in Florida. The longest underwater

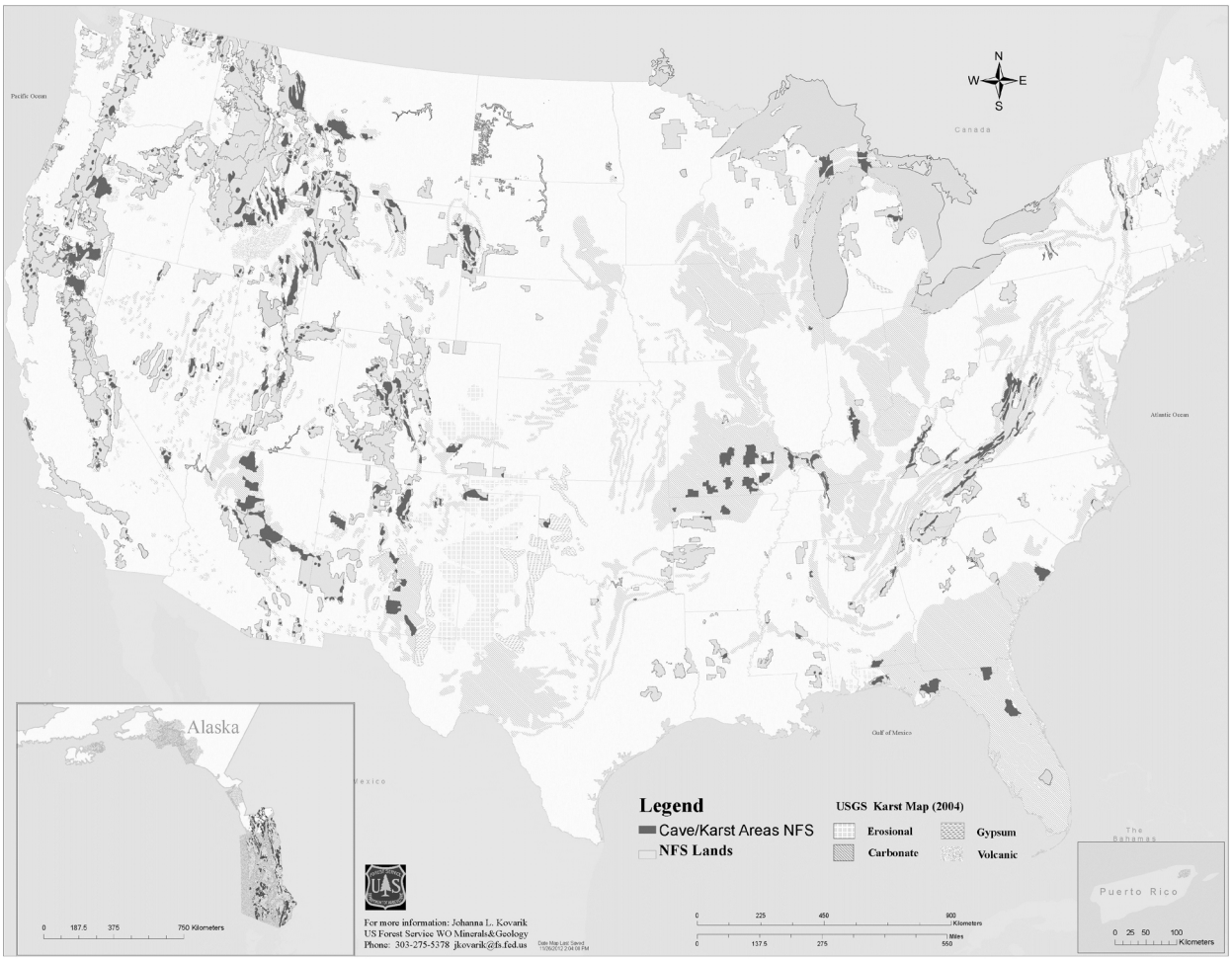

Figure 1. *Caves and Karst on National Forest System Lands.*

cave system, and thirteenth longest cave overall in the U.S. is hydrologically connected to springs on the Apalachicola National Forest. The Mark Twain National Forest in Missouri is underlain almost entirely by carbonate rock and includes approximately 600 caves. In the western U.S., a broad diversity of cave resources include sea and glacier caves on the Tongass and Chugach National Forests in Alaska; ice caves on the Mt. Baker-Snoqualmie National Forest, Washington; lava tubes on Deschutes and Umpqua National Forests; and hypogene solution caves on the Lincoln National Forest in New Mexico and the Humboldt-Toiyabe National Forest in Nevada as several examples. As the Forest Service is working to inventory and document historic and current cave data, it is anticipated that the list of significant caves and resources within their passages will grow exponentially. This section highlights a selection of the caves and cave resources currently known on NFS lands.

Long and Deep Caves

In the Southern Region, Omega Cave is currently the longest mapped cave known on NFS lands, the longest mapped cave in the state of Virginia, and the sixteenth longest cave in the U.S. at 47.07 kilometres (29.25 miles) (Gulden 2012). It is the tenth deepest cave in the U.S. with a vertical extent of 379 meters (1,243 feet), and the sixty-sixth longest cave in the world (Gulden 2012). Exploration began in 1996 and 1997 in a non-Forest Service entrance called Blowing Hole and a Forest Service entrance called "Lori Cori Canyon Cave". In November of 1998, exploration continued with the connection of these two entrances and pushing of further leads. This cave is located on the Washington and Jefferson National Forests in Virginia. In the Eastern Region, Sloan's Valley Cave is currently the twentieth longest cave in the U.S. at 36.3 kilometres (22.56 miles) of passage (Gulden 2012). Many of the entrances are privately owned, however one entrance is on NFS land, and a portion of this total length underlies the Daniel Boone National Forest.

In the Northern Region, Virgil the Turtle's Great House Cave is located in the Bob Marshall Wilderness on the Flathead National Forest in Montana, and is the fifth deepest cave in the U.S. at 423 meters (1586 feet) (Gulden 2012). Also in this area on NFS land is Tickle Me Turtle Cave, which is the twenty-first deepest cave in the U.S., at 271 meters (890 feet) (Gudlen 2012). In the Rocky Mountain Region, Columbine Crawl is the sixth deepest cave in the U.S. at 472.7 meters (1551 feet) deep and 3,703 meters (2.3 miles) long (Gulden 2012). It is located in the Teton National Forest in Wyoming. The Uinta-Wasatch-Cache National Forests in the Intermountain Region contain well-developed alpine karst areas which include Main Drain Cave, as well as Neff's Canyon Cave. Main Drain and Neff's Canyon are also on the deep caves list in the U.S., with Main Drain ranking eleventh at 374 meters (1227 feet) and Neff's ranking thirteenth at 354.5 meters (1163 feet) (Gulden 2012). An additional cave on NFS lands in this area is Nielsen's Well, the twenty-second deepest cave in the U.S. at 268 meters (880 feet) (Gulden 2012). Down in the Southwestern Region, Three Fingers and Virgin Caves are on-going cave survey projects on the Lincoln National Forest in New Mexico. Virgin Cave is the thirty-sixth deepest cave in the U.S., and Three Fingers is the sixty-third deepest cave in the U.S (Gulden 2012). Both of these hypogene caves were discovered in the 1960s and 70s, and are currently undergoing remapping projects.

In Pacific Northwest Region, Deadhorse Cave and Ape Cave, the two longest mapped lava tubes in North America are located on the Mt. St. Helens National Volcanic Monument in Washington State (Gulden 2012). Puffin Grotto is the ninth longest sea cave in the world at 287 meters (942 feet) in length, and is located in the Alaska Region on the Tongass National Forest (Gulden 2012). It is thought to have formed through mechanical wave action as well as dissolution of the Silurian-aged marble, and is uplifted to approximately 15 meters (50 feet) above current sea level.

Cave Biology

Forest Service caves in the eastern and western U.S. provide habitat for a wide range of life from all three domains: bacteria, archaea, and eucaryota. This ranges from several species of troglophiles (eutroglophile), trogloxenes (subtroglophile), troglobites (troglobiont), and stygobites such as bats, salamanders, spiders, crayfish, and loaches to biofilms commonly described as speleothems such as moonmilk. Additionally, cave and karst systems on NFS lands play a critical role in the overall biological productivity of an area, including the geochemistry of waters emanating from karst systems impacting the productivity of fish; and the development of karst features impacting vegetation productivity on the surface (Aley et al. 1993, Harding and Ford 1993, Bryant and Swanston 1998).

Researchers have documented microbial communities in caves on NFS lands as part of a growing discovery of the role of bacteria and archaea in speleogenesis and speleothem formation. University researchers found microbial activity integral in pool finger precipitation in Hidden Cave, Lincoln National Forest, New Mexico as well as in development of subaqueous moonmilk in the form of "cottonballs" on the Tongass National Forest, Alaska (Curry et al. 2009, Melim et al. 2010).

Federally endangered bat species found utilizing Forest Service caves include the Gray bat (*Myotis grisescens*), Indiana Bat (*Myotis sodalis*), the Ozark big-eared bat (*Corynorhinus townsendii ingens*) and the Virgninia big-eared bat (*Corynorhinus townsendii virginianus*). Additional bat species found in Forest Service caves such as the Little brown bat (*Myotis lucifugus*), the Big brown bat (*Eptesicus fuscus*), and the Tricolored bat (*Perimyotis subflavus*) are not currently listed as threatened or endangered, but Forest Service caves provide important habitat as the population numbers of these bats are dropping due to White-nose Syndrome (WNS).

The largest diversity and richness of troglobitic and stygobitic species is currently documented primarily in the eastern U.S., which is covered by the Eastern and Southern Regions (Culver et al. 2001). In the Southern Region, Blanchard Springs Caverns on the Ozark-St. Francis NF is second only to Tumbling Creek Cave in Missouri for the Ozark Plateaus ecoregion in biological richness in Arkansas with 96 total and 9 obligate species (Graening et al. 2003).

In the Eastern Region, the Monongahela, Hoosier, Shawnee, and Mark Twain National Forests have designated many vertebrate and invertebrate cave species as Regional Forester Sensitive Species, such as the Marengo Cave ground beetle (*Pseudanophthalmus stricticollis*), the Carter Cave spider (*Nesticus carteri*), Eastern cave-loving funnel web spider (*Calymmaria cavicola*), Fountain cave springtail (*Pseudosinella fonsa*), and Dry Fork Valley cave pseudoscorpion (*Apochthonius pauscisinosus*). Many of these species are found only in a handful of caves in the eastern U.S., and some of these species are rare and ound only in a single particular cave on NFS land.

Paleontology

The Forest Service is working to collate information from the wide variety of paleontological studies conducted in caves on NFS lands. Researchers have conducted a great amount of work which is well documented in Forest Service caves across the western half of the country, from Alaska to California, through Nevada and into South Dakota. Samwel Cave and Potter Creek Cave on the Shasta-Trinity National Forest in the Pacific Southwest Region are significant fossil repositories, with 52 species excavated in Potter Creek Cave, and 21 of those species extinct (Merriam 1906). These 52 species include the, "short-faced bear (*Arctotherium simum*), shrub ox (*Euceratherium collinum*), hores (*Equus*), mammoth, bison, and camelid" (Payen and Taylor 1976). Faunal deposits in Samwel Cave included 45 mammal species, a portion of which were a large variety of rodents, which were utilized in a recent study assessing the impact of global warming on mammal populations (Faranec et al. 2007, Blois et al. 2010).

In the Alaska Region, the Tongass National Forest's caves are repositories for a large quantity of paleontological resources. Work in eighteen caves in this region by Heaton (2002) documented species of mammals not previously found in southeast Alaska, such as red fox (*Vulpes vulpes*) and wolverine (*Gulo gulo*). Additionally Heaton found a 10,750 year old black bear skeleton (*Ursus americanus*) and 12,295 year old brown bear (*Ursus arctos*) bones on Prince of Wales Island where currently only black bears are found (Heaton 2002).

Archeology

Archeologists have conducted research in Forest Service caves for years, often with the initial discovery of artifacts occurring when volunteers from the NSS or CRF locate artifacts during cave surveys, such as the case of the 8,000-year-old man from Hourglass Cave in region two (Mosch and Watson 1997). Archeologists unearthed one of the most significant discoveries for Forest Service cave archaeology in On Your Knees Cave on Prince of Wales Island in southeast Alaska after discovery and survey of the cave by the Tongass Cave Project of the NSS. In 1992, the 10,300 year-old remains of young man called Shuká Kaa ("Man Ahead of Us" in the native Tlingit language) were excavated and studied along with paleontological artifacts in a ground-breaking cooperative effort with the native Alaskan groups in southeast Alaska as well as with several universities (Fifield 2008). Results from genetic studies on the individual's remains contained significant implications regarding the settlement of the North American continent

(Kemp et al. 2007). This discovery and the studies based upon the artifacts excavated from On Your Knees Cave were given wide press attention, including articles in National Geographic Magazine and Smithsonian.

On the Ozark St Francis National Forests, 64 caves and 55 rock shelters were inventoried as prehistoric sites (Jurney and McCluskey 2012). Rock art panels were discovered in Gustafson/Wingard Cave, and are the, "only known Native American art work in cave dark zones in Arkansas" (Jurney 2009). The rock art panels included the only depiction of a bison currently known about in the state of Arkansas, as well as a centipede which is not common in the eastern U.S. (Jurney 2009). Archeologists also found artifacts in Gustafson/ Wingard Cave including Mississippian pottery shards and archaic dart points. In 1955, cavers discovered human remains in Blanchard Springs Caverns and later discoveries included torch remnants and other items which suggested that human use of the cave spanned 760 years, A.D. 225-985 (Wolfman 1974).

On the Humboldt-Toiyabe National Forest in Nevada, Archeologists have documented a history of cave usage from pictographs in caves in central Nevada to signatures from early miners in the 1800s documenting early recreational use.

Forest Service Policy

There are approximately 40 federal laws directly and indirectly impacting the many facets of cave and karst resource management, including the FCRPA, NEPA, the Organic Administration Act, Endangered Species Act (ESA), Paleontological Resources Preservation Act (PRPA), Archeological Resources Preservation Act (ARPA), and the Watershed Protection and Flood Prevention Act (WPFPA). These laws relate directly to the management planning and responsibilities of geology, archaeology, wildlife biology, and recreation in cave and karst resource management.

Code of Federal Regulations

In the Code of Federal Regulation (CFR) Title 36 – Parks, Forests, and Public Property, there are several sections which relate directly to Forest Service-specific cave resource management. CFR Part 290, Cave Resources Management, contains explicit direction for the Forest Service on cave resources including definitions, the nomination, evaluation, and designation of significant caves, confidentiality of cave information, and collection of information related to caves.

