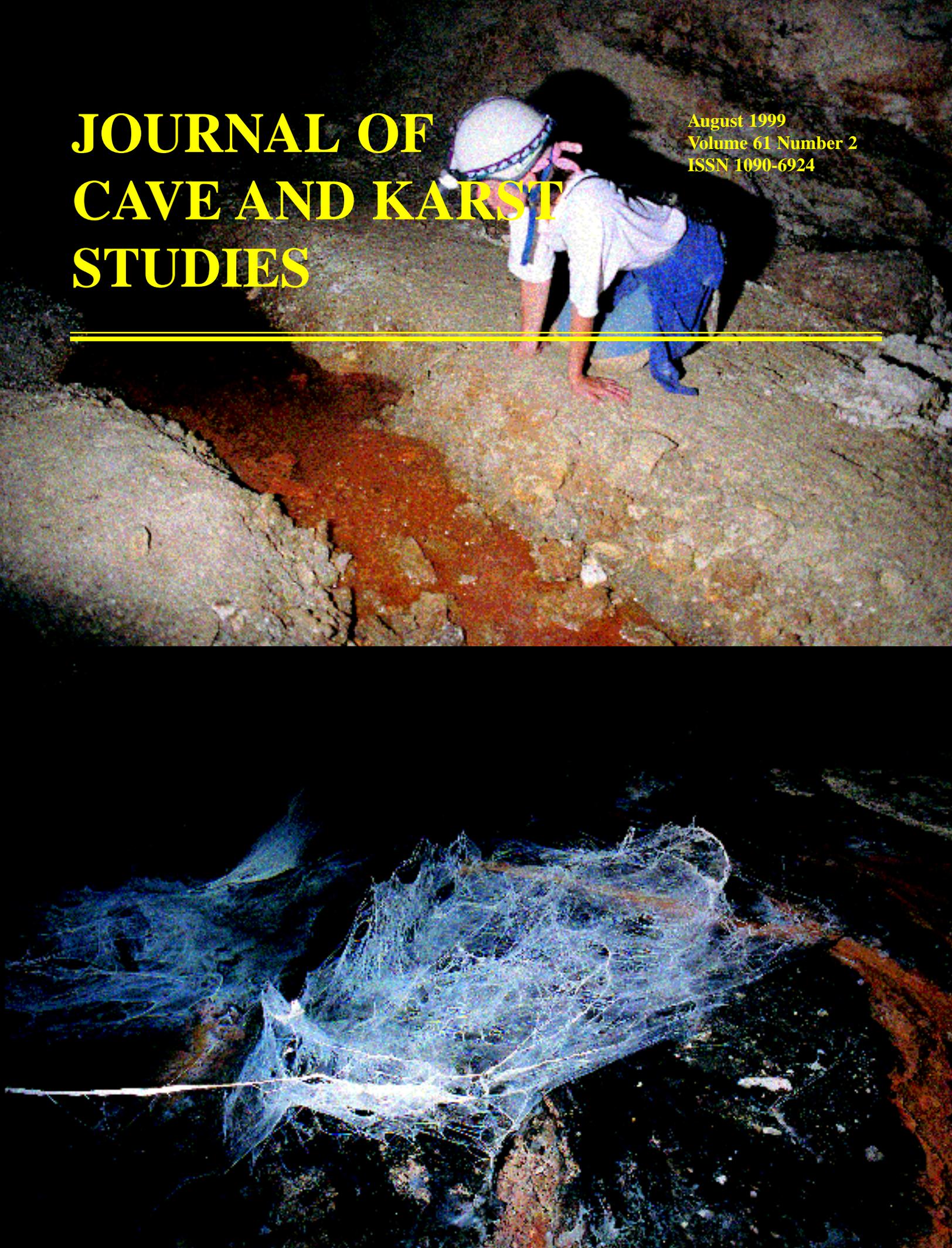


# JOURNAL OF CAVE AND KARST STUDIES

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August 1999  
Volume 61 Number 2  
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# Journal of Cave and Karst Studies

Volume 61 Number 2 August 1999

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Cover: Lower Kane Cave, Wyoming, location of a NSS pre-convention field camp. Jessica Lang at the Iron Spring (top). Chemoautotrophic microbial colonies in one of the springs in the cave (bottom). Photos by J.A. Pisarowicz.

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## BOOK REVIEW

### **An Atlas of Tasmanian Karst, Research Report No. 10**

Kiernan, Kevin (1995). Tasmanian Forest Research Council, Inc., 2 volumes: 607 pp. Cost is \$40 Australian dollars per volume. Approximately \$51 USD for both volumes plus postage.

The ever prolific Kevin Kiernan has once again presented us with a voluminous tome that is more than just an atlas. If you are looking for a full set of maps of Tasmanian caves, forget it! There are only five cave maps in the entire atlas. It is, after all, a karst atlas.

Chapter one, entitled, "The Nature of Karst Systems," is the first of two that make up Part A: "Karst Systems: A Tasmanian Context." The chapter is a short lesson in karst landform classification. The heart of chapter one is six tables that categorize everything from limestone lithologies and controls on karst evolution (Table 1.1) through surface karst landforms (Table 1.3) to human use and aesthetics (Table 1.6). This single chapter could be the core of a short course on karst phenomena.

Chapter two is focused on the specific karsts of Tasmania. The author describes the lithologic systems where karst formed on the island. Contemporary climate and paleoclimatic systems are addressed, as are their influence on limestone denudation and karst morphology development.

Once this framework is set Kiernan goes about describing the karst systems formed on Tasmania. He has developed seven process-oriented systems (with associated subsystems) by which he describes the Tasmanian karst. Those systems are defined by lithologic, structural, climatic, solvent, denudation, topographic and exposure style processes. (The exposure style is the manner in which a limestone outcrop is exposed to weathering.) The chapter concludes with a discussion on the influence of time on these systems. There is also a caution to be aware of the great complexity of karst systems. The reader is told that the parameters presented are very broad and that the many systems described are not spatially exclusive. Rather, they often overlap and interact with each other. This is good advice for studying karst systems anywhere, as we sometimes seem to get focused on one event or process and lose the big picture.

Part B is composed of six chapters following a short introduction. This is the actual heart of the atlas. The introduction explains the format of the atlas and the keys to the degree or intensity of karstification of the locations. Some three hundred confirmed or probable karst areas are defined in this atlas. The individual karst areas are delineated by using natural features such as watersheds rather than human-derived boundaries (e.g., townships). The introduction to Part B also contains a table listing all carbonate rock occurrences on the island and for each listing the following information is given: a code number, the name of the area, its grid reference, the Forestry District it is located in, a simple yes or no on whether this site

was confirmed by a visit, and, finally, the intensity of karstification of the area. Two maps of Tasmania are also included. One shows the six regions of the island used in this atlas. The second is an index map showing the coverage and names of the 1:100,000 topographic maps that were reduced for inclusion in this study.

The following six chapters each cover one of the six regions of Tasmania: North-west, Western, South-west, South-east, North-east, and the Bass Strait Islands. Each of the six chapters begins with an introduction describing the topography, climatology, geology and general geomorphology of the area. This is followed by the outline map of the general locations of the outcrops of the karstified rocks in the region using the above-mentioned reduced topographic sheets. Each karst area or potential karst outcrop has its own unique code number such as NW 1 or W 59 (for example, the North-west region has 57 unique karst areas). Each chapter is then made up of tables of data on each of the unique karst areas. Topographic maps and geologic maps of the karst areas are listed. Other listed information includes: types of carbonate or other rocks, climate, karst system types, existing documentation on the area, number of trips to the area, who were the investigators (cavers, geologists, biologists, etc.), type of land ownership, management problems and issues, and much more. In addition a few paragraphs may be devoted to where to find more extensive information on the area. If available, information is given on the water chemistry (mostly collected by the author) and analysis of the rock (from a variety of sources). Each of the chapters ends with remarks that summarize all of the data on that specific region. The author then discusses the significance of the karst found in that given region, as well as other values such as archaeology and the impact of modern society.

"Part C: Discussion and Conclusions" is perhaps the most significant part of the atlas. In this part, there is one chapter of some 30+ pages on "The Management of Tasmania's Karst Estate". This is must reading for those interested in karst management. Everything from pesticides, construction, and sewage, to recreation and its impact on the values of karst, is covered.

Finally, Kiernan, in his usual thorough style, provides the reader with a 24-page bibliography of international scope on karst and karst management. This resource greatly increases the value of the atlas.

There is little negative one can say about the atlas. The author has given karst researchers another superb product. I recommend the atlas, not only to the collector, but as a model for similar research done elsewhere. I anxiously await Kiernan's next production.

Reviewed by: George N. Huppert, Department of Geography and Earth Science, University of Wisconsin-La Crosse, La Crosse, WI 54601, [huppert@mail.uwlax.edu](mailto:huppert@mail.uwlax.edu)

# CAVE SCIENCE NEWS

## CAVE RESEARCH GRANTS

The Research Advisory Committee of the NSS accepts grant proposals aimed to further speleological research in different areas. For further information, please contact Aldemaro Romero, Ph.D., Chair, NSS Research Advisory Committee, Environmental Studies Program, Macalester College, St. Paul, MN 55105-1899, USA.

## INTERNET MAIL LIST FOR KARST HYDROLOGY AND WATER QUALITY

An Internet email discussion list has been established to facilitate dialogue about karst hydrology and water quality. The list is meant to be international in scope and welcomes discussion on a wide variety of topics under the umbrellas of karst hydrology and water quality. Subscription is made by sending email to [bonac@bioge.ubbcluj.ro](mailto:bonac@bioge.ubbcluj.ro) and including the line SUBSCRIBE KARST HYDROLOGY in the message section. No other text or subject line should be included. Questions about the email list should be directed to Doug Boyer at FOK Meeting in Romania

## KWI LOWERS PUBLICATION PRICE

The Karst Waters Institute announced that they lowered their price on Special Publication #5, *Karst Modeling Proceedings*, to \$38.00. Copies of the 265-page proceedings from their February 1999 symposium may be obtained from KWI, R.R. #1, Box 527, Petersburg, PA 16669-9211 USA.

## NPS CAVE AND KARST WEBSITE

The U.S. National Park Service cave/karst page has a new look, it can be accessed at the following URL:

<http://www2.nature.nps.gov/grd/geology/caves/index.htm>

The Inside Earth newsletter can be linked to from this page as well as other information about NPS caves. Included is a "tour" of some NPS cave areas and links to Federal legislation regarding caves. We will be adding to the page as time goes on. The latest edition of Inside Earth is also posted, Spring of 1999. It has been up for some time and subsequent issues will be posted on the site throughout the year. Just check back from time to time. Our webmaster is working on a method to make it easier to access Inside Earth, although he does web relating work for our entire division, so cave/karst has to wait its turn for upgrades.

*Submitted by Ron Kerbo*

## ERRATUM

An error appeared in the v. 60, n. 3 article by Veronica Toth. The Smart *et al.* reference should be: Smart, P.L., Finlayson, B.L., Rylands, W.D., & Ball, C.M. (1976). The relation of fluorescence to dissolved organic carbon in subsurface waters. *Water Research* 10: 805-811.

## FOK MEETING IN ROMANIA

Friends of the Karst, an informal group of karst geologists and geographers who typically gather twice a year, announced a meeting in Alma Mater Napocensis, the city of Cluj, Romania, where the first Speleological Institute in the world was born. The dates, 14-23 July 2000, including 6 to 7 days of excursions, allow folks to also attend the paleoclimate karst conference in Krakow, Poland (31 July - 4 August).

More information may be obtained at:  
<http://www.uib.no/People/nglbn/karst2000.htm>

Pre-registration forms are available at:  
<http://www.geocities.com/Yosemite/Geyser/3479/prereg.htm>

You may be placed on the mailing list by writing [bonac@bioge.ubbcluj.ro](mailto:bonac@bioge.ubbcluj.ro).

## UIS COMMISSION ON KARST HYDROGEOLOGY AND SPELEOGENESIS WEBSITE ANNOUNCED

As part of an ongoing effort by the International Speleological Union's Commission on Karst Hydrogeology and Speleogenesis (UIS KHS Commission) to develop an effective framework for communication between karst and cave scientists and disseminate relevant information, the WWW site of the Commission is now started. The site can be accessed at:

[http://happy.carrier.kiev.ua/~klim/UIS\\_KHS/index.html](http://happy.carrier.kiev.ua/~klim/UIS_KHS/index.html)

It contains an updated information about the Commission activity, members, past and current projects, calls for papers, "The Karst Conduit" newsletter, new publications and other information resources. Information will be frequently updated so you are invited to visit this site regularly. I kindly ask you to announce the UIS KHS Website among karst and cave scientific community by all possible means, including cross-links from other karst-related pages, announcement in newsletters and journals, etc.

I'd like to call your particular attention to the KHS Commission projects (planned books). Feedback and contributions from interested scientists are crucial for the projects to be effectively advanced.

*Submitted by Alexander Klimchouk.*

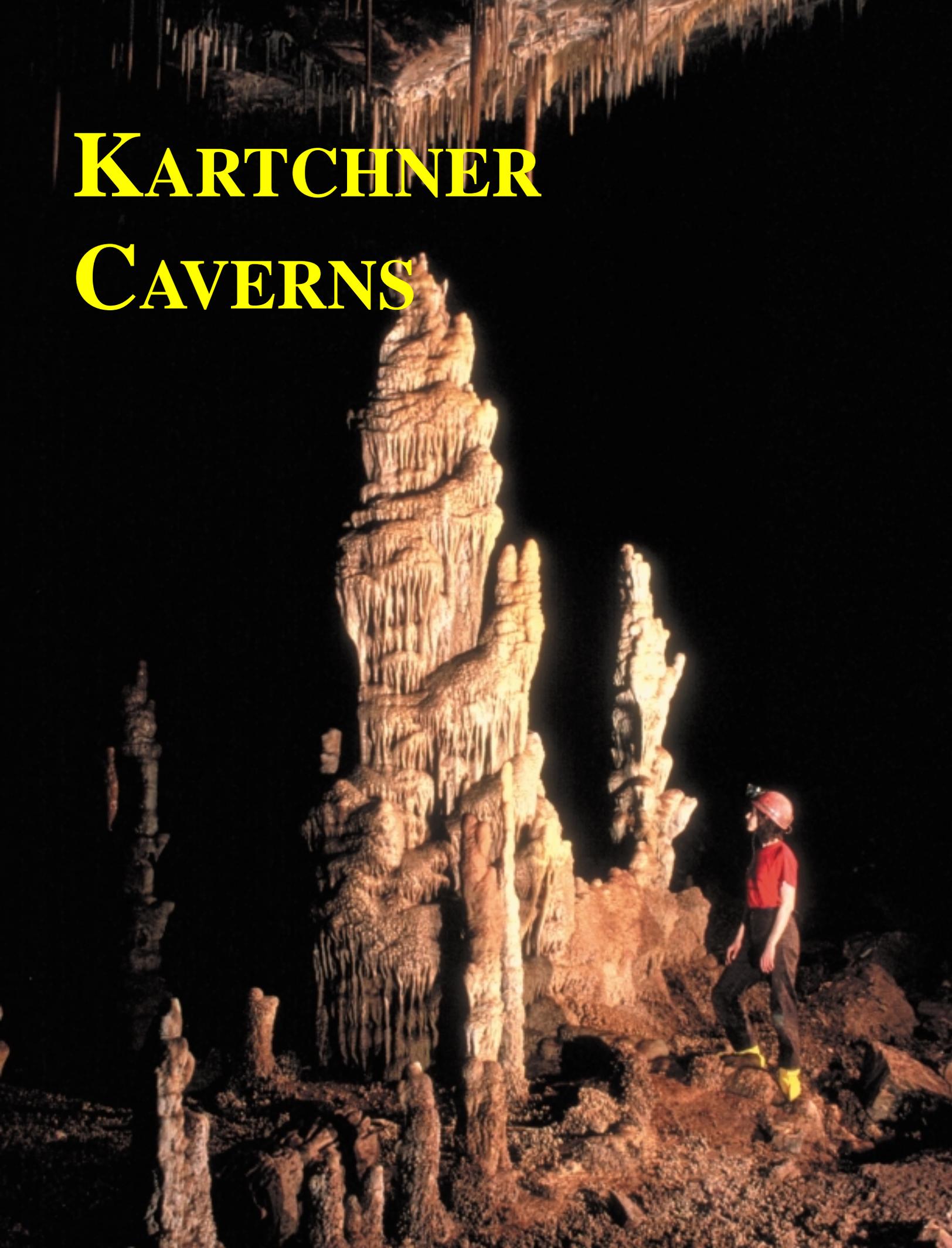
## RUSSIAN CAVE WEBSITE ANNOUNCED

Vladimir A. Maltsev, a recent contributor to the *Journal of Cave and Karst Studies*, encourages readers to check at his website at

[http://fadr.msu.ru/~vkor/maltsev/kugitang\\_caves.htm](http://fadr.msu.ru/~vkor/maltsev/kugitang_caves.htm)

The site features Russian caves, including the Cupp-Coutunn System. Text is in English and Russian.

# KARTCHNER CAVERNS



# Kartchner Caverns - Research Symposium

ROBERT H. BUECHER AND CAROL A. HILL  
*Kartchner Caverns State Park Symposium Organizers*

LOUISE D. HOSE AND JAMES A. PISAROWICZ  
*Editors*

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# INTRODUCTION TO THE KARTCHNER CAVERNS STATE PARK SYMPOSIUM

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CAROL A. HILL

17 El Arco Drive, Albuquerque, New Mexico 87123 USA

Kartchner Caverns State Park is in the Whetstone Mountains, Cochise County, Arizona, USA, just south of Interstate 10 and west of State Highway 90, ~80 km southeast of Tucson and 13 km south of Benson (Fig. 1). The park site, at an average elevation of 1430 m (4700 ft), encompasses 220 ha (550 ac) along the San Pedro Valley. The arid climate of the park mostly supports Sonoran desert vegetation, with woody vegetation such as mesquite, hackberry, and acacia adjacent to intermittent streams. The mean monthly temperature at near-Benson, Arizona, is 17.1°C (62.8°F), and the average annual precipitation is 290 mm (11.4 in), over half of which falls during July and August. Past climates have been wetter than the present, and from 30-10 Ka (thousands years ago), lakes existed in the San Pedro Valley and fauna, such as Mammoths, inhabited the region.

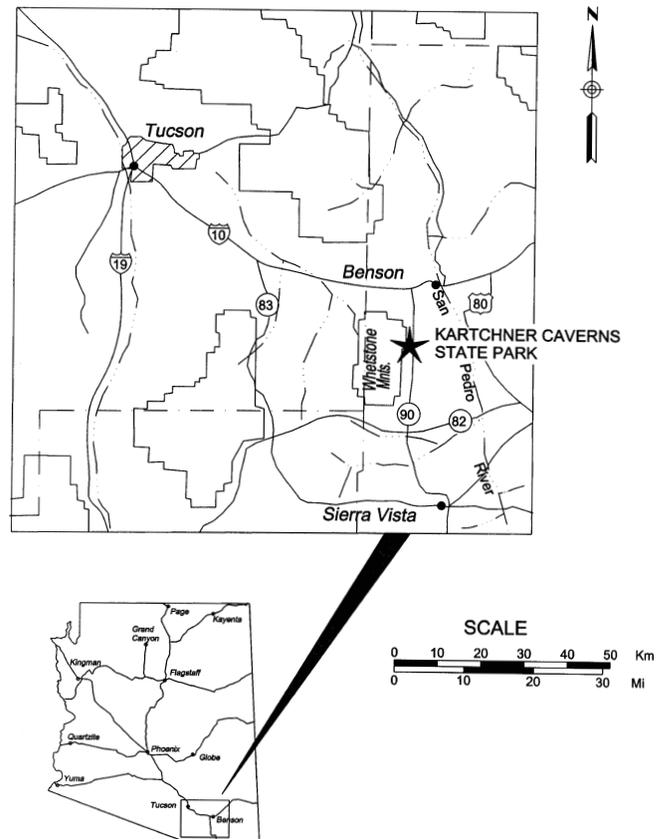
Geologically, Kartchner Caverns State Park is within the Basin and Range Province of the western United States, which is characterized by a series of horsts and grabens. The San Pedro Valley is in one such graben, just east of the park. A prominent fault block, called the Kartchner Block, has been downropped along the edge of the graben, and it is in this fault block of Mississippian Escabrosa Limestone that Kartchner Caverns developed. In the past, when the alluvium in the San Pedro River Valley was at a higher elevation, Kartchner Caverns formed along the level of the then-present water table. Guindani Wash and Saddle Wash drain the Whetstone Mountains to the west, and are the source of undersaturated water which still sporadically floods the cave.

Kartchner Caverns is the prime feature of Kartchner Caverns State Park. It is over 3 km (2 mi) long and contains spacious rooms, one is as long as a football field (100 m). The cave formed along one level at an elevation of ~1410 m (4625 ft). The park contains three species of bats, one of which (*Myotis velifer*) resides in the cave during the summer months. The cave is also home to other invertebrate species, some cave adapted, and to intermittent visitors such as ringtail cats. Beautiful, multicolored, cave formations (speleothems) are one of the main attractions of Kartchner Caverns, and the cave contains rare minerals and speleothems.

In order to prepare for the public opening of the cave in an environmentally sensitive manner, Arizona State Parks contracted for multi-disciplinary scientific studies to be done at Kartchner Caverns. This Symposium presents the results of these studies. The importance of these scientific endeavors should not be underestimated: Kartchner Caverns is one of the

most thoroughly studied caves in the world. As such, it has become the model of how a cave ought to be explored, researched, and commercialized. During the exploration and the scientific study of Kartchner, great care was taken to preserve the cave so that all subsequent visitors would be able to see it in the same pristine condition as Randy Tufts and Gary Tenen first experienced when they discovered it 25 years ago. It is hoped that future generations will continue to take great care of this exceptional cave.

*Kartchner Caverns State Park Symposium Organizers: Robert H. Buecher & Carol A. Hill*



**Figure 1. Location map of Kartchner Caverns State Park.**

# OVERVIEW OF KARTCHNER CAVERNS, ARIZONA

CAROL A. HILL

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*In this paper, the sequence of events for Kartchner Caverns and surrounding region are correlated and traced from the Mississippian Period to the present. Pre-cave events include the deposition of the Escabrosa Limestone during the Mississippian Period and block faulting and hydrothermal activity in the Miocene Epoch. The cave passages formed in the shallow phreatic zone ~ 200 Ka. Vadose events in the cave include the inwashing of pebble gravels and a maximum deposition of travertine during the Sangamon interglacial. Backflooding by undersaturated water caused bevelling of the limestone and travertine. Recent events include the habitation of the cave by vertebrates and invertebrates, and the discovery and development of the cave by humans.*

This paper provides an overview of events affecting Kartchner Caverns. An outline of this sequence of events, integrated with respect to regional events, has been compiled from the literature and from the results of this Symposium (Table 1).

Kartchner Caverns is located in the Whetstone Mountains, ~13 km south of Benson, Arizona, USA, just west of Arizona State Highway 90. The cave is developed in a downdropped block of Mississippian Escabrosa Limestone. The cave is over 3 km long, and is developed primarily along one level at an elevation of ~1410 m (4625 ft). The cave contains spacious rooms, one as long as 100 m. Kartchner Caverns is Arizona's 25th and newest State Park and is due to open in November 1999.

## PRE-CAVE EVENTS

Mississippian Escabrosa Limestone deposition began around 320 Ma (million years ago). These limestone units are currently exposed in the cave walls and ceiling (Jagnow 1999). The permeability of these units has influenced later groundwater movement and cave development.

The next major pre-cave event happened during the Miocene Epoch (13-5 Ma). Basin and Range tectonics created a graben and horst topography in Arizona where disconnected mountain ranges and valleys, such as the Whetstone Mountains and San Pedro Valley, became the predominant features. During this time the Escabrosa Limestone was faulted, and the block of limestone in which Kartchner Caverns was later developed was progressively downdropped against Precambrian alaskite granite (Jagnow 1999). Hydrothermal solutions ascended along fault zones which became filled with illite clay, quartz, and hematite. Temperatures of these hydrothermal solutions ranged from about 125-170°C as evidenced by fluid inclusion temperatures of the quartz. During this time the processes of cooling and thermal-mixing corrosion (Bögli 1980) may have dissolved some karstic cavities along the fault zones.

After the main Basin and Range thermal events, solutions cooled and deposited calcite as vein and spar material within the host limestone and along faults. Carbon-oxygen isotope

values for two analyses of vein calcite are:  $\delta^{13}\text{C} = -0.3\text{‰}$ ,  $+0.6\text{‰}$  and  $\delta^{18}\text{O} = -12.4\text{‰}$ ,  $-10.5\text{‰}$ , respectively. Calcite depositional temperatures based on these oxygen isotopes range from 30-40°C. Movement along these faults disaggregated or pulverized some of the vein calcite and the older vein quartz.

## SHALLOW-PHREATIC EVENTS

Main cave passageways of Kartchner began to form during the Late Pleistocene Epoch. This time correlates with maximum filling of the San Pedro Valley with the fluvial and lacustrine St. David Formation, the upper unit of which is <730 Ka (thousand years ago) (Johnson *et al.* 1975). Cave passages in Kartchner are essentially horizontal and cut across bedding even where bedding dips at high angles. This indicates strong water-table control on cavern dissolution. The water table must have been stable at one level for a long period of time, and it must have been aggressive in order for it to cut across bedrock, impermeable fault gouge, and quartz veins alike. Cave dissolution began around 200 Ka or somewhat earlier. This age is known from dating the cave travertine: the oldest age of any dated speleothem in the cave is ~194 Ka (Ford & Hill 1999). This time may correlate with water table development in the St. David Formation. It is not known if the St. David Formation ever extended as high as the cave, but if it did, it could have provided the regional water table necessary for cave dissolution at the 1408-1411 m (4620-4630 ft) level.

A variety of domes, solution pockets, channels, and anastomoses exist in the Kartchner Caverns ceiling. These features also indicate that cave dissolution occurred at or near the water table in the shallow-phreatic zone. Ceiling solution pockets are interpreted to form primarily by the process of mixture-corrosion (Bögli 1980). However, gravitational convection may also play a secondary role (Ford & Williams 1989). Where vadose water descending along a joint or fracture encounters and mixes with water at the water table, a renewed aggressiveness occurs so that dissolution takes place up and into the joint. Convection of water then enlarges these voids to form ceiling pockets or domes along the joints.

**Table 1. Sequence of events in Kartchner Caverns correlated with that of the surrounding region. Regional geologic events are taken mainly from Linsay *et al.* (1990).**

| Time Interval                     | Events   |
|-----------------------------------|--|
|                                   | <b>Pre-Cave Events</b>   |
| Mississippian (~320 Ma)           | Deposition of the Escabrosa Limestone.   |
| Miocene (~15-5 Ma)                | Basin and Range faulting and uplift. Time of heating, influx of hydrothermal solutions along fault zones; solutions enriched in Si, Fe and other metals. Illite clay from underlying Piñal Schist fills fault zones. Quartz veins form at T=125-170°C within fault zones. Minor paleokarst development along fault zones. 'Birdsnest' quartz needles grow from hot solutions into illite-rectorite clay matrix in paleokarst cavities. San Pedro Valley forms by block faulting; Escabrosa Limestone segments are let down against Precambrian alaskite granite. |
| Pliocene-Pleistocene (~5-1 Ma)    | Wet and cool period; perennial streams and marshes; fluvial and lacustrine sediment of the St. David Formation fills San Pedro Valley. Subsequent progradation of coarse-grained alluvial fans. Calcite precipitates as vein material within limestone and along faults at T=30-40°C. Renewed faulting pulverizes some of the calcite and quartz.  |
| Late Pleistocene (<730 Ka)        | Time of maximum valley filling. Upper part of St. David Formation <730 Ka.   |
|                                   | <b>Shallow-Phreatic Events</b>   |
| ~200 Ka                           | Water table stable (in St. David Formation?) at about 1410 m (4625 ft) elevation. Cave passages dissolve at or near the water table. Fault clay gouge residue from fault zones settles to the cave floor and forms blocky clay unit. Cave becomes air-filled and travertine starts to grow.  |
|                                   | <b>Vadose Events</b>   |
| Illinoian glacial (170-120 Ka)    | Granite wash unit deposits on erosional surface of St. David Formation. Granite wash debris washed into cave. First pebble-gravel (pg1) influx at ~130 Ka.   |
| Sangamon interglacial (120-70 Ka) | Downcutting of valley fill; development of Whetstone Terrace across San Pedro Valley. Time of warm, humid, more-forested climate. Major amount of speleothem growth. Second pebble-gravel (pg2) influx at ~100 Ka. Aggressive flood water enters from downcutting Guindani Wash and creates bevels. Alteration of illite clay to nontronite under high pH, low Eh conditions. Sloth bones wash into the cave ~85 Ka.   |
| Wisconsin glacial (70-10 Ka)      | San Pedro River cuts down through Whetstone Terrace. A Pleistocene lake exists in San Pedro Valley from 30-10 Ka. Travertine growth declines. Bats inhabit the cave by 50 - 40 Ka.   |
| Holocene (10 Ka to present)       | Downcutting of San Pedro River to present level. Wetter climate replaced by arid desert climate. Travertine growth continues to decline. Earthquake activity causes minor speleothem damage. Flood water still backs up into lower sections of the cave. Discovery and development by humans.  |

Since no deep-phreatic pits or other bathyphreatic features are known in the area of Kartchner Caverns (Lange 1999), the phreatic regime of cave development was probably entirely shallow rather than deep. Phreatic scallops in the cave measure 0.3-0.6 m in length, corresponding to a water velocity of ~1.2 cm/s (Curl 1974). Joints, rather than faults, have controlled the position of cave passages in Kartchner Caverns. This is typical of caves in general (Ford & Williams 1989).

#### VADOSE EVENTS

Even later (<200 Ka), after the main episode of cave development at or near the water table, aggressive solutions continued to dissolve the host limestone as indicated by the many corrosion notches and bevels in the cave. Corrosion notches are indentations in bedrock walls formed by seasonal flooding, where the incoming water has not equilibrated with limestone and is still aggressive with respect to it. Corrosion bevels are an extension of notches, where a flat roof is created by aggressive back-up flood water, regardless of geologic structure (Ford & Williams 1989). Corrosion bevels in Kartchner

Caverns are well developed in many areas of the cave, and they occur both in limestone (Graf 1999, Fig. 4) and travertine (Ford & Hill 1999, Fig. 3). Leveling data on more than 80 different corrosion bevels in Kartchner show that these features occur at many elevations. Hence, the bevels most likely correspond to a number of flood events, where water became ponded at different levels between impermeable fault 'locks' during the cave's vadose history (Graf 1999).

Vadose scalloping can be found on travertine and bedrock in some parts of the cave. The size and asymmetry of these scallops record the direction and velocity of past intermittent vadose stream flow. Also, vadose downcutting of sediment and the presence of black, manganese-coated stream clasts in downcut channels is further evidence of vadose flow in Kartchner Caverns (Hill 1999b).

Sometime after the cave became air filled, it was inhabited by bats and also visited by other animals. Sloth bones found in the cave have been uranium-series dated at ~85 Ka (J. Mead & C. Johnson, pers. com., 1999), and bat bones (from *Myotis velifer*, the same species that resides in the cave today) have been dated at ~50-45 Ka (Buecher & Sidner 1999). Fossil

insects (mites) have been isolated from travertine dated at ~100-90 Ka (Davis 1999), and insects have continued to populate the cave until the present time (Welbourn 1999).

Travertine decoration in Kartchner also occurred under air-filled vadose conditions (Hill 1999a). This travertine has been dated from almost 200 Ka to ~40 Ka, and records a major amount of deposition during the warm, humid climate of the Sangamon interglacial (Ford & Hill 1999). A higher percentage of trees and sagebrush existed on the surface during the period ~176 – 78 Ka, as determined by pollen analysis of cave travertine (Davis 1999). A number of speleothems are still growing in Kartchner Caverns today, even under the arid desert surface conditions, and this 'live' travertine accounts for the exceptional beauty of the cave.

The most recent events in the history of Kartchner Caverns were the discovery and exploration of the cave by cavers Tufts and Tenen (1999), and the development of Kartchner Caverns into an Arizona State Park. Of special conservation significance is the study by Buecher (1999) on the microclimate of the cave. The parameters of air temperature, soil temperature, relative humidity, airflow, and carbon-dioxide and radon levels in the cave were all monitored so that the original pristine conditions of the cave could be known and maintained in the future.

#### CONCLUSIONS

This paper is a synthesis of information that relates to the history of events for Kartchner Caverns. In summary, these events are:

- (1) Pre-cave events. Deposition of the Escabrosa Limestone took place in the Mississippian Period, and Basin and Range block faulting and hydrothermal activity occurred in the Miocene Epoch. Minor paleokarst development along faults may have also developed during the Miocene. The clay mineral, illite, in the faults was changed to rectorite by hydrothermal solutions, and quartz needles grew into the rectorite within paleokarst cavities.
- (2) Shallow-phreatic events. Dissolution of Kartchner Caverns in the shallow-phreatic zone took place at about 200 Ka or somewhat earlier. Autochthonous residue from the dissolution of the Escabrosa Limestone formed a blocky clay unit on the floor in parts of the cave.
- (3) Vadose events. Pebble gravels were washed into the cave from the surface and overlie the blocky clay unit. Illite-rectorite clay was reconstituted to nontronite under high pH, low Eh back-water flood conditions, and back-up flood water also bevelled limestone and cave travertine. Maximum speleothem growth took place during the Sangamon interglacial when the climate was more humid and the surface more forested than it is today. Invertebrate and vertebrate animals inhabited the cave soon after it became air filled. Finally, the cave was discovered by humans and developed as Arizona's newest State Park.

#### ACKNOWLEDGMENTS

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# DISCOVERY AND HISTORY OF KARTCHNER CAVERNS, ARIZONA

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*Efforts to give Kartchner Caverns protective park status required over 13 years to complete following the cave's discovery by Gary Tenen and Randy Tufts in 1974. These efforts involved the discoverers, selected cavers, the Kartchner family, the Nature Conservancy, and the Arizona State government—especially Arizona State Parks. Throughout that period, the cave and the efforts to conserve it were kept secret from the wider caving community and the public. Once in State Parks hands, extensive baseline testing was conducted before development began to help ensure that the cave environment is preserved. Cave environmental and show-cave experts have been involved in development planning and implementation. Surface facilities and a major part of the cave are set to open to the public in late 1999. The continuing support of cavers, the public, and Arizona government will be necessary to ensure that Kartchner Caverns is preserved in excellent condition.*

As we first conceived it in 1977, the purpose of Kartchner Caverns State Park is to protect Kartchner Caverns for future generations. Park status allows the cave to be supervised, thus preventing the vandalism which has destroyed so many other caves. As a public park, the cave provides the visitor with a recreational and inspirational experience that creates an appreciation of caves and other natural environments. A big factor in our decision to pursue park status was the location of the cave close to a major Arizona state highway. This location made the cave accessible to vandals who would destroy it, but also made it accessible to supervised park visitors who could learn from it.

Since we discovered the cave in 1974, all our efforts have been for the purpose of protecting the cave for posterity. At first we simply explored the cave and kept it secret. But, by 1977, we realized that secrecy alone would not protect the cave for the long term and that park development afforded the best chance for protection. We were particularly inspired by the concept of "conservation through commercialization" described by Russell Gurnee (1971). So, in 1978 we approached the owner of the cave, James Kartchner, and proposed that his family protect the cave by developing it and that we be kept involved. However, by 1981, the Kartchners had decided that they could not develop the cave themselves, so we sat on the discovery, waiting for another opportunity to make the cave into a park. Then, in 1984, we and the Kartchners approached Arizona State Parks. With the help of former Governors Bruce Babbitt and Rose Mofford, State Parks officials, key legislators, the Nature Conservancy, selected cavers, and a few other helpful individuals, Kartchner Caverns was granted State Park status in 1988, thirteen and one-half years after we discovered it. During that time, those of us involved in the project kept the cave secret from the wider caving community and from the public.

In this paper we present key elements of the history of

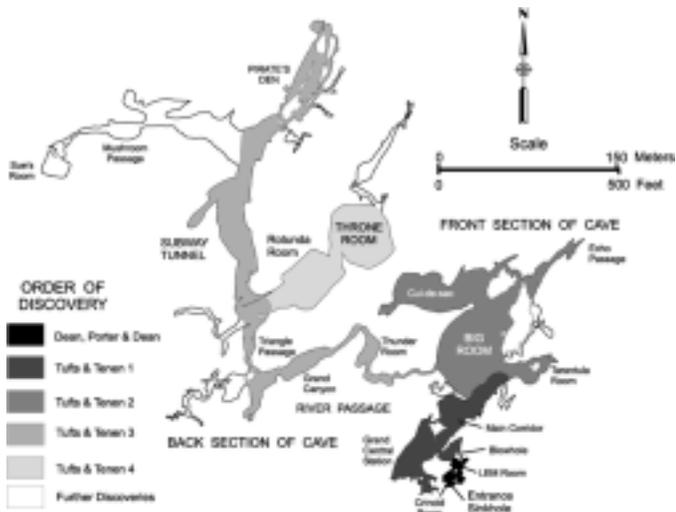
Kartchner Caverns. We begin with a first-person account of the discovery of the cave, followed by a chronology of events leading to the achievement of State Parks status for the cave. Then we summarize the development process, which includes the environmental studies conducted before development of the cave interior began. We conclude by reiterating the goal of conserving Kartchner Caverns, and mentioning two strategies we believe are essential in achieving that aim.

The description of the discovery and the events chronology draw heavily on (Tufts 1989a) which was based on interviews with principals and on our personal recollections. The discussion of the development process comes from personal communications with Arizona State Parks officials as well as consultant reports. Locations in the cave, and the sequence of discovery are shown on the accompanying map (Fig. 1) which is based on one by Arizona Conservation Projects, Inc. (1992).

## DISCOVERY OF THE CAVE

We discovered Kartchner Caverns through deliberate cave-hunting. Randy Tufts had begun searching for caves in southern Arizona in the mid-1960s and targeted the Whetstone Mountains because of the limestone exposures there. A tip from a miner that an entrance lay in the area led him to discover the cave sinkhole entrance in 1967 along with his uncle Harry M. Walker and a few friends. However, the only possible lead at the bottom of the sinkhole—a narrow crack—did not appear to "go," so the group left without entering the cave.

In 1974, Randy returned with caver and friend Gary Tenen to re-examine the sinkhole (Tufts 1989b; Negri 1998). Unlike the 1967 visit, this time a warm, moist breeze blew out of the crack Tufts had examined seven years before. With this unexpected evidence that a cave might lie beyond we squeezed through the crack into a small cave room now called the Crinoid Room (Fig. 1). The room was dry and dusty and there



**Figure 1. Generalized map of Kartchner Caverns showing locations mentioned in the text and indicating the order of early discoveries. Map layout by Bob Buecher.**

were a few human footprints and broken formations. A similar room (LEM Room) connected to the first, but neither was large enough to account for the breeze.

After some searching we traced the breeze to a tight crawlway leading out of the LEM Room. Tufts crawled into the crawlway for about 8 m (25 ft) where the passage seemed to stop at a rock barrier that had a 8 cm (3 in) hole in it. The breeze flowed through that hole. We laid in the crawlway for two hours, widening the hole with a 3 pound (1.4 kg) sledgehammer and a chisel. Finally we were able to squeeze through the hole, Tenen first and then Tufts, but only by taking off our belts and exhaling.

Beyond the tight squeeze, which we named the Blowhole (Fig. 1, T&T1), the cave became very moist and there was no sign of any previous traffic. After about 30 m (100 ft) of crawling through low passages, we emerged into a corridor where we could stand up. The cave was quite humid, very well-decorated, and apparently pristine. Trying not to damage the formations, we slowly made our way along the corridor, which linked three small rooms. At a spot we named the Mud Flats, we stopped, realizing that no one knew where we were. If there had been an accident, no one would have known where to find us. So, we turned around and left.

We explored the cave, which we named Xanadu, for the next two years, eventually finding about 4 km (2.5 mi) of virgin passageways. The two rooms before the Blowhole, which had been visited by others before us, constituted only about 30 m (100 ft). We found large parts of the cave in single trips. For example, the next weekend we found the Big Room and Cul-de-sac (Fig. 1, T&T2). Two weeks later we found the Thunder Room, Grand Canyon, Subway, and Pirate's Den (Fig. 1, T&T3), and a few months later we found the Rotunda Room and Throne Room (Fig. 1, T&T4).

To ensure that the cave was not subjected to vandalism, we kept it secret, even from the local National Speleological Society Grotto. We told only a trusted, small group, so that someone could rescue us without alerting public authorities. To avoid attracting attention to the cave we did not gate it until after we had told the Kartchner family about it and after there had been an unauthorized entry by some local cavers who had heard about the cave via a "leak." We did not treat the cave we found as a recreational cave. Instead, we marked trails, flagged off passages that did not "go anywhere," and tried our best to minimize damage from our own visits.

#### CHRONOLOGY OF EVENTS THROUGH THE APPROVAL OF PARK STATUS

Below is a chronology of major events in the history of Kartchner Caverns, including the 13.5 years from the discovery of the cave until the cave was declared an Arizona State Park. The purpose of this chronology is to show how development of a cave can proceed along a circuitous and difficult route involving many players including cavers, landowners, and public officials. While specifics will vary from case to case, this timeline is intended to exemplify the attention required in such efforts.