CFR Part 261, Prohibitions, contains prohibitions against such things as occupying, having domestic animals, lighting fires, and discharging firearms underground.

Forest Service manual

The Forest Service Manual (FSM) contains program level guidance for cave and cave ecosystem management, and assigns roles for leadership and coordination. The sections relevant to cave and karst resources are chapters 2356 and 2880. Chapter 2356 outlines the cave management responsibilities of Recreation, Heritage, and Wilderness Resources, and Chapters 2880 describe the cave and cave ecosystem management responsibilities of Geologic Resources, Hazards, and Services.

In section 2356, the FSM outlines the roles and responsibilities of Recreation, Heritage, and Volunteer Resources, including controlling cave use, establishing use limits, developing cave management plans in coordination with other resources, acquiring cave inventory data in order to consider human cave use impacts, and coordinating and developing cave interpretive and educational materials and alerting the public to cave hazards.

In section 2880 of the FSM, the Forest Service manages geologic resources, and caves and karst resources are defined as geologic resources here. This section identifies the Director of Minerals and Geology as being responsible for sharing the lead responsibility for cave and cave ecosystem related management, specifically acting as the lead for all caves which are not designated for recreational use:

> "Coordinate lead responsibility for cave and cave ecosystem management on National Forest System lands with the Washington Office Director, Recreation, Heritage, and Wilderness Resources. Forest Service Manual 2356 provides the direction for significant caves and karst features developed for recreational use; FSM 2880 provides direction for protection and management of non-recreational significant caves and their associated ecosystems."

Forest Supervisors are tasked with making certain the caves under their jurisdiction are being evaluated for

significance by a qualified geologist in accordance with the FCRPA of 1988, and CFR 36 290.

Under FSM 2880, the Forest Service is required to collect and evaluate material to rate the potential for presence of caves and cave ecosystems, and to assess the quantity, quality, and vulnerability of groundwater dependent ecosystems (karst aquifers). For caves and cave ecosystems, the Forest Service is tasked with collecting information on existing caves from the caving community and tribes utilizing spatial data in order to depict a regional description of known caves (locations confidential). In order to designate geologic factors affecting resource allocations and presence or absence of caves, reconnaissance mapping of bedrock and surface geology should occur. The addition of inventorying the extent of known caves is added, and finally field surveys including mapping caves and karst areas/ features, dye tracing, and air flow studies are required in order to evaluate the extent of resources and sensitivity to human disturbance. All cave-related documents should be secured to protect cave locations.

MGM According to FSM 2880, the Forest Service identifies management activities affecting caves, cave ecosystems, and karst environments and determines the effects of proposed activities on the hydrologic function and biological significance, safety, recreational opportunities, and cultural and paleontological resources of cave resources and ecosystems. The Forest Service additionally determine the need for protection of cave resources and ecosystems as critical wildlife or aquatic habitat. The Forest Service then then protect caves and cave ecosystems with the assistance of the scientific community and / or recreational caving groups in accordance with Federal law. The Forest Service protects and preserves significant caves by regulating or restricting use, as appropriate, and monitoring the condition of cave resources. Finally, the Forest Service also manages hazardous geologic conditions which includes the potential for flooding and sinkhole collapse in karst areas.

Land Management

As mentioned in FSM section 2880, the Forest Service is tasked with identifying management activities impacting caves, cave ecosystems, and groundwater dependent ecosystems such as karst ecosystems. Where active management occurs on NFS lands, standards and guidelines written in forest plans provide mitigation measures as guided by the policy described above to protect significant caves and karst resources where appropriate.

Examples exist in many national forest plans for standards and guidelines to manage the impact of timber harvest on cave resources. These examples include no-harvest buffers placed around significant caves and karst features and guidelines for building roads in karst areas. Studies on the Tongass National Forest in southeast Alaska established 30 meter (100 foot) buffers as the scientific standard for cave and karst resource protection; however the actual buffer diameter differs and on some forests in different ecosystems may be greater or less (Aley et al. 1993). If the appropriate official has designated caves found within planned mining areas to be significant, those caves are protected. However, caves not designated as significant cannot be protected as per the 1872 Mining Act once a U.S. citizen has placed a valid claim on an area where that cave is found. If caves are located during mining operation, they are documented; however the mining claimant has the right to continue operation including destruction of located caves.

Recreation is also a managed activity on NFS lands. During surveys, caves that lack sensitive resources and are deemed safe for visitation are identified as possible recreation sites. The Forest Service contains quite a few show or commercial caves including Wonderland, Blanchard Springs Caverns, Minnetonka, and El Capitan Caves. These caves are managed by cave management plans drafted to protect all cave resources found within those caves, but are often run by outside entities with Forest Service guidance. Visits to these caves for visitors with no caving experience are led by Forest Service guides or contractors. Self-guided cave and karst educational trails and boardwalks also exist on NFS lands including: Big Ice Cave on the Custer National Forest, Ape Cave Interpretive Trail on the Mt. St. Helens National Volcanic Monument, Ice Caves Trail on the Mt. Baker-Snoqualmie National Forest, Beaver Falls Karst Trail on the Tongass National Forest, and the Leon Sinks area on the Apalachicola National Forest. These include Forest Service-placed interpretive signs and structures, such as boardwalks, which educate visitors with information about cave and karst features and provide for the safety of visitors and protection of sensitive

features. Finally, permitted recreation in cave systems is open to cavers of all skill levels on the Lincoln and Tonto National Forests. Current restrictions are in place such as decontamination due to White-nose Syndrome. Caves in the Eastern, Southern, and Rocky Mountain Regions are currently closed to recreational caving with exemptions for operating commercial caves.

The Forest Service is managing the impacts of White-nose Syndrome (WNS) in the U.S. through blanket closures in the eastern and southern regions and blanket and targeted closures with exemptions for science and exploration in some of the western regions. Established national decontamination protocols are in place for cave entry regardless of the area. Detailed NEPA procedures are ongoing in Forest Service units across the U.S. including Categorical Exclusions (CEs) and Environmental Assessments (EAs) in order to further evaluate the impact of cave and mine closures due to WNS.

Future Goals and Conclusions

The Forest Service is currently working to improve agency cave and karst management through targeting several specific management goals. Minerals and Geology Management (MGM) and Recreation, Lands, and Heritage are working together at the national level to identify roles and responsibilities for each respective department. The Forest Service has renewed MOUs with stakeholders such as the National Speleological Society (NSS) and the Cave Research Foundation (CRF). Tasks such as system-wide inventory of caves and identification and designation of significant caves, development of a corporate spatial database with protections for locational information, and establishment of best practices and technical field guides are identified as crucial.

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Biography

Johanna Kovarik is currently the Cave and Karst Coordinator for Minerals and Geology Management Centralized National Operations, United States Forest Service. She has worked for the Forest Service for ten years, beginning on the Tongass National Forest in southeast Alaska. Johanna is a doctoral candidate at the University of South Florida in the School of Geology, Geography, and Environment and received her MS in 2007 from Western Kentucky University. She has active research projects ongoing in southeast Alaska and Chiapas, Mexico. Johanna is an active caver involved in cave survey and cartography in the U.S. and abroad.

CHALLENGES OF CAVE MANAGEMENT IN A DEVELOPING COUNTRY: A CASE STUDY OF GROTTE MARIE-JEANNE, DEPARTEMENTE SUD, HAITI

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Abstract

As with many developing countries, Haiti has environmental, economic and cultural challenges that complicate natural resource management. Karst landscapes dominate Haiti and caves are abundant as recent cave and karst inventory data indicate. Though the caves and karst are subject to environmental challenges they also provide the potential for the development of tourism that would improve local economic conditions. There are 500 documented caves in Haiti of which, five are show caves. Of those, only one, Grotte Marie-Jeanne, located in Port-ấ -Piment in Departement Sud, has a structured cave management plan that addresses identification of cave resources, visitor access, interpretive guidelines, cave conservation and preservation. Despite economic and political challenges, this recently implemented community-based initiative toward cave development and management is showing success in promoting sustainable ecotourism to the area and providing the basis for the study, conservation and protection of caves and karst throughout Haiti.

Introduction

The country of Haiti consists of the western third of the island of Hispaniola with the remaining landmass in the Dominican Republic (Figure 1). Haiti is reported to have 500 documented caves. Of those, five are show caves: Basin Zim and Grotte Saint-Fransique (Plateau Centrale), Grotte Marie-Jeanne and Grotte Konoubois (Departement Sud), and Grotte des Indiens aka Trois Cheminees, (Grande Anse). With the exception of Grotte Marie-Jeanne, the cave management mode of these sites is individual-entrepreneurial based consisting of varying degrees of controlled access and guided tours. This reflects the lack of financial resources, and cave management expertise that is not uncommon in developing countries.

Caves and Karst of Haiti

Approximately 70% of Haiti is composed of limestone terrain (Clammer 2013). Coastal karst and caves (littoral, flank margin and hybrid types) abound in the reef terraces that occupy the country's shorelines. The mountain chains that make up the backbone of Haiti contain spectacular cone karst with many deep sinkholes, disappearing streams, resurgence springs and of course caves (Hadden and Minson 2010).

Prior to the 1980's the limited documentation of caves in Haiti were provided in colonial era narratives and later biological (Miller 1926) and archeological (Rouse and Moore 1985) reports. Prior to the 1980's there were no known cave exploration expeditions to systematically document caves in Haiti. The first documented modern cave explorations were undertaken by two separate French expeditions in the early nineteen eighties and the late nineteen nineties respectively (Mouret 1981, Lips 1997).

In 2007, starting at Grotte Marie Jeanne (Figure 2), a Haitian-American team began documenting caves in southern Haiti and have since expanded their efforts country wide. In 2009 a French reconnaissance effort also began documenting caves in Haiti. The Haitian-American team began a survey/inventory project at Grotte Marie-Jeanne resulting in 4.7 km of survey to date, making it the longest mapped cave in Haiti. Along

Figure 1. *Map of Haiti with location of Grotte Marie-Jeanne site. Modified from www.travelinghaiti.com/*

with exploration/documentation efforts, were initiatives to sustain ably develop the cave for eco-tourism while preserving its unique ecology, geology and cultural setting. A further outcome of the Haitian-American team activities was the formation of the Haitian Speleological Survey whose goal it is to document and protect all caves and karst areas of Haiti.

Challenges of Cave protection and preservation in Haiti

The perceived value of caves in Haiti has traditionally been from the perspective of mining and quarrying as well as cultural uses - contemporary, historical and ancient. Limestone is an important building material for all aspects of human development including road construction, housing and hydrological infrastructure. Ritual cave uses range from pre-contact (archaic through Taino period) ceremonial use to historical and contemporary religious purposes. Remnant evidence of these activities is manifested in lithics, ceramics, shell materials and rock art in many of Haiti's caves. Typical human impacts that affect caves everywhere are also apparent in Haiti, including agricultural land use, groundwater pollution and vandalism.

With the exception of Grotte Marie-Jeanne, the cave management strategies for Haiti's other show caves is individual-entrepreneurial based consisting of controlled access and guided tours. There are no comprehensive management plans, maps, or resource inventories, to document important features of the caves or to promote future research. There is a lack of guidelines for conducting interpretive tours and no consideration is given to cave conservation or preservation. In Haiti, the absence of structured cave management reflects the lack of financial resources and expertise necessary

Figure 2. *Main entrance of Grotte Marie-Jeanne.*

to generate and institute cave management plans, and the overlapping interests of multiple government ministries who share different aspects of cave resource management. At Grotte Marie-Jeanne, a community-based initiative (unique in Haiti) is proving successful in demonstrating sustainable cave management and in bringing the potential economic benefits of ecotourism to the Departement Sud.

Ecotourism Development of Grotte Marie-Jeanne

The management and ultimate development of Grotte Marie-Jeanne differs from the management styles in Haiti's other show caves. The local development initiative was conceived by community leaders from Port-ấ-Piment, a small town located in the South Department of the country of Haiti. Though the group initially lacked expertise specific to cave resource management, in 2007 they developed a Haitian-American partnership to document the cave, inventory natural resources and propose a management and development plan (Kambesis et al. 2010). The ongoing effort has supported an evolving community-based ecotourism management plan that effectively integrates resource preservation with long term, sustainable regional ecotourism centered around the unique setting of Grotte Marie-Jeanne. The management plan has led to a UNEP-local government financed initiative of $150,000 to improve visitor access to the Grotte Marie-Jeanne.

Grotte Marie-Jeanne is expected to be a key attraction in a regional plan that will see the development of other at-risk biospheres such as the tropical mountain forest of Pic Macaya and the coastal coral reefs and mangrove swamps on the southwest coast. Forty percent of Haiti's flora and fauna are endemic (including several species in

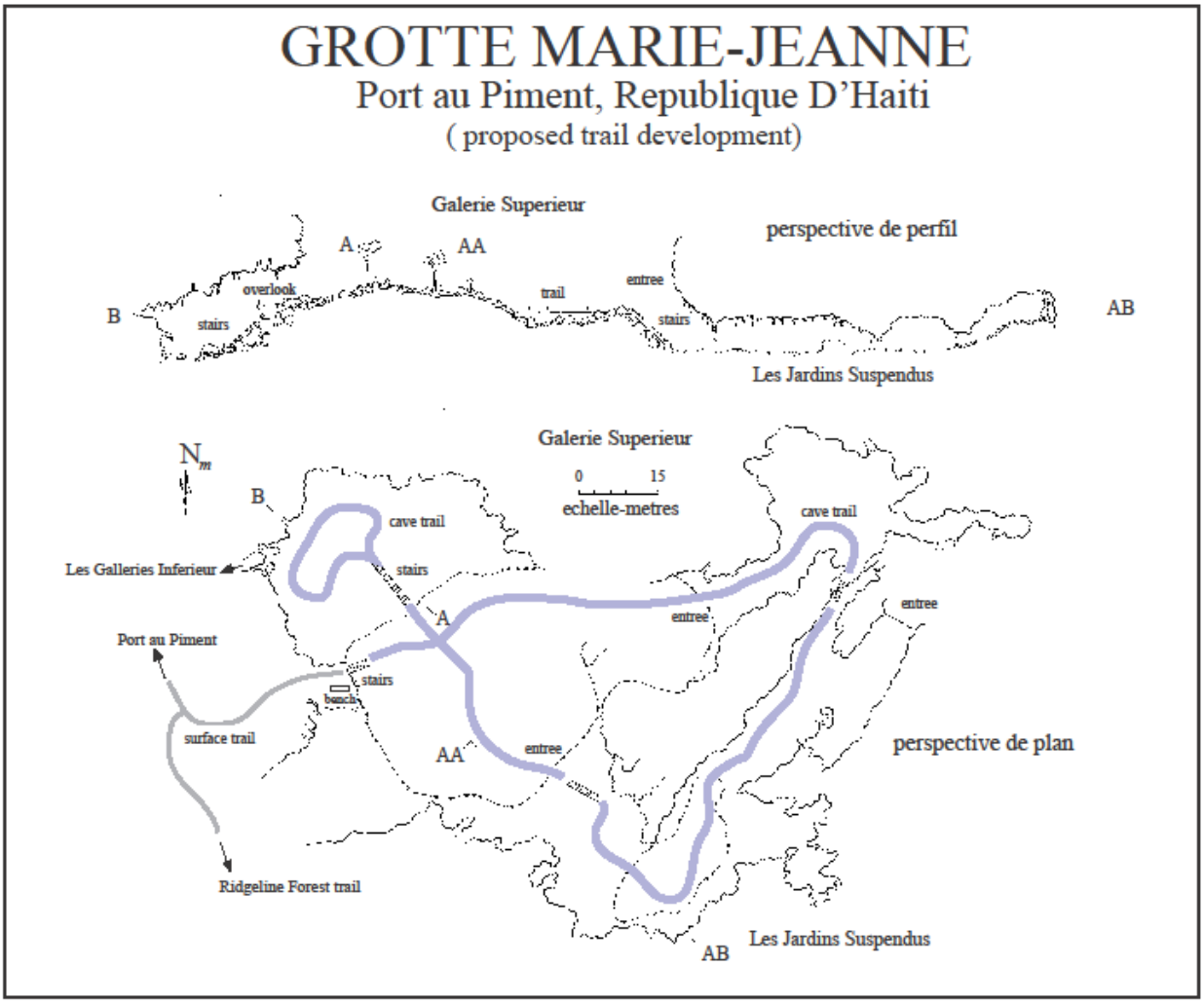

Figure 3. *Map of proposed trail for Grotte Marie-Jeanne.*

the cave itself) and will provide additional incentives for research and development.

The Grotte Marie-Jeanne development plan includes improved access to the site, trail construction within the cave (Figure 3), marketing and interpretation resources in conjunction with direct involvement of a broad cross section of community members throughout the process.

Establishing an effective natural resource management program can be a challenge within a minimally-developed tourism industry. As with most developing countries there are challenges associated with the management of natural resources which can often be considered solely as generators of revenue. Guide training and retention can be an issue, as is long term, adaptive maintenance of the overall management plan.

In contrast to the private-entrepreneurial approaches currently employed at Haiti's other show caves, the community-based ecotourism strategy applied to Grotte Marie-Jeanne offers a unique opportunity to not only support the infrastructure and preservation of the cave ecosystem and invest in the economic growth of the community of Port-a-Piment but also serve as a pivotal component in the areas broader economic development.

Haiti presently has an extremely dynamic Minister of Tourism undertaking a number of initiatives to promote the sector. As there is little tourism infrastructure in the country and few sites have been developed, and considering the wealth of natural and cultural resources still to be found, it is generally believed that eco-tourism should be encouraged and will serve Haiti well in the future.

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INCORPORATING CAVE AND KARST MANAGEMENT INTO THE FOREST PLAN REVISION PROCESS OF ARIZONA FORESTS

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Abstract

Arizona National Forest land managers have a multitude of tasks and priorities; historically, caves and karst management has not been amongst the priorities receiving any significant allocation of resources. When caves and karst management is not included in the Forest Plan, even when large and significant cave and karst areas exist, active cave and karst management often falls below the waterline of available manpower and resources. Additionally, there is entropy associated with normal changes in personnel assignments and new staff coming onboard. When combined with a general lack of written policies and guidelines, these personnel transitions lead to unnecessary degradation of the karst and caves. Three areas impacted by lack of caves and karst policy include timber management (sales and thinning), water recharge protection (buffer zones), and cave management (under the recreation department).

This paper is intended for Forest managers whose units contain significant karst and caves, but have no allocated staff in these areas. The paper presents clear and acceptable guidelines and policies that can be implemented in a uniform manner. Integral to these guidelines is the inclusion of Karst and Cave Areas as a separate land use designation in the Forest Plan. With karst listed as a land use designation in the Forest Plan, references to a separate Cave and Karst Management Plan document can be made. Additionally, the Cave and Karst Management Plan can be updated without having to go through the extremely long Forest Plan amendment process.

The Arizona National Forest Cave and Karst Management Plan has been created to address this need. It is located at http://centralarizonagrotto.webstarts.com/index.html and provides clear management tools for the Forest cave resources.

Introduction

Arizona has six National Forests, and all six of those forests are revising their Forest Plans from their prior 1980s era releases (refer to Table 1 for details). These revised plans are in various stages of the writing, review (both internal and public), and acceptance processes. All six Forests have significant caves, and at least four of the Forests have large, significant, and active karst. None of these six Forests have staff dedicated to karst or caves and the management and issuance of cave gate keys is primarily handled by cavers. **Of the three Arizona Forests that have published new Forest Plan drafts in 2012 and 2013 for public review, a total of one page has been dedicated to cave and karst management.** This appears in large part to be due to:

1. Lack of cave and karst management awareness
2. Lack of public/caver/academic input before and/or during the drafting of the new Forest Plans.
3. Lack of clear karst management procedures that allow implementation of other stakeholder goals (e.g. timber harvesting) while addressing the resource mitigation needs. Table 1 lists the status of the existing Arizona forest plans - May 2013.

Arizona Forest Karst

To date, cave and karst management has received very little priority in Arizona forests. Some examples of the recent status of cave management from several of Arizona's Forests may clarify the issue. The Kaibab National Forest Plan draft of April 2012 includes the words "karst" 8 times, and "cave" 27 times. As indicated in Figure 1, below, the Northern unit of the Kaibab National Forest is dominated by a massive karst plain, which is likely to be the recharge zone for the many springs in Grand Canyon National Park – including the spring that feeds their tourist facilities. Most of the references in the Kaibab National Forest plan are

Table 1. *Arizona Forest Plan Statuses – May 2013.*

Table 1 – Arizona Forest Plan Statuses

National Forest	Year of Signed Forest Plan	Forest Plan being updated?	Forest has Significant Caves/Karst?		Caves/Karst in Current Forest Plan?	Caves/Karst in New Forest Plan? *		Where in Planning Process?
			Caves	Karst		Caves	Karst	
Apache-Sitgreaves	1996	Yes	Yes	Yes	No	Yes?	Yes?	90 day comment complete 5/2012
Coconino	1987	Yes	Yes	Yes	No	Yes?	Yes?	Writing
Coronado	1986	Yes	Yes	No	No	Yes?	Yes?	Prep for 90 day comment
Kaibab	1985?	Yes	Yes	Yes	No	1 page		90 day comment complete 4/2012 - near final draft
Prescott	1986	Yes	Yes	No	No	No	No	90 day comment complete 11/2012
Tonto	1985	Yes	Yes	Yes	No	Yes?	Yes?	Writing

* As of 5/31/2013

oriented around White Nose Syndrome mitigation strategies. All of the instances of "cave" and "karst" are contained within the:

- Table of Contents.
- One page of text in the document.
- The FCRPA summary listed in the Authority section.

Figure 1 highlights several of the North Kaibab National Forest karst features. These may include the primary recharge areas for Grand Canyon National Park's tourist facilities (both North and South rim).

The Prescott National Forest Plan draft of August 2012 has no references to caves or karst. While it appears that Prescott National Forest does not have large karst, it does have large, significant caves that serve as the primary water sources for nearby communities.

The Apache-Sitgreaves National Forest Plan draft of January 2013 has no reference to "karst", although caves are named and included when addressing aspects of resource management. Caves are included in lists for management when addressing habitats, archeological, biological and geological features. Figure 2 lists several of the Apache-Sitgreaves National Forest's larger karst features. There are many more which are not large enough to be referenced individually on maps at this scale.

Addressing the Forest Cave and Karst Management Issues and Needs

Arizona Forests do not currently have staff whose primary job descriptions include cave and karst management.

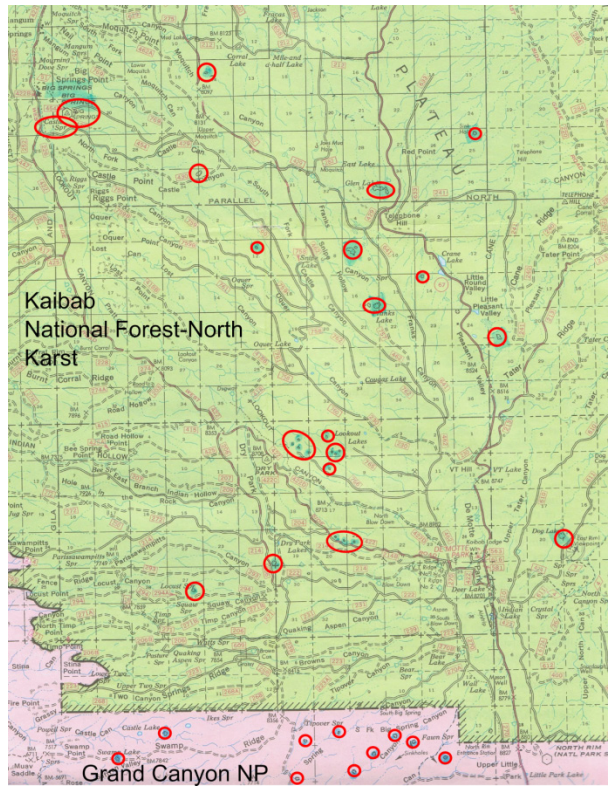

Figure 1. *North Kaibab Karst Larger Features*
Large karst features circled. Grid lines are section boundaries.

These forests rely on their specialists in timber sales, grazing, biologic, geologic, and archeological, disciplines to understand and prescribe appropriate procedures when their individual disciplines intersect cave and karst management tasks. Considering that staff turnover happens from time to time, new personnel can benefit from documents that are written in such a way as to be used at multiple levels. Ideally, one reference document could be used for training, research proposal policies, file management (public and controlled), and public involvement and participation.

Given the various issues and needs illustrated above, the primary needs for improving cave and karst management on National Forests lands are:

1. Listing karst and caves as a separate land use designation, with corresponding goals and objectives clearly defined in the Forest Plan.
2. Providing clear policies and guidelines that address timber harvesting methods, non-sealed road construction, and other surface management on karst.

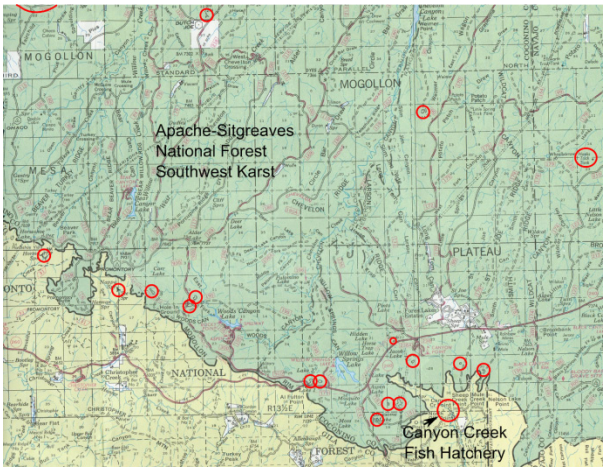

Figure 2. *Southwest Apache-Sitgreaves Larger Karst Features Large karst features circled. Grid lines are section boundaries.*

3. Providing a clear, Forest-level cave management plan that describes the "how to" of cave management.

Note that item 1) above is needed at the Forest Plan level, while items 2) and 3) are more appropriately included in a cave and karst management document.

To address these needs, the Arizona Cave and Karst Management Plan (Keeler and Bohman, 2013) draws from and highlights relevant portions of federal laws and statutes including the United States Code(USC), the Code of Federal Regulations (CFR), and Forest Service Manuals (FSM) (US Forest Service, 2009). In addition to these regulatory requirements, the Arizona Cave and Karst Management Plan has drawn upon the following sources for guidance:

- Tonto National Forest (AZ) Cave Management Plan (unsigned draft) (Dixon, 1991; US Forest Service, 1992).
- Coconino National Forest (AZ) Cave Management Plan (unsigned draft) (Bodenhamer, 1990).
- Sierra Vista Ranger District (Coronado National Forest, AZ) Cave Management Plan (draft) (US Forest Service, 1990).
- Lincoln National Forest (NM) Cave Management Plan (US Forest Service, 1995)
- Tongass National Forest (AK) Land and Resource Management (US Forest Service, 2008)
- Karst Inventory Standards and Vulnerability Assessment Procedures for British Columbia (British Columbia Ministry of Forests, 2003)
- Karst Management Handbook Training, Ministry Forests and Range, British Columbia (CAN) (British Columbia Ministry of Forests, 2003)
- Strategy for Cave Management XYZ National Forest (Gifford Pinchot NF) (1994) - USFS Region 6 (Nieland, 1994).

The Tonto National Forest, Coconino National Forest and Sierra Vista Ranger District documents made it to the draft level, but were not signed as amendments to their respective Forest Plans. These documents remained as informal guidelines for management.

Three Possible Forest Management Plan Improvements

Create the Karst and Caves Land Use Designation in the Forest Plan

For Forests that have significant karst and caves, it is needed for Caves and Karst Areas to be included as a specific land use designation in the Forest Plan. If this is achieved, Goals and Objectives can be included in the Forest Plan. Both Surface and cave management approaches for each of the areas of concern (FCRPA related) can reference a Cave and Karst Management Document.

The creation and inclusion of this new land use designation is an attempt to institutionalize an increased awareness of cave and karst resources in each forest. The current methods for transferring knowledge, relying heavily upon word of mouth, are inefficient, and do not adequately protect the resource. One example of this breakdown in communication and knowledge transfer happened recently on the Tonto National Forest. As part of a region-wide initiative to improve forest health through targeted thinning projects, one project in particular was proposed that happens to encompass most of the watershed for the largest single karst system in Central Arizona. While an Environmental Assessment (EA) was dutifully performed, there was only a minor mention of sinkholes, and no mention of the significant cave and karst region that is included in the area. This initial omission was further exacerbated by the lack of open two-way communications between the caving community and the USFS personnel at the district level. Fortunately, the District Ranger and members of the caving community have since been able to hold productive meetings on the ground to revise the specific guidelines of that timber sale and thinning activity.