5/19/42. The land overlying the cave is purchased by James and Lois Kartchner for cattle grazing purposes. The property is in the foothills of the Whetstone Mountains of southern Arizona.

ca. 1963. Arizona Hwy 90 is constructed, making the Kartchner land very accessible. The highway coincides with part of the Kartchner property's eastern boundary and passes



**Figure 2. James Kartchner, 78, (right foreground) on his second trip to the cave, 21 April 1979. In the rear are cave co-discoverers Gary Tenen (beard) and Randy Tufts (moustache). In addition, from left to right are Milo Kartchner, Dwight Kartchner, Dean Kartchner, Kevin Kartchner, and Fred Kartchner. Photo by Max Kartchner.**

0.8 km (0.5 mi) from the cave.

ca. 1964. Sierra Vista (Arizona) cavers John Porter, Charles Dean and his son, Tom, find the Sinkhole (entrance to the cave). Tom Dean enters the first two small rooms (Crinoid and LEM Rooms) through a tight crack in the bottom of the sink (Fig. 1).

ca. 1967. Randy Tufts finds the Sinkhole but does not enter the cave.

4/13/71. Porter and Tucson (Arizona) caver Lane Larson enter the Crinoid and LEM Rooms but go no further.

11/74-ca.1976. Gary Tenen and Randy Tufts enter the Crinoid and LEM Rooms. They push a crawlway at the edge of the LEM Room, widen a constriction in it (the Blowhole) and discover the main cave. Over the next two years, they continue to explore the cave (Fig.1, T&T1-4), with the assistance of a few others. In all, they find 4 km (2.5 mi) of virgin cave passage with beautiful formations. They perceive the cave's accessible location as creating the opportunity for rediscovery and vandalism, so they adopt a strict secrecy policy. They set out to find a long term means of protecting Xanadu.

2/20/78. Disillusioned with a secrecy-alone policy, Tenen and Tufts approach the owner of the property, St. David, Arizona, educator and rancher, James Kartchner, and tell him of the cave's existence. They invite Kartchner to see the cave and ask him to consider their idea of commercializing it as a means of protection.

5/6/78. James Kartchner and five of his sons visit the cave with Tenen and Tufts. Kartchner requests a written development proposal.

10/78. Tenen and Tufts propose that development as a show cave be acknowledged as the best means of long term protection and that background information on show cave development be gathered before making a final decision to proceed. In writing the proposal they begin to gather information from national cave experts while concealing their own identities and the cave's location. The Kartchners accept the recommendations and begin to work with Tenen and Tufts on the project.

Fall 1978. Tenen attends the first of two National Caves Association (the trade group for show cave operators) conventions. He uses an alias to keep word of his trip from spreading among cavers.

12/14-19/78. Texas cave mappers Orion and Jan Knox map the cave as far as the Throne Room. Roy Davis of Tennessee, a cave development expert, visits the cave and recommends that it receive "first class treatment."

Winter-Spring 1979. To observe environmentally sensitive methods of cave development, Tenen takes time off and works for four months at the Caverns of Sonora (Texas) building trails and Luray Caverns (Virginia) helping Roy Davis install new lights. While working on those projects, he continues to use his alias. A series of mapping trips begin to complete the map of the whole cave.

4/21/79. James Kartchner, 78, and sons makes their second trip to the cave, going all the way to the Throne Room (Fig. 2).

ca. 1981. After much consideration, James Kartchner decides his family will not develop the cave themselves. It appears to him to be too risky an investment. A gate is installed at the Blowhole after an unauthorized entry. The project pauses for the next three years.

12/84-2/85. Tenen, Tufts and the Kartchners approach Arizona State Parks. Tufts meets with parks official, Charles Eatherly, who visits the site in January 1985. They recruit Bob and Debbie Buecher to help with technical aspects of the project. Tufts begins frequent telephone contacts with national cave experts, especially Russell and Jeanne Gurnee, and Tom Aley, while using an alias.

3-4/85. Tenen and Tufts approach Governor Bruce Babbitt to seek his advice on project feasibility. Babbitt asks to see the cave. Tenen, Tufts, and Bob Buecher prepare a wider entry for the Governor near the Blowhole in case a rescue is required. (This new passage is called the Babbitt Hole, and is soon gated.) Babbitt visits the cave on 4 April 1985 and becomes enthusiastic about bringing it into the Arizona State Parks system.

ca. 5/85. Babbitt brings environmentalist William Roe and the Arizona Nature Conservancy into the project. Roe visits the cave and begins conversations with the Kartchners.

ca. 6/85. Discussions begin on how to arrange an appraisal, there being considerable uncertainty on how to determine the monetary value of a cave. A natural resources appraiser, H. C. Cannon, is obtained through the Arizona Nature Conservancy. The parties agree to fund and direct his work jointly.

ca. late 1985. Staff changes occur within Arizona State Parks and Governor Babbitt approaches the end of his term, which dilute efforts on the cave. Dan Campbell, Executive Director of the Arizona Nature Conservancy, begins to look for another suitable public land partner. He contacts the National Park Service but arouses no interest. Tenen, Tufts, and the Buechers add local cavers Steve Holland and Scott Gibson to their caver group. They and the Kartchners head off an excavation attempt by other Tucson cavers at a lead on the main cave hill. These cavers had heard a rumor about the cave's existence.

ca. 1986. Campbell and Tenen begin a series of trips to the cave with public officials to identify a protective agency. BLM officials see the cave but are not interested. However, State Senators John Hays and Greg Lunn plus State Land Commissioner Bob Lane show great interest. So, Campbell turns his attention back to Arizona State Parks and new Director Don Charpio. But, Charpio resigns in early 1987 and the Kartchners become very discouraged. In their eyes, the appraisal process has also halted. They are unaware that it is Campbell who is urging Cannon to slow down until the State can become committed again. The Buechers complete the first systematic assessment of the cave, including the quality of its features and its favorability for development.

6/12/86. James Kartchner dies at the age of 85.

4-8/87. Ken Travous, formerly Deputy Director of Arizona State Parks, is hired as Executive Director, replacing Charpio.

He begins a planning process to select priorities for new park development. The cave begins to emerge as a prime park candidate. Tufts, Tenen and Travous meet to plan for discussions between the State and the Kartchner family.

ca. Fall 1987. Travous, and new Arizona State Parks Deputy Director Courtland Nelson visit the cave on 7 September 1987. Nelson suggests that a video be prepared for the Arizona legislature. Campbell tells Travous that the Arizona Nature Conservancy could buy the cave if repaid by the State. Travous obtains approval from the Arizona State Parks Board to proceed. The appraisal process is revived including a separate appraisal for the land surrounding the cave. Travous makes initial contacts with *National Geographic Magazine* with help from Campbell. Its editor expresses an interest in including the cave in a planned article on the Nature Conservancy (Grove 1988). Travous secures agreement from KTVK television in Phoenix to produce a video to show to the Arizona legislature. Cavers hold frequent meetings to plan for the creation of a “cooperating association” to act as a “friend of the cave.”

ca. 11/87. Arizona State Parks sponsors a tour of southern Arizona for key legislators on 23 November 1987. Tenen, Tufts, the Buechers and Holland give a presentation to State Representatives Larry Hawke and Joe Lane, followed by a visit to the surface site. Hawke and Travous work out an initial legislative strategy. This strategy includes creating an “acquisition and development fund” to pay for purchase and development costs of new parks out of revenues from existing parks. The cave would be the first use of that fund. The fund would be created by a late amendment to another bill which would not refer initially to the cave or the park, thereby preserving secrecy in case the legislative plan collapsed.

ca. 12/87. Tenen and Tufts insist on controls over TV use of the planned video to ensure cave protection. KTVK agrees to withhold airing the video of the cave publicly until Travous approves it.

11/87–1/88. In view of the strong likelihood that the bill creating the Acquisition and Development Fund would be approved by the Legislature, Campbell obtains authorization from the Nature Conservancy executive staff and the board of its Arizona chapter to use Conservancy funds to buy the cave and hold it for the State of Arizona. The State of Arizona would then reimburse the Conservancy with interest.

1/20/88. Cavers incorporate Arizona Conservation Projects, Inc., (ACPI) as a non-profit organization to encourage the stewardship of the cave.

3/88. KTVK and *National Geographic Magazine* send crews to the cave within the same three-day period starting 1 March 1988 and both complete “shooting.” Later, Travous and Tufts help KTVK producer Steve Bodinet and videographer Bruce Haffner script and edit the final video. Appraisals of the land and the cave are now complete, for a total value of \$1.8 million. Campbell meets with the Kartchners who offer to sell the property to the Arizona Nature Conservancy for a limited time at \$250,000 less than the appraised price, as an incentive

to the State to buy the cave.

4/88. Travous meets with key legislative leaders to apprise them of the cave and of the legislation to be amended, Senate Bill 1188, introduced by State Senator John Hays. The bill makes progress through preliminary action in the Senate and goes over to the House of Representatives.

4/22/88. The *Phoenix Gazette* newspaper picks up the cave story and plans to run an article on 23 April. Travous persuades them to delay for one week. He arranges with legislative leaders for the bill to be voted on within that week. With approval of Governor Mofford’s office, Dick Ferdon, Manager of Picacho Peak State Park, is put on the cave property to guard it.

4/26/88. Travous meets with the Senate caucuses and shows the cave video. KTVK, with Travous’ approval, runs a brief story about the cave and the impending legislative vote on the 10:00 p.m. news.

4/27/88. The *Phoenix Gazette* runs its story about the cave on the front page of its morning edition (Kossan 1988). Travous meets with the House of Representatives caucus and shows the KTVK video of the cave. The House and Senate begin a pre-planned sequence of actions designed to approve the legislation that day. First, the House makes a technical amendment to Senate Bill 1188, which is rejected by the Senate, triggering a conference committee. Then the conference committee amends the bill to include the cave, listed as the JAK Property, as the first use of the new Acquisition and Development Fund. Next, the Senate approves the conference report and the bill by a vote of 27-0. Then, the House takes the same action by a vote of 52-4. Last, Senate Bill 1188 is sent over to Governor Mofford who signs it into law. The park is named the “James and Lois Kartchner Caverns State Park.” Over 13 years of protective secrecy ends.

#### THE DEVELOPMENT PROCESS

Once the State of Arizona purchased the cave from the Kartchners in September 1988, the development process began. Arizona State Parks immediately initiated a multi-year program of environmental baseline studies (Arizona Conservation Projects, Inc. 1992). These studies were conducted by Arizona Conservation Projects, Inc., the non-profit organization that cavers Bob and Debbie Buecher, Steve Holland, Scott Gibson, and the authors formed to advocate the welfare of the cave. The study project was managed by Bob Buecher. Researchers included Tom Aley, Cathy Aley, Bob Buecher, Debbie Buecher, Larry Coats, Owen Davis, Derek Ford, Chuck Graf, Carol Hill, Dave Jagnow, Art Lange, Jim Mead, Blaine Schubert, Ronnie Sidner, Ken Thomson, and Cal Welbourn. Assisting with the ACPI organization after the legislation passed were cavers Ron Bridgemon, Anita Pape, Tom Strong, and Dave Thayer.

By the mid-1990s, Arizona State Parks began to solicit direct consultation from the national caving and cave environmental community. Show cave experts such as Russell Gurnee

and Jeanne Gurnee, Tom Aley, Orion Knox, and Jack Burch were recruited to assist with the actual planning and development of the cave. At their suggestion, Bruce Herschend from Missouri was hired to plan the trail layout and Bob Burnett from Texas was employed to supervise the underground construction. During this time, plans were made and construction begun on surface park facilities, including a 2100 m<sup>2</sup> (23000 ft<sup>2</sup>) visitor center (Vernon Swaback Associates 1992; Travous 1995). Plans for the surface park development were made taking cave environmental considerations into account (McGann & Associates 1992).

Underground development by Arizona State Parks has been painstaking, with considerable efforts being made to minimize changes in the cave and to create a safe and educational tour. Two parts of the cave are being developed—the Rotunda/Throne Room complex and the Big Room/Cul-de-sac area. The Rotunda/Throne Room is set to open to the public in November 1999, which is the twenty-fifth anniversary of the discovery of the cave. The Big Room/Cul-de-sac is set to open about two years later. Total project costs will exceed \$25 million. Arizona State Parks estimates that ~150,000 people will visit the park and 100,000 people will visit the cave each year (McGann and Associates 1992). A Friends of Kartchner Caverns organization has been created. Composed of local community leaders, the Friends will help raise funds for the park's grand opening and for educational programs.

#### CONCLUSIONS

While the discovery of Kartchner Caverns was personally exciting, the real story is the conservation of the cave. The vast majority of the effort involved in this project has been directed at creating long term protection. In this regard, the pre-development environmental studies are invaluable. It is important that we support Arizona State Parks in its efforts to manage the cave using these studies in concert with ongoing environmental monitoring. It is also important to tell the public, on a continuing basis, that: (1) caves are unique and non-renewable resources; (2) it is our responsibility to protect caves for future generations; and (3) this protection can be achieved with proper care and attention. We hope that the conservation of Kartchner Caverns as detailed in this paper sets a good example.

#### ACKNOWLEDGMENTS

Tremendous effort has been expended by many people and groups throughout this project. Thanks go to cavers Bob and Debbie Buecher among many others, the cave researchers who participated in the pre-development environmental studies, and the consultants who helped plan the park. We owe our deep gratitude to the Kartchner family, the Nature Conservancy, and the Arizona State Legislature. Particular thanks go to Arizona State Parks, its Board, friends, and staff and especially its Executive Director, Ken Travous.

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# GEOLOGY OF KARTCHNER CAVERNS STATE PARK, ARIZONA

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*Kartchner Caverns is developed entirely within the Mississippian Escabrosa Limestone in an isolated fault block along the east flank of the Whetstone Mountains in southeastern Arizona. The geology of the cave, along with the detailed surface geology, was studied and mapped in preparation for commercial development of the cave. Seven black to dark-gray marker beds throughout the lower Escabrosa section provided the key for unlocking the geology of Kartchner Caverns and the surface area. A 130 m measured stratigraphic section shows the distribution of these key organic-rich marker beds. More than 60 mapped faults cut Kartchner Caverns and probably date to the Miocene emplacement of the Kartchner block. Three geologic cross-sections illustrate how Kartchner Caverns developed near the 1408 m msl base level, and then stoned upwards along faults to resistant ceiling beds. Kartchner Caverns has been stable in its development for >50Ka.*

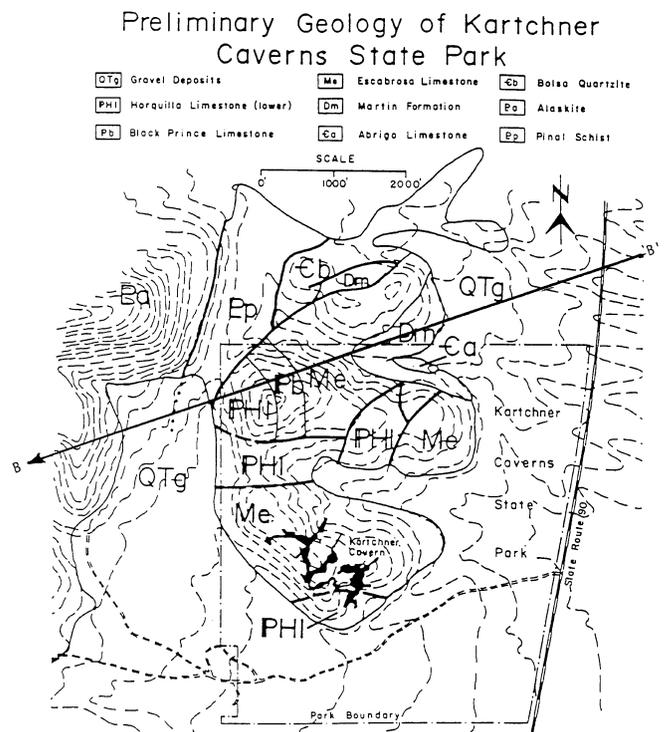
This study of Kartchner Caverns during 1990 and 1991 provides a detailed understanding of the geology in preparation for the commercialization of this spectacular cave resource. Initially, the subsurface geology was mapped within the cave. Later, the author also mapped the Park's surface geology. Key dark marker beds within the lower Escabrosa Limestone were used to tie the geology within the cave to the surface geology. Marker beds were also used to calculate displacements on more than 60 faults cutting Kartchner Caverns.

Geologic cross-sections provided a better understanding of where to locate the entrances of Kartchner Caverns for commercial development. Mapping of potentially hazardous ceiling blocks also helped determine the eventual layout of the commercial trails. Structural analysis of the cave helped with the understanding of how present-day water infiltrates the cave along faults and fractures, and forms perched aquifers on top of impermeable marker beds. Detailed mapping of the faults and fractured zones also helped determine where the tunnel excavations would experience difficulties and additional expense. Understanding the geology of Kartchner Caverns should ultimately allow for better management of the cave.

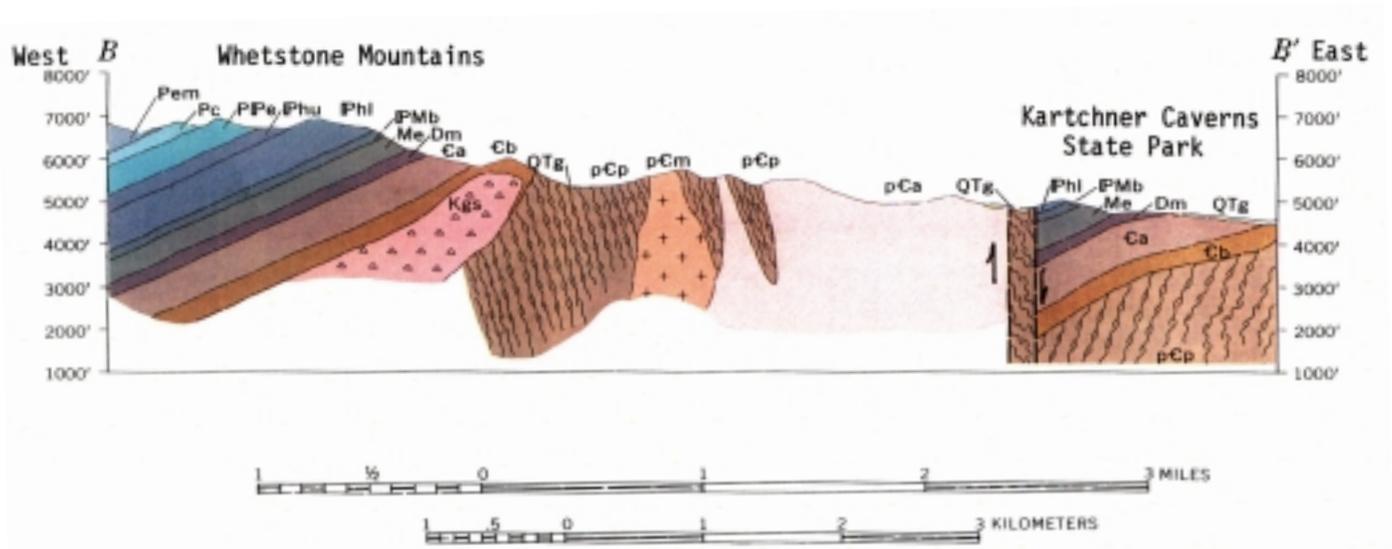
Upon discovery in 1974, Kartchner Caverns had only one small entrance. Early explorers had to crawl 100 m and negotiate one tight squeeze before they discovered the Big Room (Tufts & Tennen 1999). To get to the Rotunda and Throne Rooms, explorers had to wade through waist-deep mud. In order to develop the cave for visitors, more-accessible entrances and routes needed to be constructed. The preferred access points should lead conveniently to the cave's key features, dovetail into a planned traffic pattern, and accommodate the number of people that the cave can carry. Access points should also be amenable to microclimate controls, structurally stable, easily excavated, and accessible to security supervision. A total of ten different locations were originally considered for potential entrances.

Based on a weighted point system, three potential entrances were finally selected for detailed geologic studies.

Each potential entrance was also considered for handicapped-accessible ramps, stairs, or elevators. Ultimately, the two current entrances were selected and successfully excavated. The geology of Kartchner Caverns, as presented in this paper, played a critical role in the selection of those entrances.



**Figure 1. Surface geology of Kartchner Caverns State Park as depicted by Creasey (1967). A portion of cross-section B-B' is shown in Figure 2 (from Wruckel *et al.* 1983, with geology modified slightly from Creasey 1967.)**



**Figure 2. Structural geology cross-section B-B' from Creasey (1967) showing relationship of Kartchner Caverns State Park to the Whetstone Mountains to the west. Kartchner Caverns is in the Escabrosa Limestone (Me).**

Figure 2 Legend:

| Age:                                 | Geologic formations:  |
|--------------------------------------|---|
| Tertiary & Quaternary                | QTg = Gila Conglomerate. Locally includes capping of pediment gravels.  |
| Cretaceous                           | Kgs = fine-grained granodiorite sill  |
| Lower Permian                        | Pem = Epitaph Formation, middle limestone and marl member.<br>Pel = Epitaph Formation, lower dolomite member.<br>Pc = Colina Limestone. |
| U. Pennsylvanian                     | PPe = Earp Formation.   |
| Middle & U. Pennsylvanian            | Phu = Horquilla Limestone, upper member.<br>Phl = Horquilla Limestone, lower member.  |
| U. Mississippian or L. Pennsylvanian | PMb = Black Prince Limestone.   |
| Mississippian                        | Me = Escabrosa Limestone (contains Kartchner Caverns)   |
| Devonian                             | Dm = Martin Formation   |
| Cambrian                             | Ca = Abrigo Limestone<br>Cb = Bolsa Quartzite   |
| Precambrian                          | pCa = Alaskite, includes aplite dikes.<br>pCm = Quartz monzonite.<br>pCp = Pinal Schist   |

REGIONAL GEOLOGIC SETTING

The regional geologic setting for Kartchner Caverns is best illustrated by the Geologic Map compiled by Creasey (1967). The Whetstone Mountains, immediately west of Kartchner Caverns, are a simple monoclinial uplift of westward- to south-westward-dipping rocks. This north-trending uplift is broken by relatively few faults, and exposes a more complete Paleozoic section than any other range in southeastern

Arizona. The Whetstone Mountains are part of the highly faulted Basin and Range Province, which covers the south-western half of Arizona, and continues to the north and west into Nevada and western Utah. Most of the ranges within this province are bounded by north-trending horst and graben faults, and the intervening valleys are filled with thick Tertiary and Quaternary sediments. Kartchner Caverns State Park encompasses the majority of a down-dropped block of Paleozoic rocks on the east flank of the Whetstone Mountains.

Figure 1 shows the geology of this fault block as mapped by Creasey (1967). The mineral resource potential of this area was further studied by Wrucke *et al.* (1983). Creasey's cross-section B-B' (Fig. 2) illustrates the structural nature of this fault block. It is bounded to the west by a high-angle normal fault that has down dropped the Paleozoic section nearly 3.2 km. Rocks in the low carbonate hills overlying Kartchner Caverns generally dip 15-35°SW (Fig. 2).

The area is actually much more faulted than indicated by Creasey, and has also been mapped by Thomson (1990). Kartchner Caverns lies entirely within the Mississippian Escabrosa Limestone, contrary to Creasey's map that shows the entrance within the Horquilla Limestone.

#### GEOLOGIC MAPPING

The author's original report to Arizona State Parks included a subsurface geology map of Kartchner Caverns at a scale of 1" = 50', a subsurface stratigraphic section at 1" = 20', and three cross-sections, A-A', B-B', and C-C', at 1" = 20' (Jagnow 1990). Original full-scale copies of these maps and cross-sections are available through Arizona Conservation Projects, Inc. In 1991, the author constructed a detailed surface geology map of Kartchner Caverns at a scale of 1" = 50'. The portion of that map directly over Kartchner Caverns is reproduced in this report at a smaller scale (Fig. 3). Upon completion of the detailed surface geology mapping, cross-sections A-A', B-B', and C-C' were revised slightly to more accurately tie together the surface and subsurface features (Fig. 4).

#### MAPPING METHODS AND PROCEDURES

Mapping the geology inside a cave is often easier than mapping the same geology on the vegetated surface because, except where obscured by secondary deposits, caves provide the geologist with an excellent three-dimensional, internal view of stratigraphy and structure and nearly "fresh" bedrock surfaces. For these reasons, the subsurface geology of Kartchner was mapped first, and then expanded to the surface. While Thomson (1990) mapped the Escabrosa Limestone as a single unit over all of Kartchner Caverns State Park, Jagnow (1991) mapped the detailed geology directly above Kartchner Caverns, subdividing the Escabrosa Limestone into multiple units.

Strikes, dips, fault traces, and major fracture traces were sketched on the 1" = 50' base maps during in-cave and surface inspections. The maps proved very accurate. Powerful battery-operated spotlights and numerous photographs allowed geologic mapping from existing trails within the cave.

#### STRATIGRAPHY

The Kartchner Caverns geologic section is so broken by faults that there is no single location within the cave or on the surface displaying an uninterrupted stratigraphic section. The

measured stratigraphic section (Fig. 5) was pieced together throughout the cave and on the surface. Some surface locations have complete sections, but are partially covered by talus.

Initial observations throughout the cave revealed a series of "black beds" (actually dark gray) that can be traced throughout the entire cave. These prominent dark beds have been mapped as key stratigraphic marker beds, designated by the numbers zero (0) through five (5) in ascending order on Figure 5. Although similar in outward appearance, each bed has its own characteristic lithology and fossil assemblage, with distinctive intervening sequences. These six beds, plus a horn coral bed between units zero and one (also colored), provided the keys for mapping the entire cave and the detailed surface geology.

The measured stratigraphic section was established as follows: 1) Powerful spotlights were used to examine the geologic section along the northeast wall of the Big Room (within a single fault block) and northeast wall of the Throne Room (Fig. 6). Bed thicknesses were estimated and coloration was accurately described. 2) The identical section was then located and measured on the surface, immediately east and north of the cave. This allowed for accurate lithologic description and for an additional measured section above the Big Room section. 3) Additional section was described throughout the River Passage and out to Granite Dells. The abundance of faults in this area made it difficult to accurately determine thicknesses of this upper portion of the section. 4) Photographs were taken showing the bedding and faults in the Big Room and Throne Room. 5) Laser cross-sections were made through the Big Room and Throne Room, pinpointing the location of all prominent beds. This provided accurate thickness measurements, as well as the dip of the bedding plane ceilings. 6) Laser cross-sections were combined with the photographs and surface descriptions to produce the detailed stratigraphic section shown in Figure 5.

Kartchner Caverns is developed in 69 m of the Mississippian Escabrosa Limestone. The thickness of specific beds varies throughout the cave, and a range of thicknesses is given for some of the more studied units. The lowest portion of the geologic column (marker bed 0) is exposed in Echo Passage and Pirate's Den, along the northeast side of the cave. The highest portion of the stratigraphic section (marker bed 5) is located in Granite Dells, the southwestern extremity of the cave.

Figure 5 shows the minimum thickness of beds, and as such, best represents the measured section in the Big Room or front section of the cave. The bedding thicknesses in the back section of Kartchner Caverns (Throne Room, Rotunda Room, and beyond) are consistently thicker than in the front section of the cave. The entire section thickens to ~82 m as indicated on cross-sections B and C. These differences will be described in more detail in the discussion of the cross-sections, but may indicate a substantial amount of strike-slip movement along the fault zone between the Throne Room and Cul-de-sac Passage.

The key stratigraphic marker beds, 0 through 5, each have



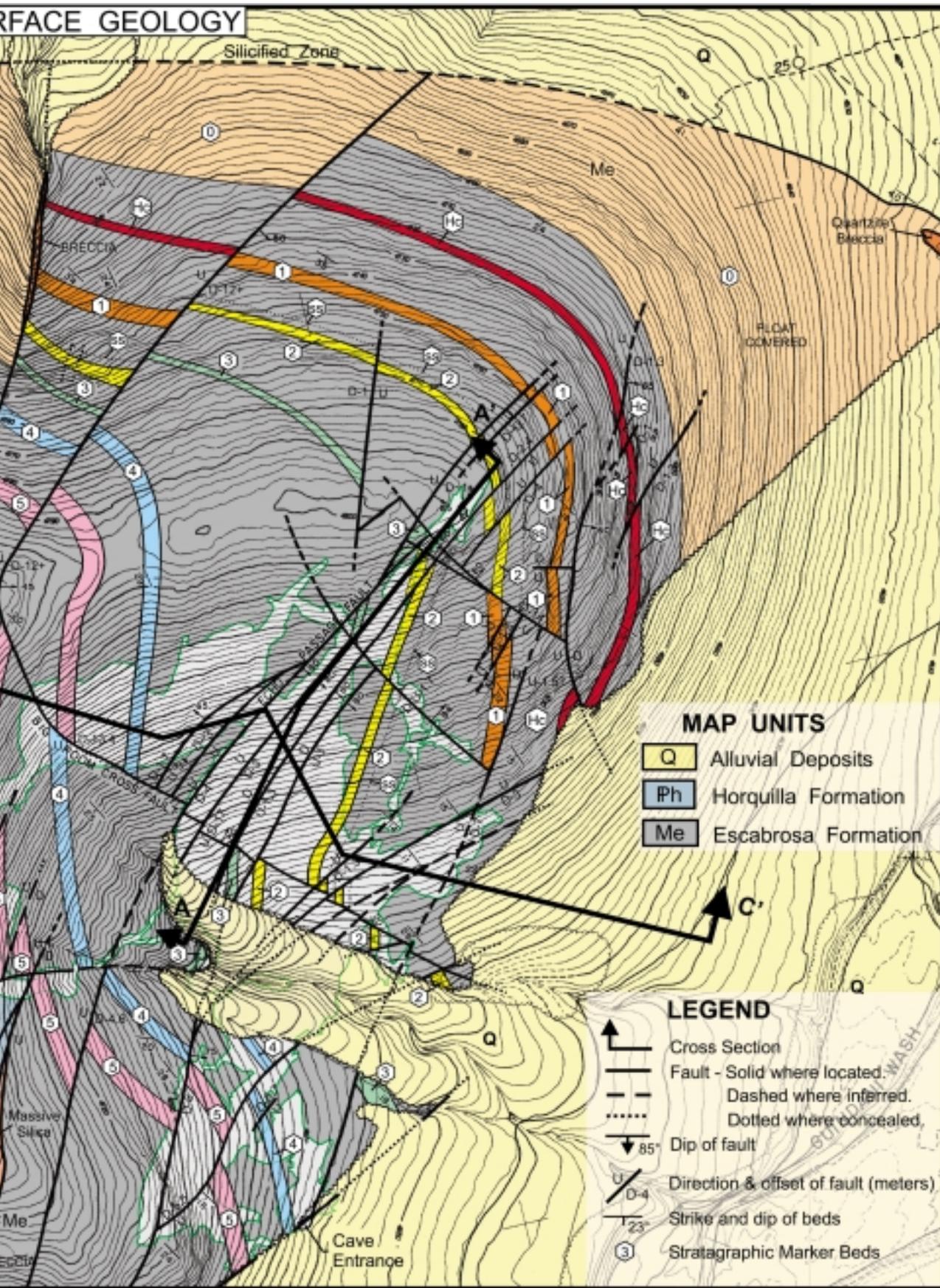


Figure 3.  
Detailed surface geology of Kartchner Caverns.

distinctive lithologies (Fig. 5). All of the units appear black in the cave due to a high percent of organic matter. When broken, the rock yields a “fetid odor”; i.e., smelling faintly like oil. On the surface, these units are more easily eroded, forming slopes between the adjacent cliff-forming limestones and dolomites. Most of these dark beds are aquicludes, unable to absorb water because of the high organic content within the rock. They serve as perched aquifers, with water seeping into the cave along the top of each bed, commonly forming rows of stalactites from the bed. Within the cave it is often impossible to determine the character of a bed if it is well out of reach on the cave ceiling or wall. Therefore, the unique intervening sequences above and below each marker bed often determined stratigraphic position.

Figure 7 is a wide-angle photograph and overlay interpretation of the northeast wall of the Big Room. It shows marker beds 1, 2, and 3, as well as the fault interpretation, and the location of cross-section A-A'. The unique stratigraphic signature of the interval below bed 2 is perhaps the most easily recognized sequence in the entire cave (Fig. 5). Bed 2 is underlain by 0.6 to 1 m of very light tan limestone, which is underlain by 1 to 1.2 m of red-brown sandstone or sandy limestone. The sandstone is underlain by a lighter tan limestone, which is underlain by another distinctive series of three thin, wavy beds—reddish limestone, over tan limestone, over more reddish limestone. This unique signature very closely matches a sequence in the Throne Room and provides positive identification of the Throne Room section.

#### REGIONAL STRATIGRAPHIC COMPARISON

Creasey (1967) measured a 170 m section of Escabrosa Limestone along the north flank of the Whetstone Mountains, ~11.2 km west-northwest of Kartchner Caverns. Judging from the location of Kartchner Caverns relative to the surface outcrops, the Kartchner Caverns stratigraphic section should be equivalent to the bottom half of the Escabrosa section. Indeed, the bottom 146 m of Creasey's section correlates very well with the 130 m Kartchner Caverns section with equivalent units shown in Table 1. It appears that the lowest stratigraphic point within Kartchner Caverns, the northeast end of the Pirate's Den and Echo Passage, must come within a few meters of the top of the Martin Formation.

The Kartchner Caverns stratigraphic section (Fig. 5) includes the lower 130 m of Escabrosa Limestone. The underlying Martin Formation crops out at the eastern tip of the Kartchner block. The actual thickness of the basal dolomite (marker bed 0) is uncertain. This unit is truncated by faulting along the northern edge of the Kartchner block, and is truncated by the eastern end of the South Valley fault where it contacts the Martin Formation.

Aside from variations in thickness, the only major differences are that marker bed 4 is missing in Creasey's section, and interval 3-4 is a cherty limestone at Kartchner, but has been altered to a cherty dolomite in Creasey's section. These dis-

tinctive marker beds in the Escabrosa Limestone may, perhaps, correlate for great distances.

**Table 1. Correlation of Kartchner Caverns stratigraphic section to that of Creasey (1967).**

| Kartchner Caverns Section:                 | Creasey's Section F:                     |
|--|--|
| Interval 5+: 9.1 m cherty limestone        | 5. 7.9 m massive cherty limestone        |
| Marker Bed 5: 3.0 m dk. gray ls.           | 6. 6.0 m dk. to med. gray thin limestone |
| Interval 4.7: 6.7 m cherty dol. slope      | 7. 15.2 m cherty dolomite slope          |
| Interval 4.2: 6.4 m cherty ls. cliff       | 8. 8.3 m massive ls. cliff               |
| Marker Bed 4: 3.0 m crin. ls. slope        | —————missing—————                        |
| Interval 3-4: 21.3 m cherty ls. pinkish    | 9. 15.2 m cherty dol. pinkish in part    |
| Marker Bed 3: 1.5 m black dol. w/hematite  | 10. 9.7 m black dol. local pink          |
| Interval 2-3: 8.5 m massive gray ls. cliff | 11. 8.5 m massive gray ls. cliff         |
| Marker Bed 2: 2.4 m dk. gray dol. slope    | 12: 7.6 m dk. gray dol. slope            |
| Interval 1.4+: 6.4 m ls. w/ ss. cliff      | 13: 20.4 m massive ls. cliff             |
| Interval 1.2: 3.0 m wavy-bedded thin ls.   | 14: 4.3 m thin-bedded dk. gray dol.      |
| Marker Bed 1: 3.4 m dk. gray ls. w/corals  | 15: 3.7 m dk. gry. ls. w/ss streaks      |
| Interval 0.9: 3.0 m thinly bedded ls/dol   | 16: 4.0 m thinly bedded impure ls.       |
| Interval 0-0.9: 21.3 m massive ls. cliff   | 17: 17.7 m massive ls. cliff             |
| Marker Bed 0: 30.5 m dk. gray sandy dol.   | 18: 17.0 m gray massive dol.             |
| Martin Formation—————                      | Martin Formation—————                    |

#### STRUCTURAL GEOLOGY

Compared to most of the Basin and Range, the Whetstone Mountains are relatively simple and unfaulted. However, the down-dropped block that contains Kartchner Caverns has been broken by thousands of small displacement faults. More than 60 mapped faults cut Kartchner Caverns. All the major passages and rooms in the cave are controlled by base-level solution along these faults.

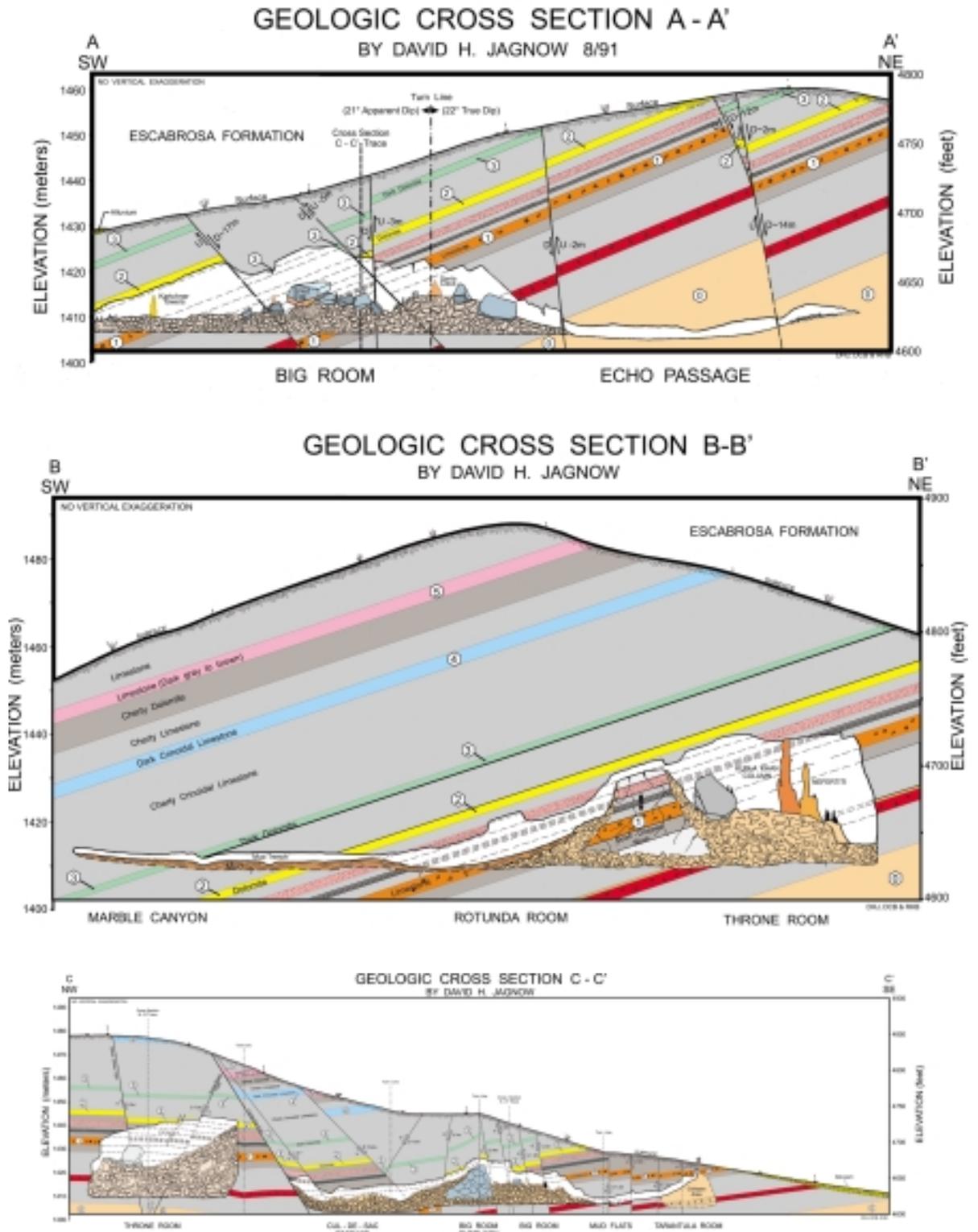
The majority of faults exposed in the Caverns are high-angle normal faults trending northeast from 20° to 60°. Most of these faults are vertical or dip steeply to the southeast. Fault displacement is usually <3 m. The faults are highly variable, curving along strike, changing dip, bifurcating and merging with one another. The southwest end of the Australia Room is a good example. The fault swarm from Sharon's Saddle merges with the more northerly fault from Grand Central Station. The amount of displacement along the faults also varies, occasionally dying out into a fracture with no displacement. The Red River fault/fracture is an example with no surface expression.

Most of the faults are marked by an abundance of reddish-brown limonite (iron-oxide) staining. About one-third of the fault zones are also filled with quartz (Hill 1999). The best example of a quartz-filled fault is at the Quartz Divide, where the main Throne Room-Rotunda Room fault zone is filled with 0.3 m of white quartz. The quartz-filled fault zone has been left standing while the cave dissolved out around it, leaving a quartz wall from floor to ceiling. The trail leads through a break in the quartz wall. On both sides of the Quartz Divide, quartz has also filled the fractured bedrock, allowing exquisite quartz boxwork to weather out in the ceilings.

The Cul-de-sac fault (Fig. 3), which terminates the west end of the Cul-de-sac Passage and controls the alignment of the River Passage, appears to structurally separate the east and

Figure 4.

Geologic cross-sections A-A', B-B', & C-C'.



west sections of Kartchner Caverns. This fault has at least 16 m of vertical displacement between the Throne Room and Cul-de-sac (Fig. 4, C-C'). The eastern section of the cave is cut by many more faults than the western section. Faults cut most of

the Big Room every 6 to 15 m. Fewer faults cross the western section of Kartchner Caverns (from the Throne/Rotunda passage to the northwest), which has a thicker stratigraphic sequence. Individual units are 2-4 m thicker than the equiva-

lent units immediately east of the Cul-de-sac fault, as if laterally offset some distance. Thus, it appears that the Cul-de-sac/River Passage fault may also have a substantial amount of strike-slip movement. Major movement on this fault is substantiated by the mineralized (primarily hematite) breccia zone at the end of the Cul-de-sac, and by the 1.8 m breccia zone between faults near the Shelf Passage.

Faulting in the western section of Kartchner Caverns is straight forward and easily mapped. Most of the faults are near vertical and of small displacement. Pirate's Den is, perhaps, the most structurally interesting area in the western section. It is developed entirely in the lowest black dolomite (marker bed 0), and the passages trace the outlines of the crossing faults.

Pirate's Den is terminated abruptly to the north by the intersection of a major east-west fault, the South Valley fault (Fig. 3). Within the cave, this fault is marked by abundant rust-colored limonite staining and fault gouge. However, on the surface the South Valley fault is the southernmost of a series of three major east-west faults composing a major fault zone 91 m across (K. Thomson 1990, pers. com.). Kartchner Caverns is terminated to the north by this major fault zone, which contains thick veins of quartz. There may be other caves north of this fault zone, but it is doubtful that Kartchner Caverns crosses this major insoluble zone.

#### DISCUSSION OF CROSS-SECTIONS

Cross-sections A, B, and C were all constructed at a scale of  $1' = 20'$  (Fig. 4). Wherever possible, laser generated profiles were incorporated into the cross-sections to provide accurate passage profiles and precise locations of specific marker beds.

Cross-section A-A' starts near the entrance to the River Passage, crosses the entire Big Room, and continues to the northeast out Echo Passage. The dipping ceiling above Kartchner Towers, along the base of marker bed 4, was used to determine the dip along the line of section. This dip,  $21^{\circ}\text{SW}$ , corresponds well to the  $20^{\circ}$  dips measured farther out in the Big Room, and a  $35^{\circ}$  dip just west of the Overlook. Section A-A' crosses two normal faults and three reverse faults. The geology is beautifully displayed along the northeast wall of the Big Room. The most complete, unfaulted section in the entire cave extends from the top of the Big Room into Echo Passage. The cross-section can be matched with the wide-angle photograph in Figure 7. The north end of Echo Passage must be close to the base of the Escabrosa Limestone, above the Martin Formation.

Cross-section B-B' begins in the southwest in the Marble Canyon Passage, crosses the Mud Trench, and climbs up through the Rotunda Room into the Throne Room at the northeast end. The Throne Room profile is laser generated and tied to the geology. The remainder of this profile was generated from the original survey data (floor elevations and ceiling heights). Once again, the location of known marker beds indicated an apparent dip along the section of  $18^{\circ}$ , which correlates well with a true dip of  $22^{\circ}$  measured in the Throne Room.

The Rotunda Room and Throne Room are collapse rooms. These rooms originally dissolved out near the 1408 m msl elevation, and then the ceilings slowly collapsed, or stopped, upwards 12-21 m until they reached competent beds that supported this great expanse. Finally, the rooms stabilized at their current configuration, and travertine grew on top of the breakdown floors. Judging by the size of the massive speleothems, these rooms have been stable for tens of thousands, if not a hundred thousand years. Dates on bat guano piles on top of the breakdown indicated there has been no significant collapse for at least 50 Ka (Buecher & Sidner 1999). The only true solutional cave shown on cross-section B-B' is at the southwest end (Marble Canyon, Mud Trench, and SW end of Rotunda Room).

The large block between the Rotunda and Throne Rooms is interpreted to have dropped more or less intact, as the rock units in the block correspond to the ceiling about 1.5 m above. The geologic interval below marker bed 1 correlates very closely to the front of the cave. The bottom of the Throne Room comes very close to intersecting the black dolomite of marker bed 0, which is actually exposed just inside the North Passage.

Cross-section C-C' is, perhaps, the most revealing of all three cross-sections. With several of the faults in the cave, it was impossible to determine the amount of vertical displacement underground. However by matching the measured stratigraphic section with the known locations of marker beds on the cross-sections, a reasonable displacement could be determined for almost all of the faults.

The cave passages depicted in cross-section C-C' were mostly laser generated, except from the Cul-de-sac turn-line east to the Big Room Overlook turn-line. That portion of the cross-section, cutting up the back side of the Big Room Overlook, is based on estimated ceiling heights. Of primary importance on this cross-section is the relationship of the Cul-de-sac Passage to the Throne Room. These rooms are closer

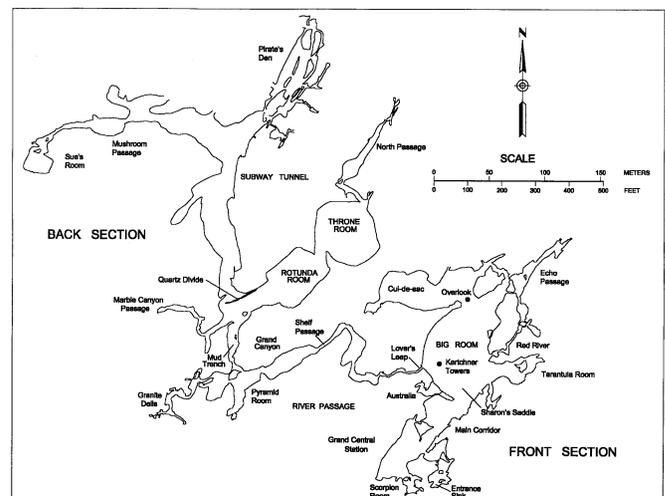


Figure 6. Kartchner Caverns place names index map.

than the original maps showed, and are separated by at least one major fault. The Cul-de-sac/River Passage fault appears to have at least 16 m of throw. There are actually two parallel faults, dipping 70°SE. Between these two faults, separated by about 9.1 m, is a highly mineralized (limonite) zone of fault breccia. The stability and lateral extent of this zone was of major concern in considering construction of a tunnel between the Cul-de-sac and Throne Rooms, and proved a major obstacle during the blasting of the Throne Room entrance tunnel.

A second concern was the profile of breakdown beneath the southeast end of the Throne Room. Section C-C' shows a nearly vertical breakdown/bedrock contact. An alternative interpretation would have the breakdown/bedrock contact dipping 53°, and intersecting the end of the Cul-de-sac. However, this does not appear to be the case. The limonite-stained wall at the end of the Cul-de-sac is interpreted as highly-fractured bedrock, rather than cave breccia.

Cross-section C-C' also illustrates that the Big Room Overlook is perched atop another large breakdown block similar to the block between the Throne and Rotunda Rooms. This block is visible along the northwest wall of the Big Room, just southwest of the Overlook.

The southeast end of C-C' illustrates how close the Tarantula Room comes to the surface. The Tarantula Room is a large collapse cone. The highest surveyed point is within 1.8 m of the surface. When considering a commercial entrance to the cave, this location was given high priority, and eventually became the exit for the tour. The area southeast of the Tarantula Room collapse was more highly fractured than depicted on the cross-section, and proved very difficult to excavate because of its instability.

#### CONCLUSIONS

Kartchner Caverns is developed entirely within the lower portion of the Mississippian Escabrosa Limestone in an isolated fault block along the east flank of the Whetstone Mountains in southeastern Arizona. Seven black to dark-gray marker beds throughout the lower Escabrosa section provided the key for unlocking the geology of Kartchner Caverns as well as the surface geology. A 130 m measured stratigraphic section shows the distribution of these organic-rich marker beds. Kartchner Caverns is cut by more than 60 mapped faults that probably date to the emplacement of the Kartchner block during Miocene time. Three geologic cross sections illustrate how Kartchner Caverns developed near the 1408 m elevation base level, and then stoped upwards along faults to resistant ceiling beds. The massive speleothems that rest atop the breakdown floors attest to the fact that Kartchner Caverns has been stable in its development for more than 50,000 years.

#### ACKNOWLEDGMENTS

The author wishes to thank the Arizona State Parks and Arizona Conservation Projects Inc. for their support of this project. Special thanks are in order to Bob and Debbie Buecher who helped in many ways and did all of the cartography and final drafting. I wish to further thank Jeff Dexter, Anita Pape, Carol Hill, Cyndi Mosch, Tom Faulkner, and the other cavers and employees who assisted with my underground mapping. The findings in this paper and the accompanying maps represent only a portion of the combined efforts of the members of the National Speleological Society.

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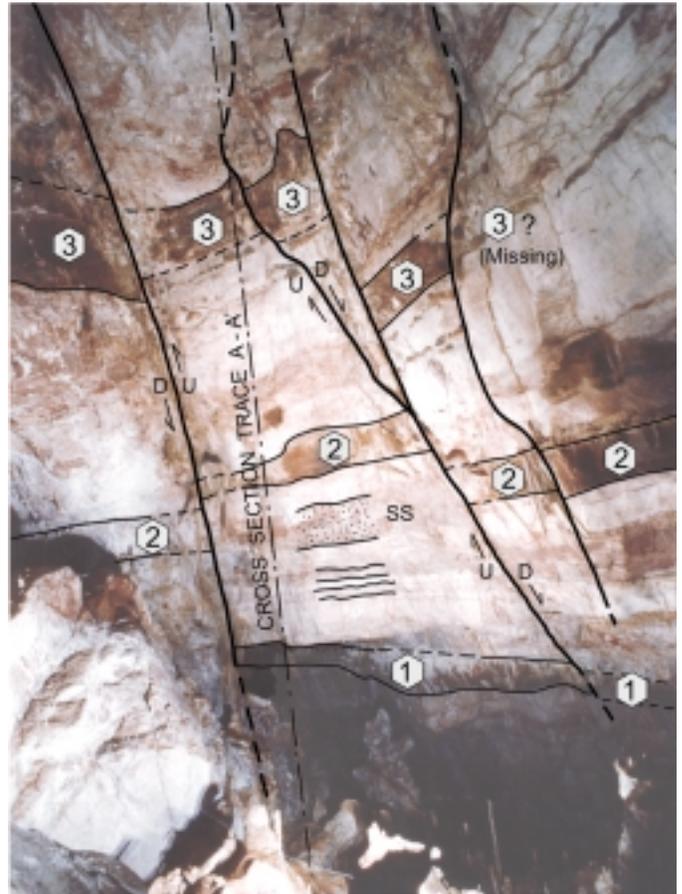
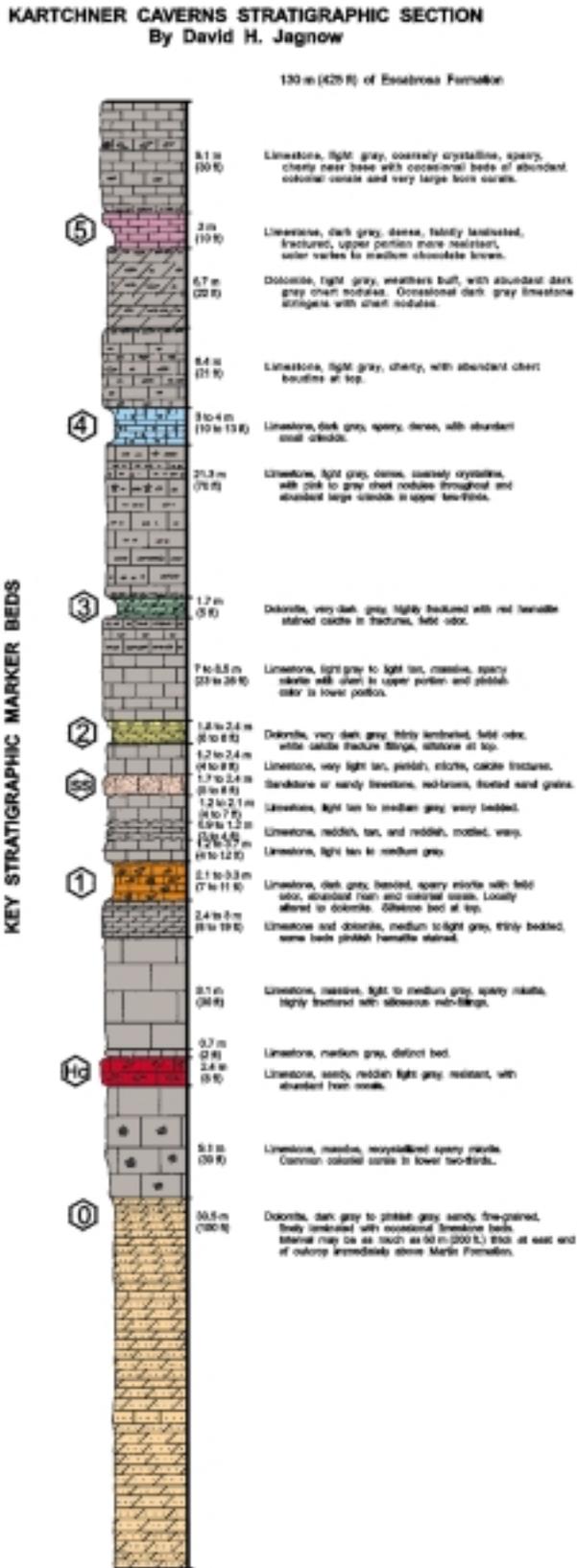


Figure 7. Photograph with stratigraphic interpretation of the northeast wall of the Big Room, showing key marker beds, fault interpretation, and location of cross-section A-A'. The unique stratigraphic signature of the interval below marker bed 2 is matched in the Throne Room.

Figure 5. Kartchner Caverns stratigraphic section.

# HYDROGEOLOGY OF KARTCHNER CAVERNS STATE PARK, ARIZONA

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2725 East Silverwood Drive, Phoenix, Arizona 85048 USA

Three distinct hydrogeologic systems occur within Kartchner Caverns State Park, Arizona, each in fault contact with the other two. The southeastern corner and eastern edge of the park is part of the large graben that formed the San Pedro Valley during Miocene Basin and Range faulting. A thick alluvial sequence fills this graben and contains a regional aquifer covering 1000 km<sup>2</sup>. One well in the park penetrates this aquifer. The groundwater level measured in this well was 226 m below land surface (1167 m msl), which is 233 m lower than the lowest measured point inside of Kartchner Caverns (1400 m msl).

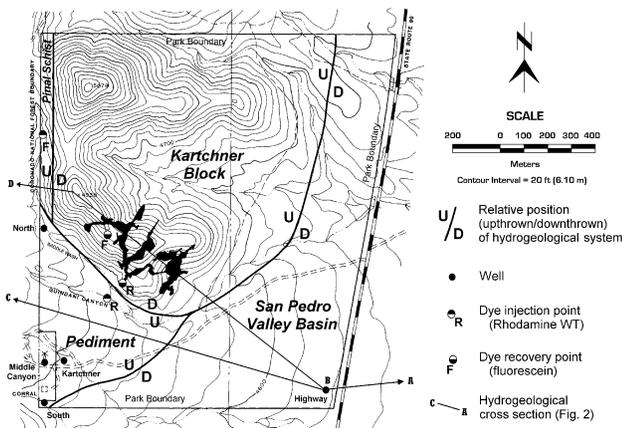
A pediment occupies a small part of the southwestern corner of the park. Structurally, this feature is part of the Whetstone Mountains horst rising above the park to the west. The pediment consists of a bedrock surface of Precambrian Pinal Schist overlain by a few tens of meters of "granite wash" sediments. Groundwater occurs at depths of 4-18 m below land surface in wells tapping the granite wash sediments. Data from these wells indicate that the zones of saturation within the granite wash sediments are probably of limited lateral extent and yield little water to wells. At the boundary between the pediment and the carbonate ridge containing Kartchner Caverns, the water table in the granite wash aquifer is 20 m higher than the bottom of the nearest known cave passage, located about 200 m to the east.

The arid carbonate hills occupying the northwestern part of the park are the erosional remnants of a fault block (the Kartchner Block) that was displaced downward with respect to the Whetstone Mountains horst to the west. Kartchner Caverns is wholly contained in a ridge of highly faulted Mississippian Escabrosa Limestone and cuts conspicuously across Escabrosa beds dipping 10-40° to the southwest and west. Meteoric water enters the Kartchner Block and Kartchner Caverns from infiltration of runoff in washes that border the block and from overhead infiltration of precipitation. A small amount of groundwater also may flow into the Kartchner Block from the schist pediment to the south. Response in the cave to these fluxes is slow. As calculated from past records, the probability of flooding in the cave in any one year is about 57%.

Kartchner Caverns State Park, Cochise County, Arizona, encompasses 223 ha of arid limestone hills and adjacent alluvial slopes at the base of the eastern flank of the Whetstone Mountains. These mountains steepen rapidly west of the park, cresting 5 km away at 2252 m msl (above mean sea level). The

park's highest point, a limestone hill near the northwest corner at 1548 m msl, overlooks the broad San Pedro Valley to the east. A pediment overlain by alluvium occupies the southern part of the park, forming the upper end of an alluvial plain that slopes gently to the San Pedro River 13 km to the east (Figs. 1 & 2).

Guindani Canyon cuts deeply into the mountains west of the park. Within the park, this drainage is an ephemeral desert wash (Guindani Wash) that flows along the limestone hills, separating them from the alluvium-covered pediment to the south (Fig. 1). Sporadic storm-water runoff from the Whetstones flows through the park in Guindani Wash, as well as calmer flows from undependable winter snowfalls. Runoff in Guindani Wash and its tributary, Saddle Wash, is the major source of water infiltrating to Kartchner Caverns.



**Figure 1. Hydrogeologic boundaries, well locations, and dye trace injection and recovery points.**

## FIELD INVESTIGATIONS

A variety of field activities have contributed to knowledge about the hydrogeology of Kartchner Caverns State Park. Graf (1989) inspected the park and surrounding area for water wells. Six wells were inventoried that bear on this report, four located within the park and two in adjacent areas (Figs. 1 & 2;

Table 1). Wellhead elevations were determined by spirit leveling, and water levels and well depths were measured. A continuous water level recorder was installed on the well nearest Kartchner Caverns (North Well) on 18 June 1988. Water levels in three other wells were measured weekly for more than three years. Water samples were collected from wells, and specific electrical conductance and temperature were measured. Pumping tests of three wells were conducted to assess well and aquifer yield for a potable water supply for the park (Johnson 1991; Buecher 1992).

**Table 1. Selected water well data.**

| Well Name:<br>Highway                                | Black              | North              | Middle<br>Canyon    | Kartchner           | South              |
|--|--------------------|--------------------|---------------------|---------------------|--------------------|
| Arizona Well Identification Number:                  |                    |                    |                     |                     |                    |
| (D-18-20)<br>30cdc                                   | (D-18-20)<br>21dcb | (D-18-19)<br>25dbb | (D-18-19)<br>25dcb1 | (D-18-19)<br>25dcb2 | (D-18-19)<br>25dcc |
| Well Depth (m):                                      |                    |                    |                     |                     |                    |
| 240.8 R  | 175.3 R            | 10.4 M             | 62.5 R              | 67.1 R              | 17.7 M             |
| Well Diameter (cm):                                  |                    |                    |                     |                     |                    |
| 16.5   | 20.3               | 81.3               | 15.2                | 16.5                | 91.4               |
| Construction Method:                                 |                    |                    |                     |                     |                    |
| Drilled  | Drilled            | Dug                | Drilled             | Drilled             | Dug                |
| Date Constructed:                                    |                    |                    |                     |                     |                    |
| ca. 1984   | 1976               | 1930s (?)          | 1948                | 1977                | —                  |
| Use:   |                    |                    |                     |                     |                    |
| Capped   | Stock              | Unused             | Stock               | Capped              | Unused             |
| Pump:  |                    |                    |                     |                     |                    |
| None   | Windmill           | None               | Windmill            | None                | None               |
| Land Surface Elevation (m msl):                      |                    |                    |                     |                     |                    |
| 1392.30  | 1286.9             | 1438.87            | 1436.61             | 1432.13             | 1427.59            |
| Water Level Depth Below Land Surface, June 1989 (m): |                    |                    |                     |                     |                    |
| 225.3  | 157.9              | 7.36               | 18.29               | 16.38               | 6.96               |
| Elevation of Water Level, June 1989 (m msl):         |                    |                    |                     |                     |                    |
| 1166.47  | 1128.9             | 1431.40            | 1418.63             | 1415.76             | 1420.6             |
| Water Temperature (°C):                              |                    |                    |                     |                     |                    |
| —  | 26.5               | 20.5               | 24.0                | —                   | 21.0               |
| Specific Elec. Conductance at 25°C, (µS/cm):         |                    |                    |                     |                     |                    |
| —  | 377                | 393                | 318                 | —                   | 859                |

Notes:

1. Well depth measurements: R = Reported in driller's log, M = Measured during this investigation.
2. Samples for temperature and specific electrical conductance measurements were pumped from windmills and bailed from other wells.

Flows and floods in the normally dry surface drainages of the park were noted and correlated with water level changes in the wells and hydrologic observations in the cave. Precipitation and other data from the surface weather station augmented these observations, along with results of a cave drip water study, water quality measurements, and surface-to-cave dye tests (Buecher 1992). Jagnow (1990) mapped the subsurface geology of the cave, including paleocurrent directions based on analysis of solutional scallops. Hill (1992) and

Jagnow (1990) interpreted 82 corrosion bevels in the cave as evidence of multiple late-stage flooding events. Lange *et al.* (1990) conducted surface geophysical surveys using natural potential (NP) profiling, electromagnetics (EM), and gravity techniques. These surveys further defined hydrogeologic relationships in the park and caverns.

#### REGIONAL HYDROGEOLOGIC SETTING

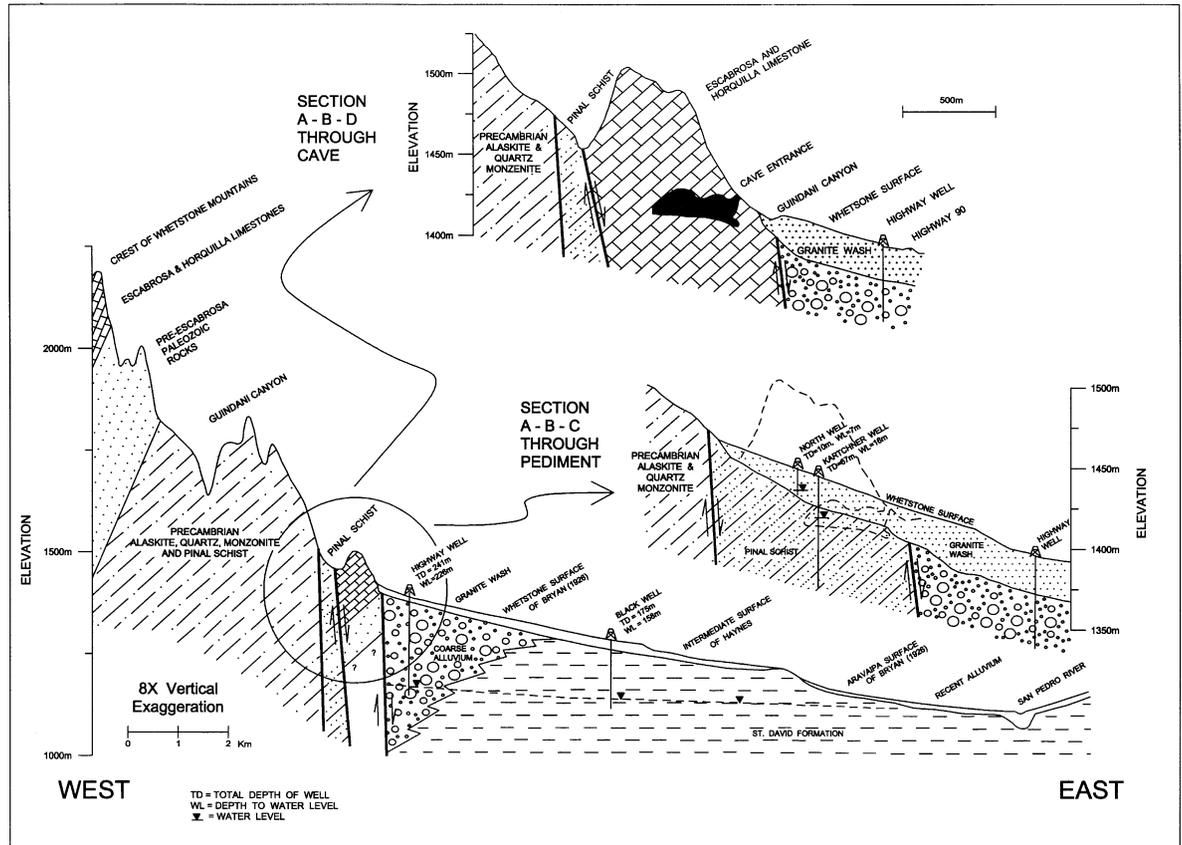
Basin and Range tectonism shaped the scenic landscape of the San Pedro Valley and bordering Whetstone and Dragoon Mountains. This tectonic event, the Basin and Range Disturbance, created a horst-and-graben topography throughout western and southern Arizona during Miocene time by uplifting ranges along generally north and northwest trends about 10-30 km apart and depressing the intervening basins. In the San Pedro Valley, the Basin and Range Disturbance probably began between 13 and 10 Ma and ceased between 8 and 5 Ma (Menges & Pearthree 1989).

As the San Pedro Valley graben subsided, alluvial sediments washed in, eventually accumulating to a substantial thickness. Most of these deposits are Pliocene and Pleistocene, fine-grained, fluvial and lacustrine sediments named the St. David Formation by Gray (1967). This sequence is overlain by younger deposits of "granite wash" and Holocene alluvium. The total thickness of the alluvial sequence is not known, but water wells drilled to over 300 m in depth near St. David bottom in sediments similar to those of the St. David Formation (Gray 1967). The St. David Formation extends across the basin and is bounded by the Basin and Range faults that coincide with the mountain fronts. Paleomagnetic dating of the St. David Formation indicates that the uppermost extant sediments were probably deposited soon after the Brunhes-Matuyama paleomagnetic chron boundary (Johnson *et al.* 1975), now dated about 780 Ka.

A well drilled for livestock watering in about 1984 at the southeast corner of the park establishes with some certainty the location of the main Basin and Range fault in the park area. This well, the Highway Well, was drilled to a depth of 241 m without encountering bedrock (see Fig. 1 for well locations and Table 1 for well data). The driller logged "fairly well cemented alluvial materials consisting of fragments of decomposed granite, limestone, and quartz" (Don Weber, pers. com.). These sediments probably represent a coarser, cemented facies of the St. David Formation deposited at the basin margin contemporaneously with fine-grained sediments deposited toward the basin center. The Highway Well is thus located on the basinward side of the main Basin and Range fault, placing the fault between this well and shallow wells penetrating bedrock 1.1 km to the west. Lange *et al.* (1990) and Lange (1999, Figs. 2 & 3) used data from these wells to calibrate a gravity survey that enabled further definition of bedrock topography and the location of Basin and Range faulting. The western limit of the San Pedro Valley hydrogeologic system, as depicted in Fig. 1, was drawn by the author to coincide with points in the gravity

Figure 2.

Hydrogeologic cross-sections through Kartchner Caverns State Park.



survey cross sections of Lange *et al.* (1990) where the underground bedrock surface steepens appreciably toward the San Pedro basin. This steepening generally was evident at a depth of about 30-60 m below land surface in the cross sections. Based on this delineation, the southeastern corner and eastern edge of the park (35% of the park area) lie within the San Pedro Valley hydrogeologic system.

The Highway Well was capped after drilling due to poor yield. A water level measurement of 226 m below land surface was obtained from the well on 24 June 1989, during this investigation. The water level in Black Well, located 4 km eastward in the San Pedro basin, was also measured on the same date and was 158 m below land surface. The altitude of these two water level measurements define a low apparent gradient (0.012), basinward potentiometric surface that probably represents the unconfined mountainward extension of the regional confined aquifer underlying the San Pedro River near St. David. The water level elevation in the Highway Well is 1166 m msl, which is 233 m below the lowest measured point inside of Kartchner Caverns (1400 m msl in the Red River Room). In 1991, the Highway Well was uncapped and tested again for production, but yield was too small for use as a park water supply.

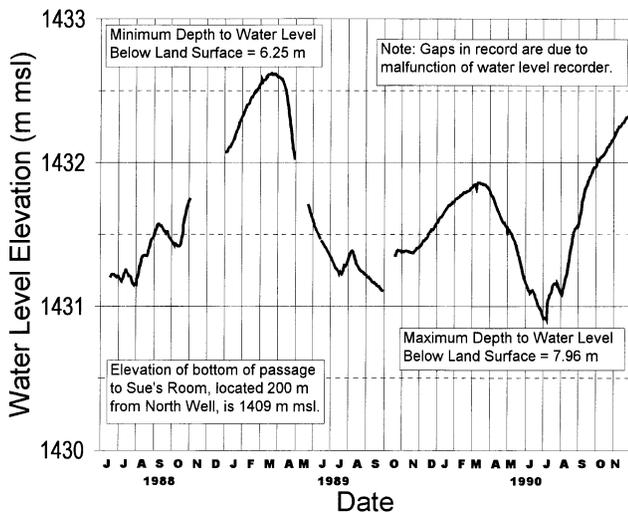


Figure 3. Hydrograph of water level in North Well.

HYDROGEOLOGY OF THE ALLUVIUM-COVERED PEDIMENT

The large number of wells constructed so close to Kartchner Caverns is fortuitous considering the paucity of groundwater development along the eastern side of the Whetstone Mountains. Originally constructed for stock watering and mining use, these wells have provided an understanding of the hydrogeology of the park that otherwise would have been largely speculative. This statement is particularly true in discerning the nature of the alluvium-covered pediment, which

was penetrated by four wells (North, Middle Canyon, Kartchner, and South Wells; Fig. 1).

The pediment surface, mapped by Bryan (1926), extends along the base of the Whetstone Mountains and slopes eastward into the San Pedro Valley for a distance of about 6 km, where it is truncated by a lower erosional surface (Fig. 2). This pediment surface, termed the Whetstone Surface by most later investigators including Melton (1965), is underlain by bedrock near the mountains and older alluvial deposits toward the basin. In the park, the Whetstone Surface is at the top of a deposit of granite wash, which blankets an erosional surface of Precambrian Pinal Schist. Gray (1967), who applied the informal name "granite wash" to this deposit, describes it as reddish-brown alluvium resembling decomposed granite and consisting of alluvial fan, mud flow, and stream deposits. Melton (1965) suggested an Illinoian age (170–120 Ka) for the granite wash based on stratigraphic relationships, and a Sangamon age (120–70 Ka) for the development of the red soil that formed at the top of the Whetstone Surface.

The thickness of the granite wash varies, but is not believed to be greater than a few tens of meters based on: 1) the depth of North Well and South Well (10.4 m and 17.7 m deep, respectively; Fig. 1), which appear to bottom at the schist contact; 2) the predominance of schist cuttings found beside the two drilled wells, Middle Canyon and Kartchner; and 3) the gradual slope of the schist surface exposed at the upper edge of the granite wash immediately west of the park boundary. Lange *et al.* (1990), using this information to calibrate the gravity survey, drew the trace of the main Basin and Range fault a short distance south of South Well. Based on this interpretation and the author's examination of the geophysical cross sections described in the previous section, the alluvium-covered pediment (Pinal Schist bedrock overlain by granite wash) comprises 9% of the park area (Fig. 1).

Non-pumping water table depths in the four wells penetrating the granite wash varied from 7–18 m below land surface in June 1989. Water table elevations of 1431, 1419, 1416, and 1421 m msl for the North, Middle Canyon, Kartchner, and South Wells, respectively, indicate that the water table probably lacks continuity over the area covered by these wells. In the North and South Wells, the source of groundwater is a zone of saturation above the schist bedrock surface within the granite wash sediments. The specific electrical conductance of water samples collected from the North and South Well differed considerably (393  $\mu\text{S}/\text{cm}$  and 859  $\mu\text{S}/\text{cm}$ , respectively), also suggesting a lack of connectivity of the saturated interval within granite wash sediments. At some locations, the granite wash may be unsaturated, and groundwater may occur within the schist below the alluvium contact.

Groundwater in the granite wash is assumed to flow in a generally southeast direction, consistent with the down dip direction of the underground Pinal Schist surface as depicted by Lange *et al.* (1990). East of the buried Basin and Range fault scarp, the groundwater level is more than 200 m deeper than west of the scarp. Groundwater flowing from the granite

wash west of the scarp is assumed to contribute to recharge of the regional San Pedro basin aquifer east of the scarp. However, the volume of flow through the granite wash aquifer is very small based on tests of the Middle Canyon and Kartchner Wells. The Middle Canyon Well was drilled in 1948 to a depth of 62.5 m. This well, used for livestock watering, presumably penetrates the Pinal Schist to a significant depth. Despite the possibility of obtaining some groundwater yield from weathered or fractured schist, the well can produce only about 380 L/day (Buecher 1992).

The Kartchner Well was tested more rigorously to determine its suitability as a park water supply. This well, located about 120 m southeast of the Middle Canyon Well, was drilled to a depth of 67 m in 1977 and capped. It also probably penetrates the Pinal Schist to a significant depth. After pumping at a rate of 42.4 L/min for 100 min with a water level drawdown of 18.4 m below pre-pumping level, the water level recovered only 0.58 m in 1 hr. The well still had not fully recovered 8 days later (Johnson 1991). Based on these pumping test results and all other data, groundwater yield from the granite wash aquifer is considered to be very minor. This condition is probably due to a combination of small saturated thickness, low hydraulic conductivity, and limited lateral extent and continuity of the saturated zones.

#### KARTCHNER CAVERNS HYDROGEOLOGY

##### THE KARTCHNER BLOCK AND CAVE SOLUTIONAL LEVEL

Kartchner Caverns is wholly contained within a ridge of highly faulted Mississippian Escabrosa Limestone. This ridge is structurally part of a fault block (the Kartchner Block) that was displaced downward with respect to the Whetstone Mountains horst to the west. The fault along which displacement occurred is located a short distance inside of and parallel to the west boundary of the park. The fault juxtaposes Escabrosa Limestone in the downthrown Kartchner Block against Pinal Schist to the west (Thomson 1990). The Pinal Schist similarly is downthrown with respect to intrusive Precambrian alaskite along a parallel fault located a few hundred meters further to the west, a short distance west of the park boundary. On the upthrown side of this fault, the Whetstone Mountains rise steeply, exposing an upward sequence of outcrops of alaskite, intrusive Precambrian quartz monzonite, Pinal Schist, and nearly the entire Paleozoic section, including Escabrosa Limestone, near the crest of the mountains (Creasey 1967, Fig. 2).

The Kartchner Block comprises 54% of the total park area (Fig. 1). (A narrow zone of exposed Pinal Schist, comprising 2% of the park area, parallels the west boundary of the park immediately west of the Kartchner Block). Within the Kartchner Block, Kartchner Caverns cuts conspicuously across Escabrosa Limestone beds dipping 10°–40° to the southwest and west. The profile of the cave is nearly horizontal, reflecting its initial development under shallow phreatic conditions. The water table must have been stable between an elevation of

1408-1411 m for a long period of time in order for the cave to have developed across dipping beds, poorly permeable fault gouge, and quartz veins (Hill 1999b). The most plausible explanation for this cave profile is the presence of a regional water table that once extended from the San Pedro Valley basin into the Kartchner Block.

The regional water table responsible for initial dissolution of Kartchner Caverns could have existed no later than 70 Ka, nor earlier than 780 Ka based on stratigraphic and geomorphic relationships. The 1408-1411 m cave solutional level is inferred to be lower in elevation than the adjacent Pinal Schist pediment surface, interpreted from the total depths of the dug North Well and South Well. The bottom elevations of these wells are 1428 and 1410 m, respectively, which probably represent where digging stopped at the schist surface. This also places the cave below the level of the granite wash (Fig. 2), which is Illinoian (170–120 Ka) (Melton 1965). According to Melton, a red soil formed on the granite wash during Sangamon time (240–70 Ka). Therefore, it is possible that a regional water table in the San Pedro basin could have developed to a level high enough to extend into the granite wash and Kartchner Block at the 1408-1411 m level through Sangamon time. However, by early or pre-Wisconsin time (ca. 70 Ka), the San Pedro River had cut down through the Whetstone Surface (Haynes 1967), lowering the base level and, hence, causing a decline in the water table. This downcutting event establishes the youngest possible date for initial cave formation, because a high enough regional water table could not have developed thereafter. It is not known if the St. David Formation extended high enough above the 1408-1411 level to contain a regional water table at that level, but an erosional unconformity at the St. David Formation-granite wash contact indicates that St. David Formation sediments once extended higher (Gray 1967). Because these sediments were deposited after 780 Ka (Johnson *et al.* 1975), this date establishes the maximum age for initial cave dissolution. These minimum and maximum dates for dissolution of Kartchner Caverns are consistent with radiometric dates from speleothems reported elsewhere in this issue (Ford & Hill 1999).

#### SOURCES OF CAVE WATER

Determined by the water level measurement from the Highway Well, the regional water table southeast of the Kartchner Block is more than 200 m below any known passage in Kartchner Caverns. Current hydrologic processes in the cave are vadose. Meteoric water enters the Kartchner Block and Kartchner Caverns from infiltration of runoff in washes that border the block and from overhead infiltration from precipitation.

It is unlikely that much groundwater occurring in the granite wash aquifer flows toward the Kartchner Block. This assumption is based on the gravity survey (Lange *et al.* 1990; Lange 1999), which depicts the surface of the schist bedrock dipping to the south adjacent to the contact between the pediment and the Kartchner Block. Thus, most groundwater in the

granite wash aquifer flows away from the block. However, some surface flow in Guindani Wash and its northern tributary, Saddle Wash, infiltrates into the granite wash aquifer immediately adjacent to the Kartchner Block and moves into the block.

The North Well provides further insight into the nature of the hydrogeologic relationships at this contact. This well, probably constructed in the 1930s for prospecting, was dug into the alluvium cover of the pediment less than 30 m from the south edge of the limestone ridge containing Kartchner Caverns. The water level in the North Well fluctuates between 6.3 and 8.0 m below land surface (1432.6 and 1430.9 m msl; Fig. 3). This level corresponds to a water table elevation that is more than 21 m above the bottom of the passage leading into Sue's Room (1409 m msl), which is located about 200 m from the North Well. However, water only enters Sue's Room if washes above are flowing, and then infrequently. Therefore, any groundwater moving from the alluvium-covered pediment into the Kartchner Block must drain deeper, bypassing all known passages of the cave. Although there appears to be no direct hydraulic connection between the water table at the North Well and known cave passage, measurement of the water level in this well is valuable as a sensitive indicator of the overall balance between groundwater recharge and discharge in the vicinity. Because there is no nearby pumpage of groundwater, rises and falls of the water level in the North Well reflect short- and long-term precipitation and climatological trends, which also affect cave microclimate and hydrology.

Meteoric water enters the cave through overhead infiltration of precipitation down faults and fractures, and on top of relatively permeable beds. The profusion of fractures and faults crossing cave passages is a major reason for the abundance and variety of cave decorations that distinguish Kartchner Caverns (Hill 1999a). Rows of stalactites grow on the ceiling along these weaknesses, sometimes accompanied by massive stalagmites below. Additionally, water from the land surface accumulates on and moves laterally into the cave



**Figure 4. Corrosion bevel in passage off of Mushroom Passage cuts horizontally across dipping bedding planes and truncates a large stalactite. Photo by Bob Buecher.**

on top of dipping, relatively impermeable beds within the Escabrosa Limestone. Jagnow (1999) mapped these beds inside the cave and noted rows of stalactites where the top of the beds cross cave ceilings.

Buecher (1992; 1999) conducted a drip study in the cave and estimated that ~230,000 L of water enters the cave by this mechanism per year, equivalent to a depth of 7.6 mm of water over the floor area of the cave. This rate corresponds to a recharge rate of about 2% of total precipitation on this limestone terrain. Buecher determined that drips form in response to storms within 4-12 days, depending on travel path length. The average flow rate of groundwater contributing to drips was about 15 m/day. The specific electrical conductance of the drip water increases with increasing flow path length, reaching a maximum of 450-490  $\mu\text{S}/\text{cm}$  after 80-110 m of travel, at which point the drip apparently reaches saturation with calcium carbonate. Buecher (1992) noted that deposition of calcite from drip water does not occur if the specific electrical conductance is less than 330  $\mu\text{S}/\text{cm}$ . Although drip water is important for speleothem formation and maintenance of high moisture levels in some parts of the cave, it is a small part of the cave water budget—10% or less—on a volume basis.

#### SURFACE FLOWS, CAVE FLOODING, AND CORROSION BEVELS

The most important component of the cave water budget is water entering the cave from infiltration of surface water flows into Guindani Wash and Saddle Wash (Fig. 1). Both washes trend adjacent to the limestone ridge containing Kartchner Caverns. Nonetheless, response in the cave to surface flows in the washes is slow. Sometimes significant surface flows do not result in any water entering the cave. For example, in August and September 1988, during a 30-day period when 158 mm of rain was recorded in the park's gage, Guindani Wash flowed almost continuously. Yet no flows or inundated areas were

noted in any part of the cave.

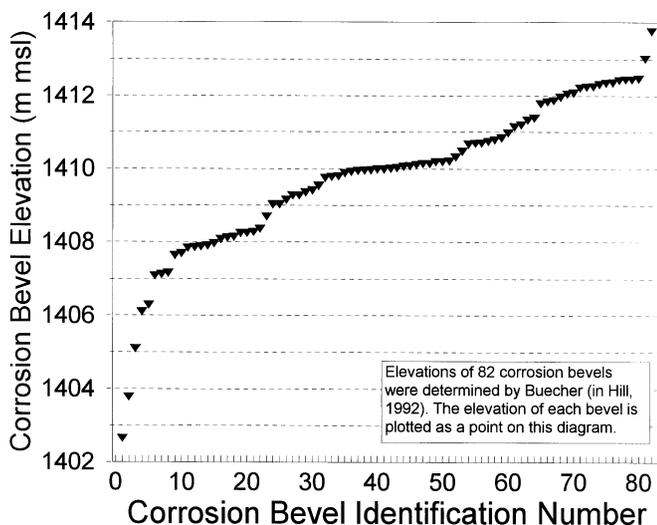
Buecher (1992; pers. com.) studied flows and flooding of the cave during the flood events of August 1990, January through August 1991, and April 1992. He developed the following predictors for the onset of flow and flooding in the cave:

1. Surface flows in Guindani Wash or Saddle Wash for a week or more.
2. Excess soil moisture exceeds 30.5 mm for a single month, or 38.1 mm for two consecutive months, as computed by the Thornthwaite method for determining potential evapotranspiration.