Unfortunately, these sorts of examples are all too common. As a first step to prevent future occurrences, the creation of a separate land use designation for karst and caves will improve the visibility of these resources at the highest levels of Forest management. Once the management needs of caves and karst have visibility, personnel can be assigned to manage those needs as part of their regular responsibilities. Then when personnel are regularly assigned to manage these resources, the likelihood of unintentional oversights such as the examples listed above will be greatly diminished.

Provide Clear Karst Management Policies and Guidelines

After reviewing karst management papers and receiving comments from NCKRI and a Forest hydrologist, it became apparent that clear Forest management policies for karst needed to be specifically described to improve the odds of their implementation. These policies and guidelines needed to complement existing forest management documents and processes, so a separate Karst Management Appendix was added to the Arizona National Forest Cave and Karst Management Plan. Within that karst management appendix, the various sub-categories include:

- Field assessments
- Ground disturbance mitigation
- Buffer zones
- Providing clear policies and guidelines

Karst buffer guidelines have been established with a focus on timber harvesting, and have been reduced to three numbers that allow for adjustments when caves extend outside the surface buffer zones.

- 300 foot reduced ground disturbance buffers around karst features
- 100 foot wide reduced ground disturbance corridors upstream to karst features
- 1000 feet long reduced ground disturbance corridors upstream to karst features
- Buffer adjustment when a cave extends outside the surface buffer zones

The size and significance of the karst feature may affect the guideline distances above.

Figure 3 shows the karst buffer guideline distances. Figure 4 shows the cave extension buffer outside the surface karst buffer. Figure 5 shows a surface management rule of thumb (The 45 Degree Guideline) to be used over significant cave passages. The 45 Degree Guideline becomes especially relevant when the cave is deep below the surface. It is also helpful when the cave continues for a substantial distance beyond the entrance buffer zone.

Provide a forest level cave management plan

Provide a forest level cave management plan that describes **the "how to" of cave management.**

National Forests are staffed by competent personnel that come from many disciplines, but cave management is not likely to be in the majority of the backgrounds of those personnel. What has become obvious is the need

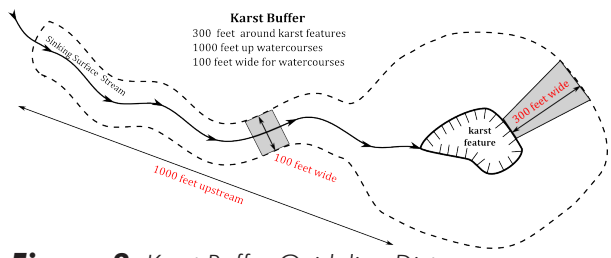

Figure 3. *Karst Buffer Guideline Distances.*

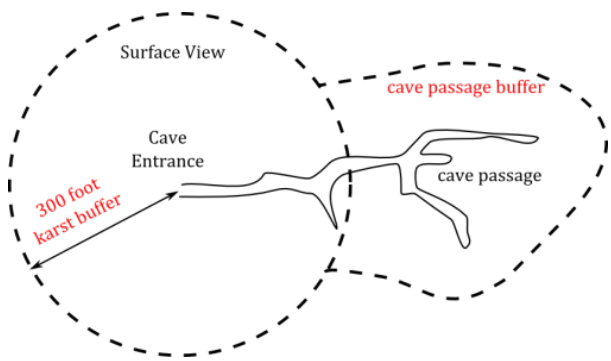

Figure 4. *Cave Extension Buffer.*

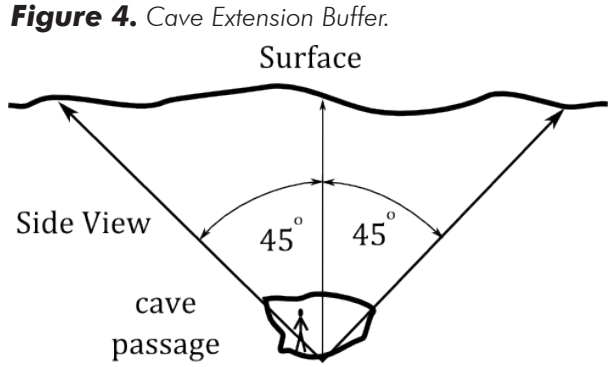

Figure 5. *45 Degree Guideline.*

for a document that Forest Service personnel can use as a "how to" for cave management. The document needs to cover guidelines and policies that the recreation officers and their field technicians can implement, use as a training guide, and use as a reference when approached by researchers and volunteers.

The 45 page Arizona National Forest Caves and Karst Management Plan (Keeler and Bohman, 2013) is an attempt to cover these needs and is located at http://centralarizonagrotto.webstarts.com/index.html The document contains the following:

- Relevant laws and regulations including the Federal Cave Resources Protection Act (FCRPA).
- Cave Management Objectives, Policies, and strategies. In most cases, the "strategy" is taken verbatim from the relevant CFR.
- Karst management goals and objectives. The karst management appendix serves as a standalone document for surface implementation.
- Public Involvement – MOUs in place at the national level between USFS and the NSS.
- Cave Evaluation and rating criteria – allows standardized ratings for data comparison.
- Cave Classification – is based on the evaluation and rating criteria. The Cave Opportunity Spectrum (COS) provides the associated management guidelines.
- Caving ethics – practical training for both Forest personnel and the general public.
- Research proposal guidelines.
- Cave exploration limitation guidelines – cultural, digging, biological, airflow management.
- Inventory procedures.
- Monitoring categories – research and volunteer opportunities.
- Permits and user limits.
- File Management – Content of public files and access protected files.

Areas of Discussion

Most discussions about cave management end up focusing on these three topics at some point. Given the frequency of their discussion, it is no surprise that these topics are subject to a wide spectrum of opinions.

- For timber harvesting, what are the appropriate buffer sizes to allow harvesting while using disturbance reducing methods? The size and significance of karst features vary greatly. The buffer distances presented represent a strategic guideline. Tactical buffer implementations will vary. The important thing is the buffers are comparable to the other Forest Streamside Management Zones (SMZs).
- Digging to discover caves (entrance digs) and continued passage exploration (in cave digs) are concerns. Forest managers want to maintain control of the resource. They have responsibility for conserving the significant categories.

There is one "shall" in the cave management document: if any cultural artifacts are discovered, NEPA processes will be followed before the dig continues. Also, if a significant cave is discovered, any airflow restrictions should be patterned towards the original dimensions.

The forest service has limited resources for going out to check digs if they have been notified. Dig policies need to allow room for cavers and explorers to discover the resource, while including clear restrictions where needed.

Cleaning equipment and clothing protocols to reduce possible spreading of microbial material from being transported from one caving region to another caving region. Current science shows that sustained washing of clothes and equipment in very hot water (50 degrees C for 15 minutes) greatly reduces the possibility of transporting harmful microbes.

Conclusions

- When caves and karst are present on the forest, they need to be included as a separate land use designation in the Forest Plan.
- Cave and karst management issues are not currently given management priority on most Arizona forests.
- Karst management policies need to be clear and direct. They provide strategic direction for Forest planning activities.
- Karst management guidelines need to be implementable. The guidelines provide tactical direction for day-to-day activities. For example, buffer distances around karst features can vary based on significance, size and terrain.
- Land managers need a document that covers the many aspects of cave management. The document needs to be available when opportunities arise.

- Bats are the poster child for caves.
- Caves are a poster child for karst.
- Use the poster children to come out of the darkness.

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PHOTOGRAPHIC AND SEDIMENT MONITORING PROCEDURES AND INITIAL RESULTS FOR A BRAZILIAN IRON ORE CAVE

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Abstract

The definition, development and application of monitoring procedures for caves are currently in demand in Brazil. The need for environmental licensing processes and effective environmental control actions has been increasing since the beginning of this century due to the intensification of economic activities.

This work discusses the development of a method of photographic and sediment monitoring and the application of this method in an iron ore cave. This cave is located inside an industrial area currently under development by a mining company. This situation demands effective and specific environmental control measures.

The method's simplicity, effectiveness and multidisciplinary approach indicate that it has potential for use in future works to define management decisions and protection measures for iron formation caves and other examples of karst heritage.

Introduction

Since the Federal Constitution Laws Revision in 1988, Brazil has experienced a substantial increase in the studies related to environmental licensing. The New Federal Constitution includes a new approach to the environmental issues and affects all the major development initiatives in mining, energy generation, transport infrastructure, and urbanization. This increase was especially notable from the beginning of the 21st century, when studies to protect and control effects on caves became more common. This broad and diverse field of studies includes cave prospecting, accurate and detailed cave mapping, geospeleological and biospeleological studies and multidisciplinary monitoring and management actions.

In response to this new demand, the objective of this work is to develop, test and implement adequate methods to monitor environmental alterations in caves through the use of photographic and sediment monitoring techniques. Photographic monitoring is a broad-spectrum technique that is able to show alterations in different cave attributes such as speleothems, rock surfaces and structural features, among others. Sediment monitoring can be a sensitive environmental indicator, providing numeric data and allowing the quantitative analysis of the alterations.

Cave location and geologic and environmental context

The CAI-03 cave is located in the eastern escarpment of the southern part of the *Espinhaço* Ridge (Figure 1), a collisional orogeny in southeast Brazil that was formed in the Mesoproterozoic Era. This ridge is composed mainly of quartzite, followed by phyllite, conglomerate and varied volcanic rocks (Carste, 2012). The *Espinhaço* Ridge, a UNESCO biosphere reserve, acts as a hydrographic boundary between three important river basins. The eastern escarpment is characterized by forest vegetation and a humid tropical climate that differs from that on the western side.

Iron formations with economic interest occur discontinuously in this complex geologic context and are

enclosed by quartzite, conglomerates and phyllite rocks. The CAI-03 is part of a local ridge named *Serra do Sapo*, a more resistant prominence sustained by banded iron formation rocks (Carste, 2012).

The east part of the *Espinhaço* Ridge was a site of gold exploration in the 18th century. This activity resulted in the development of cities that caused different grades of environmental alteration. Currently, the area is in the initial economic exploration process, focusing on iron ore extraction, and this process is led by different mining companies. In this age of new exploration, the caves remain an important heritage site to be studied and protected.

The CAI-03 cave is located within a mining company area that is in the initial process of implementation. It is positioned on the lower part of a slope characterized by the presence of sparse escarpments surrounded by tropical forest. The cave is located in a preliminary protected area with restricted access that is to be converted into a private protected area owned by the mining company. Some measures have been taken to control to the effects on the cave, such as the installation of a protection fence, identification and warning signs, security procedures and a monitoring program.

Cave morphology and monitoring conditions

The CAI-03 cave is 74 meters long and 2.5 meters deep and has an area of 396 m^2 and a volume of approximately 485 m^3. Despite its small volume in comparison with caves in carbonate rocks, CAI-03 is classified as a high relevance iron formation cave in Brazil. From the entrance room (Figure 2), after a restriction, the cave extends as two parallel passages heading south and southwest. In some chambers, one can observe contact between the banded iron formation and lateritic crust, which is prominent in the entrance room ceiling and walls (Figure 3). The cave floor is defined by an accumulation of lateritic crust and centimeter-long clasts in the entrance room and by sandy sediments forming a smooth ascending slope in the passages. In the rainy season, the cave floor in the inner deeper passages becomes filled with small ponds, and this water reappears in a small spring at the northeast of the entrance room. As iron formation caves are very shallow, this water is linked with sub-superficial flow and does not reflect the rising of the water table.

The cave presents some challenges to photographic monitoring due to the small size of some chambers and the strong interference with compasses caused

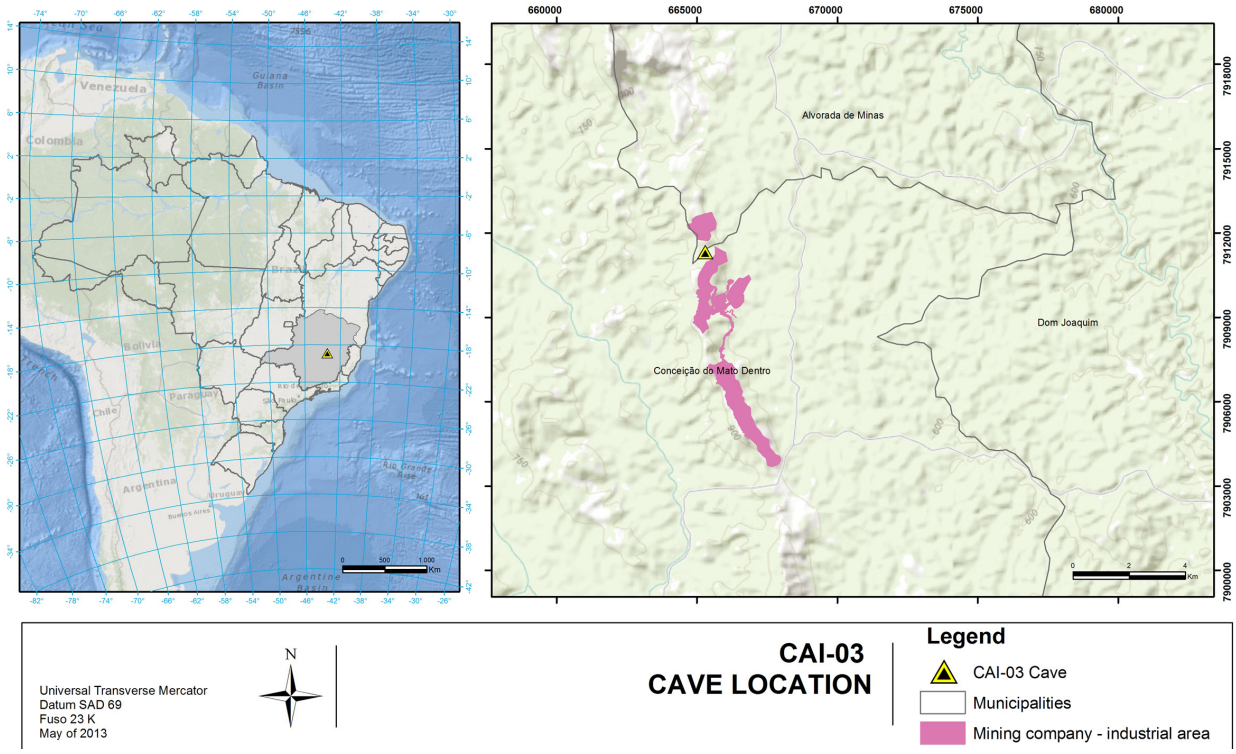

Figure 1. *Location of the CAI-03 cave.*

Figure 2. *View of the entrance.*

Figure 3. *View of a passage, showing the ceiling formed by lateritic crust and the flat sandy floor.*

by the magnetite present in the iron rock formations. Sediment monitoring is facilitated by the nearly flat cave floor.