Although not perfect, these predictors reflect the two main factors appearing to control the onset of water flow into Kartchner Caverns: antecedent moisture conditions and sufficient water in the surface washes. Applying the excess moisture criterion listed above, Buecher (1992) analyzed the weather records from September 1954 through February 1991 for nearby Fort Huachuca/Sierra Vista, which has similar altitude, ambient air temperatures, and precipitation as Kartchner Caverns. He accurately predicted flooding in the cave in December 1978 and March 1985. These flooding events are the only ones during prior years that had been observed in the cave. Perhaps the cave flooded more often, but the events were missed due to the infrequency of cave visits during those years. Buecher (1992) determined that the excess moisture criterion would signal onset of flooding in 21 of the 37 years of record, a 57% probability of flooding in any one year. On a seasonal basis, 60% of the probable floods occurred in winter, 36% in summer, and 4% in fall.

Corrosion bevels in Kartchner Caverns provide striking physical evidence of past flooding episodes. Corrosion bevels are sharp, horizontal indentations, notches, and overhangs cut into cave walls and ceilings (Fig. 4). In Kartchner Caverns, corrosion bevels also have been etched into breakdown blocks and speleothems, in some cases completely truncating large stalactites or notching stalagmites (Ford & Hill 1999, Fig. 3). About two-thirds of the 82 corrosion bevels catalogued by Buecher (Hill 1992) cluster within an altitude range of 1408-1412 m, and 20% are incised within an altitude interval of  $1410 \pm 0.25$  m (Fig. 5).

Corrosion bevels typically form under static water level conditions when the water is undersaturated with respect to calcite (Ford & Williams 1989). Both Hill (1992; 1999b) and Jagnow (1990) considered the development of corrosion bevels in Kartchner Caverns to be the result of late stage flooding events under vadose conditions. They also noted that little speleothem growth has taken place since bevel incision, indicating a fairly late date of incision. Corrosion bevel development was probably aided by the aggressiveness of water entering Kartchner Caverns, inferred from the predominance of igneous and metamorphic rocks exposed in the catchment area of Guindani Canyon. Jagnow (1990) suggested that each bevel



**Figure 5. Distribution of 82 corrosion bevels by elevation (Hill 1992). Data supplied by R. Buecher.**

level corresponds to a nearby spillpoint, with the water surface stabilizing and then receding to a lower spillpoint as the cave drains. Jagnow noted that much more work is needed to fully understand the nature and significance of these features in Kartchner Caverns.

The mechanics of flooding in Kartchner Caverns were observed in detail by Buecher (1992; pers. com.). In some ways, the term *flooding* is inappropriate, as the process is prolonged over days and weeks—there is little danger of anyone being trapped in the cave. Inflows to the cave start on the land surface, where three infiltration points have been identified:

1. Saddle Wash downstream from North Well (1434 m msl, 23 m above Sue's Room, horizontal distance of 110 m from cave).
2. Junction of Guindani Wash and Saddle Wash (1423 m msl, 12 m above end of Granite Dells, horizontal distance of 49 m from cave).
3. Guindani Wash upstream of trail to cave (1419 m msl, 11 m above Crinoid Room, horizontal distance of 174 m from cave).

Lange *et al.* (1990) and Lange (1999) provided indirect evidence for the latter two locations, detecting natural potential (NP) anomalies that may indicate enhanced infiltration. The first two infiltration points were directly confirmed by use of a dye tracer during episodes of flow in the washes (Buecher 1992). In early September 1990, fluorescein dye was traced from Saddle Wash to a small stream emerging in Sue's Room after several weeks of intense rains and flooding on the land surface (Figs. 1 & 6). In January 1991, Rhodamine WT dye was traced from Guindani Wash to Granite Dells/Water Room. During the test, Guindani Wash was flowing, but Saddle Wash was dry, providing clear evidence of the linkage with Guindani Wash. Sustained flows in Guindani Wash are more frequent than in Saddle Wash due to a larger and higher drainage basin. Thus, Guindani Wash is expected to be a more frequent source of water to Kartchner Caverns than Saddle Wash.

#### CAVE FLOODING OBSERVATIONS

When Guindani Wash is the water source, flooding in the cave occurs from Granite Dells to the front of the cave (Fig. 6) in a relatively gradual, stair-step manner (Buecher 1992). Each chamber fills to a spillover point, then drains to another chamber. Flood levels are highest in the chambers closest to the points of inflow. Some lower chambers either do not fill or fill out of the stair-step sequence due to complex and incompletely understood connecting passages. The presence of granite wash in the cave (Hill 1999c) indicates that, at one time, a significant hydraulic connection was open to the surface. In Granite Dells, granitic material composed of sand, gravel, cobbles, and boulders up to 0.3 m in diameter is found in deposits as thick as 2.4 m. At present, flow into Granite Dells is relatively subdued. During the flood of early 1991, inflow into this room was estimated at about 0.8 L/s, which created a pool of

water that rose at a rate of 18 mm/hr (Buecher, pers. com.).

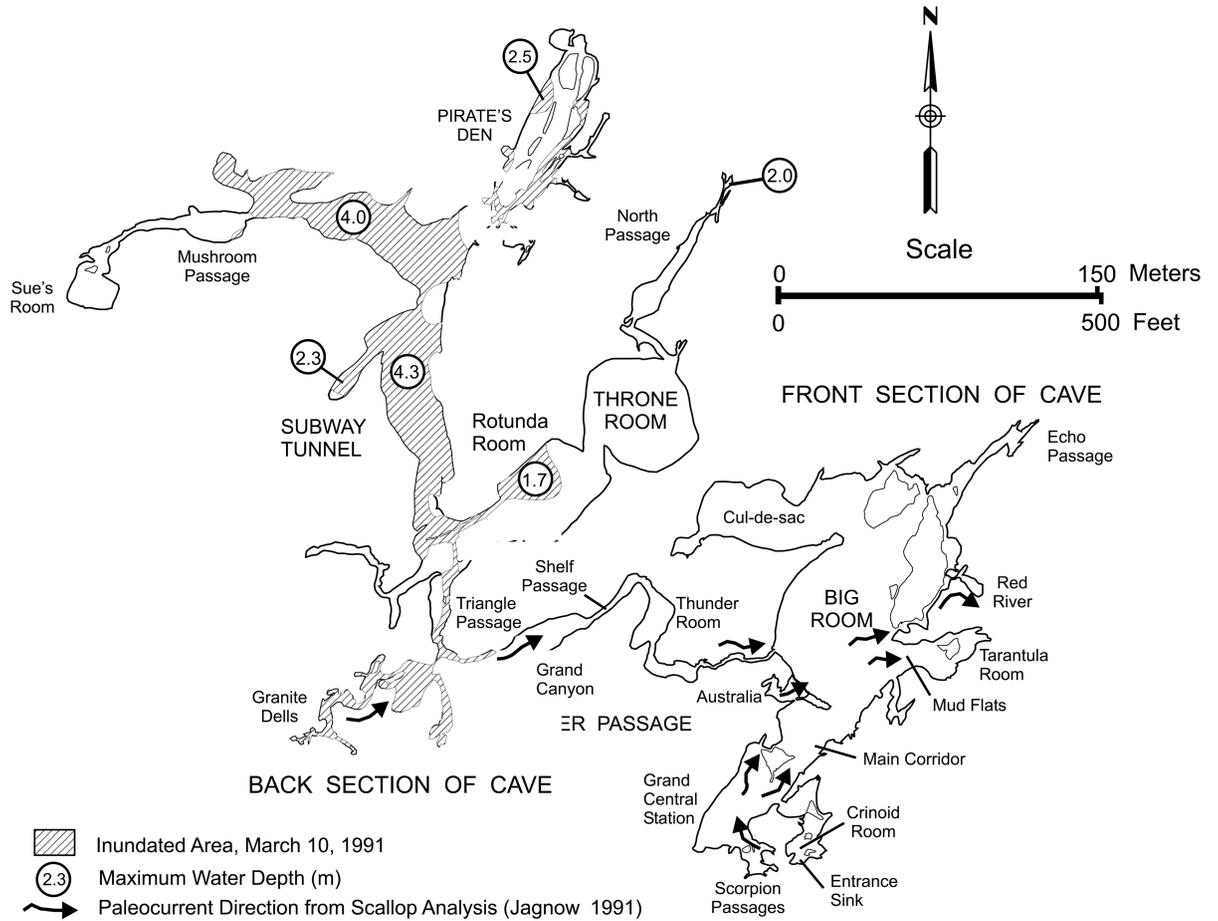
From Granite Dells, water flows through the Triangle Passage into the Back Section of the cave, where it rises to a maximum elevation of 1412.4 m msl and floods the Subway Tunnel, Mushroom Passage, Sue's Room, and parts of the Rotunda Room, Throne Room, and North Passage (Fig. 6). The Back Section of the cave becomes inaccessible through the Triangle Passage, which is the only natural entrance to this section, because water rises to a height of 0.2 m above the top of this passage at the maximum flood level. Water then spills over into Grand Canyon, where a flow of 14.4 L/s was measured during the flood of April 1992. From there, a stream forms in the Shelf Passage and cascades into the Thunder Room, so named for the noise during flooding. Although the Cul-de-sac Passage is 5 m lower than the Thunder Room and only 60 m away, it is not hydraulically connected and does not flood. Pools then begin forming near the start of the River Passage, in the Australia passage, and at the downstream (north) end of Grand Central Station. All of these chambers are at the same elevation and must be connected.

From Grand Central Station, water then starts to flow into Red River from under the breakdown pile in the Big Room. This discharge was measured at 12.5 L/s during the April 1992 flood. The drain in the Red River Room, the lowest point in the cave at an elevation of 1400 m msl, has little capacity, causing backflooding into Echo Passage up to an elevation of 1404 m msl. Finally, a stream emerges in the Crinoid Room, apparently due to a small connection to Grand Central Station. The above sequence reflects the scenario for a very severe episode of flooding. During lesser events, the primary impact is varying levels of inundation in the Back Section of the cave. During the August 1990 flooding, an estimated  $1.9 \times 10^6$  L of water accumulated in the cave (Buecher 1992). The flood of early 1991 was much larger, with an estimated inflow of  $3.7 \times 10^6$  L of water. Figure 6 shows the extent of inundation in the cave and maximum water depth at selected locations.

For the three modern flood events that have been observed in detail, draining of the cave is much slower than flooding. The flood of August 1990 took about two months to drain completely from the cave. This duration yields an overall drainage rate of about 22 L/min. Buecher (1992) measured significantly higher rates at individual drain locations, indicating that different sections of the cave do not drain equally. Flood pools linger in some areas of the cave while disappearing quickly in others. This is particularly evident in the Back Section of the cave, where deposits of mud in many passages impede drainage of pooled water. No water draining out of the cave resurges on the land surface. Instead, flood water exits the cave by percolating downward through the Kartchner Block. Then, this water descends to the water table and flows basinward to recharge the regional alluvial aquifer in the San Pedro Valley.

**Figure 6.**

**Area inundated by flood water, March 1991. Paleocurrent directions determined from scallop marks are by Jagnow (1990).**



**PALEOFLOW FROM SCALLOP MARKS**

An earlier record of flow in Kartchner Caverns is preserved in the form of scallop marks. Jagnow (1990) analyzed the size and distribution of scallops to produce a paleocurrent map (Fig. 6). Scallops are spoon-shaped scoops dissolved into the walls, ceilings, and floors of a cave that indicate both water current direction and velocity at the time of scallop formation (Ford & Williams 1989). The downstream edge of a scallop is more broadly concave and the upstream edge more sharply concave, reflecting the configuration of the eddy that formed in the water next to the cave surface. As the velocity of the current increases, the eddies become more intense and shorten, forming shorter scallops. Curl (1966) developed an equation based on fluid dynamics that relates paleovelocity to scallop length. For the purpose of paleocurrent mapping, Jagnow (1990) divided the scallops in Kartchner Caverns into the following categories:

| Class  | Size (diameter in m) | Velocity (m/min)  |
|--------|----------------------|-------------------|
| Small  | Less than 0.34       | Greater than 3.05 |
| Medium | 0.34 to 0.91         | 3.05 to 1.07      |
| Large  | Greater than 0.91    | Less than 1.07    |

In the areas where scallops can be observed (~25% of the cave), paleocurrent directions generally match observations of flows during recent floods (Jagnow 1990). Paleoflow was also from Granite Dells to the Red River Room in the Front Section of the cave (Fig. 6). Although paleoflows also probably originated in Sue's Room, which according to Jagnow may have been the most likely original inflow point for the majority of early cave development, most scallops in the Back Section of the cave have been obliterated by backflooding. Jagnow mapped the largest scallops nearer to the ceiling and the smaller scallops close to or at floor level. He proposed two possible interpretations for this distribution: (1) When the cave flooded to high levels, the velocity was slow, increasing as the cave drained; or, (2) significant dissolution of the cave occurred under very low-velocity vadose conditions, followed by higher velocity conditions as downcutting occurred.

Jagnow (1990) also noted some interesting paleocurrent relationships in the Front Section of the cave. At present, a dry drainage extends from the Entrance Sink through the Crinoid Room, reappears in the Scorpion Passages, and courses through Grand Central Station to disappear under breakdown near the start of the Main Corridor. When this channel flows, cavers have heard water moving down a drain near the Main Corridor trail. This water may flow to a point beneath the

Tarantula Room or Red River Room. Today, the only visible drain is in the Red River Room. Jagnow noted that medium-sized scallops flank this route, indicating that the Entrance Sink was once a significant source of inflow to the cave. The scallops also indicate significant paleoflows not only to the Red River Room, but to the Tarantula Room, which is now disconnected from the contemporary, visible flow system.

#### CONCLUSIONS

The hydrogeology of Kartchner Caverns State Park involves interactions among three distinct, mutually adjacent hydrogeologic systems within the park: 1) the San Pedro Valley basin, a deep, alluvium-filled graben; 2) an alluvium-covered pediment characterized by a few tens of meters of "granite wash" sediments overlying an erosional surface of Pinal Schist; and 3) a downdropped fault block of Paleozoic rocks, which includes the Mississippian Escabrosa Limestone containing Kartchner Caverns. Groundwater occurs within the San Pedro Valley basin at a depth more than 200 m below the lowest known Kartchner Caverns passage, and in the granite wash sediments at a level more than 20 m higher than nearby cave passages. The source of most water to the cave is meteoric water infiltrating from runoff in washes bordering the fault block and from overhead infiltration from precipitation. The cave floods relatively frequently (estimated at a 57% probability in any one year), when high antecedent soil moisture combines with sustained runoff in the washes flowing adjacent to the limestone ridge containing Kartchner Caverns. An abundance of corrosion bevels in the cave attests to past episodes of flooding. Mapping of solutional scallops reveals that paleocurrent directions generally correspond to historic flow patterns.

#### ACKNOWLEDGMENTS

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# GEOPHYSICAL STUDIES AT KARTCHNER CAVERNS STATE PARK, ARIZONA

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*Geophysical studies over Kartchner Caverns State Park mapped structure and groundwater patterns beneath valley alluvium and determined the geophysical expression of the caverns at the surface. Three techniques were employed: electromagnetics (EM), gravity, and natural potential (NP). Electromagnetic traverses in the area failed to detect the voids, owing to the very low conductivity of the carbonate rock. On the other hand, the EM method succeeded in defining the boundary between carbonate rock and alluvium, and in detecting the high-conductivity underflow beneath the drainage system. Resolution of the gravity survey over outcrop was limited to ~0.1 mgal, due to severe terrain effects. Nevertheless, two of the three major cavern passages were expressed as gravity lows at the surface, and fifteen additional small gravity anomalies could be the effect of fracture zones or unexposed caves. East of the carbonate block, the gravity profiles delineated the range-front fault and afforded interpretations of bedrock structure beneath valley fill.*

*Natural-potential profiles, coincident with those of the gravity survey, produced a prominent compound anomaly over the mapped caverns. The 55 mV NP high was flanked by broad lows measuring ~15 mV over two of the main cavern galleries. The high was incised by a third low over a middle passage of the caverns. The lows are tentatively attributed to filtration downward toward the cave ceilings; the highs, to evapotranspiration from a deeper groundwater reservoir. Elsewhere over the outcrop, continuous NP trends are the likely expressions of faulting and fracturing, possibly accompanied by solution activity.*

During September and October 1989, The Geophysics Group, under contract to Arizona Conservation Projects, Inc. (ACPI), carried out geophysical studies over Kartchner Caverns State Park. The caverns consist of three main chambers and connecting passages, whose ceilings are beautifully decorated with dripstone and flowstone (Hill 1999). The caverns are situated in west-dipping Paleozoic carbonate rocks of an outlier on the east flank of the Whetstone Mountains in Cochise County, Arizona. The State Park, which surrounds the caverns, consists of one section of land (2.23 km<sup>2</sup>) located 13 km south of the town of Benson (Fig. 1). The purpose of these investigations was to map structure and groundwater beneath the alluviated portions of the park and to characterize the surface geophysical expressions of the mapped caverns and other likely voids beneath the areas of rock outcrop. Three geophysical methods were employed: electromagnetics (EM), gravity, and natural potential (NP). Results of the work were documented in a project report (Lange *et al.* 1990a) and summarized in a paper by Lange *et al.* (1990b).

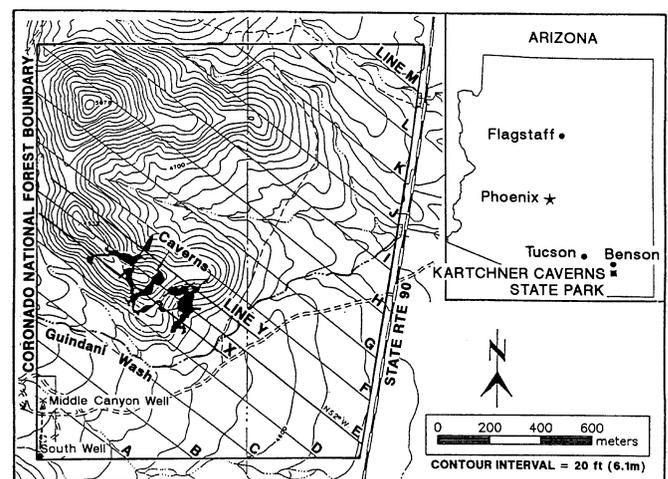
## SURVEY GRID

The layout of the geophysical grid consisted of thirteen primary traverses, designated A through M, oriented in a direction 127°(NW-SE). The lines were ~150 m apart and extended between State Route 90 on the east and the south boundary of the Park northwestward to the west and north boundaries of the park (Fig. 1). The EM measurements were made along Lines D, E and F, while the gravity and NP surveys occupied

the entire grid. In addition, two intermediate natural-potential traverses—Lines X and Y—were run over the area of mapped caverns.

## ELECTROMAGNETIC SURVEY

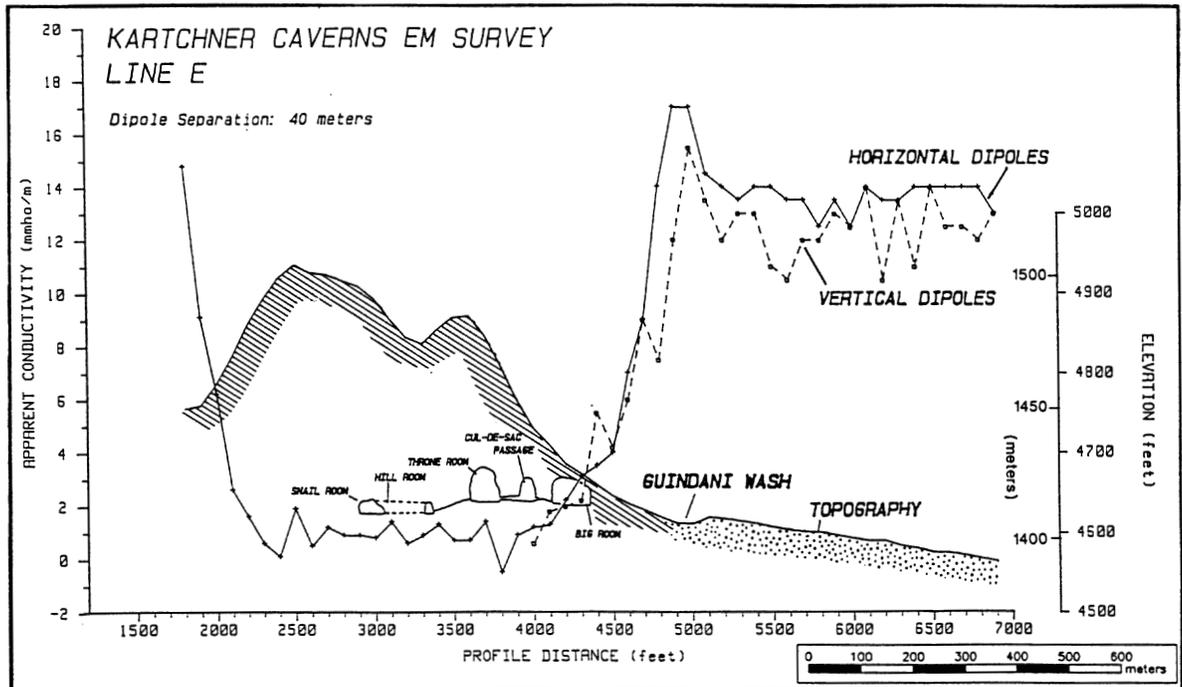
The EM study was undertaken in the hope of mapping low conductivity zones in bedrock corresponding to voids, and to



**Figure 1. Location map of Kartchner Caverns State Park, showing the cavern configuration and layout of the geophysical lines. Base map from Wrucke & Armstrong (1984).**

Figure 2.

Electro-magnetic profile on Line E, illustrating the contrast between the high conductivity valley fill and the very resistive carbonate rock of the hill above the caverns. Note the conductivity peak over Guindani Wash.



determine if water-table depths could be resolved beneath the alluvium. A Geonics Ltd EM-34XL Terrain Conductivity Meter produces a time-varying magnetic source field by energizing a portable transmitter coil (McNeill 1990). This source field causes a system of electric eddy currents to flow in the ground, whose strengths depend on the electrical conductivity of the earth materials. The eddy currents, in turn, generate secondary magnetic fields that are detected by a receiver coil at the surface. A coil spacing of 40 m was adopted on Lines D, E and F, while a spacing of 20 m was also employed on Line E.

The background response of 0-2 mS/m of the limestone was at the lower limit of the operational range of the instrument; hence, it proved not feasible to resolve the cavern voids with the method. On the other hand, the EM data were effective in defining the boundary between limestone and alluvium and the high conductivity underflow zone of Guindani Wash, south and east of the rock outcrop (Fig. 2). A calibration traverse between Middle Canyon Well and South Well (Fig. 1), having water depths of 20 and 7.3 m, respectively, showed a net change of +3.5 mS/m in the direction of shallower water, demonstrating that relative changes in groundwater depth of 2-3 m (corresponding to an instrumental resolution of  $\pm 0.5$  mS/m) could be detected using the coils in horizontal mode.

#### GRAVITY SURVEY

A gravity meter measures variations in the gravitational field at the ground surface, which correspond to density changes in the subsurface. Density variations come about, for example, when crossing from soil to rock and from less dense

sedimentary to denser volcanic rocks. By virtue of the absence of rock, air- and water-filled caves are ideal targets for exploration by the gravity method (Neumann 1967). At Kartchner Caverns, a gravity survey was implemented to detect likely unmapped voids in the bedrock and to delineate geologic structure beneath the alluviated portion of the Park.

Underlying voids give rise to corresponding gravity anomaly lows (expressed in milligals) at the surface. Because of the severe variations in relief over the survey grid, errors in the estimated terrain effects were as great as 0.1 mgal. For this reason, the normal exploration instrument—a LaCoste & Romberg Model G gravimeter—was employed, rather than a machine of greater precision applicable to a *microgravity survey* in more gentle terrain. ACPI personnel measured station coordinates and elevations to within 1.5 cm using a transit and spirit level. Terrain elevations were mapped within a radius of 2 m of each gravity station and combined with measurements from a topographic map to generate complete Bouguer profiles and the corresponding anomaly contour map supplied in the project report (Lange *et al.* 1990b, Pl. VI).

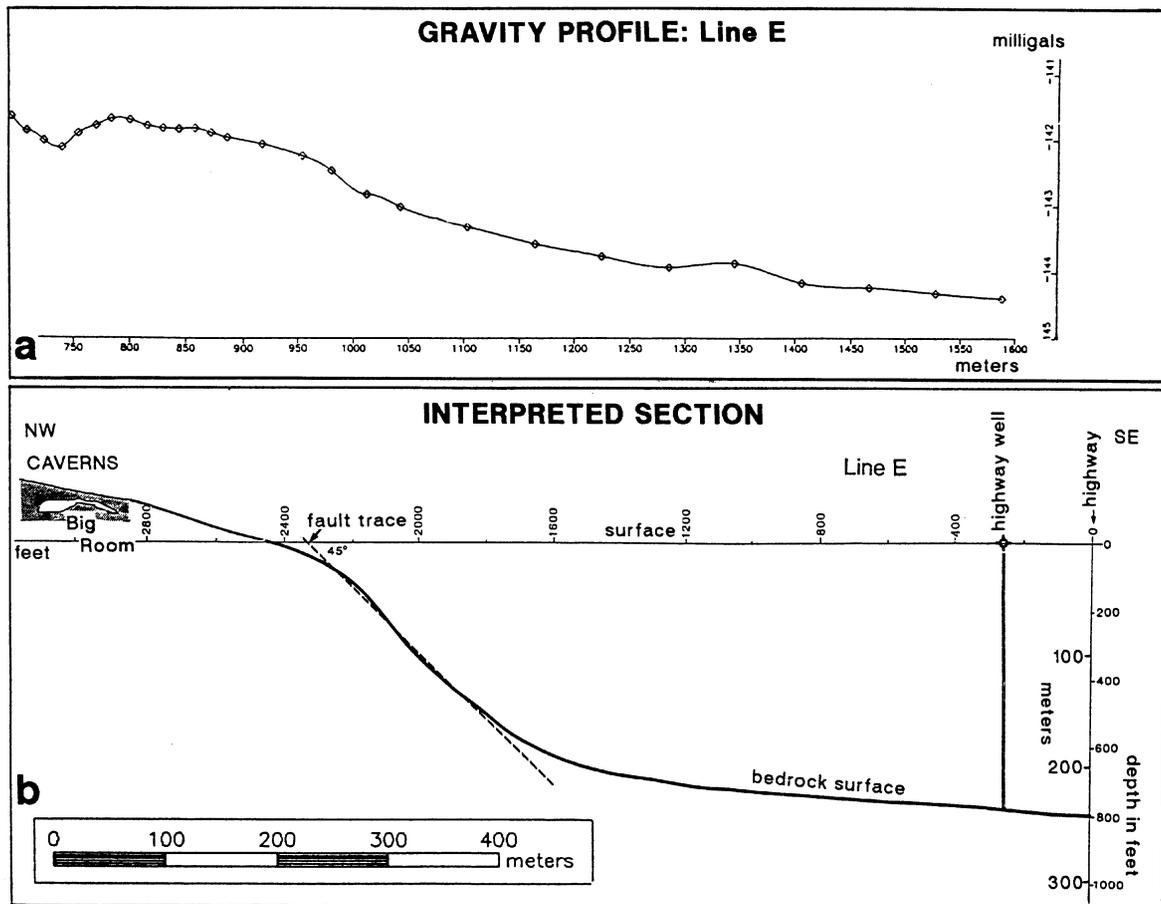
A prominent feature of the final gravity profiles is a sharp gravity gradient delineating the range-front fault system (Fig. 3). By applying an inversion procedure for interpreting gravity data (Cordell & Henderson 1968), profiles of bedrock structure were generated for each of the gravity traverses, utilizing a density contrast of 0.2 mgal. These profiles were intended to aid in the siting of roads, water wells, and a waste disposal facility at the Park.

On bedrock, gravity lows typical of voids turned up at a number of places, including the cavern site itself. Figure 4 shows the gravity profile on Line E over three of the cave pas-

Figure 3.

3 a) The eastern portion of the gravity profile along Line E between the Big Room of Kartchner Caverns and a well in the valley.

3 b) Configuration of bedrock surface beneath valley fill on Line E, as derived by modeling of the gravity profile.



sages. The largest expression (-0.65 mgal) occurred over the Big Room, whose minimum ceiling depth is only ~8 m. Two-dimensional modeling, utilizing the Talwani algorithm (Talwani *et al.* 1959) and a rock density of 2.67 g/cm<sup>3</sup>, yielded a calculated anomaly of -0.50 mgal. A marginally detectable gravity low of only -0.13 mgal appeared over the 55-m deep Subway Passage/Hill Room, where modeling produced a theoretical anomaly of only -0.10 mgal. The intervening Rotunda Room, at a depth of 58 m, produced no resolvable gravity anomaly at the surface, while modeling yielded a value of -0.1 mgal. The discrepancies between the observed and calculated anomaly amplitudes are very likely due to the fact that the cave passages open out into larger galleries beyond Line E, while the modeling procedure views the passages as simple tunnels.

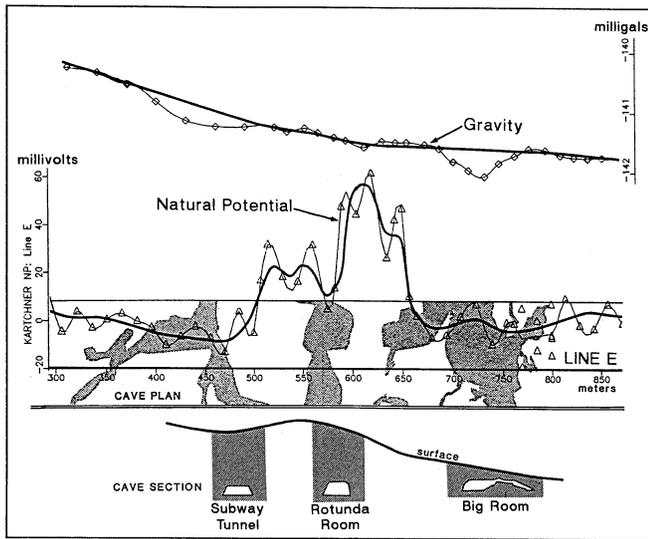
Fifteen gravity anomalies having amplitudes ranging between -0.15 and -0.50 mgal were noted elsewhere over the carbonate outcrop. While some of these may relate to fractures or filled fissures, four were associated with natural-potential anomalies and are likely the expression of underlying voids (Lange *et al.* 1990a).

#### NATURAL-POTENTIAL SURVEY

The flow of water underground generates minute dc electric currents that can be measured at the ground surface as a

voltage, or *streaming-potential* distribution. This *electrokinetic* phenomenon has been demonstrated in the laboratory by passing water through a container of sand and measuring voltage and pressure differences along the flow path (Ahmad 1964). The resulting streaming potential is linearly proportional to the driving pressure. Similar results have been obtained from aqueous solutions flowing in simulated fractures (Bogoslovsky & Ogilvy 1972) and in open tubes up to 2.54 cm (1 in) in diameter (Binder & Cernak 1963).

In field practice, differences of potential along ground-surface traverses are measured in millivolts (mV) using sealed non-polarizing electrodes, a color-calibrated cable on a reel, and a high-impedance multimeter (a meter having a 1000 M $\Omega$  input impedance used for desert work). One electrode is fixed near the center of the survey and implanted in soil at shallow depth, while a second staff-mounted electrode samples the earth in shallow holes at regular (typically 3 to 4 m) intervals along the survey lines. Due to temperature variations of the electrodes and soil, drift measurements must be made periodically at the base electrode, and a corresponding correction applied over time to all of the data readings along a line. In moist and hilly terrain, elevation corrections may also be necessary, though they were not needed at the Kartchner site. The corrected survey data are then plotted out as profiles, line-by-line, and as areal maps of natural-potential contours. The more



**Figure 4. Gravity and natural-potential profiles over three portions of Kartchner Caverns. The heavy curves are smoothed from the original data (fine curves). The caverns are shown partially in plan view and as cross-sections beneath Traverse E. NP lows occur over the void space of the three galleries, while highs appear over the intervening rock. Gravity lows are associated with the Big Room and Subway Tunnel. Void space off to the side of Line E contributes to both the NP and gravity lows.**

difficult task of interpreting the results must then be undertaken.

Natural-potential anomalies (both positive and negative) have been observed over air-filled caverns (Lange & Kilty 1991), and attributed to the downward filtration of meteoric water through the more permeable rock comprising the cave roof. Under hot, dry conditions, typical of summer at Kartchner Caverns, evapotranspiration and capillary flow can transport water upwards towards the surface, giving rise to corresponding inverted NP anomalies.

Laterally moving water, as in the case of a cave stream, has been found to generate a streaming potential generally, but not always, positive in the direction of flow (Kilty & Lange 1991). This effect gives rise to the more complex (sommbrero-like) anomaly observed over karst springs, where not only the ends of the flow system become polarized, but the walls of the flow path as well.

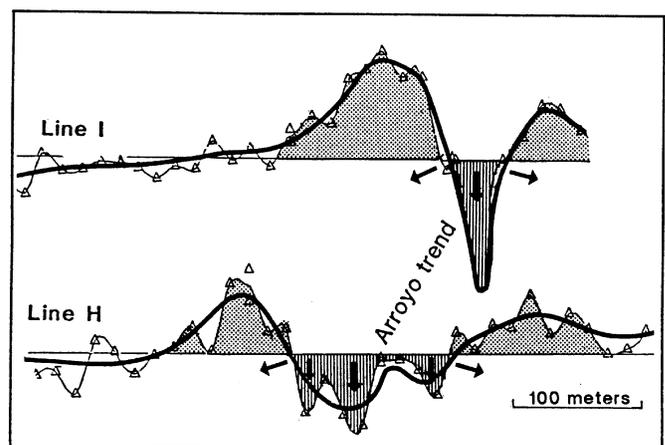
At Kartchner Caverns, NP data collected from the sparse soil on outcropping rock produced very noisy records due to high contact resistance and solar heating of the ground. The NP work on the hills had to be suspended in the afternoons and deferred to the cooler morning hours. Collecting data in the relatively level valley area was easier, due to greater soil moisture and some shading by vegetation. Along the arroyo of Guindani Wash, distinct M-shaped anomalies were encountered (Fig. 5), wherein downward percolation (alternatively

underflow) may account for the central lows, while lateral filtration into the banks may explain the positive shoulders of the anomalies.

Figure 4 displays a portion of the NP profile obtained on Line E over the cavern system. The overall anomaly is a compound affair (a double sommbrero) made up of three NP lows over particular cavern passages, and two exaggerated highs associated with the intervening rock walls. The peak-to-peak amplitude of the anomaly measured 70 mV.

Without additional NP measurements made both underground in the caverns and above ground during winter conditions, it is difficult to conceptualize the electrokinetic mechanisms contributing to the complex NP expression registered at the surface. Considering that the cavern system represents the solutional enlargement of a fractured carbonate mass, one can deduce that downward percolation towards the cavern ceiling (evidenced by the stalactite deposits) brings about the observed NP lows. The intervening fractured rock, meanwhile, may serve as pathways for upward capillary movement of water derived from a groundwater reservoir beneath the cavern floor which at times rises to flood portions of the caverns. This upward water movement is locally interrupted by the presence of the galleries, leaving the NP highs coincident with the underlying wall rock and absent over the void space.

In addition to the NP anomalies associated with the mapped caverns, three major anomaly trends could be traced across adjacent traverses. These trends may relate to fault- or fracture zones as well as to associated voids.



**Figure 5. Natural-potential profiles over streams: Two typical profiles across Guindani Wash in Kartchner Caverns State Park. Water was not flowing at the surface at the time of the survey. The M-shaped (inverse sommbrero-type) anomaly suggests underflow beneath the gravels of the wash and/or electrofiltration both downward into the channel and laterally into the stream banks.**

## CONCLUSIONS

Although the electromagnetic survey failed to detect voids in the carbonate bedrock, it successfully mapped the boundary between carbonate rock and valley fill where buried beneath soil cover. The gravity survey was most effective in mapping the bounding fault and contours of the bedrock surface beneath alluvium, facilitating the siting of water wells, roads and other construction features. Gravity anomaly lows over two of the cave galleries demonstrated the suitability of the method for detecting voids even in terrain as rugged as the carbonate outcrop at Kartchner Caverns.

The natural-potential survey mapped zones of underflow and infiltration in the washes, where its strongest expressions may be indicative of underlying voids. Structural features—faults and pervasive fractures, possibly enlarged by solution—were indicated by throughgoing NP anomaly trends. One of these anomaly trends is associated with the cavern system, which is expressed as a prominent compound anomaly consisting of highs associated with the interior cave walls, and lows related to the cavern galleries.

## ACKNOWLEDGMENTS

The geophysical surveys at Kartchner Caverns were carried out by Philip Walen and Arthur Lange of The Geophysics Group. Surveying was performed by Bob and Debbie Buecher of Arizona Conservation Projects, Inc. Able assistants participating in the field work include Hans Bodenhamer, Jeff Dexter, and Anita Pape. Funding for the geophysical studies was provided by the Arizona State Park Department, via ACPI.

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# MINERALOGY OF KARTCHNER CAVERNS, ARIZONA

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*The mineralogy of Kartchner Caverns is both diverse and significant. Six different chemical classes are represented in this one cave: carbonates, nitrates, oxides, phosphates, silicates, and sulfates. It is significant primarily because: (1) the silicate minerals, nontronite and rectorite, have never before been reported from a cave occurrence; (2) the nitrate mineral, nitrocalcite, has never been described using modern techniques; (3) 'birdsnest' needle quartz has been reported only from one other, non-cave, locality; and (4) extensive brushite moonmilk flowstone has not been reported from anywhere else in the world. Kartchner is a beautiful cave because its carbonate speleothems are colorful (shades of red, orange, yellow and tan) and 'alive' (still wet and growing).*

Kartchner Caverns is in the Whetstone Mountains, ~13 km south of Benson, Arizona, USA, just west of Arizona State Highway 90. The cave developed in a downdropped block of Mississippian Escabrosa Limestone. It is a wet, 'live' cave, >3 km long, which features a wide variety of multicolored speleothems.

Kartchner Caverns has a diverse mineralogy that ranks it among the most mineralogically interesting caves in the world (Hill & Forti 1997). Unlike most limestone caves, Kartchner is adjacent to an igneous and metamorphic terrain. Alaskite granite borders the Escabrosa Limestone along fault zones to the west and the Pinal Schist underlies the cave. These fault zones, within an active tectonic region with a high geothermal gradient, have previously acted as avenues for ascending hydrothermal solutions and for the formation of the minerals quartz, illite and rectorite. The dry Arizona desert also contributes to cave mineral formation; e.g., the low relative humidity causes the efflorescence of nitrocalcite in the entrance zone of the cave. Periodic flooding of the cave allows for pH-Eh conditions favorable for forming the mineral nontronite. Bats add the last ingredient, bringing phosphates and nitrates into the cave via their guano and urine.

Cave minerals and speleothem types and subtypes in Kartchner Caverns are listed in Table 1. Figure 1 is a map of Kartchner Caverns that shows the location of the most important minerals and speleothems in the cave. Of these, only the more unusual or new minerals/speleothems will be discussed.

## CARBONATE MINERALS AND SPELEOTHEMS

Carbonate minerals include both calcite and rare aragonite speleothems, such as poorly developed frostwork. Magnesium carbonate minerals do not exist in the cave because the Escabrosa Formation is a relatively pure limestone containing very little dolomite.

Calcite speleothems are abundant, but only a few types are unusual. The world's longest known soda straw, 6.45 m, resides in the Throne Room (Figs. 1 & 2). Shields are a common speleothem in the cave, and form especially where the

bedrock has been highly fractured by Basin and Range tectonism. Welts, a variety of shields, formed along horizontal bedding or on fractured speleothems. 'Turnip' shields formed along vertical fractures in the ceiling of the Big Room. The origin of these turnip-like speleothems has not yet been completely determined, but they may be the vertical equivalent of welts. Coral pipes are unusual as they formed in bat guano rather than mud. Red, orange, yellow, and tan flowstone is exceptionally beautiful (cover photo). The dripstone column in the Throne Room, 'Kubla Khan', is 17.7 m (58 ft) high (Fig. 3), and is the tallest column in Arizona. The Big Room displays well-developed 'fried-egg' stalagmites (Fig. 4).

## NITRATE MINERALS AND SPELEOTHEMS

Nitrocalcite has been found in Kartchner Caverns as cave cotton growing from sediment in scattered areas along the entrance passages (Hill & Buecher 1992). Mineralization occurs as efflorescent mats consisting of colorless to milky-white, silky to transparent, slender needle crystals up to 0.5 mm long and <0.1 mm wide (Fig. 5).

The growth of nitrocalcite in the entrance passage correlates with episodes of low relative humidity in the winter months. A humidity of about 50% appears to be needed for the crystallization of nitrocalcite (Hill & Forti 1997), and this humidity needs to remain low before significant cotton can effloresce. These conditions correspond to a time in Kartchner when the cave is "breathing in"; that is, when cold, dry, winter air moves in along the entrance passage (Buecher 1999). The nitrocalcite in this passage is highly transient. Once the cave "breathes out" again, warm, moist, cave air quickly (in a matter of hours to days) causes the nitrocalcite to deliquesce and disappear back into the cave sediment.