Methods

Photographic monitoring

Photographic monitoring is a fundamental tool for monitoring environmental alterations in caves. With this systematic record, alterations in physical, biotic and cultural features can be identified and analyzed. The concept of photographic monitoring must be based on the construction of a dynamic image databank. The images must be taken from fixed stations, enabling accurate repetition over a long time period (Hildreth-Werker, 2006).

Some monitoring efforts have achieved effective results with respect to the identification and analysis of natural processes and the effects of visitation on caves. One of these efforts applied mapping based on the use of GIS software, such as ArcGIS® and Compass® (Hale, 2008). Another work used detailed sketches of fixed stations to record the conditions of image capture (Furhmann, 2007). Both methods are adequate for large volume caves where small variations in image framing are not critical. In the morphological context of the CAI-03 cave, which has small chambers and passages, it is critical to ensure an accurate repetition of images. Due to the small distance between the camera and the surfaces, it is important to avoid variations in image framing and camera location.

Marking of the fixed stations

One of the main challenges in photographic monitoring work is establishing adequate, durable and low-impact fixed stations in the field that permit the accurate reproduction of the images. In CAI-03, monitoring was performed with the aid of homemade flags constructed of stainless steel and yellow plastic tape (Figure 4). Werker (2006) classifies stainless steel as a safe and adequate material for use in cave environments and in direct contact with sediments. The plastic tape is less durable but has a lifespan compatible with the duration of the monitoring work.

Angular registration method

A commonly used method to record the angles of photographs in caves is to measure the azimuth with a compass and inclinations with a clinometer. However, in iron ore caves, it is necessary to avoid compass measurements due the magnetic interference. This interference has a random behavior, and variations of more than 20 degrees are common. To avoid this problem, we have developed a method based on the measurement of horizontal and vertical angles using a modified tripod and a pair of flags defining a fixed segment or vector.

Figure 4. *Flag used as fixed station marker.*

In this method, the tripod is positioned and leveled right above the station flag, and the image frame center is pointed to the target flag (Figure 5). The horizontal angle is recorded assuming that the line between the two flags has a 0-degree relative bearing, obviating the need for the use of a compass. The vertical angle is measured directly with the proper graduated disk for each image taken from the fixed station, obviating the need for clinometer measurements (Figure 6).

Image capture, processing and recording

In addition to the CAI-03 cave, another 33 caves were first monitored in December 2010. At the time, a Nikon® D-200 digital camera with a Nikkor®AF 18-70 mm f/3.5-4.5 ED-IF AF-S DX lens and a Nikon® SB-800 dedicated TTL speedlight were used. A second monitoring visit was performed only in CAI-03 in October 2012. At this time, one super wide-angle Tamrom® 10-24 mm f/3.5-4.5 DI-II LD Aspherical (IF) AF lens was added to the prior equipment. This lens allowed an increase in image capture efficiency because of the wider field of vision, especially considering the small distances between the camera and the surfaces being monitored.

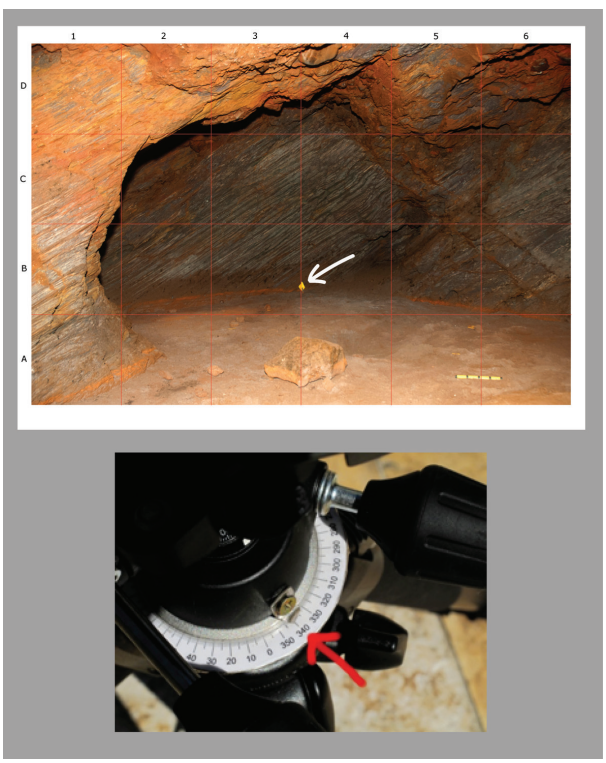

Figure 5. *Top, image showing one target flag (white arrow). Bottom, close-up view of the modified tripod base with a graduated disk with a 0- to 360-degree range (red arrow).*

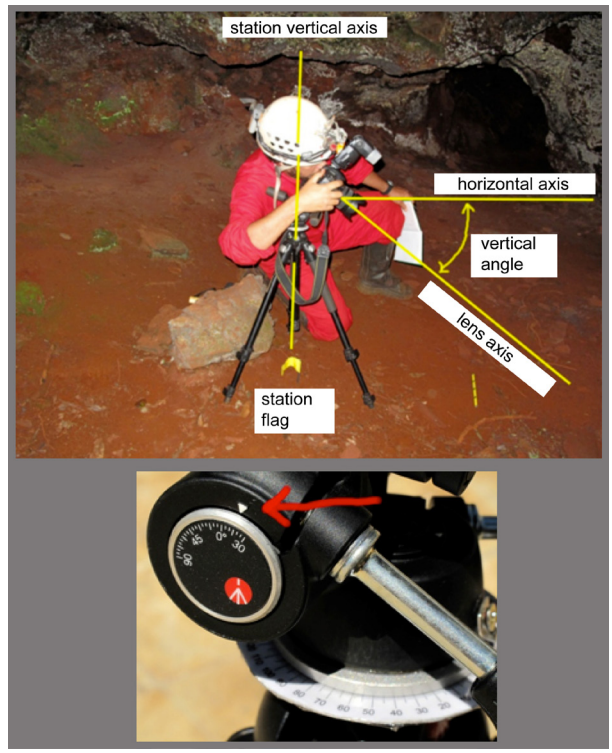

Figure 6. *Top, field image illustrating the measurement of the vertical angle . Bottom, close-up view of the graduated disk for vertical angle measurement on the tripod (red arrow).*

The digital images were captured as RAW (Digital Negative) files, assuring better quality and support for future image processing. For capture, the SLR camera and a hot shoe mounted TTL dedicated flash were used, and both were set in auto mode to facilitate the reproduction of the images. During shooting, a 20 cm yellow scale was used, which was easily viewed against the sediment or rock surfaces.

All images were converted to JPEG format, and a frame of 24 quadrants and a bottom identification tag were added to ease the accurate description of the image characteristics and future alterations in the environment (Figure 7). The images were organized in a databank permitting easy access and addition, which was standardized by the use of the same frame and tags.

The representation on the cave map is useful to understand how the cave surfaces were recorded and to promote quick access to a specific image. Using the cave map,

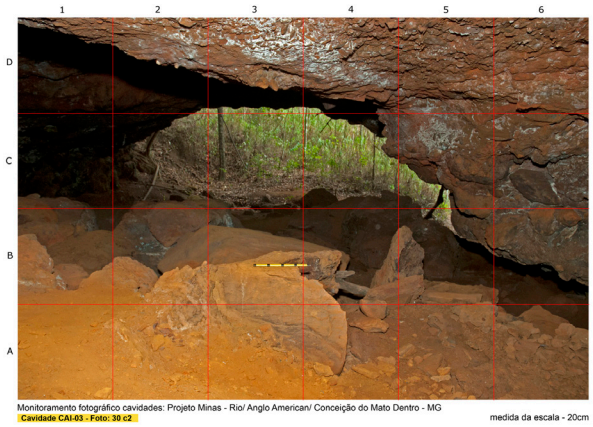

Figure 7. Image processed with the addition of the 24-quadrant frame and the bottom identification tag.

each photographic monitoring station and target flag were located and represented with a specific number (Figure 8).

A red line represents each image's horizontal angle, indicating the features covered by the image. This cartographic representation ensures a multidisciplinary approach that enables the accurate reproduction of the images.

Sediment monitoring

Monitoring sediment deposits in caves is a useful tool to understand and control environmental changes over time. In theory, this process will record local variations in the sediment banks inside the cave through quantitative analysis of both depositional and erosional areas.

For this monitoring, stainless steel erosion pins were used in accordance with the methodology described

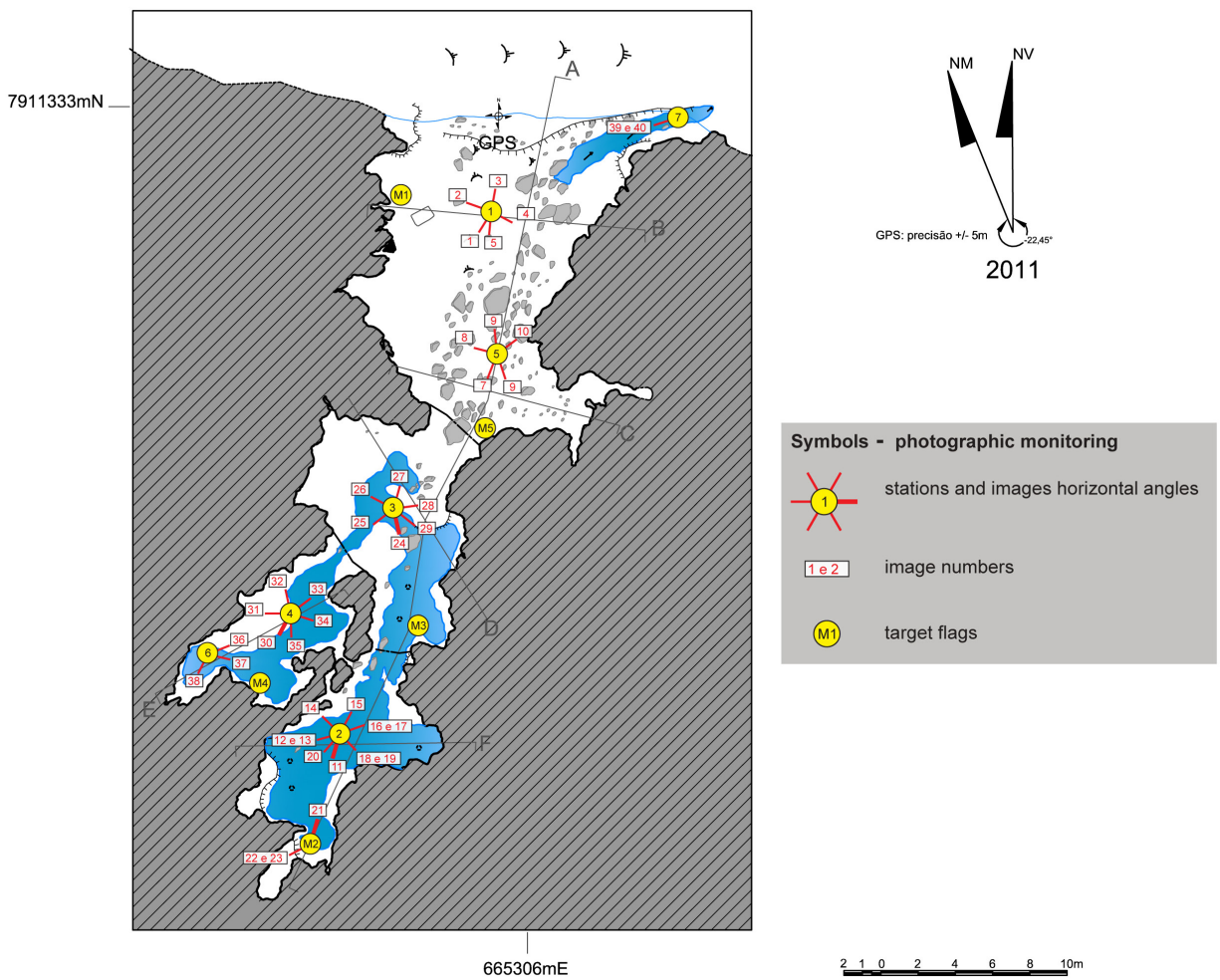

Figure 8. *CAI-03 cave map showing the fixed stations, target flags, horizontal angles and reference numbers of the images.*

in Hudson (1993) and adapted from Cole (1985) and Moura (2011). These pins were also identified with a yellow plastic flag, as for the photographic station flags. After installation, the height of each pin was measured in millimeters with a laser meter. Three measurements were taken for each pin to ensure the correct registration of the height relative to the surface of the sediment (Figure 9). In the office, the arithmetic average of the measurements for each pin was calculated.

The 15 erosion pins were installed in the cave during October 2012, at the beginning of the rainy season. A total of 6 pins were installed in accumulation areas or ponds, and 9 were installed in water input areas. The goal was to detect aggradation with the accumulation area pins and sediment loss with the water input area pins. In the case of a major sediment modification in the cave, this erosion pin network will be able to record the alterations both qualitatively and quantitatively.

Figure 9. *Erosion pin being measured with a laser meter.*

Results and discussion

Photographic monitoring: initial results

After nearly two years, some alteration in the cave's sandy sediments is visible in the images. A comparison of images for the southern passage of the cave (Figure 10) shows that the area initially had many drip marks on the floor (image bottom). Due to the trampling in this area, the image from 2012 shows the loss of these drip marks and reveals a new dark spot.

During the photographic monitoring interval, the cave was also the subject of a monthly geospeleological monitoring process. This intense activity and other visitation events resulted in the trampling because the cave had no marked trail to control caver's routes.

Another image taken from the final part of the southwest passage reveals the loss of a drip concentration area over the same interval. This spot is indicated in the December

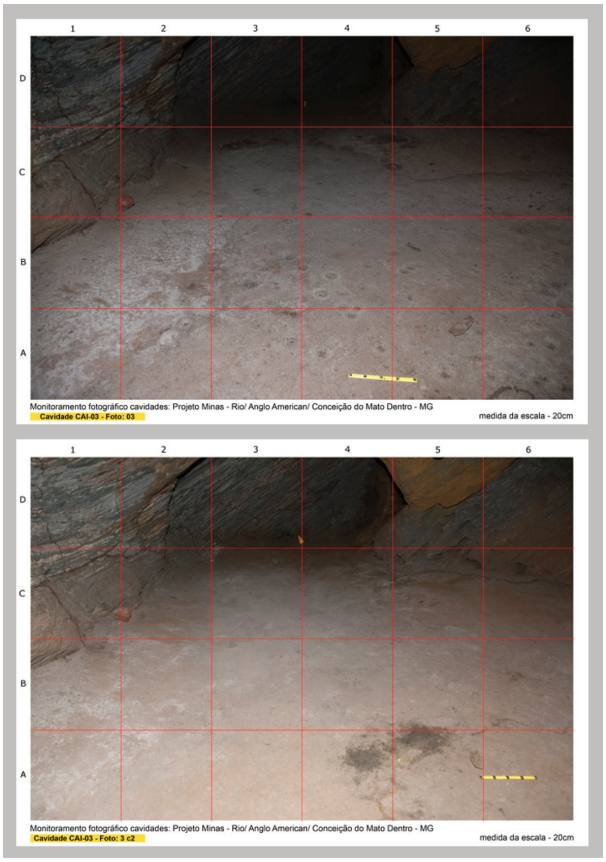

Figure 10. *Top: photographic monitoring image of the southern passage of the CAI-03 cave from December 2010. Bottom: image from October 2012.*

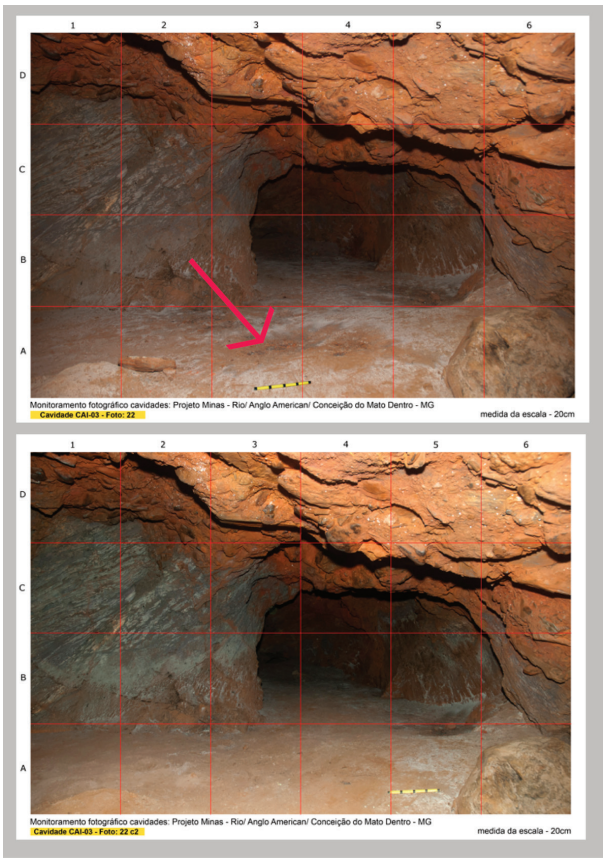

Figure 11. *Top: photographic monitoring image of the southwest passage from December 2010. Bottom: image from October 2012.*

2010 image with a red arrow (Figure 11). Radial spreading of sandy sediments by drips is responsible for this feature. The 2012 image shows disturbed sediment in this area, and it is impossible to identify the original drip concentration.

The initial photographic monitoring results for CAI-03 also reveal the potential to record changes in clast arrangement on the cave floor.

A clast not previously recorded is visible in the image taken from the southeast part of the entrance room (visible in the 2012 image – red arrow - Figure 12). This alteration was most likely caused by anthropic activity during the biospeleological monitoring or other visitation activity. In iron formation caves, it is relatively common for a clast to fall from the cave's ceiling; these clasts are usually formed of lateritic crust. However, in this case, the fall has to be confirmed by appearance of a scar in the roof caused by the clast detachment. As there is no roof scar visible in the 2012 image, anthropic activity remains the most probable cause for the alteration. In the 2010 image, a round and dark clast in the A6 quadrant is visible. In the 2012 image, this clast seems to be turned upside down and moved to the A4 quadrant (red arrow).

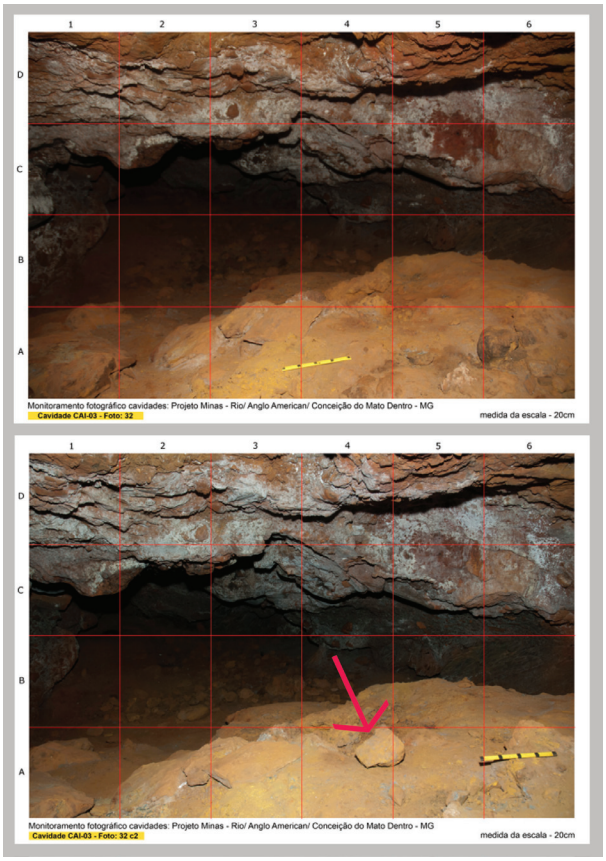

Figure 12. *Top: photographic monitoring image of the southeast part of the entrance room from December 2010. Bottom; image from October 2012.*

Table 1. *Heights of the CAI-03 cave erosion pins in October 2012 and April 2013.*

EROSION PINS	AVERAGE HEIGHT (mm) OCTOBER, 2012	AVERAGE HEIGHT (mm) APRIL, 2013	VARIATION (mm)
1A	293.0	293.2	-0.2
1B	284.7	285.3	-0.6
1C	402.0	406.3	-4.3
1D	386.0	427.3	-41.3
1E	301.7	303.0	-1.3
2A	282.0	289.3	-7.3
2B	339.3	342.3	-3.0
2C	278.3	277.7	0.6
2D	289.7	290.0	-0.3
2E	273.0	277.0	-4.0
3A	283.3	285.3	-2.0
3B	320.0	317.7	2.3
3C	304.3	305.0	-0.7
3D	263.7	267.0	-3.3
3E	274.7	277.0	-2.3

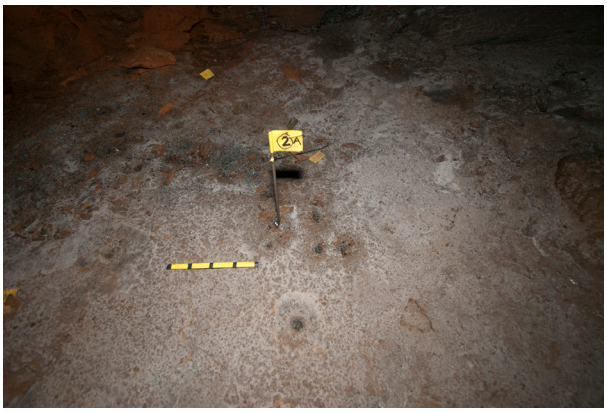

Figure 13. *View of the area around the number 2A erosion pin with a concentration of new drip marks, one of which was at the erosion pin's base and caused sediment loss.*

Sediment monitoring: initial results

After five months, the heights of the 15 erosion pins were measured again at the end of rainy season.

From the total, only two pins indicate aggradation, and the other 13 record sediment loss (Table 1).

Variations in height were considered insignificant below 2 millimeters (yellow), low between 2 and 5 millimeters (orange) and high above 5 millimeters (red). Negative variation values indicate sediment loss, and positive values indicate aggradation.

The number 1D erosion pin indicates a strong sediment loss of 41.3 millimeters over the 5-month interval. The

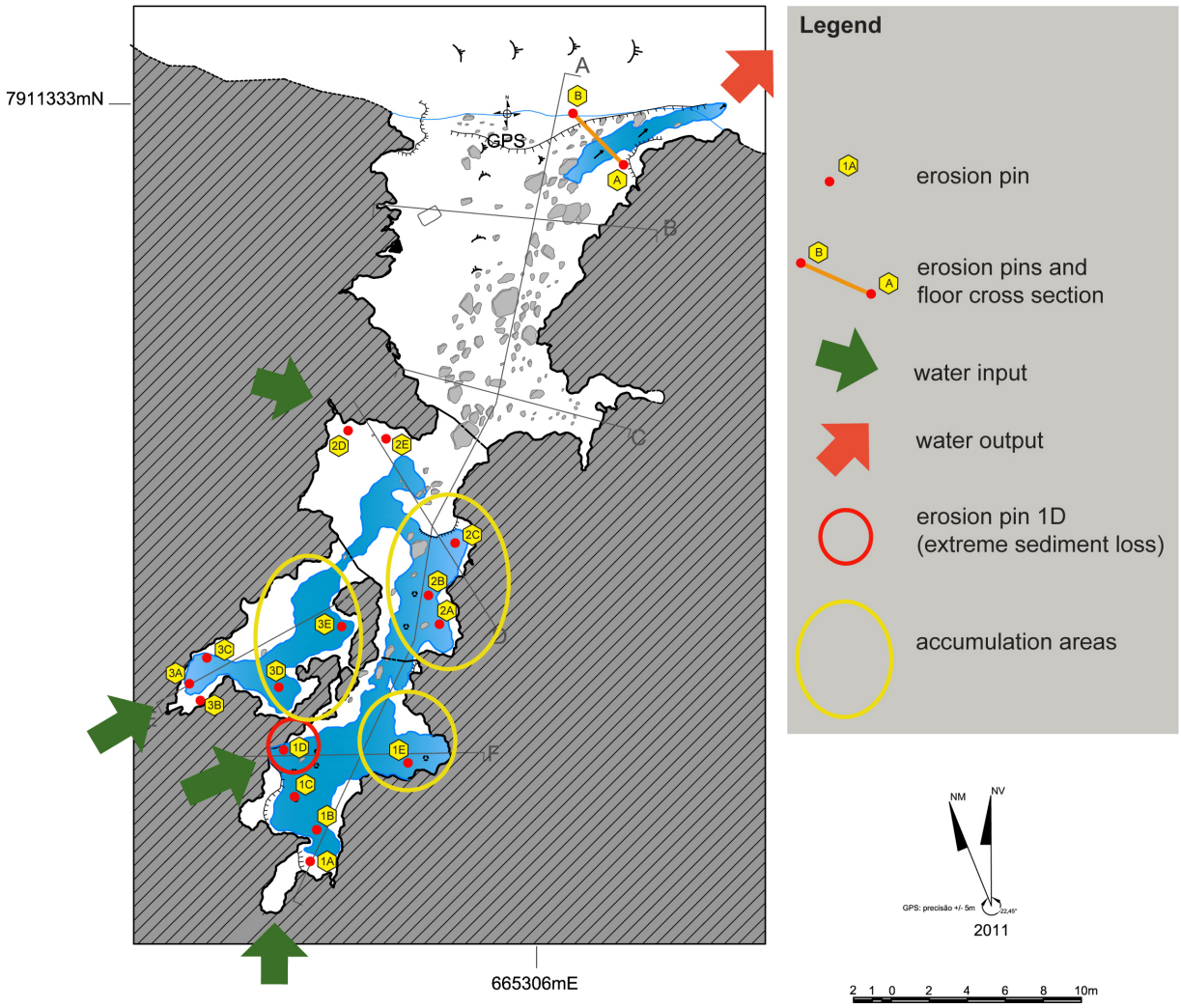

Figure 14. *CAI-03 cave map showing the sediment monitoring stations and a schematic of the water flow.*

pin's location in a water input area helps explain the sediment loss, but other measurements will be necessary to better understand the extreme sediment loss. The number 2A erosion pin revealed the second highest sediment loss, totaling 7.3 millimeters of variation in 5.5 months. During the second measurement trip, one drip point at the pin's base was identified, explaining the sediment loss (Figure 13).

The ability to locate the erosion pins on the cave map was very important for visualization and to support further analysis (Figure 14).

On this map, the water input and output points were located, as well as the accumulation areas. The location of the number 1D erosion pin most likely indicates the main water input point of the CAI-03 cave.

Conclusions

The photographic and sediment monitoring in the CAI-03 cave demonstrates the usefulness of these techniques for recording environmental alterations, understanding cave dynamics and supporting further analysis. These monitoring results can serve as valuable tools especially for geospeleological, sedimentological and management analysis.

This study demonstrates that the frequency of speleological monitoring was excessive, causing major sediment perturbation. In management terms, this result demands a reduction in the number of speleologic monitoring visits to protect the cave's attributes.

Trail delimitation was another management decision that followed the results of this monitoring. A few months after this simple action, it was possible to note drip marks developing outside the delimited trail (Figure 15).

Figure 15. *View of the trail delimited after the photographic monitoring analysis.*

The use of inexpensive materials and simple techniques permits the application of this method in other caves by minimally trained personnel.

All the photographic monitoring station flags, target flags and erosion pins are non-destructive and can be easily removed from the cave without causing any environmental alteration. This minimum-impact approach is fundamental in cave monitoring actions.

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Biography

Born in 1973. Caver and member of the Bambuí Speleological Research Group since 1991, one of most active South American caving clubs. Co-founder of Instituto do Carste in 2007. Graduated in architecture in 1997, with a master's degree in architecture design technology (2005) and a doctorate in physical geography (2011), both with emphasis in protected area management. Working since 1998 with protected areas and cave management, cave mapping and monitoring, educational activities, environmental licensing and protected areas infrastructure planning.

MANAGING A GLOBALLY UNIQUE NEXUS OF ACID MINE DRAINAGE, KARST AND WORLD HERITAGE SITE

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Abstract

The Cradle of Humankind World Heritage Site (COH WHS), South Africa, is located downstream of the actively decanting West Rand Goldfield (a.k.a. the Western Basin). It is therefore the only UNESCO-protected karst landscape in the world that is under threat from acid mine drainage (AMD). The perceived threat has generated wide and considerable concern for the preservation of the fossil sites. This perception has been fuelled by a poor understanding of the surface and groundwater resources of the WHS which, in turn, has precipitated often alarmist reporting in the media, some even hinting at the possible delisting of the site by UNESCO. These circumstances have presented significant challenges to management efforts directed at protecting the aquatic environment and outstanding universal value of the site. Not the least of these challenges has been gaining the support of direct stakeholders (e.g. landowners and local authorities) and interested and affected parties (e.g. non-governmental organisations, environmental lobbies, the media). Contrary to popular expectation, the mining industry has collaborated freely and copiously in its provision of mine water data and information, in stark contrast to an embargo placed on municipal wastewater quality data and information by a local authority. Against this background, the poster describes the challenge of informing the perception of typically non-scientific interested and affected parties regarding the impact and risk to the environment and its inhabitants, with a credible scientific understanding of the magnitude of this impact and the natural resilience that characterises the affected environment.