## OXIDE MINERALS AND SPELEOTHEMS

Red hematite powder was collected and identified (by X-ray diffraction) from two locations in Kartchner Caverns: (1) the Red River Passage, where it alternates with greenish-gray,

**Table 1. Cave minerals and speleothems, Kartchner Caverns. Classification of types and subtypes after Hill & Forti (1997).**

|   |
|---|
| CARBONATES  |
| Aragonite, CaCO <sub>3</sub>  |
| Coatings and crusts   |
| Frostwork   |
| Helictites  |
| beaded  |
| Stalactites   |
| spathites   |
| Calcite, CaCO <sub>3</sub>  |
| Boxwork   |
| Coatings  |
| Conulites   |
| bird baths  |
| Coralloids  |
| popcorn   |
| grape   |
| subaqueous  |
| Coral pipes   |
| Crusts  |
| Draperies   |
| bacon   |
| sawtooth  |
| Flowstone   |
| waterfall   |
| canopies  |
| bell canopies   |
| Helictites  |
| anemolites  |
| Moonmilk  |
| Pearls, cave  |
| Rafts, cave   |
| Rims  |
| Rimstone dams   |
| Chinese walls   |
| Shelfstone  |
| crescent  |
| Shields   |
| welt  |
| turnip  |
| Spar  |
| phreatic  |
| pool  |
| Stalactites   |
| soda straw  |
| Stalagmites   |
| columns   |
| broomstick  |
| fried eggs  |
| NITRATES  |
| Nitrocalcite, Ca(NO <sub>3</sub> ) <sub>2</sub> ·H <sub>2</sub> O   |
| Cotton  |
| OXIDES  |
| Hematite, Fe <sub>2</sub> O <sub>3</sub>  |
| Powder  |
| PHOSPHATES  |
| Brushite, Ca <sub>4</sub> PO <sub>4</sub> ·2H <sub>2</sub> O  |
| Moonmilk  |
| Hydroxylapatite, Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> (OH)   |
| Crusts  |
| SILICATES   |
| Nontronite, Na <sub>0.3</sub> Fe <sub>2</sub> <sup>3+</sup> (Si,Al) <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub> ·nH <sub>2</sub> O |
| Rectorite, 1:1 interstratification of mica & smectite   |
| Quartz, SiO <sub>2</sub>  |
| Boxwork   |
| Needles   |
| SULFATES  |
| Gypsum, CaSO <sub>4</sub> ·2H <sub>2</sub> O  |
| Cotton  |
| Starburst   |
| RELATED FORMS   |
| Rootsicles  |
| Vermiculations  |

illite-clay layers (Fig. 6); and (2) in the Thunder Room area, where it occurs as colloidal hematite staining illite and rectorite clay. The hematite is most likely derived from primary pyrite, which occurs along the fault zones, and it may be of hydrothermal origin due to hot waters having moved up the fault zones.

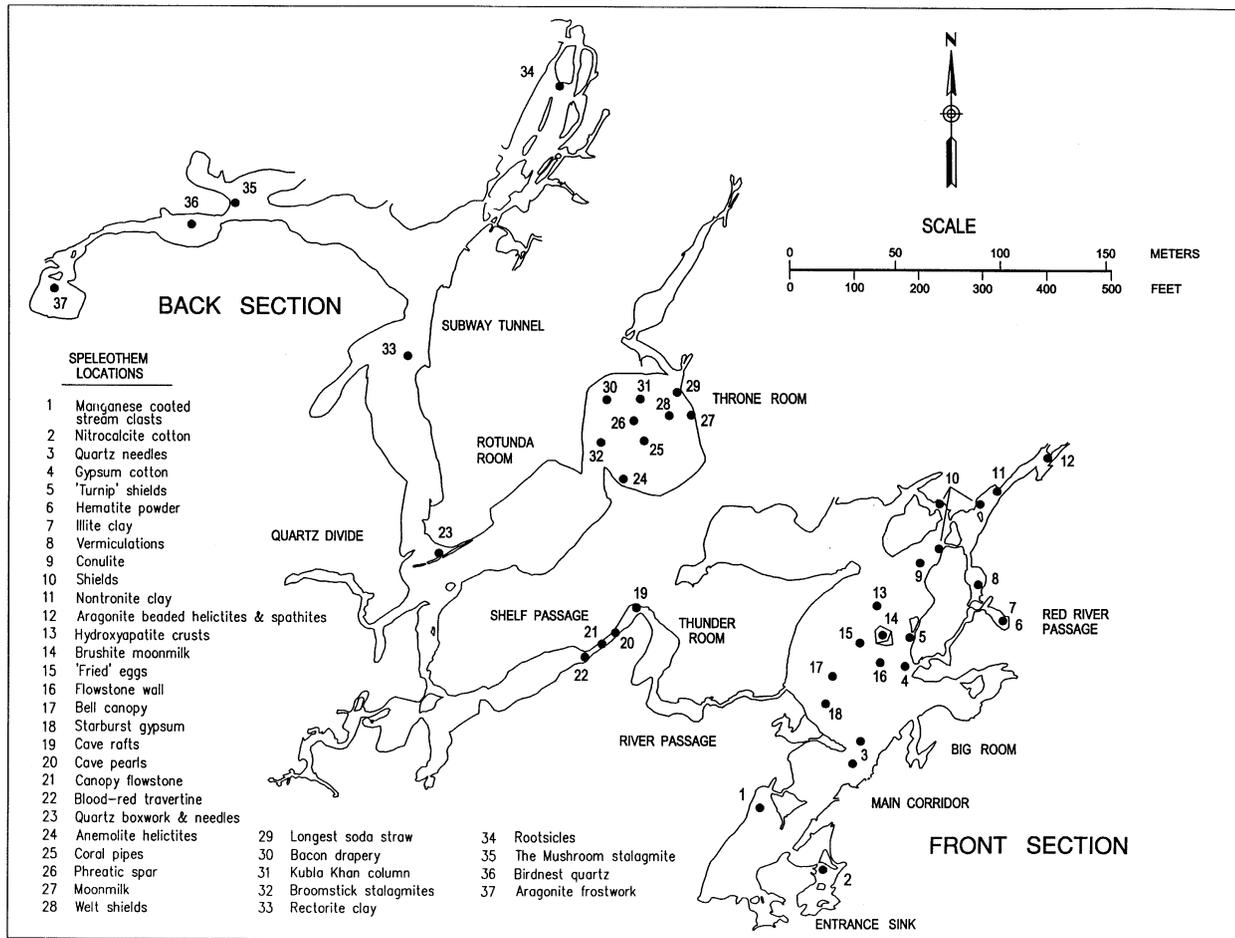
#### PHOSPHATE MINERALS AND SPELEOTHEMS

The phosphate minerals brushite and hydroxylapatite have both been identified by X-ray diffraction analysis. The hydroxylapatite in the Big Room forms a thin, orangish-brown crust, but is not particularly extensive or noteworthy in its occurrence. The brushite in the Big Room, however, is noteworthy. It is one of the most extensive brushite deposits ever reported from a cave. This brushite consists of masses of creamy-colored material (moonmilk) over 2 m long, 0.3 m wide, and 6 cm thick. The moonmilk issues forth from beneath a fresh bat guano pile on a large piece of breakdown in the Big Room, it has 'crept' down the side of the breakdown, and then it continues out of sight beneath the breakdown. Brushite derives from decaying bat guano in an acid-rich (pH<6), damp environment (Hill & Forti 1997). Both of these conditions exist beneath bat roosts in the Big Room (Buecher & Sidner 1999).

#### SILICATE MINERALS AND SPELEOTHEMS

Silicate minerals found in Kartchner Caverns are illite, nontronite, rectorite and quartz. Illite fills fault zones and also occurs as clay floor deposits derived from the dissolution of the cave and fault zones (Hill 1999). Rectorite is a mixed-layer clay composed of a 1:1 regular interstratification of a dioctahedral mica and dioctahedral smectite (Newsom 1978). It has been identified at two localities in the cave: (1) along the main fault zone in the Main Corridor where it appears to have replaced illite; and (2) in the Subway Tunnel as pure rectorite showing contorted foliation. Rectorite is a rare mineral, only known from a few surface localities, the most noted being the Jeffrey Quarry just north of Little Rock, Arkansas, USA (Miser & Milton 1964). The Arkansas rectorite occurrence is interpreted to have formed directly from hydrothermal solutions, and a similar origin may also apply to the Kartchner Caverns occurrence. The Kartchner rectorite is associated with 'birds nest' quartz along fault zones in the cave, where the quartz appears to have grown into a matrix of rectorite clay.

A brown, unctuous, nontronite floor clay in the Echo Passage contains layers, pods, and seams of a black, amorphous, manganese-rich material (Fig. 7). Nontronite forms under alkaline (pH = 7 to 10) and reducing (Eh = 0.2 to -0.8) conditions in areas of restricted drainage (Harder 1976). It has a marked cation exchange capacity, which means that cations like calcium, potassium, manganese, and metal ions can readily exchange within the structure of the mineral. In addition, nontronite forms from solutions containing high amounts of



**Figure 1. Map of Kartchner Caverns showing the location of the most important mineral and speleothem occurrences and other places mentioned in the text.**

iron and silica. All of these conditions fit the environment of the Kartchner Caverns nontronite sites. Silica and iron (as red-orange hematitic material) are present along fault zones that have been exposed by cavern dissolution. Drainage in Echo Passage is retarded, and the pH of the water is between 7-9 (R. Buecher, pers. com.). Such high pH's favor rapid nontronite formation at normal temperatures.

Quartz occurs in four different modes in the cave as: (1) vein-boxwork (Fig. 8); (2) stubby prismatic crystals on top of the boxwork, (3) 'birdsnest' needle crystals on cave walls and ceilings along fault zones (Fig. 8); and (4) prismatic crystals replacing limestone bedrock along fault zones. The Quartz Divide displays the best example of quartz boxwork. A 30 cm wide quartz vein extends from the floor to the ceiling and was left standing while the cave dissolved out around it. This quartz boxwork (and other examples in the cave) is petromorphic rather than speleothemic (i.e. it is a fault zone vein deposited long before the cave existed). Fluid inclusion measurements indicate a crystallization temperature of 125-170°C for the vein quartz.

The most unusual occurrence of quartz is as needles.

These needles form as tiny (up to 2 cm long and 0.25 cm wide), slender, euhedral, prismatic crystals that cluster together in mats in a 'birdsnest'-like fashion. The elongate structure of the needles is caused by crystals growing outward into a saturated silica 'soup'—either into a silica-rich solution or into a porous rectorite clay medium. The quartz needles appear to be speleothemic. The 'birdsnest' needle clusters either grew into open space (during an earlier, paleokarst episode) or into voids filled with clay along the faults.

The 'birdsnest' quartz in Kartchner is similar to 'haystack' quartz at the Jeffrey Quarry, Arkansas (Miser & Milton 1964), only the crystals are much smaller. The Arkansas quartz occurs along 30-cm wide, quartz vein-filled fractures and faults, suspended in a semi-liquid filling of gelatinous rectorite clay. Single quartz crystals grew suspended in a rectorite matrix while the 'haystack' quartz crystals grew out from vein quartz into the rectorite clay. Both the rectorite and 'haystack' quartz in the Arkansas occurrence formed from hydrothermal solutions, at temperatures of 146-159°C, according to fluid inclusion studies on this quartz. The similarity of the Arkansas 'haystack' quartz and the Kartchner Caverns 'birdsnest'

quartz—in its position along faults, its occurrence with rectorite, and its fluid inclusion temperatures—suggests a similar, fault-related, hydrothermal origin for the Kartchner Caverns needle quartz.

#### SULFATE MINERALS AND SPELEOTHEMS

Sulfate minerals in the cave are sparse. Small patches of gypsum cotton and starburst gypsum occur in sections of the Big Room where bat guano exists. Leaching of bat guano almost always forms gypsum as a by-product (Hill & Forti 1997) and therefore it is not surprising that this mineral exists in the bat guano-rich Big Room setting.

#### RELATED FORMS

“Related forms” are those deposits that resemble speleothems but are not speleothems in the strictest sense because they are not composed of true minerals but of mud or organic material (Hill & Forti 1997). Related forms in Kartchner Caverns are rootsicles and vermiculations. Parts of the cave are near the surface and in these places roots seeking cave water have become calcified. They are called ‘rootsicles’ by cavers.

Leopard-spot vermiculations have been found at the Quartz Divide and tiger-skin vermiculations in the Red River Passage, but neither occurrence is outstanding in terms of size or level of development. Vermiculations are thin, irregular, discontinuous deposits composed of incoherent materials (usually clay or mud) found on cave walls, floors or ceilings (Hill & Forti 1997). Their origin is still somewhat controversial, but is believed to be related to the flocculation of drying, liquid films containing fine-grained material.

#### COLOR OF SPELEOTHEMS

The calcite speleothems in Kartchner Caverns vary from a dark blood-red (Fig. 9) to red-orange to orangish-brown to delicate-peach to pure white. Color in speleothems can be caused by various factors: humic and fulvic acids, metal ions, and inorganic pigments (White 1997). Most of the coloration in Kartchner is probably derived from inorganic pigments, specifically, iron-rich hematitic fault-clay residue incorporated into the speleothem while it is growing. Some of the most vividly colored speleothems in Kartchner occur along or near fault zones where red-orange clay is exposed in the ceilings or walls of the cave. Black coatings on stream clasts and clay sediments are due to manganese metal ions.

#### CONCLUSIONS

Kartchner Caverns is only a small cave but it possesses minerals from six different chemical classes. A number of factors have been responsible for the diverse mineralogy of the cave:

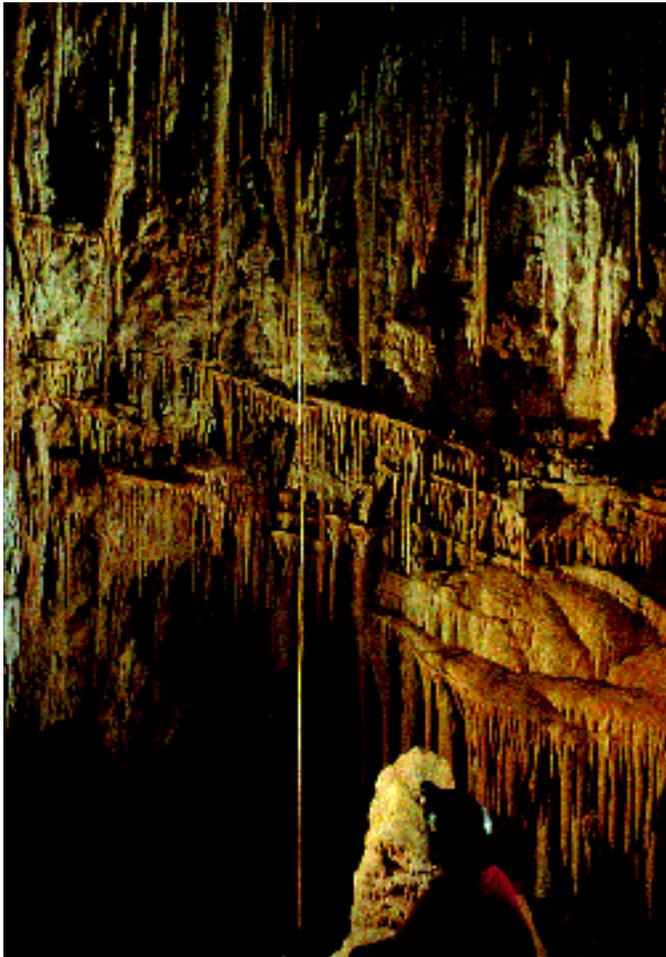
1. A tectonic setting where faults allowed the ascension of hydrothermal solutions and the deposition of the minerals illite, rectorite and quartz.
2. A nearby igneous/metamorphic terrain where ‘unusual’ ions (such as Na) are supplied to the cave, in addition to the ‘usual’ calcium and carbonate ions derived from limestone.
3. Bat guano/urine which supplies phosphate, nitrate and sulfate ions to the cave.
4. An arid climate so that the highly soluble mineral nitrocalcite can effloresce in the entrance zone.
5. Flooding of the cave which allowed nontronite to form in a high pH-low Eh environment.

#### ACKNOWLEDGMENTS

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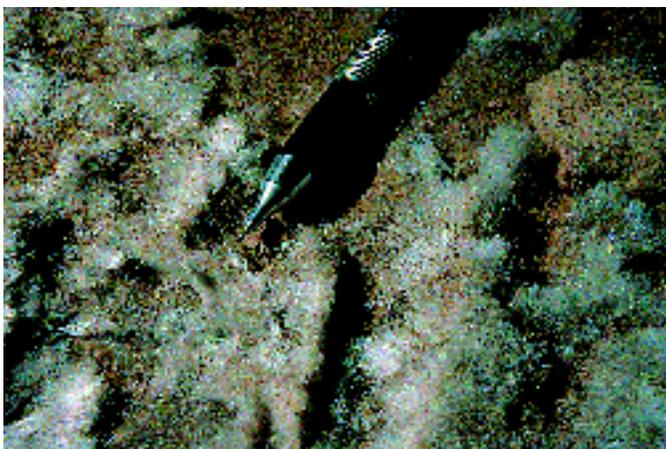
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**Figure 2.** World's longest known soda straw, 6.45 m (21.16 ft) long in length, Throne Room. Photo by K.L. Day, A.C.P.I./Arizona State Parks Dept.



**Figure 3.** 'Kubla Khan' in the Throne Room: at 17.5 m (58 ft) high, it is the tallest column known in an Arizona cave. Photo by K.L. Day, A.C.P.I./Arizona State Parks Dept.



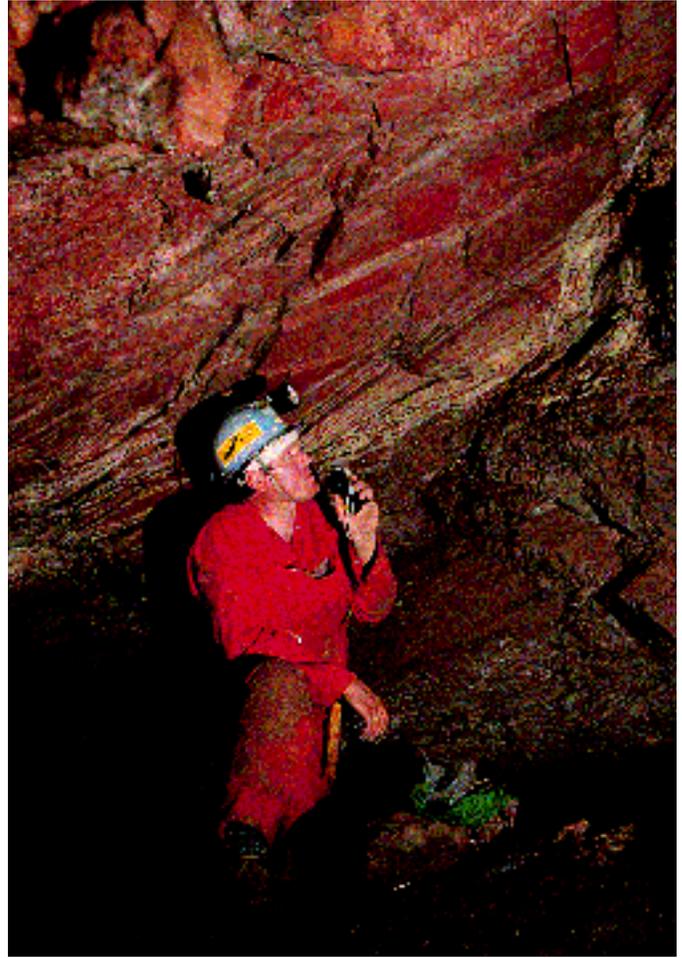
**Figure 5.** Efflorescent mats of nitrocalcite cotton in the entrance passage. Photo taken on 14 December 1989, when the relative humidity in the passage was ~50%. Photo by Bob Buecher.



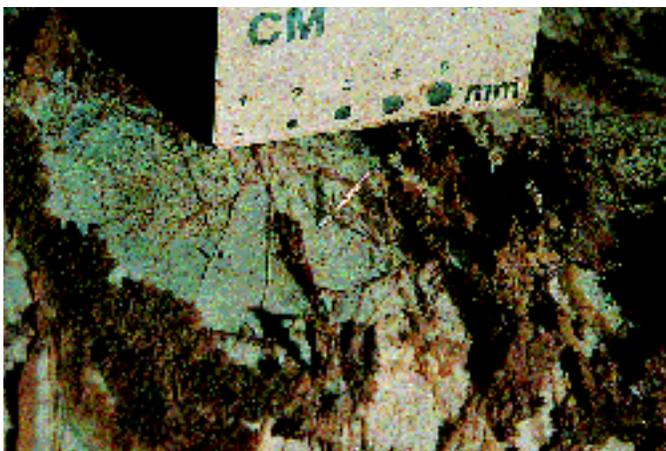
**Figure 7.** Manganese-rich black layers exposed in nontronite clay, Echo Passage. Photo by Bob Buecher.



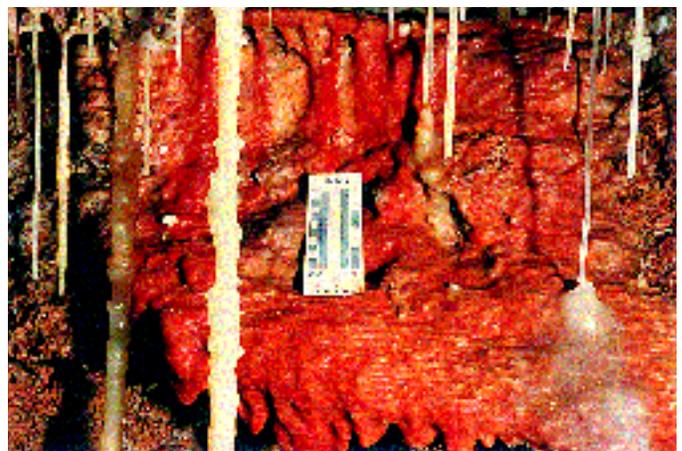
**Figure 4.** A 'fried-egg' stalagmite in the Big Room. Width of the 'yellow' part of the 'egg' is about 5 cm (2 in). Photo by Bob Buecher.



**Figure 6.** Red hematite alternating with greenish-gray illite layers, Red River Passage. Photo by Bob Buecher.



**Figure 8.** Quartz needles and boxwork, Subway Tunnel. Photo by Cyndi Mosch.



**Figure 9.** Blood-red flowstone in the Shelf Passage, located directly along a fault filled with iron-rich hematitic clay. Photo by Bob Buecher.

# SEDIMENTOLOGY AND PALEOMAGNETISM OF SEDIMENTS, KARTCHNER CAVERNS, ARIZONA

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*Clastic deposits in Kartchner Caverns consist of coarse deposits (breakdown, pebble gravel and micaceous sand) and fine-grained deposits (fault gouge and blocky clay). The coarse deposits are all related to the vadose history of the cave, while the fine-grained deposits are related to the phreatic history of the cave and, probably, to the beginning of vadose conditions. The illite clay in fault zones was possibly derived from the underlying Pinal Schist. The clay mineral rectorite is most likely a hydrothermal alteration of illite within the faults prior to the dissolution of the cave. The blocky clay unit is autochthonous sediment that was at least partially derived from residual fault gouge clay at the time of cave dissolution. The pebble gravels were deposited during different flood events in different parts of the cave, with a lateral fining of micaceous sand in back-wash areas. The blocky clay, pebble gravel, and micaceous sand are all paleomagnetically normal and date from the Brunhes/Matuyama normal (<~780 Ka). The clay mineral nontronite probably reconstituted from residual illite/rectorite under high pH, low Eh flood-water conditions within the cave environment.*

Kartchner Caverns is in the Whetstone Mountains, ~13 km south of Benson, Arizona, USA, just west of Arizona State Highway 90. The cave is developed in a downdropped block of Mississippian Escabrosa Limestone. It is a wet, "live" cave, over 3 km long, that features a variety of sediments and speleothems. Kartchner Caverns is Arizona's 25th and newest State Park.

Clastic deposits in Kartchner Caverns were studied with respect to their mineralogy, relative stratigraphic position, and absolute ages as determined by paleomagnetic dating and uranium-series dating of interbedded travertine. The clastic deposits in the cave vary in size from large breakdown pieces to cobbles and clay. The finer-grained particles constitute the muddy floor deposits of the cave, or fill fault zones exposed in the walls and roof of the cave. Figure 1 is a map of Kartchner Caverns showing sediment sample collection sites and other places mentioned in the text. Figure 2 shows the most prominent sediment sites plotted with respect to elevation.

## DESCRIPTION OF CLASTIC DEPOSITS

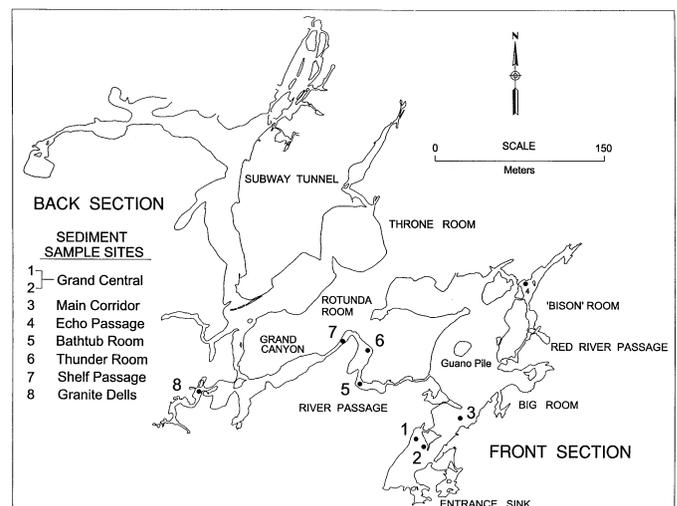
### COARSE DEPOSITS

**Breakdown.** The breakdown in Kartchner Caverns varies in size from large blocks such as at the Guano Pile in the Big Room, to smaller pieces where bedrock has been shattered along fault zones. Breakdown can be found within sediment, on top of sediment, or covered by thin layers of sediment deposited under flood-water conditions. The larger upper rooms of the cave are primarily collapse passages, formed when large sections of the ceiling collapsed to the floor. Large breakdown pieces from this collapse have sometimes blocked lower solutional passages; for example, the breakdown in the Rotunda Room blocks the Triangle Passage.

The Kartchner breakdown is either of the slab or chip variety (Davies 1949). Chip breakdown is predominant in such

places as the Grand Canyon, where movement along faults has shattered the bedrock. The shattered rock fell to the floor as small pieces of chip breakdown.

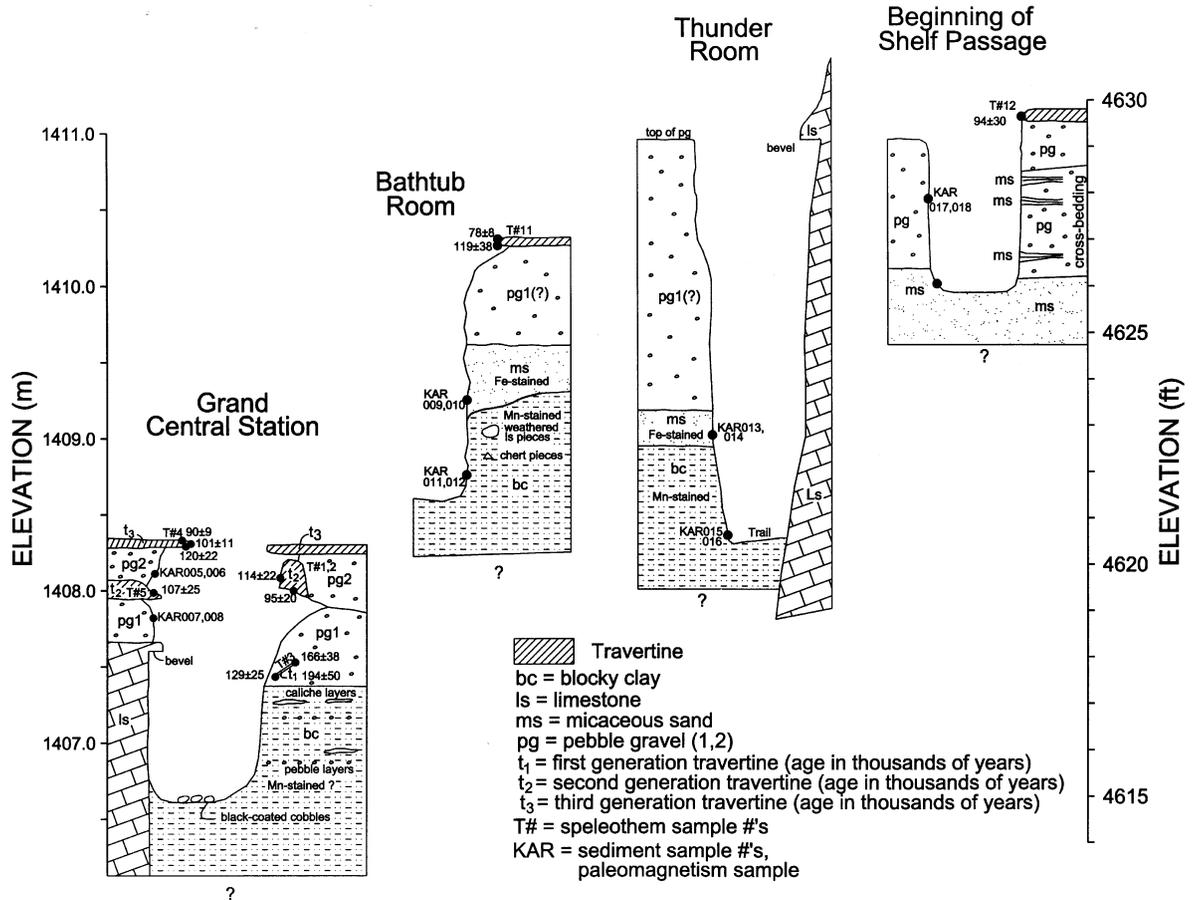
It is likely that the breakdown process in Kartchner Caverns has been going on during the entire vadose history of the cave. Breakdown falls during the air-filled, vadose stage of cave formation and can be due to the following factors: (1) removal of buoyant support when the water level lowers below a passage horizon; (2) base-level backflooding; (3) undercutting by free-surface streams; (4) crystal wedging processes, and (5) earthquake activity (Ford & Williams 1989). All of these factors may have been operative in Kartchner, but (1) was probably the foremost factor.



**Figure 1. Map of Kartchner Caverns showing location of the sediment sample collection sites (black dots), and other locations mentioned in the text.**

Figure 2.

Prominent sediment locations in Kartchner Caverns plotted with respect to elevation, interbedded travertine (t<sub>1</sub>, t<sub>2</sub>, t<sub>3</sub>), and paleomagnetism sample (KAR) collection sites.



**Pebble gravel.** The pebble gravel contains clasts up to 1.2 cm in diameter in a matrix of smaller pebbles, sand, silt and clay. A hand-lens inspection of the pebble gravel indicates that this unit is made up of ~80% quartz pebbles, 10% quartzite pebbles, and 10% sand-, silt-, and clay-sized particles. The largest clasts are the quartzite pebbles.

In Grand Central Station, the pebble gravel came into the cave in at least two episodes, as determined by uranium-series dating of interbedded travertine (Ford & Hill 1999). A broken stalactite (t<sub>1</sub> = 194-129 Ka) is encased in the oldest pebble gravel (pg1), which was then covered with a small amount of travertine (t<sub>2</sub> = 115-95 Ka or so) (Fig. 2). Later, more massive travertine (t<sub>3</sub> = 110-90 Ka or so) covered pebble gravel pg2. From the closeness of dates on t<sub>1</sub>, t<sub>2</sub> and t<sub>3</sub> travertine material, and the lack of any travertine material between the three, it seems as if the pg1 and pg2 pebble gravels may have been rapidly placed into the cave, perhaps with each gravel unit forming in a single, separate event. Finally, the whole sequence was downcut by late-stage vadose stream activity, and the second (t<sub>2</sub>) and third (t<sub>3</sub>) generations of travertine were left as hanging canopies of flowstone or dripstone—such as the ‘hanging’ t<sub>2</sub> stalagmite along the west wall of Grand Central Station (Fig. 2).

In the Thunder Room-Shelf Passage, the top of the pebble gravel is at the same level as the undercut bevel in the wall

limestone (Fig. 2), indicating that the same backflood water may have been responsible for both phenomena. In the Shelf Passage, the pebble gravel is graded (coarser at bottom to finer at top), very faintly cross-bedded, and interbedded with micaceous sand. Slump features show that the sediment slumped towards the center of the passage as the passage was being downcut.

In Granite Dells, the pebble gravel contains large (up to 0.3 m in diameter) granite cobbles and boulders that must have slumped into the cave from the surface. Surface gravel above Granite Dells resembles the pebble gravel in the cave except that it lacks the fine-grained silt and clay fraction. Mica crystals in the granite pieces have a gold-like appearance and are very noticeable. In the pebble gravel within the cave, the mica is covered with mud but is observable when the gravel is washed.

**Micaceous sand.** Micaceous sand occurs directly beneath the pebble gravel and above the blocky clay in the Bathtub Room (Fig. 3), in the Thunder Room, and intermittently in size-sorted pebble gravel at the beginning of the Shelf Passage (Fig. 2). It is a laminated sand, the laminae being highlighted by iron-rich sections. It is a very fine-medium sand (0.1-0.4 mm) composed of approximately 95% quartz sand and 5% mica flakes. The micaceous sand contains no larger clasts within it.

## FINE-GRAINED DEPOSITS

*Fault gouge clay/silt.* The fault zones exposed by the cave are filled with quartz veins and clasts, calcite, and/or a red to orange hematitic clay matrix. An example of this type of clay is the 'red fault clay' in the ceiling of the Main Corridor (Fig. 1), which is composed of an equal mixture of calcite and rectorite-illite clay. The calcite occurs both as disaggregated fragments and also as scalenohedral crystals, which may mean that some of the calcite was deposited before final movement along the fault zone (the disaggregated fragments), while some formed later, after final movement (the scalenohedrons). The clay mineral rectorite occurs as twisted scales and has formed from, and has mostly replaced, illite.

Another occurrence of fault gouge clay is found at the end of the Red River Passage. This clay is composed of 80% greenish-gray, finely-laminated illite, with minor angular quartz clasts and red colloidal hematite between laminae (Hill 1999, Fig. 6). The illite is weakly foliated, but the foliation is mimetic, meaning that the foliation of the mineral occurred before its deposition and lamination as a sedimentary deposit, perhaps when it was part of the underlying Pinal Schist.

Fault gouge material sloughs off of the ceilings and walls of the cave to accumulate on the floor beneath fault zones in a number of places. Such residue collected near Grand Central Station can be classified as a very fine-medium grained silt (0.005-0.02 mm). Probably this residue has been size-sorted; therefore the fault gouge material can be considered to be a clay, with a fine-grained silt fraction.

*Blocky clay.* The blocky clay unit is a floor clay composed of various clay minerals plus detrital and organic matter, which has compacted into separate 'blocks'. The blocky clay unit directly underlies micaceous silt and pebble gravel in the Bathtub Room (Fig. 3), in the Thunder Room, and the pebble gravel unit pg1 in Grand Central Station (Fig. 2). In these three localities, its 'block' segments are covered with thin, black, manganese-rich coatings. In the Bathtub Room, the unit encloses angular chert fragments (fallen roof breakdown) and fossiliferous limestone pieces. Harder 'caliche' layers occur in sections of the blocky clay in Grand Central Station, and there is a possible erosional unconformity between sections of the blocky clay and micaceous sand in the Bathtub Room (Fig. 2).

The composition of the blocky clay unit in the Throne Room contains an equal mix of illite clay (half altered to rectorite) and quartz needles (slender, doubly-terminated prisms). In addition, there is an abundance of organic fiber in the clay. The illite occurs in radially disposed domains and may replace feldspar.

At the Echo Passage-Bison Room junction, a transition can be seen between unconsolidated nontronite clay to compacted blocky clay over a vertical distance of ~1 m. As the clay dried and compacted, it broke up into separate 'blocks'. Black material then migrated to the surfaces of these blocks, depositing as thin layers of manganese and other metallic material (Hill 1999, Fig. 7).

*Unconsolidated clay.* Mud is encountered in numerous places in Kartchner Caverns, especially in the Back Section. The unconsolidated mud of the Subway Tunnel is composed mostly of the pasty, greasy, sticky clay mineral, rectorite, and it is possible that the 'mud' in the entire Back Section is, at least partially, composed of this mineral. The 'mud' in Echo Passage is composed of nontronite.

## PALEOMAGNETIC DATING OF SEDIMENTS

All of the floor sediments—the blocky clay unit and the different pebble gravel units—are paleomagnetically normal. Since these sediments have been correlated with uranium-series ages on interbedded travertine (Ford & Hill 1999), it is surmised that they all date from the Brunhes/Matuyama normal (<~780 Ka) rather than from an earlier normal. Locations where sediment samples were collected for paleomagnetic dating are shown in Figure 2 (KAR).

## INTERPRETATION OF THE SEDIMENTOLOGY

The coarse- and fine-grained deposits in Kartchner Caverns have different origins. The coarse deposits are all related to late-stage vadose events in the cave, whereas the fine-grained sediments have a more complex history, one extending back to the time of faulting and one involving the alteration and replacement of clay minerals. Since the fine-grained sediments are older, they will be discussed first.

## FINE-GRAINED DEPOSITS

The origin of the fault gouge clay/silt is speculative. It is known that illite fills the faults and that this mineral was altered to rectorite *in situ*, but what is not known is if there was an even earlier mineral precursor of illite *in situ*. In other words, did minerals like the feldspars and micas originally fill the faults before altering to illite (and then rectorite), or was the illite clay the original constituent of the faults?

Two clues seem to present themselves in this regard. One clue is the presence of 'birdsnest' quartz near or in the fault zones. These quartz needles probably grew into a clay matrix during the time when hot, silicifying solutions permeated the fault zones. If feldspar-mica debris did at first fill the fault zones, it must have altered quickly to illite-rectorite clay so that the quartz needles could grow into this clay matrix.

The second clue is the illite-filled fault zone at the end of Red River Passage. This illite is thinly laminated and contains angular quartz, much as one would expect of a sedimentary deposit. This illite displays mimetic foliation, which means that the foliation was assumed from some precursor mica or feldspar mineral *before* deposition and lamination of the clay. This opens up the question of whether the Pinal Schist (a foliated rock) might have been the original source of illite to the fault in Red River Passage. Might ascending solutions have carried clay material up the fault zones from the Pinal Schist and deposited it as a sedimentary deposit within some type of

paleokarst cavity? How far below the Escabrosa block the Pinal Schist resides is not known exactly, but Graf (1989) showed it as being less than 30 m. The laminated illite in the Red River Passage must be very old. It predates the cave (it is truncated by it) and its beds tilt northeast to east, not southwest as do the Escabrosa Limestone beds (Jagnow 1999). Either the illite was emplaced and tilted before the tilting of the Escabrosa block, or later movement along the fault zone caused the illite layers to tilt in a direction opposite to that of the bedrock. Curiously, the Red River fault cannot be traced to the surface (Jagnow 1999).

It is uncertain if the blocky clay unit is autochthonous in origin, as suggested by Graf (1989), if it is allochthonous, or if it might be a combination of both. In Grand Central Station, the blocky clay has sections of pebble gravel in it (Fig. 2), and in the Thunder Room it is mixed with organic matter. These occurrences both suggest an allochthonous origin for the blocky clay unit. However, rectorite clay fills the 'red fault zone' in the Main Corridor and is also the main component of the Subway Tunnel 'mud', which suggests that some 'mud' might be autochthonous fault-derived residual material. Similarly, illite is the main component of the fault gouge clay in Red River Passage and it is also the main mineralogical component of the blocky clay in the Thunder Room. Perhaps, then, the blocky clay is a combination of allochthonous and autochthonous sediment. Volume considerations favor this interpretation as does the Thunder Room blocky clay, which consists of illite and quartz needles (dissolved from the fault zone?), feldspar, and organic material (possibly brought in as allochthonous debris).

Another uncertainty exists for the origin of the nontronite clay in the Echo Passage. Nontronite is a mineral known to be derived from granitic terranes where the clay forms from the alteration and breakdown of mica minerals, and it is possible that alaskite granite and/or Pinal Schist debris could be the source of mica for the nontronite. However, granitic pebble gravel and micaceous sand do not actually occur within the Echo Passage. There is the added problem in that the nontronite and black manganese material expelled from the nontronite is enriched in metal. Such an enrichment must have involved some kind of hydrothermal activity where the faults acted as conduits for ore fluids. These factors suggest that the nontronite constituents were derived from residual fault gouge material (illite-rectorite) as the cave passages dissolved.

The following 'best-guess' scenario for the fine-grained clay deposits in Kartchner Caverns is suggested:

1. Illite was deposited in fault zones by hydrothermal solutions ascending through the Pinal Schist and into the above-lying Escabrosa Limestone. These same solutions brought up silica and iron (and other minor metallic constituents), which were deposited along with the illite in the fault zones as quartz and hematite. Hydrothermal solutions also altered some of the illite to rectorite.
2. Calcite was deposited in the fault zones as the temperature decreased. Late movement along the faults disaggregated this calcite and some of the older vein quartz.
3. Cave dissolution exposed some of the illite-rectorite fault gouge clay and this material formed the blocky clay unit.
4. Finally, vadose flood water of high pH and low Eh altered residual illite-rectorite clay to nontronite on the floor of Echo Passage.

#### COARSE-GRAINED DEPOSITS

All of the coarse-grained clastic deposits are related to vadose events in the cave. As the water table dropped, breakdown collapsed to the floor, blocking some of the lower solution passageways. Later, flood water dumped sand and gravel into the cave where they covered the fine-grained blocky clay unit. The following observations apply to the interpretation of the coarse-grained deposits in Kartchner:

1. The pebble gravels in the cave are essentially the same as surface gravels above the cave except for the fine-grained fraction. Thus, the pebble gravels were probably locally derived, entering the cave during times of heavy storms.
2. The age of the blocky clay, micaceous sand, and pebble gravel are all between 780 Ka and 100 Ka based on the travertine and paleomagnetic dating results (Ford & Hill 1999). The pebble gravels correspond to the time of greatest travertine growth in the cave—during the Sangamon interglacial where a wetter climate could have produced storms capable of moving surface gravels into the cave. It can be estimated from Hjultstrom's diagram for the transportation and deposition of sediment (Hjultstrom 1931), that the velocity of the water depositing the pebble gravels must have been between 10 and 90 cm/s; either that, or the gravel could have also partially slumped into place.
3. The Granite Dells cobbles/boulders in a matrix of pebble gravel had to have slumped into place. Granite Dells is very near the surface, and pirated surface runoff probably transported surface sediment into the cave at this location sometime in the past (176 Ka?); (Ford & Hill 1999, Table 1).
4. The micaceous sand probably represents a lateral-fining equivalent of the pebble gravel. The first particles to deposit in a back-wash situation are large pebbles; then, when the velocity has decreased markedly, the fine-grained fraction (mica flakes, fine sand, silt and clay) settles out. The fine-grained fraction typically grades laterally from the center of passages and are finest-grained in deep recesses. Thus, the pebble gravel over micaceous sand/silt may represent two episodes of flooding, the first less violent or extensive than the second. For example, for the Bathtub Room sediment sequence (Fig. 2), flood event #1 may have deposited pebble gravel in another part of the cave and mica sand as a laterally-fined sediment in the Bathtub Room. A more violent flood event, #2, could have brought gravel into the Bathtub Room, creating the



**Figure 3. Blocky clay (lower, dark unit), micaceous sand (middle, iron-stained unit), and pebble gravel (upper unit), Bathtub Room. Scale is 16 cm long. Photo by Bob Buecher.**

sequence where pebble gravel overlies micaceous sand. The interbedded graded sequence of pebble gravel-micaceous sand in the Shelf Passage (Fig. 2) attests to the probable cyclic and repetitive nature of the sediment-filling process in parts of Kartchner Caverns.

#### CONCLUSIONS

1. The illitic fault gouge clay is the oldest clastic unit in Kartchner Caverns. Its origin is speculative, but the illite probably derived from feldspars and micas of the underlying Pinal Schist before the dissolution of the present cave passages.
2. Illite was probably altered to the mineral rectorite by hydrothermal solutions. This is shown by high-temperature quartz needles which have grown into the rectorite along the fault zones.

3. The blocky clay unit is partly autochthonous in origin, having derived from the illite-rectorite fault gouge clay during the dissolution of the cave. However, it may also be partly allochthonous as suggested by sections of pebble gravel and organic matter within this unit. It is likely that the blocky clay unit represents the time of shallow-phreatic dissolution of the cave at or near the water table, and also the beginning of vadose conditions within the cave.
4. The vadose pebble gravels were brought into the cave by flooding, or from the slumping of surface deposits into the cave.
5. The micaceous sand unit probably represents a lateral-fining facies of the pebble-gravel deposits.
6. The blocky clay unit, the pebble gravels, and the micaceous sand are all <780 Ka from paleomagnetic dating of these units.
7. The mineral nontronite probably reconstituted from precursor illite-rectorite in a high pH, low Eh, floodwater environment within the cave.

#### ACKNOWLEDGMENTS

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# DATING OF SPELEOTHEMS IN KARTCHNER CAVERNS, ARIZONA

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*Uranium-series dates on calcite travertine samples collected from Kartchner Caverns range from ~200-40 Ka. These dates span from the Illinoian glacial to the Wisconsin glacial, but the majority cluster within the wetter Sangamon interglacial. Petromorphic vein quartz (>35 Ka from alpha spectrometry and >1 Ma from  $^{234}\text{U}/^{238}\text{U}$  ratios) dates from an earlier thermal episode associated with Basin and Range faulting. All that can be surmised about the time of cave dissolution from these dates is that it happened >200 Ka.*

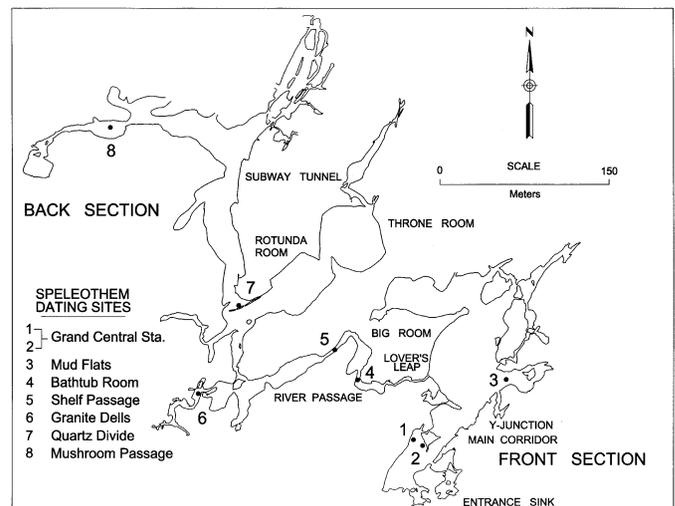
Kartchner Caverns is in the Whetstone Mountains, ~13 km south of Benson, Arizona, USA, just west of Arizona State Highway 90. The cave developed in a downdropped block of Mississippian Escabrosa Limestone. It is a wet, 'live' cave, >3 km long, which features a wide variety of multicolored speleothems. Kartchner Caverns is Arizona's 25th and newest State Park.

Thirty uranium-series dating analyses were attempted on calcite travertine collected from different areas in Kartchner Caverns (Fig. 1), of which 19 were successful (Table 1). An attempt was also made to date the vein and needle quartz by alpha spectrometry. For an explanation of the principles of the uranium-series dating technique, refer to Ford (1997).

Dating of the calcite and quartz material was hindered because of two factors: (1) many of the samples proved to be 'dirty' (i.e., they contained much mud that contributed detrital, non-radiogenic thorium); and (2) the samples were low in uranium ( $\ll 1$  ppm), making them difficult to measure accurately. Due to these factors, a number of the sample dates were 'lost'. The oldest date obtained on the calcite was ~194 Ka, and the youngest was ~41 Ka. This span of time includes the uranium-series date ( $80 \pm 6$  Ka) on travertine encasing the sloth bones in the "Bison" Room, analyzed by J. Mead and C. Johnson (pers. com.). For a correlation of travertine dates with pollen analyses, refer to Davis (1999).

## URANIUM-SERIES DATING OF CALCITE TRAVERTINE

Twelve of the 18 successful analyses of travertine were of samples at significant sediment sites in the cave (Fig. 2). The other six samples were collected at locations where key information about the cave's geologic history might be obtained. For example, it was hoped that the 'Fallen Stalactite' in the Mud Flats of the Big Room would yield an early date that might indicate the time when the water table first descended through the room (i.e., the central, oldest part of this stalactite might have started growing just after the cave became air



**Figure 1. Map of Kartchner Caverns showing the location of speleothem samples collected for dating (black dots) and other places named in the text.**

filled). However, the ages obtained on the Fallen Stalactite range from ~83 - 70 Ka (Table 1), are much younger than the travertine in Grand Central Station, and so indicate that this speleothem did not start to grow until long after the de-watering of the passage.

Two other dates came as somewhat of a surprise: the age of the flowstone collected in Granite Dells and the bevel-related age of 'The Mushroom' in the Mushroom Passage. Three samples were investigated from the Granite Dells material. Two proved too dirty to give reliable dates. The third gave an age of around 176 Ka, but this is also suspect because of detrital contamination. If correct, the flowstone age from Granite Dells is surprising because the gravels in this area look as if they were washed into the cave during a quite recent event. Possibly the Granite Dells flowstone formed in the passage before the major influx of granite pebbles and cobbles there, or

**Table 1. Uranium-series dates on calcite travertine and quartz vein, Kartchner Caverns.**

| <u>Speleothem and Location</u>                             | <u>Date (Ka)</u>           | <u>Occurrence</u>   |
|--|----------------------------|---|
| <u>Big Room</u>  |                            |   |
| ·Fallen Stalactite, Mud Flats                              | 83±18<br>72±18<br>70±15    | Stalactite that fell from ceiling and broke cross-sectionally<br>T#6 = crystalline core<br>T#7 = middle of ringed outer sequence<br>T#8 = base of ringed outer sequence               |
| <u>Granite Dells</u>                                       |                            |   |
| ·Calcite travertine  | 176±62                     | T#16 = flowstone with included pebbles  |
| <u>Mushroom Passage</u>                                    |                            |   |
| ·The Mushroom stalagmite                                   | 54±7<br>41±7               | Thin layer of flowstone growing over bevel<br>T#18B = base of flowstone<br>T#18T = top of flowstone   |
| <u>Grand Central Station</u>                               |                            |   |
| ·Travertine from t1 event, west wall                       | 194±50<br>166±38<br>129±25 | A 30 cm long stalactite embedded in pebble gravel (pg1) directly above contact with blocky clay<br>T#3C = core of stalactite<br>T#3T = top of stalactite<br>T#3B = base of stalactite |
| ·Travertine from t2 event, 'hanging' stalagmite, west wall | 95±20<br>114±22            | Stalagmite grew over pebble gravel (pg1) and was engulfed by pg2 sediment<br>T#1,2C = core of stalagmite<br>T#2O = outside of stalagmite  |
| ·Travertine from t3 event, east wall                       | 120±22<br>101±11<br>90±9   | Flowstone overlying pg2 and t2 travertine<br>T#4B = base<br>T#4M = middle<br>T#4U = upper   |
| ·Travertine from t2 event, east wall                       | 107±25                     | Flowstone underlying pebble gravel (pg2)<br>T#5T = top  |
| <u>Bathub Room</u>   |                            |   |
| ·Travertine flowstone                                      | 119±38<br>78±8             | Flowstone overlying silt<br>T#11M = middle<br>T#11T = top   |
| <u>Shelf Passage</u>                                       |                            |   |
| ·Travertine flowstone                                      | 94±30                      | Flowstone overlying sediment<br>T#12  |
| <u>Quartz Divide</u>                                       |                            |   |
| ·Quartz boxwork  | >350                       | Vein of petromorphic quartz which intruded the rock before the dissolution of the cave  |

perhaps the gravels are much older than has been assumed.

The Mushroom in the Mushroom Passage is a very massive, pristine-looking stalagmite sharply beveled by a former back-up or ponding of unsaturated water (Fig. 3). It was expected that The Mushroom bevel might be very young, as very little travertine has grown since the beveling event. However, from the youngest date of ~40 Ka on calcite that has grown over the bevel, it appears that the beveling event happened long ago and that even the most youthful-looking travertine in Kartchner may not have formed in the very recent past.

The oldest travertine dated from the cave was a piece of broken stalactite (t<sub>1</sub>) located just above the blocky clay unit in Grand Central Station (Figs. 2 & 4). This stalactite started

growing about 194 Ka and was possibly broken by, and incorporated into, the pebble gravel (pg1) influx at about 110 Ka. Since this is the oldest date that indicates an air-filled passage environment for the growth of subaerial travertine, all that can be surmised about the time of cave dissolution (when the cave void itself formed) is that it happened sometime before ~200 Ka.

The ages of the calcite travertine combined with the paleomagnetic dating of sediment (Hill 1999) can be used in conjunction to obtain a rough sequence of events for deposits in Kartchner Caverns. All of the sediment in the cave is paleomagnetically normal; that is, the age of the sediment appears to be <780 Ka, before the Brunhes/Matuyama magnetic reversal.



Figure 3. The beveled 'Mushroom' in the Mushroom Passage. Age of the beveling event was ~40 Ka. Photo by Bob Buecher.

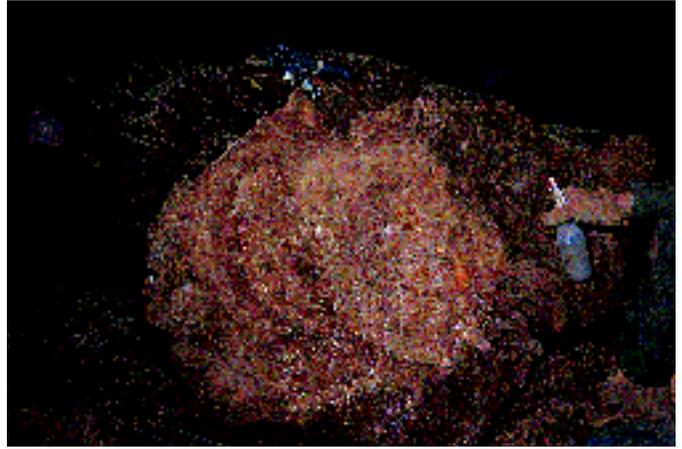


Figure 5. Naturally-broken cross-section of the Fallen Stalactite, Mud Flats, Big Room. Note the middle crystalline center (A) and outer ringed part (B) of the speleothem. This transition may represent a change in climate from wetter to drier conditions. Photo by Bob Buecher.

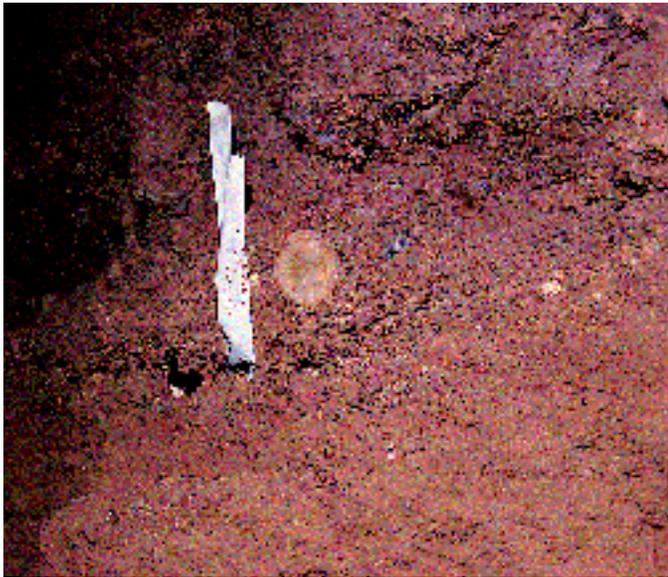


Figure 4. Stalactite T#3 from  $t_1$  event (Table 1) encased in pebble gravel (pg1), just above the blocky clay unit, Grand Central Station. Flagging is hanging just to left of embedded stalactite. Photo by Bob Buecher.

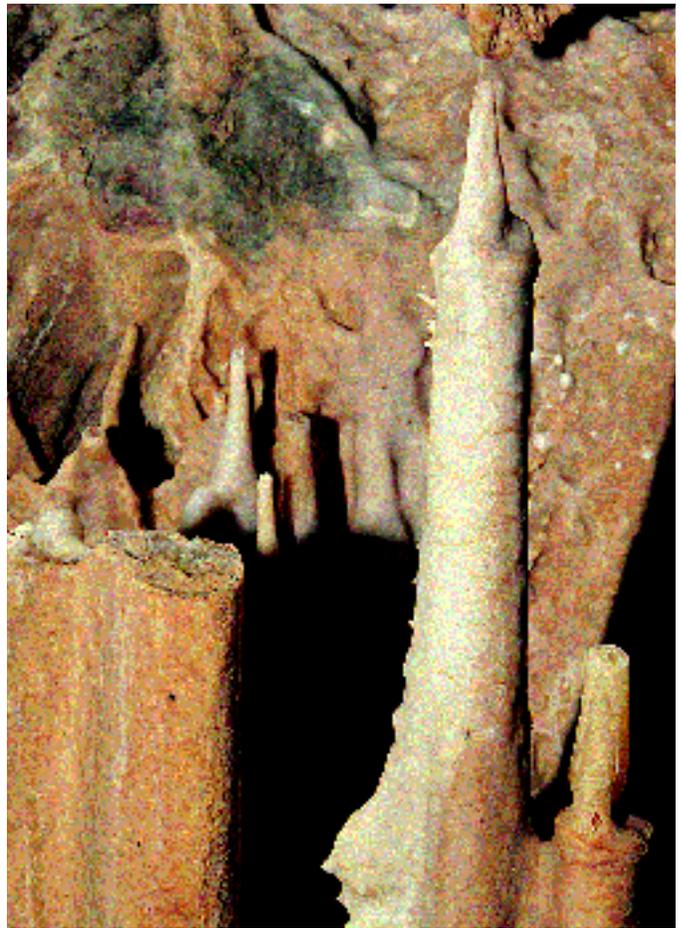
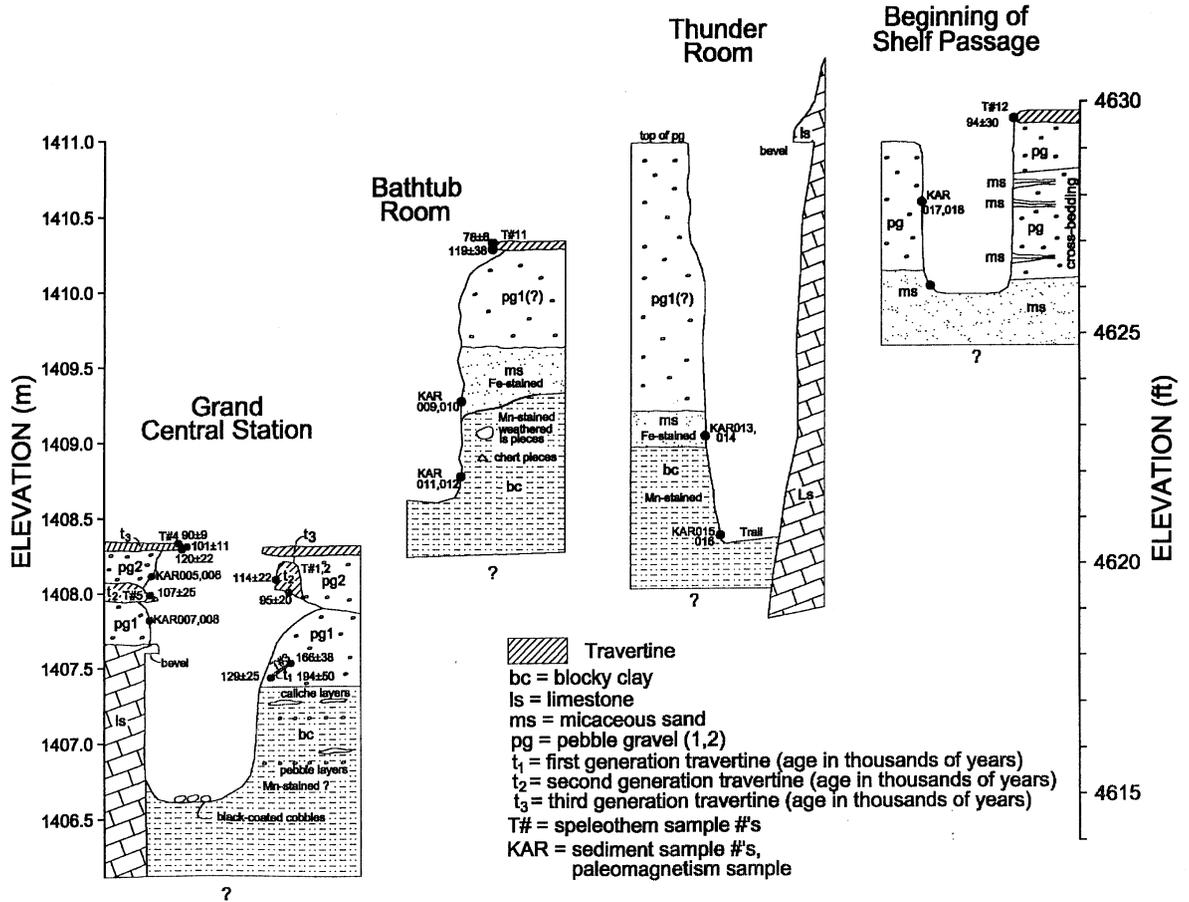


Figure 6. Natural breakage and regrowth of travertine at the Y-junction in the Big Room. The Great Sonoran Earthquake of 1887 may have caused the damage.

Figure 2.

Relative elevations of speleothems and sediments collected from Grand Central Station, the Bathtub Room, Thunder Room, and Shelf Passage. "T" numbers refer to speleothem samples collected for uranium-series dating, and "KAR" numbers refer to sediment samples collected for paleomagnetic dating.



From the travertine dates at Grand Central Station, the blocky clay unit appears to be >200 Ka (older than the travertine that overlies it), while the first influx of pebble gravel (pg1) took place at <129 Ka (the youngest age of the stalactite  $t_1$  embedded in the pebble gravel). There was a period of ~20 Ka (115 - 95 Ka) when travertine ( $t_2$ ) grew over the pebble gravel (pg1) before another influx of pebble gravel (pg2) came into the cave. Finally, the last travertine ( $t_3$ ) event occurred at about 100 - 90 Ka in Grand Central Station before downcutting of the sediment-travertine series occurred without further vadose sediment deposition in this area (Fig. 2; Hill 1999).

It is not known if the pebble gravels in the Bathtub Room and Shelf Passage are part of the Grand Central Station pg1 or pg2 depositional events or if, instead, they entered via a different part of the cave along a different route at different times. The pebble gravel, micaceous sand, and blocky clay units are at different elevations in these areas (Fig. 2), so it is probable (but not certain) that the sediments are not correlative. Flowstones overlying the pebble gravels in the Bathtub Room and Shelf Passage were dated at 78 Ka, 94 Ka and 119 Ka; these dates could either indicate a pg1 or pg2 time of origin for the underlying gravels in these areas.

URANIUM-SERIES DATING OF QUARTZ

Vein and needle quartz were analyzed by the uranium-series alpha spectrometry method. The one successfully dated quartz vein sample has a  $^{230}\text{Th}/^{234}\text{U}$  age of >350 Ka (the upper limit of this dating method) and a >1 Ma date estimated from  $^{234}\text{U}/^{238}\text{U}$  ratios in this sample. These greater ages were expected since quartz is a high-temperature mineral that should date from an event related to Basin and Range faulting and associated hydrothermal activity. The quartz vein material is petromorphic rather than speleothemic; that is, it formed within the rock during an earlier thermal episode and then was exposed by later cave dissolution at the water table. Thus, the veins are older than the cave passages and not related to the dissolutional development of the cave. Attempts to date the needle quartz failed because the samples were too contaminated with detrital thorium for reliable ages to be obtained.

SPELEOTHEMS AND PLEISTOCENE CLIMATE

The clustering of speleothem dates between almost 200 Ka to ~40 Ka is important to the understanding of climate changes in the southwestern United States during the later part of the Pleistocene epoch. The Kartchner Caverns dates are similar to speleothem dates in Carlsbad Cavern, New Mexico, another

Southwest cave. Brook *et al.* (1990) found maximum speleothem growth in Carlsbad Cavern to be during the latter part of the Illinoian glacial (170 - 140 Ka), the Sangamon interglacial (140 - 70 Ka), and into the Wisconsin glacial. This same trend is displayed by the Kartchner Caverns travertine. Some growth occurred during the Illinoian glacial and some in the Wisconsin glacial, but most occurred during the Sangamon interglacial. The Sangamon is thought to have been characterized by a warm, humid climate throughout the southwestern United States (Harris 1985).

A change in climate may be reflected by the Fallen Stalactite in the Mud Flat area of the Big Room. A date of ~83 Ka was obtained for the macrocrystalline, blocky-calcite center of the stalactite which indicates a period of continuous growth under wet conditions during this time (Fig. 5). Then the record changes at about 72 - 70 Ka to a ringed sequence indicative of intermittent wet-dry climatic conditions. This change may document a transition from the wetter Sangamon interglacial to the drier Wisconsin glacial.

#### SPELEOTHEMS AND EARTHQUAKES

Speleothems can be important indicators of earthquake activity in a region (Forti 1997). In Kartchner Caverns, a recent tectonic event is possibly recorded by broken travertine at the Y-Junction in the Main Corridor (Fig. 6) and in the River Passage just past Lover's Leap. In each of these areas the tips of some stalactites are broken off and 3-6 cm of new material has regrown since the breakage. Also, there are a number of fallen soda straws in the Rotunda Room. All of these occurrences suggest earthquake activity. While it is not possible to know the absolute age of travertine without dating it, the world-average figure for travertine growth is a few millimeters per year (Hill & Forti 1997). Using this number, one can speculate that the small amount of travertine breakage in Kartchner may correlate with the Great Sonoran Earthquake of 1887.

#### CONCLUSIONS

1. Although the calcite travertines in Kartchner Caverns are often 'dirty' and low in uranium, 18 satisfactory age analyses have been completed.
2. These ages range from almost 200 Ka to ~40 Ka and cluster (13 out of 18 dates) within the Sangamon interglacial (140-70Ka).
3. The transition from the wetter climate of the Sangamon interglacial to the drier climate of the Wisconsin glacial (~70 Ka) may be recorded by the Fallen Stalactite in the Big Room where there is a change from macrocrystalline blocky calcite in the inner core to a ringed sequence of calcite in the outer layers.
4. The Great Sonoran Earthquake of 1887 may be recorded by broken travertine in the cave.
5. From the uranium-series dates on calcite travertine, all that can be said about the age of the limestone dissolution

that created the cave is that it took place around 200 Ka or somewhat earlier.

6. The quartz mineralization in the cave dates from an earlier hydrothermal episode that probably took place in the Miocene.

#### ACKNOWLEDGMENTS

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# POLLEN AND OTHER MICROFOSSILS IN PLEISTOCENE SPELEOTHEMS, KARTCHNER CAVERNS, ARIZONA

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*Pollen and other microfossils have been recovered from six carbonate speleothems in three Kartchner Caverns rooms: Grand Central Station (samples T2, T3, T4), the Bathtub Room (T11, T12), and Granite Dells (T16). The carbonate samples were dated from 194-76 Ka. The pollen concentration is greatest (~2 grain/cm<sup>3</sup>) in sample T11, which has many layers of clastic sediment, and the concentration is least in T4 (~0.05 grain/cm<sup>3</sup>), which has few mud layers. Therefore, the pollen was probably present in sediments washed into the cave, perhaps during floods. Although the pollen abundance in sample T4 is too low for confident interpretation, modern analogs for the five other samples can be found on the Colorado Plateau in areas that today are wetter and colder than the Kartchner Caverns locality. Agave pollen in samples T2 and T4 indicates that this important source of nectar was in the area during at least the latter part of the Pleistocene. Two oribatid mite exoskeletons recovered in speleothem T4 were probably washed into the cave with the pollen and mud trapped in the speleothems.*

Kartchner Caverns is at ~1400 m msl on the eastern slope of the Whetstone Mountains in Cochise County, Arizona. Six speleothem samples for pollen analysis were selected from the samples dated by Derek Ford at McMaster University using uranium-series techniques (Hill 1992; Ford & Hill 1999). The samples were from three locations in the cave (Fig. 1): Grand Central Station (sample T2, T3, T4), the Bathtub Room (T11, T12), and Granite Dells (T16).

The vegetation near the cave is desert grassland with abundant mesquite (*Prosopis juliflora*) and yucca (*Yucca elata*). The cave entrance is near an intermittent stream with woody riparian vegetation including mesquite, hackberry (*Celtis reticulata*), and acacia (*Acacia* spp.). The mean monthly temperature at nearby Benson, Arizona, is 17.1° C and the average annual precipitation is 290 mm, over half falling during July and August (Sellers & Hill 1974).

## METHODS

A large fragment of each speleothem sample was crushed, and pollen was extracted from 60 cm<sup>3</sup> of the cleaned pea-sized fragments (Table 1.) Low pollen content of the Kartchner Caverns speleothems necessitated the large sample size. Pollen samples from lakes, cienegas, or packrat middens contain tens of thousands of pollen grains per cm<sup>3</sup> of sediment. In contrast, the entire 60 cm<sup>3</sup> speleothem samples usually contained <100 pollen grains.

## RESULTS AND DISCUSSION

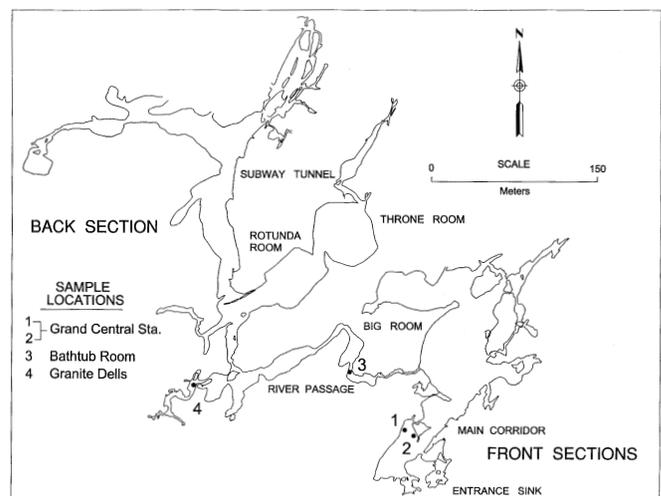
### SOURCE OF POLLEN

The concentration of pollen in the speleothems is 2 grains/cm<sup>3</sup> or less (Table 2). In contrast, the pollen concentration in sediment from Saint David Cienega, ~10 kilometers to the southeast and in similar vegetation, is 17,000 - 20,000 grains/cm<sup>3</sup> (Davis 1994). Such low concentrations in the speleothems indicate that pollen was transported into the cave

in much lower abundance than it occurred at the surface.

Brook *et al.* (1990) have reported good concentration of pollen (~1000 grains/cm<sup>3</sup>) in African cave deposits. They infer an airborne source for pollen in speleothems located near cave entrances. The much lower concentrations of pollen in the Kartchner Caverns speleothems probably reflects a different pollen transport mechanism. The pollen concentration is greatest (up to 2 grains/cm<sup>3</sup>) in T11 and T12, which have many layers of sediment (mud inclusions), and the concentration is least in T4 (~0.05 grains/cm<sup>3</sup>), which has few mud inclusions. T11 and T12 are from the Bathtub Room, near a submerged conduit for water coming into the cave. This avenue may have been the source of pollen and sediment to those speleothems. All samples are in rooms far from the modern natural cave entrance.

This study suggests that flowing water washed the pollen along with mud into the cave where the growing speleothems



**Figure 1. Map of Kartchner Caverns showing location of samples taken for pollen analysis.**

**Table 1. Pollen extraction procedure.**

- a. Speleothem sample crushed into pea-sized fragments.
- b. Fragments washed over 250 µm screen and rinsed thoroughly to remove smaller fragments and pollen contaminants
- c. 60 cm<sup>3</sup> of speleothem fragments placed in Nalgene® beakers and covered with dilute HCl. Concentrated HCl added periodically until speleothem fragments completely dissolved (~3 weeks).
- d. Residue transfer to 50 ml Nalgene® test tubes and centrifuged.
- e. 40 ml HF overnight and 1 hr in boiling water bath centrifuge, decant, water rinse, transfer to 15 ml centrifuge tubes.
- f. Acetolysis\*
- g. 10 ml 10% KOH 2 minutes in boiling water bath centrifuge, decant, rinse with hot water until clear.
- h. Stained with safranin "O".
- i. Transferred to labeled 1 dram shell vials.
- j. Few drops of glycerin added, mixed thoroughly, desiccated over anhydrous clay.

\*ACETOLYSIS

- a. 5 ml glacial acetic acid centrifuge and decant.
- b. Stir sample, add 5 ml acetic anhydride (volumetric dispenser)
- c. Add 0.55 ml H<sub>2</sub>SO<sub>4</sub> to acetic anhydride solution (volumetric pipet), mix centrifuge, decant into glacial acetic acid.
- d. 5 ml glacial acetic acid centrifuge and decant.

incorporated it. This interpretation is supported by the relatively high percentages of pollen from streamside plants (*Populus*, *Cyperaceae*, and *Urtica*) within the speleothems (Table 2 & Fig. 2). The abundance of poorly preserved pollen and fungal spores, which are characteristic of soil horizons that could have been eroded from nearby uplands and washed into the cave, also supports the hypothesis.

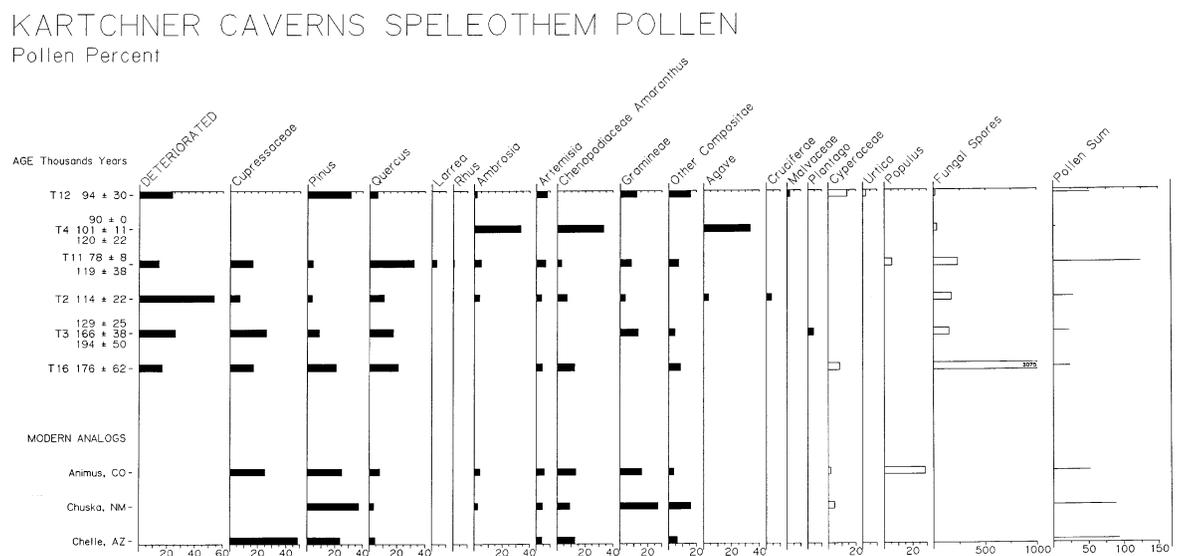
AGE OF POLLEN SAMPLES

The uranium-series radiometric ages of the speleothems analyzed for pollen range from 194 ± 50 to 78 ± 8 Ka (Ford & Hill 1999; Table 2). This age spans the Illinoian glaciation, the Sangamon interglacial, and the beginning of the Wisconsin glaciation. The age of individual speleothems (T3, T4, & T11) span tens of thousands of years, and the position of the pollen within these speleothems is unknown. Thus, the exact age of the pollen sample is undetermined. The sequence shown in Figure 2 is based on the median age of speleothems with multiple dates.

ENVIRONMENTAL INTERPRETATION

Sample T4 has too little pollen to confidently interpret, but the other 5 samples are similar in composition to the pollen rain found in the area today (Davis 1995; Hevly & Martin 1961). The percentages of some herbs (Gramineae, *Chenopodiaceae-Amaranthus*, Compositae, and *Ambrosia*) are lower than in modern vegetation, whereas the percentages of trees (*Quercus* and *Cupressaceae*) and sagebrush (*Artemisia*) are higher. Mesquite (*Prosopis*), which currently dominates the vegetation near the cave, is absent. The winter precipitation indicator *Plantago* is present in sample T3, but summer precipitation indicators like *Boerhaavia*, *Kallstroemia*, and *Euphorbia* are absent (Table 2; Fig. 2). Overall, the pollen assemblage indicates more trees than in the modern vegetation, possibly due to greater precipitation and lower temperature

**Figure 2. Percentage pollen diagram of the Kartchner Caverns pollen samples (upper) and 3 modern analogs from the Colorado Plateau: Animus, Colorado (Maher 1963), Chuska, New Mexico (Bent & Wright 1963), and Chelle, Arizona (Fall 1987).**



**Table 2. Percentages of pollen and spores from Kartchner Caverns speleothems. Speleothem labels and ages are from Hill (1992).**

| SAMPLE            | 1      | 2      | 3      | 4      | 5     | 6      |
|-------------------|--------|--------|--------|--------|-------|--------|
| SPELEOTHEM        | T2     | T3     | T4     | T11    | T12   | T16    |
| U-Series Age (Ka) | 114±22 | 129±25 | 90±0   | 78±8   | 94±30 | 176±62 |
|                   |        | 166±38 | 101±11 | 119±38 |       |        |
|                   |        | 194±50 | 120±22 |        |       |        |
| SUM               | 28     | 23     | 3      | 124    | 51    | 24     |
| DETERIORATED      | 53.6   | 26.1   | 0.0    | 13.7   | 23.5  | 16.7   |
| Pinus             | 3.6    | 8.7    | 0.0    | 4.0    | 31.4  | 20.8   |
| Cupressaceae      | 7.1    | 26.1   | 0.0    | 16.1   | 0.0   | 16.7   |
| Quercus           | 10.7   | 17.4   | 0.0    | 32.3   | 5.9   | 20.8   |
| Larrea            | 0.0    | 0.0    | 0.0    | 3.2    | 0.0   | 0.0    |
| Rhus              | 0.0    | 0.0    | 0.0    | 0.8    | 0.0   | 0.0    |
| Ambrosia          | 3.6    | 0.0    | 33.3   | 4.8    | 2.0   | 0.0    |
| Artemisia         | 3.6    | 0.0    | 0.0    | 6.5    | 7.8   | 4.2    |
| Other Compositae  | 0.0    | 4.3    | 0.0    | 7.3    | 15.7  | 8.3    |
| Gramineae         | 3.6    | 13.0   | 0.0    | 8.1    | 11.8  | 0.0    |
| Cheno-Am          | 7.1    | 0.0    | 33.3   | 3.2    | 0.0   | 12.5   |
| Agave             | 3.6    | 0.0    | 33.3   | 0.0    | 0.0   | 0.0    |
| Cruciferae        | 3.6    | 0.0    | 0.0    | 0.0    | 0.0   | 0.0    |
| Malvaceae         | 0.0    | 0.0    | 0.0    | 0.0    | 2.0   | 0.0    |
| Plantago          | 0.0    | 4.3    | 0.0    | 0.0    | 0.0   | 0.0    |
| Populus           | 0.0    | 0.0    | 0.0    | 5.6    | 0.0   | 0.0    |
| Cyperaceae        | 0.0    | 0.0    | 0.0    | 0.0    | 13.7  | 8.3    |
| Urtica            | 0.0    | 0.0    | 0.0    | 0.0    | 2.0   | 0.0    |
| Fungal Spores     | 175.0  | 147.8  | 33.3   | 236.3  | 17.6  | 3075.0 |

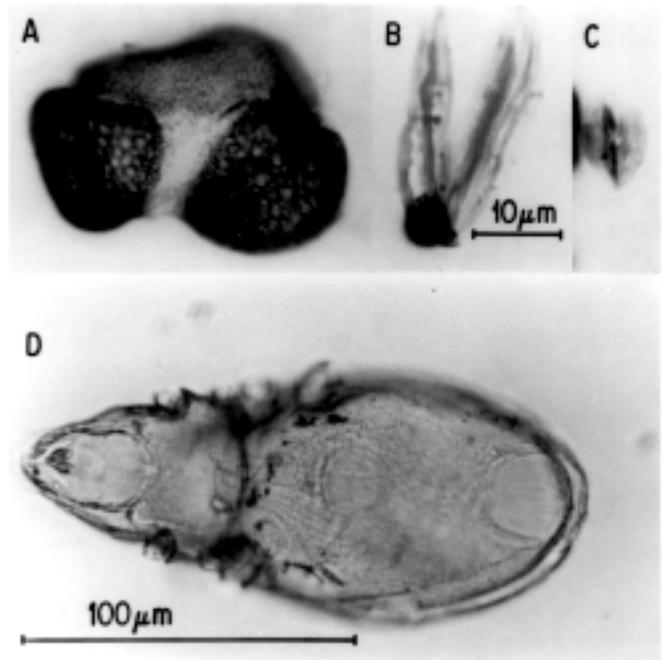
when the samples were deposited 194-75 Ka (Fig. 2).

A numerical comparison between the Kartchner Caverns samples and modern pollen samples in the western United States used the squared chord distance (scd) statistic (Overpeck 1985). Close modern analogs (scd < 0.14) for the speleothem pollen samples were found on the Colorado Plateau. These modern samples are shown in the lower portion of Figure 2. The climate where the modern samples were collected is wetter (300-900 mm/yr v. 290 mm/yr) with a much colder mean annual temperature (6-10°C v. 17°C) than at Kartchner Caverns today.

Low pollen concentration of the speleothem pollen samples makes this climatic interpretation tentative. Also, the original pollen assemblage may have been altered by water transport into the cave. The modern analogs shown in Figure 2 all have a squared chord distance of <0.15, which is considered a close match (Overpeck 1985). However, the higher percentage of oak (*Quercus*) than in any of the analog samples (Fig. 2) and the two *Agave* grains suggest less than the 10°C cooling indicated by the Colorado Plateau analogs.

#### AGAVE POLLEN

An important feature of the modern ecology of Kartchner Caverns is the presence of a nesting colony of bats (Buecher & Sidner 1999). Two samples (T2 & T4) each contain single grains of *Agave* pollen, thus confirming that this important source of nectar for the bats was present in the past when the speleothems were deposited (~194-76 Ka).



**Figure 3. Photomicrographs of Kartchner Caverns microfossils. A. Pine (*Pinus*) pollen from sample T12. B. Deteriorated joint fir (*Ephedra*) pollen from sample T12. C. Creosote bush (*Larrea*) pollen from T11. D. Oribatid mite from sample T4. Magnification of A, B, and C, use upper scale (10  $\mu$ m); D use lower scale (100  $\mu$ m).**

#### OROBATID MITES

Two exoskeletons of oribatid mites were recovered in sample T4 (Fig. 3). Although living mites have been photographed on modern speleothems (Welbourn 1999), this is the first report of a fossil occurrence of these organisms in speleothems. They are common as fossils in some archeological samples, but their paleoecological significance is uncertain (Davis & Buchmann 1994).

#### CONCLUSIONS

Pollen is present in low numbers in six speleothems at Kartchner Caverns, probably because it was washed into the cave from the surface. Modern analogs for the fossil pollen percentages can be found today on the Colorado Plateau, where the mean annual temperature is 10°C cooler than at Kartchner Caverns State Park. However, the climate from 194-76 Ka was not too cool for *Agave*, whose pollen is present in two samples.