Biography

Peter Mills has been involved in wildlife and conservation management for over 30 years. During this time he has gained experience in all aspects of conservation practice that includes research, reserve management, impact assessments, cultural resource management and environmental education. He is currently the environmental manager for the Cradle of Humankind World Heritage Site (COH WHS) in South Africa. His principle responsibilities comprise elements of both cultural and natural resource management. The latter focuses especially on water resources as a key ecological component of the WHS, on which he reports to the Inter-Governmental Task Team on AMD. In his spare time he lectures at the South African Wildlife College on various aspects of conservation biology. Apart from terrestrial conservation, Peter has a keen interest in water and aquatic conservation and is the current chairman of the Yellowfish Working Group which focuses on the sustainable use of rivers in South Africa.

EVALUATING THE STATUS OF CAVE WILDERNESS

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Abstract

In 1964 the United States government passed landmark legislation creating a National Wilderness Preservation System to preserve and protect natural landscapes for primitive use. Despite four attempts to create a Cave Wilderness designation, two by the Cave Research Foundation, one by the National Speleological Society and one by a unit within the National Park Service system, no Wilderness designation has been made to protect and preserve a specific cave, region within a cave or a karst region. The question remains: if and when will the US declare a cave or portion of a cave/cave system as Wilderness? Two federal acts and one pending bill are considered significant cave related legislation that may lead the way to an eventual Cave Wilderness designation.

Introduction

The1964 Wilderness Act was eight years, eighteen public hearings and over 60 drafts in the making. This landmark legislation recognized the need to preserve and protect wild lands of America. It created a land use designation called Wilderness. Input was received from numerous organizations, agencies and private citizens via reports and testimonies. The National Speleological Society (NSS) and the Cave Research Foundation (CRF) submitted reports and testified during hearings advocating caves as Wilderness.

Ultimately the legislation did not define which ecosystems would or would not be considered as suitable for Wilderness designation; instead it used the all-encompassing terms of land and landscape. As such, caves were not specifically mentioned nor excluded as wilderness areas. However, it should be noted that these terms are typically applied to surface environments and not places such as oceans and caves.

Efforts to gain Cave Wilderness status for Mammoth Cave, Mammoth Cave National Park, Kentucky occurred in 1967 and 1971. An attempt was made in 1972 to create a Karst Wilderness of the Guadalupe Escarpment in New Mexico and Texas. This would have included caves located in both Carlsbad Caverns National Park, New Mexico and the region that would become Guadalupe Mountains National Park, Texas. All three attempts for Cave or Karst Wilderness designation failed (Seiser 2003). In all three cases the proposed cave/karst wilderness was predicated on the 1964 definition of Wilderness.

Since the 1964 Wilderness Act our idea of a federally defined Wilderness has also changed, expanded as evidenced by the 1975 Eastern Wilderness Act, and the 1980 Alaska National Interest Lands Conservation Act (ANILCA). It would seem that with changing ideas of how Wilderness is defined it might be possible to have a congressionally legislated Cave Wilderness.

In 1988, Carlsbad Caverns National Park submitted a proposal for Lechuguilla Cave, a cave located beneath surface Wilderness, to be designated Cave Wilderness. If successful, the designation would have added another dimension to the idea of wilderness – that of an ever expanding wilderness based on new exploration. Unfortunately, the National Park Service did not support the proposed designation. One consequence of the proposal was the establishment of official NPS policy that caves having all entrances within a Wilderness area will be managed as wilderness (Kerbo, 2002).

The one item that is common to all Wilderness Acts is that they create Wilderness as a surface environment. Whether or not that was the intent of the original proposed legislation is not the question. It is a potential problem in terms of how the physical side of wilderness is perceived. Relevant questions include: What is meant by Cave Wilderness? And,what is the intent of such a designation?

Defining Cave Wilderness

It is perhaps easier to first define what Cave Wilderness is not than it is to define what it is. Cave Wilderness is not a federally designated Wilderness containing caves. There

are a variety of such wilderness areas. Caves within these areas are considered wilderness caves. However, some of these wilderness caves may lack wilderness qualities; nor can they provide a wilderness experience. For example, some caves located within a wilderness may be too small to provide the sense of isolation and remoteness essential to a wilderness experience, and others may have excessive impact due to human usage and visitation (Seiser 2003).

Current National Park Service policy is that all caves found within a wilderness be managed as wilderness. The benefits of such a policy includes: blocking attempts to commercialize such caves wherein access can be obtained via natural or man-made entrances outside the designated Wilderness boundaries. However, these wilderness caves are not protected by congressional legislation and policy can change, allowing for access from beyond the wilderness boundary. Policy changes can result in management decisions that could easily change the wilderness nature of the cave.

Lechuguilla Cave is located beneath the Carlsbad Caverns Wilderness. The extent and extraordinary scientific value of this cave was unknown at the time the Wilderness designation was made. While it is being managed as a wilderness cave it lacks suitable protection of a congressional designation. The lack of a specific Wilderness designation also ignores the idea of Lechuguilla Cave as a national treasure.

Seiser's (2003) doctoral research on cavers and members of Carlsbad Caverns and Mammoth Cave National Parks gateway communities defined two critical elements relevant to the intent of a Cave Wilderness designation: First, it must protect and guarantee a wilderness experience. It is not the structure (shape or size) of the cave, but the experience that makes it a wilderness. It is important that people experience caves in a way that preserves them. The sense of isolation, as defined by solitude and remoteness, and the sense of self-sufficiency are important elements in a cave wilderness experience. Second, a wilderness designation must protect a cave's scientific values and resources (physical, biological, and other) for study now and in the future. Protection as a scientific resource should be a primary goal, seeking to preserve both current and future discovery opportunities. Recreational use would become a secondary goal. It should be noted that within caves, research and recreation often meet (Seiser 2003).

Seiser's (2003) research resulted in the following definition for Cave Wilderness: those cave and cave passages exhibiting exceptional scientific and cultural resources, and wilderness qualities. These sites display a high degree of wildness, in which the physical structure and ecological systems are largely unimpacted by humans, and in which there is a sense of remoteness from the ordinary activities and works of humans. It is further defined to mean those caves and cave passages in which stewardship shall protect the cave resources, its wilderness values, and future discoveries.

This definition of cave wilderness is not meant to negate the 1964 Wilderness Act, rather it expands our idea of what wilderness is and associates it with an environment not commonly visited by the public outside of a show cave environment.

Understanding what cave wilderness is (or should be) and what is the intent of such a congressional designation, leads to asking: Why do we need such a designation? It also leads to wondering why the designation has not occurred.

The Path to a Cave Wilderness Designation

Why has there not been a Cave Wilderness designation? It would be easy to say that trying to rigidly apply the 1964 Wilderness act to caves made it virtually impossible to achieve such a designation. However, the variety of Wilderness legislation since that original enactment suggests that wilderness advocates were able to successfully negotiate an expanded understanding of wilderness. I suggest rather that three factors have been involved: first, the use of the terms land and landscape, typically associated with surface environments; second, the lack of understanding of caves from a scientific aspect (the practical side of protection); and third, an even greater lack in understanding regarding the "romance of cave exploration". In the past such deficiency's made it very difficult for both land managers and legislators to support such a designation. It also made it difficult for wilderness advocates to effectively plead the case for cave wilderness.

Much has changed since the first initial attempts for cave wilderness. Since then, federal land managers responsible for the stewardship of agency caves have been increasingly selected from cave explorers educated

in various aspects of cave science and management. Also, there has been an increase in the number of natural history shows and movies on caves and cave exploration. These programs have changed the questionable image of cavers and replaced it with the image of serious explorers and cave scientists. It would be safe to say that we have a far better "cave educated" public and federal land managers than ever before.

How far have these changes taken us toward a Cave Wilderness designation? In the past twenty years, two federal acts should be viewed as significant legislation towards this end. In both cases the legislation was proposed by the Bureau of Land Management (BLM), an agency typically associated with leasing of rangeland and extraction of natural resources, not conservation. The first legislation, the 1993 Lechuguilla Cave Protection Act, protects unknown caves, then and now. This is the first time that a cave or cave passages were given congressionally mandated protection without an associated special designation. The second cave related legislation, the 2009 Omnibus Public Land Management Act, resulted in the establishment of the Fort Stanton-Snowy River Cave National Conservation Area (FSSRC NCA). This National Conservation Area was established to: "protect, conserve, and enhance the unique and nationally important historic, cultural, scientific, archaeological, natural, and educational subterranean cave resources of the Fort Stanton - Snowy River cave system" (BLM,2011).

Seiser (2013) evaluated the 2009 federal legislation creating the Fort Stanton – Snowy River Cave National Conservation Area as a potential step in the eventual creation of a designated Cave Wilderness, using criteria used in defining Cave Wilderness and values associated with a Cave Wilderness designation. As noted earlier, the FSSRC NCA was established to: protect, conserve, and enhance the unique and nationally important historic, cultural, scientific, archaeological, natural, and educational subsurface resources. These closely align to values associated with Cave Wilderness designation. The one significant value lacking is experiential; a value closely associated with any wilderness experience (Seiser, 2013).

The significance of the Fort Stanton – Snowy River Cave National Conservation Area lies in the establishment of a designation for the protection of scientifically notable caves. The legislation mandated management priority for cave resources, regulating appropriate surface usage as a secondary priority.

At the time of this writing a bill has been introduced in the United States Senate entitled "Oregon Caves Revitalization Act of 2013." The legislation includes a Scenic River designation for the subterranean River Styx that flows through Oregon Caves National Monument, located near Cave Junctions, Oregon. This designation would be the first time the Wild and Scenic Rivers Act will have been specifically applied to a waterway flowing through a cave. The passage of such legislation would be one more indication that cave resources are being recognized as significant and deserving of special protection.

Conclusions

It appears that we are on the way toward one day establishing congressionally designated Cave Wilderness. The question is under which agency will occur the first Cave Wilderness. The National Park Service has a long history of protecting outstanding cave resources. A scenic river designation for one of its cave rivers would appear to be a step toward considering one of its caves worthy of a Cave Wilderness designation. It would not be unreasonable to assume that the first designated Cave Wilderness would be for a cave under NPS stewardship. However, the Bureau of Land Management has had legislation recognizing that caves are of national interest. The first addressed the need to protect unknown caves and the second recognized the significance of a specific region within a cave. The BLM is commonly associated with grazing, mining and petroleum extraction. Yet the two cave protection acts support its mandate to protect our natural resources. It is hard not to wonder if they will manage the first federally designated Cave Wilderness.

Why do we need a Cave Wilderness designation? In the United States, who we are as a country is strongly tied to the land, to nature and to its exploration. Our National Parks, Monuments and Forests and other protected natural areas are our greatest national treasure. To designate a natural site as Wilderness is the highest recognition we can give to one of our national treasures. Such a designation brings greater understanding of our link to the natural world around us. If we wish to achieve greater understanding of and increased respect for caves and all they have to offer, then we need to push for a designated Cave Wilderness.

2014 marks the 50th anniversary of the Wilderness Act. It would, indeed be a sign that we have expanded the definition of and deepened our appreciation for Wilderness by seeing a cave or portion of a cave designated Wilderness.

Cave Wilderness is not an intuitive concept. Understanding the associated values is critical to understanding the idea of Cave Wilderness. So too is an understanding of the intentions of the designation. The objectives delineate Cave Wilderness stewardship goals without placing specific restrictions or requirements on how they are to be achieved, thus allowing each designated site to be managed as appropriate to protect the values and resources for which it was designated (Seiser and Schuett, 2006).

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THE FORT STANTON CAVE STUDY PROJECT: A MODEL FOR AGENCY – CAVER PARTNERSHIP IN CAVE MANAGEMENT

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Abstract

The Fort Stanton Cave Study Project and the Roswell Field Office of the Bureau of Land Management have been working together to manage Fort Stanton Cave for over 40 years. This successful partnership is a shining example of resource managers and resource users collaborating to the mutual benefit of both. There are several specific aspects to this partnership which could be regarded as a model for other user groups and agencies who need or want to enter into a cooperative relationship.

Introduction

The Fort Stanton Cave Study Project (FSCSP) was formally organized as a 501.c.3 non-profit in March of 2010. However, its story, and how it came to be an integral partner with the Roswell Field Office of the Bureau of Land Management (BLM) begins much earlier. In 1970, the BLM recognized the need to put a gate on Fort Stanton Cave after the discovery of two new pristine passages in the cave in 1969 – Lincoln Caverns and Bat Cave Extension. However, BLM did not have anyone who knew how to do it, nor even where the best place to put the gate was. However, Don Sawyer, technically a recreation planner, but regarded as the first cave specialist for the BLM, did know that there was a group of cavers who spent a lot of time in the cave and asked for help. That group of cavers of the Southwestern Region of the National Speleological Society included the folks who are now the driving force behind the FSCSP. In May of 1970 the main gate of Fort Stanton Cave was installed with materials provided by the BLM and labor provided by the cavers (Figure 1). And so it began.

The FSCSP has been loosely organized since that 1970 event and has become more organized as time has gone on. A key event in the FSCSP and Fort Stanton Cave history was the discovery of the Snowy River passage on September 1, 2001. The continued management of this amazing passage required a cooperative effort between the BLM and the cavers in the FSCSP in a fashion that had not been present before. The BLM and FSCSP worked closely together to seek the designation of the area around Fort Stanton Cave as the Fort Stanton – Snowy River National Conservation Area (Figure 2).

The FSCSP now counts over 200 volunteer participants and conducts three, week long expeditions each year at Fort Stanton Cave. There are several specific aspects of the processes and procedures used which illustrate the partnership that exists between the FSCSP and BLM.