#### ACKNOWLEDGMENTS

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# INVERTEBRATE CAVE FAUNA OF KARTCHNER CAVERNS, KARTCHNER CAVERNS, ARIZONA

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*The invertebrate cave fauna of Kartchner Caverns, Kartchner Caverns State Park, Cochise Co., Arizona, was surveyed between 1989 and 1991. Thirty-eight invertebrate species were recorded during the study, including (11%) troglobites, 19 (50%) troglolithes, 1 troglolithene and 12 (32%) accidentals. Of the remaining, 1 was an obligate parasite and the other a guanophile. Most of the Kartchner Caverns cave fauna depend upon guano deposited by a summer colony of *Myotis velifer*. The dominant arthropods were mites found in the guano.*

Invertebrates, especially arthropods, make up the majority of all cave organisms. There have been few biospeleological surveys of invertebrates in the southwestern United States. Most work in this region has been concentrated in the Guadalupe Escarpment area, New Mexico (Barr & Reddell 1967; Welbourn 1978; Northup *et al.* 1995; Cokendolpher & Polyak 1996). In addition, there have been surveys of lava caves in New Mexico and Arizona (Peck 1982; Northup & Welbourn 1997). The only published studies of Arizona cave invertebrates have been in the Grand Canyon (Peck 1980; Dorst & Blinn 1997), the earth crack caves of Wupatki National Monument (Welbourn 1979; Muchmore 1981), and four lava caves in the vicinity of Flagstaff (Peck 1982). Caves in southern Arizona are widely scattered in isolated mountain ranges (i.e. Catalina, Chiricahua, Huachuca, Santa Rita and Whetstone Mountains) making a survey of the cave invertebrates more difficult. The only cavernicolous species from southern Arizona are a troglobitic isopod, *Brackenridgia sphinxensis* Schultz from the Chiricahua Mountains and a troglolithic pseudoscorpion, *Tuberochernes ubicki* Muchmore from the Santa Rita Mountains.

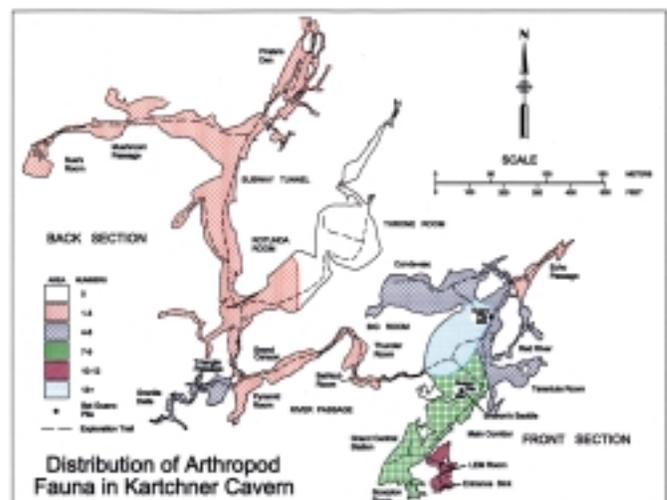
Kartchner Caverns formed in limestone isolated near the base of the Whetstone Mountains (Jagnow 1999). Kartchner Caverns was discovered in 1974 and has been kept in nearly pristine condition (Tuffs & Tenen 1999). In 1988, the State of Arizona purchased the cave as a state park and initiated plans to develop a show cave. Kartchner Caverns offered a unique opportunity to establish a baseline survey of the invertebrate cave fauna before the cave was developed, and this survey should allow future studies to assess the effects of commercial development on the cave fauna.

## MATERIALS AND METHODS

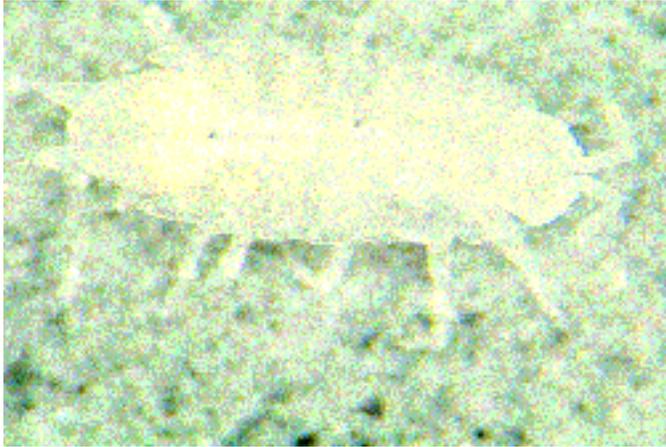
The inventory of the invertebrate cave fauna involved a total of 36 trips into Kartchner Caverns with over 164 hours underground between May 1989 and May 1991. Trips into the cave between late-April and mid-September were scheduled to minimize disturbance of the bats. This was done by avoiding

the active roost areas or by working in the active roost areas at night. The survey for invertebrates was conducted by examination of substrate, organic material, loose rocks, walls, and pool surfaces visually using an OptiVisor with a 2.5x magnification lens. Eight other caves visited during this study were surveyed in the same manner.

Collection of specimens in the cave was limited to those necessary for identification and laboratory study. Samples of *Myotis velifer* (Allen) guano (10-30 cm<sup>3</sup>) were collected from various guano sites in the Front Section of the cave (Fig. 1). Two guano sites (guano piles #20 and 9c) in the Big Room (Fig. 1) were sampled monthly for a year and examined for arthropods. Arthropods were extracted from guano samples using a Berlese-funnel. Samples were kept in the Berlese-funnel for seven days and all specimens were preserved in 75% ETOH. The mites were separated into species groups, counted using a stereo microscope (Wilde M5), and recorded as number of mites/cm<sup>3</sup> of guano. Representative specimens were mounted in a Hoyer's type mounting media on standard



**Figure 1. Distribution of arthropod fauna in Kartchner Caverns.**

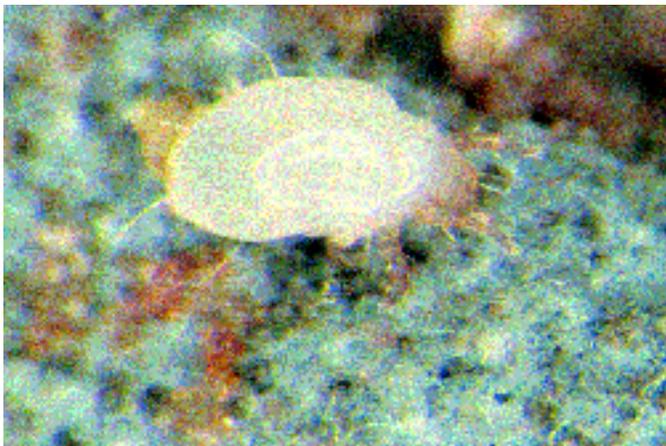


**Figure 2. Microphotograph of *Brackenridgia* sp. (Isopoda, Trichoniscidae) from Kartchner Caverns.**

microscope slides (76 x 25 x 1 mm) for identification under a compound microscope (Wilde M20 phase contrast). Unmounted specimens were stored in 75% ETOH. Samples collected in other guano piles in the Front Section (Fig. 1) were processed in the same manner. Representative specimens will be deposited in the Acarology Laboratory at Ohio State University, Columbus, Ohio, and the Florida State Collection of Arthropods, Gainesville, Florida.

Population estimates for the spider, *Eidmannella pallida* (Emerton) (Araneae, Nesticidae), in the Big Room were made by counting the number of spiders along ~175 m of marked trail that circled guano piles 9c and 20 (Fig.1). All individuals found on and up to 1 m on either side of the trail were counted.

To investigate the possible connection between a surface blowhole and the Granite Dells, 50 *Ceuthophilus pima* Hubbell (Orthoptera, Rhaphidophoridae) were collected at oatmeal bait around the surface blowhole above the Granite Dells area (Fig.



**Figure 3. Microphotograph of an adult *Saccassania* sp. (Acari, Acaridae) from Kartchner Caverns.**

1). The crickets were placed in a plastic bag with a fluorescent dye and released after about 5 to 10 minutes. Crickets in the Granite Dells area were examined for the presence of dye. Cave crickets were randomly captured in Kartchner Caverns and around the surface blowhole and examined for mites and released. Representative mites were removed from some cave crickets for rearing and taxonomic study.

RESULTS AND DISCUSSION

Thirty-eight invertebrate species were identified in Kartchner Caverns during this study (Table 1). The 38 species included 4 (11%) considered to be obligate cave dwellers (troglabites) and 19 (50%) facultative cave dwellers (troglaphiles). The camel cricket, *C. pima*, was a troglaxene because they leave the cave to feed. Twelve accidentals, one obligate parasites, and one guanophile made up the remaining 14 species. The distribution of arthropod species in Kartchner Caverns is presented in Figure 1, and a list of species found in Kartchner Caverns is summarized in Table 1.

**Table 1. Summary of invertebrate fauna collected from Kartchner Caverns. Ecological group: Accidental = an animal that wanders or falls into the cave, but cannot survive in the cave; Troglaxene = an animal that lives part of its life cycle in the cave, but must leave the cave to feed; Troglaphile = an animal that can live its entire life in the cave, but is not restricted to the cave; Troglabite = an obligate cave animal.**

**Guild: What the animal does in the cave community. P = predator; F = fungivore (including bacteria); S = scavenger; PA = parasite; U = unknown.**

**Status: How frequently a group of animals was found in the cave. C = common; R = rare.**

|  | Ecological Group | Guild | Status |
|--|------------------|-------|--------|
| NEMATODA                                       |                  |       |        |
| undetermined material                          | troglaphile?     | F     | C      |
| ARTHROPODA                                     |                  |       |        |
| Class Arachnida                                |                  |       |        |
| Order Palpigrada                               |                  |       |        |
| undetermined material                          | troglaphile?     | P     | R      |
| Order Scorpionida                              |                  |       |        |
| undetermined material                          | accidental       | P     | R      |
| Order Araneae                                  |                  |       |        |
| Nesticidae                                     |                  |       |        |
| <i>Eidmannella pallida</i> (Emerton)           | troglaphile      | P     | C      |
| Theraphosidae                                  |                  |       |        |
| undetermined genus                             | accidental       | P     | R      |
| Order Acari                                    |                  |       |        |
| Acaridae                                       |                  |       |        |
| <i>Saccassania</i> sp.                         | troglaphile      | S     | C      |
| Argasidae                                      |                  |       |        |
| <i>Ornithodoros</i> nr. <i>haser</i> (Schulze) | parasite         | PA    | R      |
| Cheyletidae                                    |                  |       |        |
| <i>Cheyletus</i> sp.                           | troglaphile      | P     | R      |
| Histiotomatidae                                |                  |       |        |
| undetermined genus 1                           | troglaphile      | S     | R      |
| undetermined genus 2                           | troglaphile      | S     | R      |
| Laelapidae                                     |                  |       |        |
| <i>Geolaelaps</i> sp.                          | troglaphile      | P     | C      |

|   |              |      |   |  |
|---|--------------|------|---|--|
| Neothrombiidae  |              |      |   |  |
| <i>Ceuthothrombium</i> sp.                              | troglobite   | PA/P | C |  |
| Pygmephoridae   |              |      |   |  |
| undetermined genus                                      | troglophile  | S    | R |  |
| Rosenteinidae   |              |      |   |  |
| <i>Nycterglyphus</i> sp.                                | guanophile   | S    | R |  |
| Rhagidiidae   |              |      |   |  |
| <i>Poecilophysis</i> sp.                                | troglobite?  | P    | R |  |
| Rhodacaridae  |              |      |   |  |
| <i>Rhodacarus</i> sp.                                   | troglophile  | P    | R |  |
| Stigmaeidae   |              |      |   |  |
| <i>Eustigmaeus</i> sp.                                  | troglophile  | P    | C |  |
| Tarsonemidae  |              |      |   |  |
| <i>Tarsonemus</i> sp.                                   | troglophile  | S    | R |  |
| Oribatida   |              |      |   |  |
| undetermined material (4 species)                       | troglophile? | S    | R |  |
| Order Pseudoscorpiones                                  |              |      |   |  |
| undetermined genus                                      | accidental   | P    | R |  |
| Class Chilopoda   |              |      |   |  |
| Scolopendriidae   |              |      |   |  |
| undetermined genus                                      | accidental   | P    | R |  |
| Class Malacostraca                                      |              |      |   |  |
| Order Isopoda   |              |      |   |  |
| Trichoniscidae  |              |      |   |  |
| <i>Brackenridgia</i> sp. nr. <i>sphinxensis</i> Schultz | troglobite   | F    | C |  |
| Oniscidae   |              |      |   |  |
| Porcellio sp.   | accidental   | F    | C |  |
| Class Insecta   |              |      |   |  |
| Order Thysanura   |              |      |   |  |
| Nicoletiidae  |              |      |   |  |
| <i>Nicoletia</i> sp.                                    | troglobite   | F    | C |  |
| Order Collembola  |              |      |   |  |
| Sminthuridae  |              |      |   |  |
| undetermined genus                                      | troglophile  | F    | R |  |
| Entomobryidae   |              |      |   |  |
| undetermined genus                                      | troglophile  | F    | R |  |
| Order Orthoptera  |              |      |   |  |
| Rhaphidophoridae  |              |      |   |  |
| <i>Ceuthophilus pima</i> Hubbell                        | trogloxene   | S    | C |  |
| Order Psocoptera  |              |      |   |  |
| Psyllipsocidae  |              |      |   |  |
| <i>Psyllipsocus ramburii</i>                            | troglophile  | F    | C |  |
| Selys-Longchamps  |              |      |   |  |
| Order Hemiptera   |              |      |   |  |
| Reduviidae  |              |      |   |  |
| undetermined genus                                      | accidental   | P    | R |  |
| Order Coleoptera  |              |      |   |  |
| Staphylinidae   |              |      |   |  |
| undetermined material                                   | accidental   | F    | R |  |
| Tenebrionidae   |              |      |   |  |
| <i>Eleodes</i> sp.                                      | accidental   | S    | R |  |
| undetermined fragments                                  | accidental   | U    | R |  |
| Order Lepidoptera                                       |              |      |   |  |
| undetermined material                                   | accidental   | U    | R |  |
| Order Diptera   |              |      |   |  |
| Muscidae  |              |      |   |  |
| undetermined genus                                      | accidental   | S    | C |  |
| Sciaridae   |              |      |   |  |
| undetermined genus (2 species)                          | troglophile  | S    | C |  |
| Order Hymenoptera                                       |              |      |   |  |
| Formicidae  |              |      |   |  |
| undetermined genus                                      | accidental?  | U    | R |  |

Invertebrates in Kartchner Caverns depend on guano deposited by the colony of about 1000 *M. velifer* between late-April and mid-September (Buecher & Sidner 1999). Small amounts of organic matter washed into the cave by periodic flooding provide a limited food supply to the Back Section. The camel crickets, *C. pima*, do not depend on organic material carried into the cave, but appear to take advantage of any available food source.

#### THE BACK SECTION

Few invertebrates were found in the Back Section (Fig. 1). Granite Dells was the exception with several invertebrate species present.

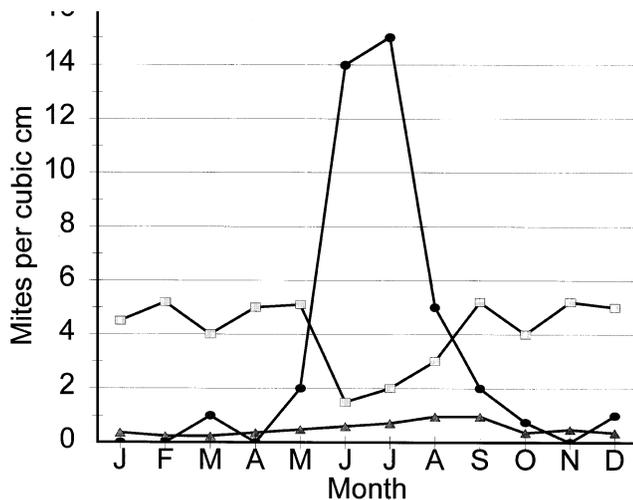
The only invertebrate regularly found beyond the Triangle Passage was a troglotic terrestrial isopod, *Brackenridgia* nr. *sphinxensis* Schultz (Isopoda, Trichoniscidae) (Fig. 2). This isopod was observed feeding on wooden trail makers and plant debris (i.e., twigs, leaves, and other plant material) in the mud-covered areas. Evidence of *B. nr. sphinxensis* was also found along the trails where many of the wooden trail markers had been eaten, leaving only reflective tape and frass. Periodic flooding of the Back Section, especially the lower Rotunda Room, Mushroom Passage, Subway Tunnel and Pirate's Den, eliminated or displaced isopods, but the plant debris left behind provides a food resource for recolonization.

The only other arthropods observed in the Back Section were occasional camel crickets (*C. pima*), a fly (Diptera) and a hemipteran (Reduviidae) that probably wandered through the Triangle Passage from a surface connection in the Granite Dells area. No invertebrates were found in the Throne Room, Sue's Room and upper portion of the Rotunda Room (Fig. 1). The wooden trail markers in these areas had not been disturbed. The bat guano deposits in the Throne and Rotunda Rooms were dated at 50–40 Ka and suggest a former opening to the surface (Buecher & Sidner 1999). No invertebrates were found in or associated with the guano in the Back Section.

Other than the main entrance, the Granite Dells area was the only part of the cave known to have a current connection to the surface. The presence of *C. pima*, an unidentified surface spider, and an unidentified lepidopteran indicated a connection to the surface through the blowhole. Even with a connection to the surface, few arthropods were observed in this area. Attempts to locate marked *C. pima* that had been released on



Figure 4. Scanning electron micrograph of a *Sancassania* sp. deutonymph (Acari, Acaridae) from Kartchner Caverns.



**Figure 5.** Average density of mites per month from samples at guano pile #20, Kartchner Caverns. ● = represents larvae, tritonymphs and adult *Sancassania* sp.; ■ = represents number of non-feeding deutonymphs (= hypopodes) of *Sancassania* sp.; ▲ represents number of *Geolaelaps* sp. (all instars).

the surface were unsuccessful, suggesting there may be other cavities between the surface opening and Granite Dells area. All the invertebrates found in this area, except *C. pima* and *B. nr. sphinxensis*, were considered to be accidentals.

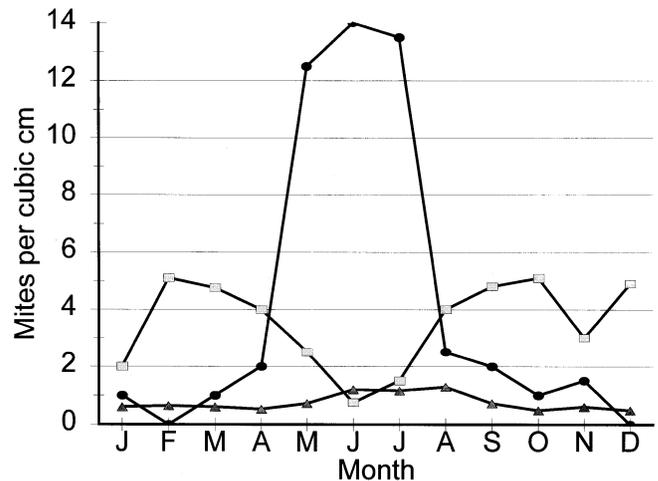
#### THE RIVER PASSAGE

The area between the Pyramid Room and Big Room (River Passage) was a transition zone between the two parts of the cave (Fig. 1). No invertebrates were regularly found in this area. Only an occasional *C. pima*, *B. nr. sphinxensis* or dipteran were observed in this section. Organic material in the River Passage was limited to occasional *M. velifer* guano pellets.

#### THE FRONT SECTION

The Front Section of Kartchner Caverns is the biological center of the cave with 38 invertebrate species distributed throughout that area (Fig. 1). Identified in the Big Room and Cul-de-sac, are numerous *M. velifer* guano piles of different size and age. These guano accumulations are the primary food source for most invertebrates in Kartchner Caverns. During this study, *M. velifer* roosted near the Lunch Spot (Fig. 1, Guano Pile #20) and Sharon's Saddle (Fig. 1, Guano Pile #9c). In late-summer, the bats were more likely to be dispersed in the Big Room, distributing guano over a wide area (Buecher & Sidner 1999). The movement of the bats significantly affected the number of invertebrates living in the guano.

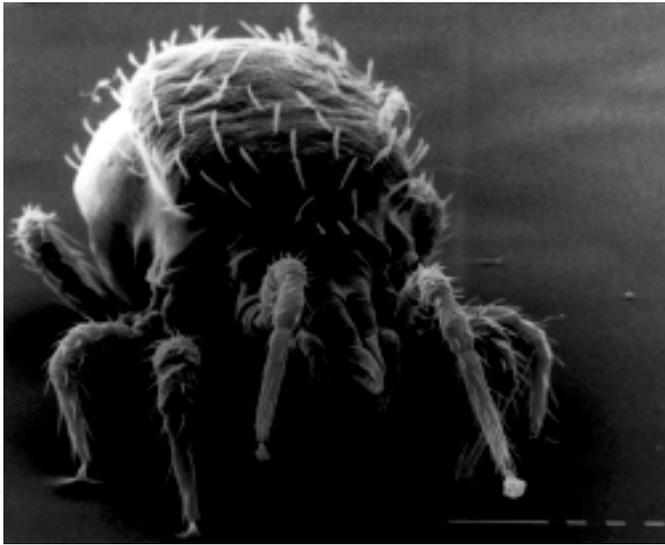
The guano piles that were refreshed regularly supported more mold growth and higher nematode and arthropod populations. The first *M. velifer* guano of the year stimulated visible mold and bacteria growth and this was followed by an increase in the nematode and mite populations. The most



**Figure 6.** Average density of mites per month from samples at guano pile #9c, Kartchner Caverns. ● = represents larvae, tritonymphs and adult *Sancassania* sp.; ■ = represents number of non-feeding deutonymphs (= hypopodes) of *Sancassania* sp.; ▲ represents number of *Geolaelaps* sp. (all instars).

abundant guano arthropod was *Sancassania* sp. (Acari, Acaridae) (Figs. 3 & 4). When fresh guano accumulated at a site, the dormant *Sancassania* sp. deutonymphs (= hypopodes) in the guano developed rapidly into adults and began their reproductive cycle. *Sancassania* sp. can be reared on fungus and yeast, but they also feed on insect eggs and larvae (Hughes 1976) and occasionally nematodes (C. Welbourn, unpub. data). Hughes (1976) reported that *S. berlesii* (Michael) completed its life cycle in 8-9 days at 22°C and 100% relative humidity and that a female could produce over 1000 eggs in 39 days. The 99.4% relative humidity and temperature of 20.9°C (Buecher 1999) provided an ideal environment for *Sancassania* sp. to increase its population very rapidly when a food source (i.e. fresh guano) was available. Within a month after the *M. velifer* deposit fresh guano on the two monitored piles (#20 & #9c), the mite population was as high as 17/cm<sup>3</sup>. The seasonal response of *Sancassania* sp. to the presence of fresh guano differed between the two major roost areas (Figs. 5 & 6). At guano pile #20, the peak period for *Sancassania* sp. was May through July, while the peak period for the same mite at guano pile #9c was July and August. Other fungivorous mites (Tarsonemidae, Histiostomatidae, and Pygmephoridae) fed on fresh guano, but never in large numbers (Table 1). Flies were also associated with the fresh guano.

In the monitored guano piles the dominant predator was another mite, *Geolaelaps* sp. (Acari, Laelapidae) (Fig. 7). While the population density of *Geolaelaps* sp. was never close to that of *Sancassania* sp., it was the second most common arthropod in the fresh guano with 0.24-1.28/cm<sup>3</sup> (Figs. 5 & 6). The peak in the *Geolaelaps* sp. population usually occurred just after the peak in the *Sancassania* population.



**Figure 7.** Scanning electron micrograph of *Geolaelaps* sp. (Acari, Laelapidae) from Kartchner Caverns.

*Sancassania* sp. and *Geolaelaps* sp. were the dominant arthropods during bat residence times (about mid-April to late-September). Other predator mites in the guano samples were *Eustigmaeus* nr. *lirella* (Summers & Price) (Stigmaeidae), *Cheyletus* sp. (Cheyletidae), and *Rhodacarus* sp. (Rhodacaridae). With the exception of *E.* nr. *lirella*, these predators were found in very low numbers. *Eustigmaeus* nr. *lirella* were in most samples from guano piles receiving a little fresh guano annually.

After the bats moved to another roost or migrated, the invertebrate fauna of the guano changed when food resources became depleted. Most *Sancassania* sp. stop development at the non-feeding deutonymphal instar (= hypopus). The deutonymph in many Acaridae can survive long periods without food and is the dispersal instar (Evans 1992). Within a month after the last fresh guano was deposited, almost the entire population of adult *Sancassania* sp. died leaving a reduced population (2-5/cm<sup>3</sup>) of deutonymphs until the next year (Figs. 5 & 6). *Sancassania* sp. deutonymphs usually buried themselves in the guano and waited for the next fresh guano. Several clumps of one to several hundred deutonymphs were observed in the guano. It is not known how long the deutonymphs of this species can survive in the guano without food, but a few individuals were found in most of the inactive guano piles sampled. As the guano aged, other arthropods moved onto the guano, including crickets, oribatid mites, spiders, psocopterans, and an occasional isopod. Guano more than a year old supported very few invertebrates.

The area from the LEM Room to the entrance is anomalous within the cave. Here there is a significant seasonal fluctuation in temperature and humidity (Buecher 1999), and organic input is predominantly scattered *M. velifer* guano pellets and occasional surface material carried in by rodents. The dominant cave arthropods identified were camel crickets, *C. pima*.

The other fauna in this area varied seasonally, but included many of the accidental species found in the cave.

#### COMPARISON OF CAVE FAUNA OF KARTCHNER CAVERNS WITH OTHER CAVES

The invertebrate cave fauna and cave community of Kartchner Caverns is unique. Although the cave fauna of southern Arizona is not well known, some comparisons can be made with eight other caves in four mountain ranges (Table 2). The most notable differences were the absence of *Sclerobunus* nr. *robustus* (Opiliones, Triaenonychidae) and a *Rhadine* sp. (Coleoptera, Carabidae). Briggs (1971) reported *S. robustus* (Packard) from fir forests at elevations of 2933-3500 m msl in Arizona and 2166-2666 m msl in New Mexico. The *Sclerobunus* nr. *robustus* from the caves in Table 2 were at least 800 m to >1200 m below levels listed by Briggs (1971). In addition, the troglotic dipluran *Plusiocampa* sp. (Diplura, Campodeidae) was in all caves examined except for Kartchner Caverns and the two caves in the Santa Rita Mountains (Table 2). Troglotic diplurans have been noted in a wide variety of caves in New Mexico and Arizona (Barr & Reddell 1967; Welbourn 1978; Northup & Welbourn 1997; C. Welbourn unpub. data).

**Table 2.** Comparison of the cave fauna in Kartchner Caverns with other southern Arizona cave fauna. + = indicates that the species was observed in at least one of the caves examined;  $\phi$  = indicates that the species was not observed in any of the caves examined; a. Only *Ceuthophilus papago* Hubbell; b. Only *Ceuthophilus paucispinosus* Rehn.

|   | Kartchner<br>Caverns | Whetstone<br>Mtns | Huachuca<br>Mtns | Santa<br>Rita<br>Mtns | Catalina<br>Mtns |
|---|----------------------|-------------------|------------------|-----------------------|------------------|
| Number of Caves Examined                  | 1                    | 1                 | 3                | 2                     | 2                |
| Elevation (m, approximate)                | 1566                 | 2033              | 1800-<br>2100    | 1733-<br>1833         | 1566-<br>1666    |
| Class Arachnida                           |                      |                   |                  |                       |                  |
| Order Opiliones                           |                      |                   |                  |                       |                  |
| Triaenonychidae                           |                      |                   |                  |                       |                  |
| <i>Sclerobunus</i> sp.<br>(troglophile)   | $\phi$               | +                 | +                | +                     | +                |
| Class Malacostraca                        |                      |                   |                  |                       |                  |
| Trichoniscidae                            |                      |                   |                  |                       |                  |
| <i>Brackenridgia</i> sp.<br>(troglobite)  | +                    | +                 | +                | $\phi$                | $\phi$           |
| Class Insecta                             |                      |                   |                  |                       |                  |
| Campodeidae                               |                      |                   |                  |                       |                  |
| <i>Plusiocampa</i> sp.<br>(troglobite)    | $\phi$               | +                 | +                | $\phi$                | +                |
| Raphidophoridae                           |                      |                   |                  |                       |                  |
| <i>Ceuthophilus pima</i><br>(troglophile) | +                    | +                 | $\phi$ a         | +                     | $\phi$ b         |
| Carabidae                                 |                      |                   |                  |                       |                  |
| <i>Rhadine</i> sp.<br>(troglophile)       | $\phi$               | +                 | +                | +                     | +                |

There are two possible explanations for the absence of these cave species from Kartchner Caverns. One is that they were present at one time, but for unknown reasons they

became extinct. Another possibility is that Kartchner Caverns was only available for colonization after climatic conditions had eliminated these species from the area around the cave. Additional information on the climatic history of the area, and more detailed study of fauna in other caves, may help to explain these differences in the cave fauna distribution.

A comparison of *Ceuthophilus* in southern Arizona with Kartchner Caverns showed *C. pima* in another cave in the Whetstone Mountains and in caves of the Santa Rita Mountains (Table 2). Hubbell (1936) reported *C. pima* from the Santa Rita and Catalina Mountains at elevations above 1633 m msl and listed *C. papago* Hubbell from the Catalina Mountains at elevations below 1633 m msl. Only *C. papago* were found in the Catalina Mountains. *Ceuthophilus pima* in Kartchner Caverns appears to be a relict population at a lower elevation than previously reported, differing from other *C. pima* populations in its pale coloration and year round breeding. No *C. pima* were found in the canyons west of Kartchner Caverns. Caves in the Huachuca Mountains had *C. paucispinosus* Rehn. This observation and the data in table 2 suggest that while Kartchner Caverns is unique, the cave fauna in the Whetstone and Santa Rita Mountains may share other cave fauna. Additional field work is needed to determine further cave fauna relationships.

#### SPECIES ACCOUNTS

##### Phylum Nematoda

Bacterial-feeding nematodes were found in the fresh bat guano of the Big Room. These invertebrates are common inhabitants of bat guano and probably serve as prey for some of the arthropod predators, especially mites.

##### Phylum Arthropoda

##### Class Arachnida

##### Order Palpigrada

##### Family Eukoeneiidae

A single immature palpigrade specimen of this family was found in the Big Room. These arachnids are uncommon and a single specimen is insufficient to determine its status or relationship to the cave.

##### Order Scorpionida

##### Family Vaejovidae

Scorpions were in the entrance area of Kartchner Caverns on several occasions. In



**Figure 8. Microphotograph of *Eidmannella pallida* Emerton (Araneae, Nestidae) from Kartchner Caverns.**

May 1991, a single specimen was found on a guano pile in the Big Room (Fig. 1, 9c). Another specimen was found in the Scorpion Room near Grand Central Station. These arachnids represent only accidentals and were not cave adapted.

##### Order Araneae

##### Family Nesticidae

*Eidmannella pallida* (Emerton) (Fig. 8) was the only species of spider regularly found in Kartchner Caverns. This troglomorphic species is a pale-colored spider that makes irregular webs in cracks and under rocks in caves throughout the southwest (Welbourn 1978; Cokendolpher & Polyak 1996; C. Welbourn, unpub. data). *Eidmannella pallida* webs were found in cracks, under rocks, and on the trail flagging, and were frequently observed near the guano piles in the Big Room. *Eidmannella pallida* was rarely observed on fresh guano, but was frequently found on older guano. On one occasion, 15 *E. pallida* were found on guano pile 9c (Fig. 1) six months after the bats had migrated. Females with egg cases were observed in May and October. *Eidmannella pallida* is a predator of small arthropods and probably utilize diptera and mites as their primary prey.

The population size for *E. pallida* was difficult to estimate because observations were restricted to sites along established trails and because the population size varied from year to year. The maximum Big Room population occurred in May 1990, with an average of one spider every 8 m. Most individuals were concentrated between Sharon's Saddle (Fig. 1, 9c) and in the Lunch Spot area (Fig. 1, 20). The population was usually much lower, with only 1 spider per 17-20 m of trail.

##### Order Acari

##### Family Acaridae

*Sancassania* sp. (Figs. 3 & 4) was the most common mite in fresh guano with 2-17/per cm<sup>3</sup> of guano. *Sancassania* sp. have been reported from bat guano from gypsum caves (Cokendolpher & Polyak 1996) and Carlsbad Cavern, New Mexico (C. Welbourn, unpub. data).

##### Family Argasidae

Engorged larvae of the soft tick, *Ornithodoros nr. hasei* (Schulze), were found on guano piles 9 and 10 (~10 m west of 9c in Fig. 1). The presence of only immatures suggests that these parasites were carried into the cave from other roosts and probably do not reproduce in Kartchner Caverns. Kohles *et al.* (1965) reported this species from *M. velifer* in Sinaloa, Mexico.

##### Family Cheyletidae

A few immature specimens of *Cheyletus* sp. were found on an old guano pile in the Big Room. These mites are predators of other mites and small arthropods.

##### Family Histiotomatidae

An undetermined histiotomatid was found throughout the sampled guano. Populations were low and most specimens came from the fresh guano. Like *Sancassania*, histiotomatids have a heteromorphic deutonymph for dispersal or survival in unfavorable conditions. Histiotomatids are filter-feeders and occur in a wide variety of habitats outside caves (O'Connor 1982).

##### Family Laelapidae

*Geolaelaps* sp. (Fig. 7) was the primary invertebrate predator in the bat guano. This mite was common in fresh bat guano where they prey upon the *Sancassania* sp., nematodes, and other small arthropods. Unlike *Sancassania* sp., *Geolaelaps* sp. does not have a non-feeding stage, but regulated its population in response to the available prey. Another species of *Geolaelaps* occurs in the bat guano at Carlsbad Cavern (C. Welbourn, unpub. data) and some gypsum caves in New Mexico (Cokendolpher & Polyak 1996).

##### Family Neothrombiidae

The genus *Ceuthothrombium* is unique in that the larval instar is parasitic on camel crickets (*Ceuthophilus* sp.) while the free-living deutonymphal and adult instars are predators of other mites and small arthropods (C. Welbourn, unpub. data). The larvae of *Ceuthothrombium* sp. were common around the coxae of *C. pima* all year, with 1 to 8 mites per cricket. The parasitic larvae did not appear to have any effect on the cricket host as nearly all adult *C. pima* examined in Kartchner Caverns were parasitized. The white and eyeless deutonymphs (Figs. 9 & 10) and adults are known only from laboratory rearing (Webb *et al.* 1977; C. Welbourn, unpub. data), but probably live in the cave soil. The species from Kartchner Caverns was distinct from *C. cavaticum* Robaux, Webb & Campbell from the Guadalupe Escarpment area, New Mexico and adjacent Texas (Robaux *et al.* 1976; C. Welbourn, unpub. data).

##### Family Pygmephoridae

A few undetermined pygmephorids were found in guano in the Big Room. These mites are probably fungivores.

##### Family Rosensteindidae

Several specimens of *Nycteriglyphus* sp. (Rosensteindidae) were found in an isolated guano pile ~30 m northwest of guano pile 20 (Fig. 1). Three *Nycteriglyphus* species have been reported from bats, and in very high populations in the guano of *Tadarida brasiliensis* (L. Geof. St.-Hilaire) and *Leptoncyteris nivalis* (Saussure) in the United States



**Figure 9.** Scanning electron micrograph of *Ceuthothrombium* sp. (Acari, Neothrombiidae) from Kartchner Caverns.

(Strandtmann 1962; OConnor *et al.* 1977; Dood & Rockett 1985). The specimens from Kartchner Caverns were closer to *N. texanus* OConnor, Whitaker & Easterla from *L. nivalis* guano in Big Bend National Park, Texas, than to *N. bifolium* Strandtmann from *T. brasiliensis* guano in Frio Cave, Texas (Strandtmann 1962) or Carlsbad Cavern, New Mexico (C. Welbourn, unpub. data). The origin of these mites is unknown, but they could have been carried into the cave by *M. velifer*, or any of the other bats in the area reported by Buecher & Sidner (1999). The low number of mites suggests this species may not be a permanent resident. *Nycteriglyphus* observed in other southwestern caves were in relatively dry caves (C. Welbourn, unpub. data). The relative humidity of 99.4% in the Big Room of Kartchner Caverns (Buecher 1999) may prevent *Nycteriglyphus* sp. from becoming established in the guano or competing with *Sancassnia* sp.

Family Rhodacaridae

A few specimens of an unidentified *Rhodacarus* sp. were found in older guano piles. These predators are usually found in the soil (Farrier & Hennessy 1993).

Family Rhagididae

Observations in the Main Corridor and near the LEM Room each revealed one specimen of the predaceous mite, *Poecilophysis* sp.. Members of this family reside in many caves as well as in soil and leaf litter (C. Welbourn, unpub. data).

Family Stigmaeidae

The predator mite *Eustigmaeus* nr. *lirella* (Summers & Price) was in guano piles that receive only small amounts of fresh guano each year, but it also occurred in active guano piles in very low numbers. The number of individuals ranged from 0.06 to 0.3/ cm<sup>2</sup> of guano. *Eustigmaeus lirella* was described from "soil and screenings" of a woodrat (*Neotoma* sp.) nest in Tulare County, California (Summers & Price 1961). Eustigmaeids are predators in soil and litter.

Family Tarsonemidae

An undetermined *Neotarsonemoides* sp. were found in the guano of the Big Room. These mites are probably fungivores.

Order Pseudoscorpiones

Two undetermined species of pseudoscorpions were found near the cave entrance, with the deepest penetration just past the Babbitt Gate. A gravid female was observed in October 1989. These arachnids are usually found under rocks and are predators of other arthropods. Only three individuals were observed, making a population estimate impossible.

Class Chilopoda

Order Scolopendra

Family Scolopendridae

A single individual of an undetermined centipede species was observed in Grand Central Station and probably represents an accidental occurrence for Kartchner Caverns.

Class Malacostraca

Order Isopoda

Family Trichoniscidae



**Figure 10.** Scanning electron micrograph of *Ceuthothrombium* sp. *prodorsum* (Acari, Neothrombiidae) from Kartchner Caverns.

The most widespread invertebrate in Kartchner Caverns was the troglobitic isopod, *Brackenridgia* nr. *sphinxensis* Schultz (Fig. 2), observed in nearly every part of the cave except the Throne Room and upper portion of the Rotunda Room. Although individuals were not always present, their frass and evidence of feeding was observed on old wooden survey markers throughout the cave. These isopods prefer damp to wet soil and mud substrate, but were occasionally found on old bat guano. They rarely occurred on breakdown or speleothems. Nothing is known of their biology. Populations were patchy throughout the cave, with no more than 5 individuals observed at a single food source (e.g., wood debris, guano, etc.).

Family Oniscidae

A surface isopod, *Porcellio* sp. was frequently observed in the entrance area and Main Corridor of the cave. Occasionally, individuals were observed on fresh bat guano in the Big Room. These surface isopods may be able to survive in the entrance area with frequent recolonization from the surface. Only adults were observed in the Big Room guano piles, suggesting they are probably accidentals and cannot survive in the deep cave.

Class Insecta

Order Collembola

Families Sminthuridae and Entomobryidae

Collembola were uncommon and only a few individuals of the families Sminthuridae and Entomobryidae were observed. Most collembolans were found between the Babbitt Gate and Main Corridor. The sminthurids were usually on the surface of small pools from the Main Corridor to the Strawberry Room.

Order Psocoptera

Family Psyllipsocidae

The psocid, *Psyllipsocus ramburii* Selys-Longchamps, is widely distributed in cave and epigeal environments (Mockford 1993). This species was found from the entrance to the Big Room, where they occurred on older guano piles and other organic material. The population levels were low with only 1-2 individuals observed at any site.

Order Thysanura  
Family Nicoletiidae

Only three individuals of this rare bristletail, *Nicoletia* sp., were observed near the entrance to the Red River Passage. The genus is known from caves in Texas and this is the second record of this genus from an Arizona cave. Nothing is known of the biology and population density of this species in Kartchner Caverns.

Order Orthoptera  
Family Rhaphidophoridae

The camel cricket, *C. pima*, was common from the entrance area to the Main Corridor. While concentrated near the entrance, crickets were frequently found in the Big Room, mostly on or near fresh guano deposits. Like other species in the genus, these crickets usually leave the cave to feed, but were observed feeding on carrion or bat guano in the cave. The Kartchner population may represent a distinct subspecies, but additional comparative study is needed to determine the status of this population (T. Cohn, pers. comm.). Counts between the entrance and Main Corridor ranged from 300 to 800 individuals, with the peak population occurring in mid to late summer. Occasionally, lost individuals (usually dead) were found in various parts of the cave, but only those areas with direct connection to the surface support cricket populations.

A second and probably small population of *C. pima* was found in the Granite Dells area of the cave, suggesting a direct opening to the surface in that area. However, no marked crickets were found in the Granite Dells area. The large number of crickets from the surface cracks and low numbers (3-12) in the Granite Dells area suggests there are additional voids between Granite Dells and the surface that can support a cricket population. *Ceuthophilus pima* was also found in two small caves on the north side of the hill from the Kartchner Caverns' entrance.

Egg deposition was observed in soft soil in the entrance area as far in as the LEM Room and into the sides of an abandoned stream passage in Grand Central Station. In the Granite Dells area, there is also a small area of soft soil that may be an egg deposition site. It is likely there are other inaccessible areas between Granite Dells and the surface that serve as cricket breeding areas.

Order Hemiptera

Hemipteran (Reduviidae) were found in several widely separated areas in 1990. They were considered accidental and not part of the regular cave fauna.

Order Coleoptera  
Family Staphylinidae

An undetermined beetle was observed in the Big Room near guano pile 9 (Fig. 1).

Family Tenebrionidae

Undetermined beetle fragments were in the Tarantula Room and an *Eleodes* sp. was in the entrance area.

Order Lepidoptera

Three undetermined moths were observed. Two were near the entrance and the third was in the Granite Dells area. The moth in Granite Dells adds additional support to the possibility of a direct connection to the surface in that area.