Essential Elements of the FSCSP – BLM Partnership

1. The FSCSP is a 501.c.3 incorporated non-profit. This provides an organizational structure and a legal point of reference for the relationship between the BLM and the FSCSP. Without formal incorporation, it is difficult for the BLM to enter into legal agreements with the organization.
2. The FSCSP has a specific person (the Project Director) designated to interact with the BLM. This person acts as a point of contact for all communication between the FSCSP and the BLM, so there is no confusion about who the BLM must talk to regarding any issues that develop.
3. The BLM has a specific person (the Roswell Field Office cave specialist) who interacts with the

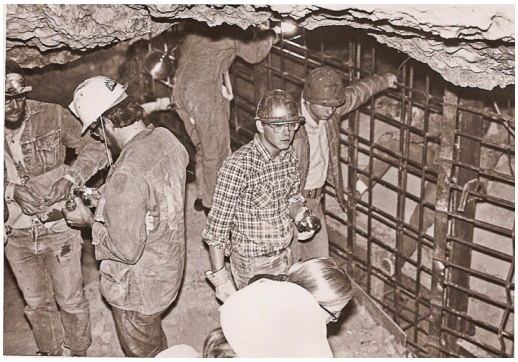

Figure 1. *Main Gate project in 1970.*

Figure 2. *In July 2005, in connection with the effort to designate the Fort Stanton-Snowy River National Conservation area, FSCSP Board President John Corcoran describes the unique aspects of Fort Stanton Cave to NM Senator Pete Domenici (sitting) while BLM Pecos District Manager Doug Burger (right) looks on.*

FSCSP. This also provides for less confusion with any communication issues.

4. The FSCSP has no membership criteria. Any interested person is invited and allowed to participate (Figure 3). Participants are able to be involved in any activity of the organization up to the limits of their abilities and experience. There is no requirement for participants to be a member of any other caving organization. This provides a non-discriminatory foundation that enhances the ability of a governmental organization (BLM) to recognize the FSCSP.

5. The New Mexico BLM has a Cave Management Team (CMT), which provides for expert review of activities conducted or planned in BLM caves in New Mexico. The CMT recommends to the BLM Roswell Field Office Manager which of the activities proposed by the FSCSP should be approved. This allows for a peer-to-peer communication of caving issues between the FSCSP and the Cave Management Team.

6. The FSCSP plans its activities in and around Fort Stanton Cave well in advance. It conducts three, nine-day long expeditions throughout the year, generally in April, July, and October. Dates for the expeditions are generally decided during the previous year. This provides plenty of lead time for the BLM to plan for other activities around the expeditions.

7. The BLM provides a Field House for centralizing the activities of the FSCSP (Figure 4). While this may be a lucky happenstance of an unused building being available, it does indicate the commitment of the BLM to the partnership. This allows the FSCSP to conduct its expeditions in a much more comfortable and professional fashion. While the BLM provides the building, the FSCSP has undertaken a large part of the maintenance and upkeep for the building.

8. The FSCSP Project Director (in conjunction with the FSCSP board of directors and other researchers and volunteers) produces a comprehensive proposal for activities during its expeditions and presents it to the BLM's Cave Management team well in advance of the expedition. The proposals are detailed and justify the activities based upon current knowledge and interests of both the BLM and the FSCSP.

Figure 3. *FSCSP volunteers along with local high school students and BLM Cave Specialist on a work trip in the cave hauling materials to Don Sawyer Memorial Hall.*

Figure 4. *Field House leased by the BLM and used as an expedition headquarters by the FSCSP.*

9. The FSCSP Project Director produces an Executive Summary of the activities conducted during an expedition and sends it to various BLM employees interested or involved in cave management (and all of the 200 or so participants of the FSCSP) in a timely fashion after the expedition. The Executive Summary is an illustrated review of what was accomplished during the expedition and keeps everyone in the loop.

10. It has been the pattern of the FSCSP to have a conference call with the FSCSP board of directors and various BLM employees (State Director, District Manager, Field Office Manager, National Cave Specialist, etc.) during the expedition to let these folks know about the progress of the expedition and any significant discoveries made. This provides for personal interaction with BLM management and the FSCSP leadership.

11. The FSCSP is a major contributor in the development of environmental assessments by the BLM regarding Fort Stanton Cave.

12. The FSCSP actively recruits experts in various arenas to assist in the development of, and/or conduct activities in and around Fort Stanton Cave. It also facilitates research activities of scientists by providing support personnel, guidance and coordination with other researchers. The FSCSP has relationships with researchers from all the major research institutes in New Mexico: the University of New Mexico, New Mexico Institute of Mining and Technology, and New Mexico State University.

13. The FSCSP has a website which is a repository for all the documents generated by the organization. The website provides a mechanism for communicating information about the project to the public and more sensitive information to scientists and resource managers through a private section. It is the go to resource for downloading specific FSCSP documents.

14. The FSCSP Project Director (again with assistance from others) produces a comprehensive report on the activities during each expedition. These documents contain trip reports by the various trip leaders, analysis of information collected during the expedition, results of surveys conducted (maps), and numerous photos of different activities that took place. This report is provided to the same folks as the Executive Summary. However, because of its size, it is typically downloaded from the FSCSP website, rather than e-mailed directly.

15. The FSCSP Project Director gives DVDs containing all the documents and photos collected during each expedition to the Roswell Cave Specialist for archiving by the BLM. All original data is available to the BLM.

16. For the last two years, the FSCSP has produced an Annual Report that summarizes the achievements of the project over the last calendar year. This document is sent to various individuals in the cooperating agencies (BLM and USFS) partner organizations, and major donors to the project.

17. The FSCSP has produced a brochure which describes the mission and activities of the project and also provides a mechanism for interested persons to make a tax deductible donation to the organization.

18. The FSCSP Project Director sends a newsletter, via e-mail, to the 200 or so participants to keep them informed about what is going on in the project and plans for the future. This keeps cavers involved and interested in the project and provides a conduit through which the BLM can communicate issues to the cavers as well.

19. The FSCSP provides financial support to cavers who actively participate in the project through the mechanism of a fuel reimbursement program, and also offers financial assistance to student researchers who pursue cave and karst research at Fort Stanton Cave. This not only enhances the abilities to have important work conducted in the cave, but increases the probability that important research will occur at the BLM managed resource.

20. The FSCSP conducts educational and other public outreach activities, such as presenting slide programs about Fort Stanton Cave at various public venues; submitting feature articles and information to the media regarding expedition findings; or conducting special events that enable the public to better understand the resource. The FSCSP also assists the BLM with the development of its own presentations about the cave, by submitting maps, photographs and scientific data. Volunteers within the FSCSP are developing a unique educational outreach tool, *"Caver Quest"* which is the topic of another paper in this NCKMS.

21. As an instrument of the partnership, the FSCSP has a group volunteer agreement with the BLM, which provides insurance coverage for the participants when involved in project activities.

The FSCSP also has an assistance agreement with the BLM providing for up to $100,000 in financial support for the FSCSP over a period of 5 years, to be matched by the contribution of the same degree of volunteer hours. (In the first year of this agreement, the FSCSP will likely contribute more than the entire amount in volunteer hours.)

22. The FSCSP is also identified as a "Friends Group" with the Conservation Lands Foundation, helping to support the BLM's management of the Fort Stanton – Snowy River National Conservation Area.

23. The FSCSP is affiliated with the National Speleological Society as an official project and with the National Cave and Karst Research Institute as a research partner. These affiliations provide a background against which the BLM can judge the FSCSP's credibility as a valid partner.

24. The FSCSP actively pursues similar partnerships with other management agencies as the need arises. Recent explorations have revealed that part of Fort Stanton Cave lies under the Smokey Bear District of the Lincoln National Forest. The FSCSP has actively involved the USFS in the discussion of issues with regards to the management of the cave.

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PARTNERSHIPS IN CAVE MANAGEMENT ON LINCOLN NATIONAL FOREST

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Abstract

National forests face many challenges in managing caves. Forming external and internal partnerships are important in managing caves in today's budget climate. This paper discusses the Lincoln National Forest's effort to form partnerships to advance its ability to manage caves.

Introduction

The US Forest Service Southwestern Region consists of eleven national forests in New Mexico and Arizona. Together these units manage over 1000 caves with limited budgets. Facing numerous challenges, many national forests have turned to partnerships to combine efforts and to co-manage cave areas. The Lincoln National Forest (LNF) has followed this trend by developing partnerships with other federal agencies, the National Speleological Society (NSS), and the US Forest Service Technology and Development Program (T&D Program) to complete cave management goals.

Interagency Partners

Across the southwest, national forest lands are bordered by different federal and state agencies along with private lands. The Lincoln National Forest is no different and shares borders with the Bureau of Land Management (BLM) and the National Park Service, as well as others. Significant cave areas cross political boundaries making partnerships with area agencies a natural priority for the LNF. By working together, overall cave management has improved and become more consistent. This combines strengths and financial support from each agency for a better outcome.

Another agency-like LNF partner is the National Cave and Karst Institute (NCKRI). This partnership includes support for environmental education, cave rescue training and organizing and supporting the National Cave and Karst Management Symposium.

In the Carlsbad area, interagency partnerships are easier to arrange, as cave managers from each agency are based in the same community. From co-management documents to local interagency meetings, these partnerships help managers discuss widespread issues and take specific actions.

National Speleological Society Partners

Organized volunteer groups from the National Speleological Society have developed partnerships of various kinds with the Forest Service. These groups have played a vital role in everything from co-writing cave management plans to surveying and inventorying caves. The LNF has expanded this partnership to include restoration, monitoring, cave survey, research, expedition coordination, training and recreational access.

For example, the NSS manages restoration projects on the LNF. Completing cave restoration after vandalism or overuse is a serious issue for many national forests. Damaged caves are usually the easier to access ones, but even the remote caves of the LNF are not immune. Prior to the late 1990's, periods of overuse caused noticeable impacts to several of the Lincoln's most precious caves. In 1999, the High Guads Restoration Project (HGRP) formed as a NSS Conservation Task Force to fix these issues. A strong partnership between the LNF and the HGRP has lasted more than 13 years. The HGRP has led expeditions and donated more than 16,000 hours restoring caves by removing human impacts. The group also completes monitoring, formation repair, trail flagging repair, and summer exit bat counts (Foote, 2012). This past year the group finished several projects including the restoration of two cave areas on the Lincoln. These areas have reopened for recreation because of their work.

Providing for recreational cave access is a big issue that causes many national forests in the southwest to look to the NSS for assistance. The Lincoln National Forest relies

on its partnerships nationally with the NSS and locally with grottos or clubs. The Pecos Valley Grotto in Carlsbad is a key partner in administering its recreation program. Volunteers within this local NSS Grotto facilitate the inclusion of the new visitors to LNF caves. The LNF also depends on the Pecos Valley Grotto and other NSS Grottos within the area to assist the LNF Trip Leader Program. Experienced NSS cavers train other potential leaders in specific cave routes, cave conservation and vertical caving safety. This way, the most current in-cave knowledge is passed directly between the individuals. This increases overall conservation and especially for more sensitive cave areas. The Lincoln National Forest completes the partnership by managing the cave permit access system, providing a Trip Leadership training class, and approving the new leaders.

Completing and collecting data of cave surveys is another monumental task facing the Forest Service. The Lincoln National Forest, like many other national forests, has large areas where cave surveys have not been completed and has many existing cave maps that were made prior to improvements in cave survey standards. The LNF has partnerships with numerous groups within the NSS that use old maps to complete resurvey projects which often lead to great discoveries. Other NSS partners routinely take lost cave locations from the past and combine them with other information they have gathered to search the hills. Many caves on the LNF have been relocated, mapped and reestablished in the cave files through these partnerships.

The most longstanding LNF partnership with the NSS is the Fort Stanton Cave Study Project (FSCSP). Through 40 years of dedicated survey efforts, FSCSP has discovered miles of cave passages for the BLM and LNF in and around the Fort Stanton Cave area (Lindsley, 2013). The BLM maintains a field house for expeditions that forms a base for scientific projects completed for both agencies. The entrance to Fort Stanton Cave is on BLM-managed land. Recent exploration of Fort Stanton Cave has extended the mapped portions of the cave under adjacent areas managed by the LNF. With these new discoveries, the longstanding partnership between the FSCSP and the LNF has progressed to a new era of cooperation.

Each one of these NSS groups is a very important partner to the Lincoln National Forest. Each group works independently to accomplish their specific tasks through expedition management and internal training. The Lincoln National Forest builds strong bonds with NSS grottos and their leaders to promote a true partnership in cave management.

Partner Within the Forest Service

A wildlife issue facing every national forest is the management of caves that have bats roosting in them.

In addition to the difficulty that comes from locating and studying these creatures, each national forest is now required to manage for the potential spread of the bat disease, White-nose Syndrome. This requires establishing a more comprehensive picture of bat populations and their locations. Currently, national forests are collecting this population data with techniques ranging from simple ones like visual counts, to more elaborate ones which use electronic dataloggers to record or count ultrasonic bat sounds over an extended period of time.

Using dataloggers to collect data on bat activity has been proven to be very useful, but requires a significant investment in equipment, training and field time. Understanding the different systems that are available can be a daunting task for a cave manager on a tight budget. At the same time, incorporating the newest technology and setting up the right system has the potential to enhance reliability, improve sensitivity in data collection, and minimize costs in material, training, and field time (Farve, 2013).

From this need has come a powerful LNF partnership with the internal Forest Service Technology and Development Program (T&D Program). The partnership, as designed, also includes a bat bioacoustics specialist contractor, NSS volunteers and commercial manufacturers. The T&D Program is a specialized unit of the Forest Service, Washington Office Engineering Staff. The mission of the T&D Program is to assist Forest Service employees and cooperators in doing their work more efficiently, effectively and safely, through the development of advanced technology (USDA, 2013). The T&D Program accepts applications for new projects each year from every national forest in the country. After acceptance the T&D Program manages and co-funds partnerships that bridge a technology gap with an individualized design.

This LNF partnership with the T&D Program has initiated a multi-year and multi-season demonstration

deployment to test the newest bat dataloggers against each other. The results will be compiled into a report that will document the advantages and cost effectiveness of using the different equipment under actual field conditions. This information will provide Forest Service managers with the information needed to choose which datalogger best fits their individual management priorities. In addition, the results will provide researchers and manufacturers with a wealth of new data for understanding bats and thinking ahead to the next generation of devices (Farve, 2013).

The design of the project is comparing the technical aspects of the Anabat Roostlogger®, Batlogger II ®, Pettersson D500x ®, and the Wildlife Acoustics SM2BAT+® across their respective operational abilities. Qualities like battery life, humidity resistance, and ease of use are of particular interest, along with bat species inclusiveness, bat call sensitivity and data accuracy. At the date of print, the project had successfully completed the first half its two-year schedule. As a leader in cave management, the LNF hopes that this partnership will serve as an example of the Forest Service's ability to innovate in the field of cave science.

Conclusions

Managing caves with limited personnel and finances is a task facing many national forests. Developing partnerships to combine efforts and to co-manage significant cave areas is an alternative chosen by many managers. The Lincoln National Forest is actively working with partners from other agencies, the National Speleological Society and the Forest Service Technology and Develop Program to enrich its ability to manage caves.

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Biography

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