Order Diptera  
Family Sciaridae

Flies are common in the Big Room, frequently attracted to cavers' lights. These flies appeared to breed in the fresh guano where diptera larvae were found between May and August. Adult flies were the most common in the Big Room between Sharon's Saddle (Fig. 1, #9c) and Kartchner Towers (Fig. 1, near #20). Undetermined fly larvae were also found in a dead cave cricket in Grand Central Station.

Order Hymenoptera  
Family Formicidae

Ants were not observed in the cave during this study, but what looked like ant trails were noted in mud areas near the entrance and along the first part of the Red River Passage. It was not possible to determine how long it had been since the ants were active in the cave, but some trails traversed footprints made during the exploration and/or mapping of the cave.

## CONCLUSIONS

Thirty-eight invertebrate species were recorded during the study of Kartchner Caverns including 4 (11%) troglobites, 19 (50%) trogloniles, 1 troglonile and 12 (32%) accidentals. Of the remaining species, one was an obligate parasite and the other a guanophile. Most of the cave fauna depend upon guano deposited by a summer colony of *Myotis velifer*. Mites were the most numerous arthropods found in Kartchner Caverns,

with at least 14 species restricted to the annual guano cycle. Preliminary comparison of the Kartchner Caverns fauna with other caves in southern Arizona shows Kartchner to be unique.

## ACKNOWLEDGMENTS

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# BATS OF KARTCHNER CAVERNS STATE PARK, ARIZONA

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*Kartchner Caverns, in southeastern Arizona, is a summer maternity roost for approximately 1000-2000 cave myotis (*Myotis velifer*). The pregnant females first arrive at the cave in late April, give birth in June, and have left by mid- September. These bats are an important element in the cave ecosystem because their excrement introduces nutrients, which support a complex invertebrate cave fauna. Bat population densities and emergence behavior was monitored between 1988-1991. Other bat species seen using the entrance areas of the cave include *Corynorhinus townsendi* and *Choeronycteris mexicana*.*

*Because bats are easily disturbed by human intrusion into the roost, the baseline study was accomplished using low-disturbance techniques in an effort to provide the greatest amount of data with the least disturbance to the bat colony. These techniques included limited visual observations in the roost and netting bats only on the surface at a nearby water tank. During the baseline study, an episode of predation by a carnivore (*Bassariscus astutus*) caused the bats to abandon the site for a short time. Carbon-14 dating of guano from the Throne and Rotunda Rooms suggests that *Myotis velifer* used the Back Section of Kartchner Caverns 50-45 years Ka.*

The purpose of the Kartchner Caverns bat study was to obtain a biological inventory of the bats using the cave at baseline level prior to development of the cave. The inventory included identification of the bat species and population estimates of the bats that inhabit the cave in the summer. The acquisition of data before the bat population is potentially impacted by human disturbance, and during and after development, provides a method by which the effects of human activities on the bat population can be evaluated.

Kartchner Caverns is home to approximately 1000-2000 cave myotis (*Myotis velifer*), a species of insectivorous bat, from May to mid-September of each year. These bats, primarily pregnant females (Fig. 1), return each summer to Kartchner Caverns to give birth and rear their young. The bats are an integral part of the cave ecosystem. Bat excrement (guano) below bat roosts is the primary source of food for other organisms in the cave and is an unusually rich source of nutrients for obligate invertebrate residents (Welbourn 1999). The various cave-adapted organisms utilize the bat guano in different ways but all depend upon it for their survival (Harris 1970; Horst 1972; Poulson 1972). Loss of the roosting bats could cause a collapse of a healthy cave environment and the destruction of the entire cave ecosystem.

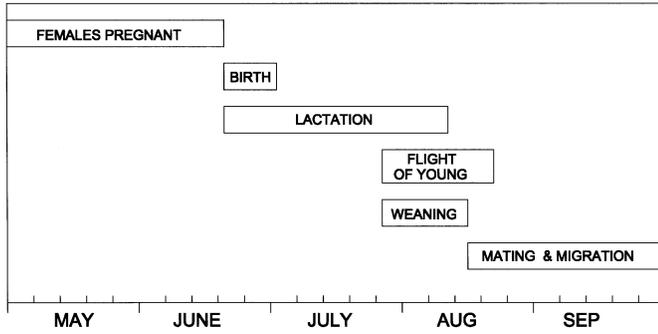
Some species of bats are extremely sensitive to human disturbance and will abandon a roost if human intrusion occurs (Brigham 1993; Harvey 1991; Mohr 1972; Williams & Brittingham 1997). Female bats choose a maternity roost, in part, for its high temperature and humidity to ensure the rapid growth of their young (Betts 1997; Kunz 1973; Tuttle & Stevenson 1982; Twente 1955). Females are highly loyal to their maternity roost and return year after year (Lewis 1995). A critical period during which the population may suffer repro-

**Figure 1.**

**A pregnant female *Myotis velifer* netted at the water tank adjacent to the cave. Photo taken by Bob Buecher.**



ductive loss due to disturbance is during parturition, (birth; Fig. 2). Immediately following parturition, it is essential that females have a time to imprint on the smell and sound of their own young (Altringham 1996). If disturbed prior to this bonding, the female may not recognize her offspring and therefore will not attempt to care for it. If disturbed following parturition, the female bats may attempt to move their pups to a safer location, either somewhere else in the cave, or to a different



**Figure 2. Maternity bat roost timetable for *Myotis velifer* at Kartchner Caverns.**

site with sub-optimal conditions. During this process the females may drop their young, resulting in juvenile mortality (Fenton 1992). Forced displacement to another area of the cave (which may be cooler and drier), or total abandonment of the cave, may jeopardize the survival of the pups.

**BASELINE STUDY**

It was with these concerns in mind that we attempted to perform a baseline survey of the bat roost at Kartchner Caverns using low disturbance techniques utilized by bat biologists (Thomas & LaVal 1988). Because “baseline” conditions in a natural bat roost entail no human intrusion, we did as much work as possible to inventory the bat roost when the bats were not in residence. In addition, the baseline study team defined the need for a biologist specialized in the study of bats, and specifically contracted a project bat biologist (Sidner) who obtained the necessary permits from governing agencies. During the winter months when the bats were absent from the cave, we examined bone material and bat carcasses for species identification and stages of development. While a couple of solitary bats were removed from the wall of an isolated passageway and observed closely to determine species, sex and general health, we never netted bats in the cave because of the potential for disturbance within the roost. We netted bats away from the roost at a nearby water tank in order to record their measurements and other characteristics, such as events in the reproductive cycle. We placed bat bands with reflective tape on any captured *Myotis velifer*. We subsequently observed reflective bands on bats emerging from Kartchner during evening flights, confirming that these animals used the cave as a daytime roost.

In addition to *M. velifer*, we observed two other species of bats using Kartchner Caverns, but these bats were seen in only the entrance portions of the cave. *Corynorhinus townsendii* (Townsend’s Big-eared Bat) was seen on occasion exiting during the middle of the *Myotis* flight, but there were never more than half a dozen of this species observed. *Choeronycteris mexicana* (Mexican Long-tongued Bat), a nectar feeding

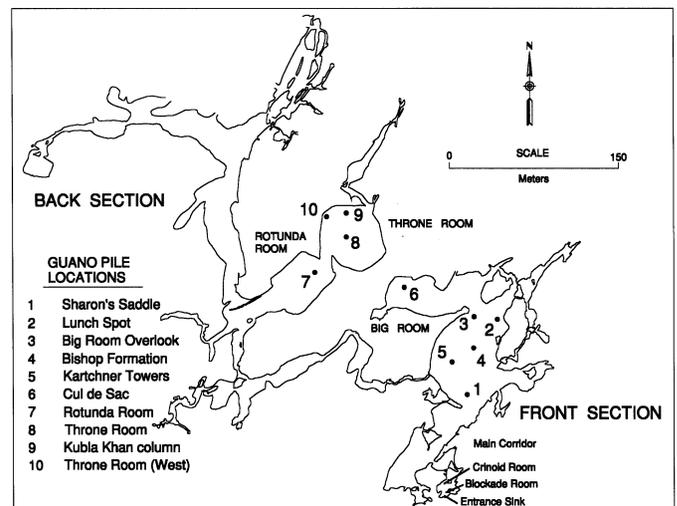
species, was also observed individually in the entrance area. Nine species of bats were netted or otherwise observed at Kartchner Caverns State Park during the summers of 1988-1991. Although *Myotis velifer* was the predominant species that utilized the cave, other bat species forage over the park or roost in small nearby caves (Table 1).

**Table 1. Bat species netted or observed on the surface at Kartchner Caverns State Park.**

| Bat Species   | Primary Food  |
|---|---------------|
| <i>Myotis velifer</i> (Cave Myotis)                       | Insects       |
| <i>Myotis thysanodes</i> (Fringed Myotis)                 | Insects       |
| <i>Myotis californicus</i> (California Myotis)            | Insects       |
| <i>Myotis ciliolabrum</i> (Western Small-footed Myotis)   | Insects       |
| <i>Eptesicus fuscus</i> (Big Brown Bat)                   | Insects       |
| <i>Antrozous pallidus</i> (Pallid Bat)                    | Insects       |
| <i>Corynorhinus townsendii</i> (Townsend’s Big-eared Bat) | Insects       |
| <i>Leptonycteris curasoae</i> (Lesser Long-nosed Bat)     | nectar/pollen |
| <i>Choeronycteris mexicana</i> (Mexican Long-tongued Bat) | nectar/pollen |

**METHODS OF OBSERVATION**

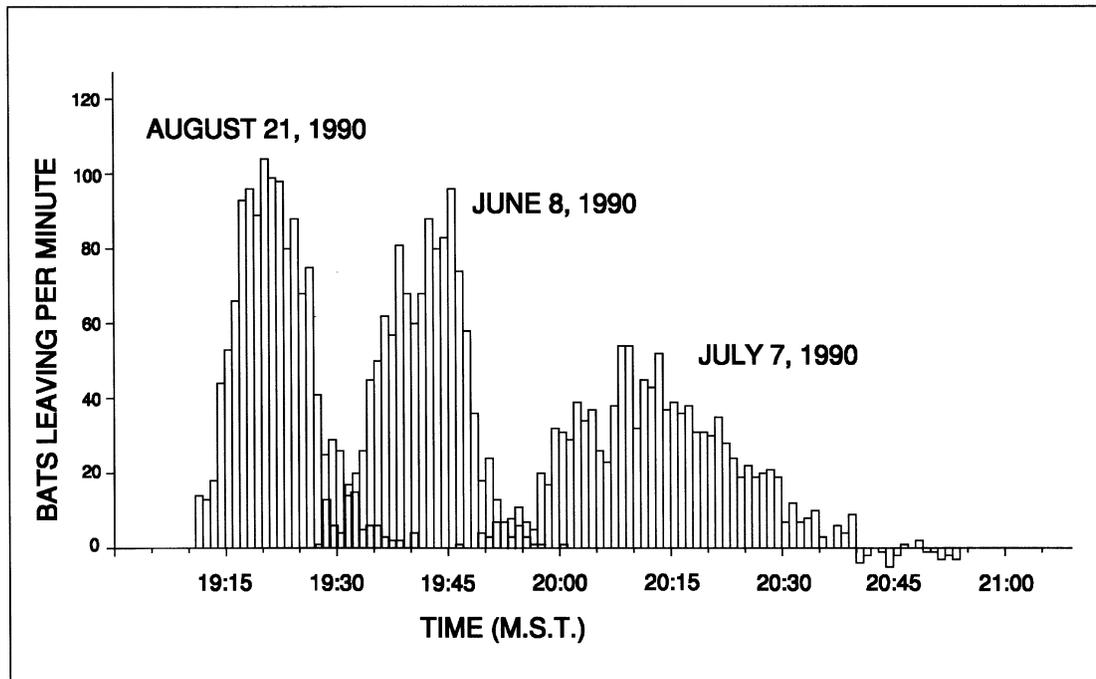
Once bats returned to Kartchner in the spring, we could estimate which areas of the cave were inhabited first due to fresh deposition of guano and a burst of invertebrate activity on the guano piles below each active roost. The bats often roosted in the general area of the Lunch Spot when they first arrived in the spring, but as the time of parturition approached, the bats moved to a “nursery roost” above Sharon’s Saddle (Fig.3). Measurements taken in the maternity roost at Sharon’s Saddle during the summer of 1990 indicate that the temperature reached 21.9°C (71.4°F) and the humidity 100% when the bats were in residence. This temperature is the highest recorded in the cave during the baseline studies, and suggests that the bats seek out the warmest section of the cave to rear their young.



**Figure 3. Outline map of Kartchner Caverns indicating significant guano piles below bat roosts.**

**Figure 4.**

Three representative plots of bat emergence flights during summer. Note change in flight characteristics during time of lactation in mid-summer.



Inventorying the deposition of fresh guano at different guano piles permitted us to monitor the bats' location in the cave without entering and disturbing the roost when bats were present. In order to do this we would quickly visit the Big Room after the evening exit flight. Fresh deposition of guano below a roost would indicate an active site. Sheets of material were laid over the existing guano piles so that new deposition could be easily monitored. These "guano sheets" were made of breathable material (fine nylon netting) so that invertebrates foraging on the guano piles did not suffocate. It was also necessary to avoid excess guano deposition on the sheets because removal of a guano sheet after a large buildup of guano could disturb the invertebrate community.

Once bats returned in the spring, trips into the cave for the baseline study were severely curtailed. If a need arose to traverse the Big Room when the bats were in residence, we used dim headlights covered with red filters and moved quickly into and out of the area. It has been our experience that filtered light causes slightly less disturbance to bats, as judged by fewer bats squeaking or taking flight during human intrusion. The presence and number of non-volant (non-flying) juvenile bats was determined by photographing (once per summer, usually during the first week of July) the juvenile cluster on the ceiling of the Big Room after the evening exit flight of adult bats. We were then able to count the total number of juveniles and roughly assess their ages by magnifying an enlarged photograph.

#### BAT POPULATIONS

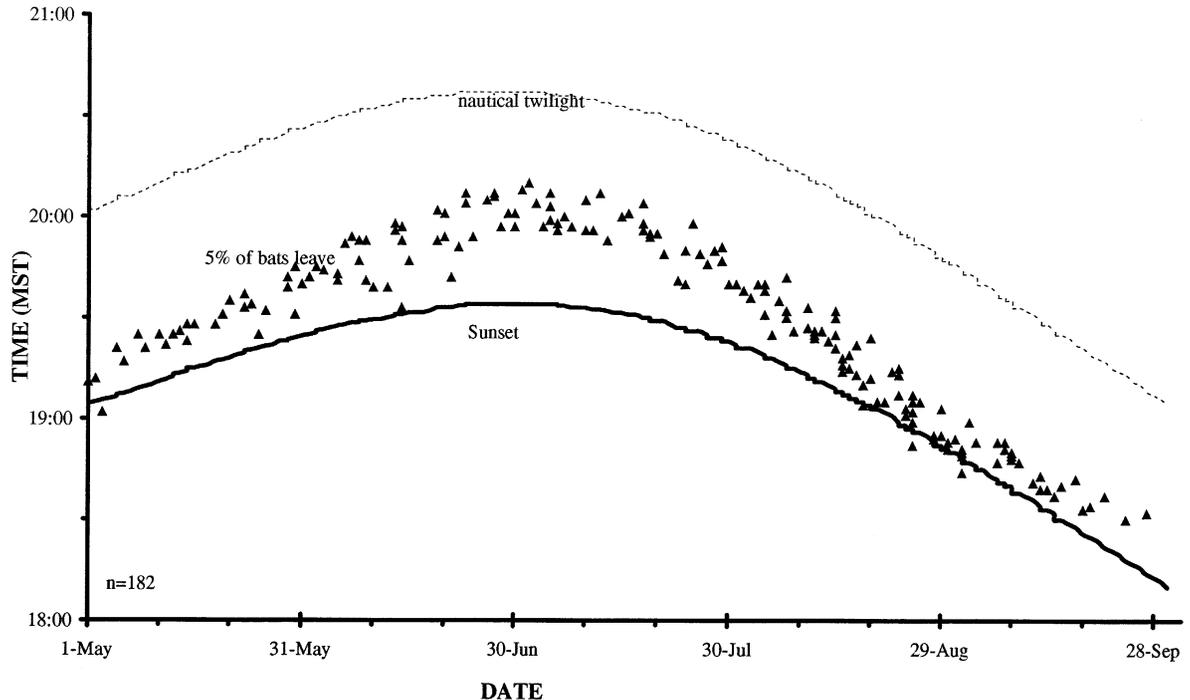
To estimate the number of bats using the cave, an unobtrusive human observer counted bats exiting during the evening

flights. Due to the constricted passages in the front portion of the cave, bats are forced to leave the cave in small groups, so they can be easily counted visually by trained personnel. These counts of exiting bats provided the best estimate of the population size of bats using the interior cavern with the least disturbance to the colony. An observer sitting against the north wall of the entrance sinkhole, out of the direct path of exiting bats, had a good view of them silhouetted against the evening sky. Each individual bat exit was recorded to the nearest second on a lap-top computer. Bats that re-entered the sinkhole were subtracted from the total count. Time plots of exiting individuals reflected the overall pattern of bat activity during the evening emergence flight. During the three years of the baseline study, bat counts were conducted on a weekly basis throughout the summer months. In addition to these visual counts, during the 1990-1991 season an observer sat inside the Blockade Room using infrared-light goggles with an external source of infrared light to view the bats exiting through a small opening called the "bat window". This small window requires that the bats use the Crinoid Room as a staging area during the evening flight, because each bat must wait its turn to exit through the window. Because some errors in counting from within the sinkhole probably occurred during low-light conditions or during inclement weather, counts in the Blockade Room with infrared goggles act as a check on the accuracy of the sinkhole observations.

#### POPULATION ACTIVITY

Initiation of the evening bat flight correlated roughly with sunset. Bats began to leave the cave to forage for insects 15 to 20 minutes after sunset, but there was a definite shift in that

**Figure 5.**  
*Myotis velifer*  
emergence  
flight pattern  
plotted  
against sunset  
and nautical  
twilight.



pattern during the period when females were nursing their young (Fig. 4). The exit flight typically lasted one hour, with the majority of bats leaving during a 15-minute period within that hour. The pattern of bat flight activity varied during the summer. Exit flights in the spring and fall were of short duration, with most bats leaving fairly quickly. During mid-summer, however, when females were nursing their young, the exit flight lasted longer, with fewer bats leaving the cave at any one time (Fig. 5).

Each spring the bats of Kartchner Caverns began reappearing in small numbers, generally during the last week of April. The population of bats fluctuated throughout May, and then stabilized in the middle of June. Netting at the water tank adjacent to the cave indicated that female *M. velifer* were pregnant in mid-June. Netting in mid-July showed that female bats were lactating, and female bats netted in mid-August were in a post-lactating condition. It is suspected that the increase in the number of exiting bats from June/July to August is partially due to the presence of young bats beginning to fly (Table 2). Observers counting at the evening bat flights have reported erratic flight patterns in the emerging bats when the young would be just learning to fly. The consistently large increase in bats using the cave in August also suggests that Kartchner Caverns may be a roost used by migrating bats that have begun to move through southern Arizona in late summer. This pattern has been observed at other sites and may reflect the migratory behavior of bats late in the season.

The bats of Kartchner Caverns act as a natural insecticide for the area. A conservative estimate indicates that the bats roosting in Kartchner devour ~900 kg (0.5 ton) of insects every summer.

**Table 2. Population numbers of *Myotis velifer* at Kartchner Caverns during baseline study.**

| Year | June/July Population | August Peak | # Increase | % Increase |
|------|----------------------|-------------|------------|------------|
| 1988 | 638                  | 1245        | 607        | 95%        |
| 1989 | 1023                 | 1804        | 781        | 76%        |
| 1990 | 1191                 | 1469        | 278        | 23%        |
| 1991 | 634                  | 1198        | 564        | 89%        |

#### EVIDENCE OF PREDATION

In spring 1991, we had a unique opportunity to observe non-human disturbance of the bat colony at Kartchner Caverns. Bats had arrived in late April and their numbers had begun to increase early in May as expected. However, in late May the exit flights became delayed, sporadic, and the total population size declined. On 4 June, the carcasses of 45 dead bats were found near the bat window. We removed these from the cave to determine the cause of death. Observers counting bats on the next two nights watched a ringtail (*Bassariscus astutus*) leave the cave. The following evening, we used a night vision scope and observed the ringtail sitting directly in the bat window. Apparently this animal was responsible for killing the bats. The ringtail was last seen in the cave on 6 June and no additional dead bats were found in the cave after that incident. However, the numbers of bats using the cave continued to decline, presumably due to the effect of the previous ringtail predation. The bat population reached a minimum on 14 June when only 49 bats were counted leaving the cave. In other years, a bat count at this time of year was ~1000 bats. The rapid decline in the number of bats using the cave illus-

trated how quickly the bat population can be impacted by an external disturbance. The number of bats slowly increased during the next six weeks as bats returned to the cave, and by the beginning of July, the population numbered 400. This increase in numbers despite the threat of predation may indicate that Kartchner Caverns is superior to other nearby roosts. The maximum number of bats counted during 1991 was the lowest of the four years of record.

#### PREHISTORIC BAT POPULATIONS

Skeletal material from *Myotis velifer* has been found in the back section of the cave, along with several piles of "old" guano. This bat guano has been severely eroded with drip water and has lost all resemblance to modern guano. The two largest guano piles are in the middle of the Throne Room, with smaller piles located along the western edge of the room. The Rotunda Room has one small guano pile located at the edge of a large breakdown slope (Fig 3, #7). Numerous other small cohesive clumps of guano are within the breakdown pile in the Rotunda Room, and the location of these clumps among the breakdown makes it difficult to envision how they would have been naturally deposited below a bat roost. There is also no evidence on the ceiling above this remnant guano to indicate that these areas were used as roosting sites by bats. One possible explanation is that these guano clumps are the remains of guano floated up onto the breakdown slope during past flooding of the cave (C. Welbourn, pers. com.). Similar clumps of desiccated guano can also be found in the Cul-de-sac area in the Front Section of the cave. Samples of this ancient bat guano were collected from the Throne and Rotunda Rooms and analyzed by the carbon-14 dating technique. Ages for this guano range from about 50-40 Ka (Table 3).

**Table 3. Bat guano C-14 dates for the Back Section of Kartchner Caverns.**

| Sample No. | Kartchner Caverns Bat Guano Age Dates |             |  |
|------------|---------------------------------------|-------------|--|
|            | Location                              | Age (years) | $\delta^{13}\text{C}_{\text{PDB}}(\%)$ |
| KC1        | Throne Room                           | 45,790      | -21.0*                                 |
| KC2        | Throne Room                           | 49,340      | -20.8*                                 |
| KC3        | Rotunda Room                          | 45,540      | -18.1*                                 |
| KC4        | Rotunda Room                          | 40,220      | -17.3*                                 |

\*Ages for these samples are near the limits of the Carbon-14 dating technique used and may represent samples that are much older than 50,000 years but contain small amounts of younger contaminants. Analysis performed by Owen Davis at the University of Arizona Dating Lab.

#### CONCLUSIONS

The predominant species of bat within Kartchner Caverns is the cave myotis (*Myotis velifer*). A small number of other bat species have been observed but are apparently represented by only a few individuals. *M. velifer* is presently known to use only the Front Section of the cave (entrance passages and Big Room area). The primary roosting sites are above Sharon's

Saddle and near the Lunch Spot. Other locations in the Big Room are used occasionally and include the area around Kartchner Towers, near the Bishop Formation and the Overlook. Small accumulations of bat guano in numerous other locations within the Big Room indicate that the roosting sites favored by the bats can change through time.

*Myotis velifer* is present in the cave from late April to the middle of September each year. *M. velifer* begins to return to the cave as early as 20 April and generally leaves by 15 September. *M. velifer* uses the cave as a maternity site during the summer months when warm temperatures and high humidity within the cave appear to be ideal for a maternity bat roost. Apparently Kartchner Caverns is an important roost because bats returned to the cave in 1991, despite an incidence of severe predation by a carnivore at that time. A limiting factor on the use of the cave may be predation, which can occur in the small entrance passages. Mid-June to early August is a critical time period during which the female bats give birth and care for their young. If disturbed during this time, the females may be induced to abandon the site.

The number of bats found in the cave varies from year to year but averages ~ 1000 individuals. The numbers increase in August when the young begin to fly and may peak at close to 2000 bats. Peak estimates of the adult population and total usage show considerable year-to-year variation.

Evidence suggests that *Myotis velifer* inhabited the Throne Room and Rotunda Room 50-40 Ka. There is no indication that bats have used these areas in modern time. The prehistoric use of these areas by bats is an indication that the cave may have had, at one time, another entrance in the Back Section of the cave.

#### RECOMMENDATIONS

Bats occupy a vital niche in the healthy cave ecosystem of Kartchner Caverns. Not only do these flying mammals use the outside environment, but due to their capacity to echolocate by sonar, they can utilize areas of the cave inaccessible to other vertebrates. Bat guano provides the basic food source for invertebrates found in the cave. These obligate cave organisms are dependent upon the continued presence of the bats. Due to the importance of the bats to the entire cave ecosystem, the bat population should be carefully monitored every summer. Disturbance of the bat colony should be minimized and this is especially true when the pregnant females and the juvenile bats are in residence. Continued use of artificial optical devices (night vision equipment and infrared lights) should increase the accuracy of visual bat counts.

The bats are an important and exciting element of Kartchner Caverns State Park, and as such they make an ideal interpretive and educational tool. For example, bat guano can be used in discussions of biology, chemistry and physics when describing the flow of energy in the natural cave environment. The bats are a valuable resource for Kartchner Caverns and they should be as well protected as Kartchner's irreplaceable

cave formations. Because so few maternity bat colonies are known in southern Arizona caves, the bat maternity colony is truly one of the elements that makes Kartchner Caverns important.

#### ACKNOWLEDGMENTS

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# MICROCLIMATE STUDY OF KARTCHNER CAVERNS, ARIZONA

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*A detailed two-year study of the microclimate in Kartchner Caverns determined that the most significant problem in maintaining the microclimate of the cave is the potential for drying out due to increased airflow. Two factors—a small, hypothesized upper second entrance and a slight geothermal warming of the cave—control natural airflow and increase the amount and intensity of winter air exchange.*

*The average amount of water reaching the cave is 7.9 mm/yr, only twice the amount lost by evaporation from cave surfaces. Kartchner Caverns has an average relative humidity (RH) of 99.4%. Useful measurement of RH required a dewpoint soil psychrometer rather than a sling psychrometer. Moisture loss from cave surfaces is proportional to relative humidity, and small changes in RH have a dramatic effect on evaporation from cave surfaces. A lowering of RH to 98.7% would double the evaporation rate and start to dry out the cave.*

*The volume of air exchange in the cave was estimated from direct measurement, changes in CO<sub>2</sub> concentration, and temperature profile models. All of these methods are consistent with a volume of 4,000 m<sup>3</sup>/day entering the cave during the winter. During the summer, the direction of airflow reverses and the volume of air leaving the cave is much smaller than during the winter months. Surface air is almost always drier than cave air—only during the summer months when rain occurs does outside air contain more moisture. However, the rate of air exchange is greatly reduced during the summer, which minimizes any potential effect of increased outside moisture.*

*Radon concentrations in the cave are high enough to be of concern for long-time employees but not for the general public. Radon<sup>222</sup> concentrations average 90 pCi/L and radon daughters average 0.77 Working Levels (WL) in the main part of the cave. During the winter, radon levels in the Echo Passage are up to six times higher than the rest of the cave due to the passage's stable microclimate and limited air movement, which greatly reduces radon removal by plateout. Natural removal by ventilation is only a minor factor in determining radon levels in the rest of the cave.*

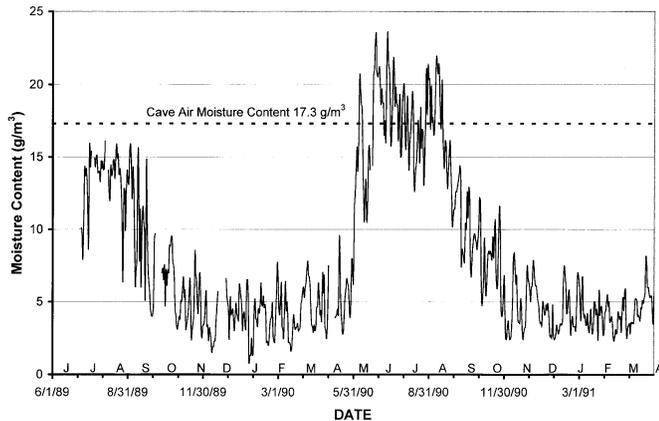
Arizona Conservation Projects, Inc. (ACPI) performed comprehensive pre-development baseline studies of Kartchner Caverns from 1989 to 1992 for the Arizona State Parks Department (Buecher 1992). This paper presents results from the microclimate portion of those studies organized into two sections: (1) general surface weather conditions at the park; and (2) microclimate within Kartchner Caverns. The cave microclimate study was designed to provide data necessary for determining the nature and magnitude of microclimate changes that may result from the development of the cave.

Maintaining the existing moisture conditions is the most important consideration in development of the cave because the small, historic entrance allows relatively little air exchange with the surface. However, development of the cave for public viewing will greatly increase evaporation due to multiple entrances, induced airflow, and increased heat from visitors and lights. Drying of the cave can result in permanent damage to many of the features that make Kartchner Caverns so attractive. This has been observed in many other show caves, but in Kartchner, the arid Arizona climate aggravates the problem.

## SURFACE CLIMATE

Surface climate monitoring provided a record of external variations that frequently drive microenvironmental changes within the cave. The Ozark Underground Laboratory (OUL) initiated the surface climate monitoring program at Kartchner Caverns. ACPI performed instrument installation, maintenance, and additional measurements. The analysis and interpretation of the collected climatological data was also performed by ACPI.

A surface weather station, including a thermograph, hygrogaph and microbarograph, was placed in a standard instrument shelter on the south side of Guidani Wash, ~165 m south-east of the natural entrance. A recording rain gauge was also installed near the weather station. Surface climate data was collected continuously from June 1989 to June 1991. The mean surface temperature measured over this 24-month study period was 16.9°C (62.4°F). For the year-long period from June 1989 through May 1990 a total of 288 mm (11.34 in) of precipitation was recorded. In the second year of the study from June 1990 through May 1991, a total of 607 mm (23.90 in) of precipitation was measured.



**Figure 1.** Average daily surface air moisture content of outside air is almost always less than the moisture content of air inside the cave.

From this climatological information, the moisture content of the air was computed for each day. The difference in moisture content between surface air and cave air is a measure of the potential airflow drying the cave. Figure 1 is a plot of the surface daily average air moisture content determined from the relative humidity (RH) and temperature. During the 24-month study period, the mean daily moisture content of the surface air was less than cave air for all but 3 months in the summer of 1990.

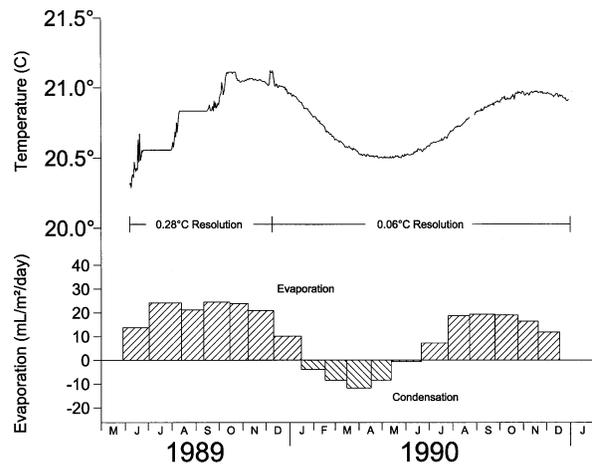
In order to ensure that the data collected over 24 months at the park was truly representative, a comparison was made with long-term records for two nearby surface weather stations at approximately the same elevation—Tombstone and Sierra Vista (Sellers & Hill 1974). Based on the long-term mean temperatures from Tombstone 17.3°C (63.2°F) and Sierra Vista 16.6°C (61.9°F), the average annual temperature at the park is estimated at 17.1°C, which agrees well with the measured mean temperature of 16.9°C (62.4°F).

The precipitation record for the park during this period also was compared with the Tombstone (352 mm/yr) and Sierra Vista (391 mm/yr) records to determine the probable long-term average precipitation. From the Tombstone and Sierra Vista records the average precipitation at the park was calculated at 419 mm/yr. This compares well with the park average of 448 mm/yr (17.62 in/yr) for the 24 months of study.

#### CAVE MICROCLIMATE STUDY

Microclimate studies at Kartchner Caverns measured:

1. Moisture balance of the cave, water reaching the cave, evaporation from cave surfaces, and RH distribution;
2. Air and soil temperature annual variations and distribution throughout the cave;
3. Rate of air exchange between the cave and surface;
4. Concentrations of the trace gases carbon dioxide (CO<sub>2</sub>) and radon<sup>222</sup>.



**Figure 2.** Typical data collected at monitoring station #13 in the Big Room. Shaded areas represent evaporation or condensation rates. Temperatures are daily averages of hourly measurements.

Twenty-two environmental monitoring stations were installed throughout the cave. Locations were chosen to represent general conditions and also areas of particular interest, such as near the entrance or in areas where a cave passage is near the surface.

Each station was equipped with the following apparatus: a 23 cm (9 in) diameter water evaporation pan with overhead drip shield, a PVC pipe stand to hold thermometers, an air temperature sensor, and a soil temperature sensor. In the front portion of the cave, each monitoring station was cabled to a computer datalogger system that recorded wet bulb, dry bulb, and soil temperatures each hour. In the back portions of the cave, temperatures were measured with a digital thermometer that stored both high and low temperatures.

Each station was visited approximately once a month and additional air, soil and water temperatures were taken with a portable thermometer to verify in-cave instruments. Also, pan evaporation, relative humidity, alpha radiation, and carbon dioxide measurements were taken at the same time. Table 1 summarizes these measurements, and Figure 2 shows typical air temperature measurements made with the datalogging system and evaporation pan.

#### CAVE MOISTURE

Kartchner Caverns is a moist cave, pools of water remain only during an unusually wet year. Thus, the supply of moisture to the cave is just barely adequate to maintain the moisture balance. The amount of water reaching the cave from the surface was estimated by monitoring the drip rate at eight locations throughout the cave. For each drip station the rate of dripping, volume of dripping water, and water conductivity was measured. The average volume of a single drip was found to be 0.08 mL.

**Table 1. Environmental Monitoring Station Data Summary.**

| #  | Station               | Evaporation<br>mL/m <sup>2</sup> /day | RH          | Temperature (°C) |           |           |
|----|-----------------------|---------------------------------------|-------------|------------------|-----------|-----------|
|    |                       |                                       |             | Water            | Air       | Soil      |
| 1  | Crow's Nest Rock      | 6.0±3.9                               | 99.07%±0.76 | 18.6±0.24        | 18.7±0.22 | 18.8±0.27 |
| 2  | Pirate's Den          | 7.1±5.0                               | 99.19%±0.71 | 18.5±0.09        | 18.7±0.13 | 18.6±0.17 |
| 3  | Sue's Room            | 2.1±0.8                               | 99.38%±0.57 | 20.1±0.11        | 20.2±0.14 | 20.2±0.18 |
| 4  | Mushroom Passage      | 16.8±7.3                              | 99.38%±0.64 | 19.3±0.14        | 19.6±0.23 | 19.6±0.32 |
| 5  | Granite Dells         | 4.5±3.1                               | 99.28%±0.51 | 18.7±0.18        | 18.9±0.26 | 18.8±0.36 |
| 6  | Pyramid Room          | 5.8±2.1                               | 99.27%±0.80 | 19.4±0.29        | 19.6±0.27 | 19.5±0.21 |
| 7  | Cul-de-sac            | 2.1±1.6                               | 99.52%±0.45 | 20.6±0.07        | 20.7±0.12 | 20.7±0.17 |
| 8  | Rotunda Room          | 5.8±2.1                               | 99.48%±0.52 | 19.8±0.10        | 19.8±0.13 | 19.9±0.18 |
| 9  | Echo Passage (end)    | 1.8±1.0                               | 99.30%±0.56 | 20.4±0.07        | 20.6±0.12 | 20.5±0.07 |
| 10 | Echo Passage (start)  | 3.1±2.9                               | 99.38%±0.52 | 20.4±0.15        | 20.6±0.15 | 20.5±0.17 |
| 11 | Tarantula Room        | 27.2±20.9                             | 98.43%±0.91 | 20.4±0.38        | 20.7±0.36 | 20.7±0.35 |
| 12 | Mud Flats             | 9.4±9.9                               | 99.15%±0.58 | 20.2±0.22        | 20.2±0.27 | 20.3±0.19 |
| 13 | Sharon's Saddle       | 6.8±13.9                              | 99.30%±0.68 | 20.4±0.29        | 20.8±0.27 | 20.5±0.28 |
| 14 | Main Corridor         | 17.8±19.9                             | 98.80%±1.67 | 19.9±0.29        | 19.9±0.32 | 19.9±0.31 |
| 15 | Scorpion Passages     | 15.2±13.4                             | 98.80%±1.18 | 18.8±0.24        | 18.9±0.24 | 19.0±0.21 |
| 16 | Grand Central Station | 47.4±43.2                             | 97.00%±3.80 | 18.6±0.48        | 18.8±0.36 | 18.7±0.45 |
| 17 | Lower Throne Room     | 8.9±1.8                               | 99.40%±0.51 | 19.6±0.12        | 19.7±0.12 | 19.7±0.13 |
| 18 | Throne Room Overlook  | 2.8±1.0                               | 99.50%±0.40 | 19.7±0.08        | 19.8±0.13 | 19.9±0.16 |
| 19 | Lover's Leap          | 1.8±5.5                               | 99.50%±0.50 | 20.2±0.15        | 20.4±0.22 | 20.3±0.20 |
| 20 | Mud Trench            | 3.7±1.6                               | 99.33%±0.69 | 19.4±0.14        | 19.4±0.17 | 19.5±0.12 |
| 21 | Big Room Overlook     | 4.7±2.9                               | 99.39%±0.69 | 20.7±0.16        | 20.9±0.21 | 20.9±0.23 |
| 22 | Kartchner Towers      | 9.2±3.4                               | 99.30%±0.67 | 20.5±0.22        | 20.6±0.25 | 20.6±0.24 |
|    | AVERAGE               | 9.0                                   | 99.15%      | 19.74            | 19.88     | 19.86     |

Environmental Station Data From June 1989 to May 1991  
 Stations 1, 2, 3, 4, 6 & 20 From June 1989 to August 1990

A lower limit on the amount of moisture reaching the cave was determined by surveying the whole cave for active drips. In each room we listened and counted the number of drips in a fixed length of time. This single "whole cave" drip rate was then adjusted to the average annual drip rate by using the 8 monitored drips as an index of conditions at the time of the "whole cave" survey. Using the average drip volume, an overall influx of drip water was determined to be equivalent to an accumulated depth of 4.3 mm/yr.

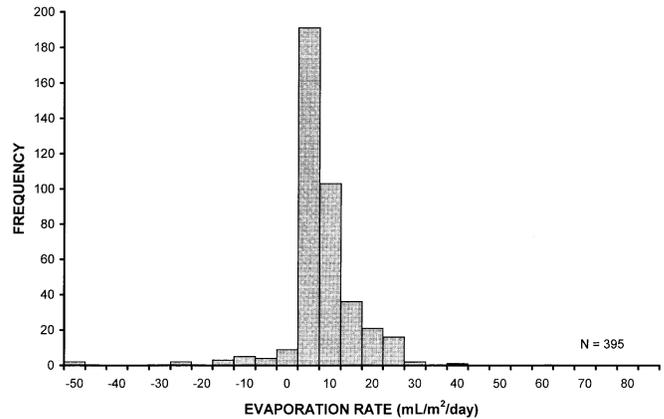
Another estimate of drip water was made by placing 23 cm (9 in) diameter pans in random locations and measuring the amount of water collected. This volume was corrected for evaporation loss and then converted to an annual average by again using the 8 monitored drips as an index. This method resulted in a slightly higher estimate of 6.9 mm/yr of drip water reaching the cave.

An upper limit on the amount of water reaching the cave was estimated by determining the evaporation rate in areas of the cave that dry out during the winter. A series of evaporation pans placed in the entrance passages shows that cave surfaces completely dry out at evaporation rates of 12.4 mm/yr, which means that moisture must be supplied at a rate less than 12.4 mm/yr (0.49 in/yr).

From these three approaches the amount of water reaching the cave in the form of dripwater was estimated to be 4.3 mm/yr, 6.9 mm/yr and 12.4 mm/yr. The average, 7.9 mm/yr is used as a reasonable estimate for the average amount of water entering the cave in the form of drips. Thus, of the 448 mm of annual precipitation, less than 2% reaches the cave.

EVAPORATION

Evaporation rates at floor level were measured at each of



**Figure 3. Distribution of monthly pan evaporation rates.**

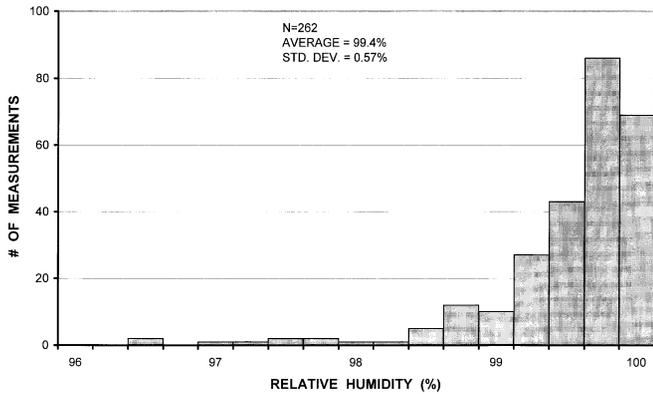
the 22 environmental monitoring stations on a monthly basis and at several other locations close to the natural entrance. At each station, a 23 cm (9 in) diameter aluminum pan (surface area 382 cm<sup>2</sup>) was filled with exactly 750 mL of distilled water by using volumetric flasks. The volume of water necessary to restore the 750 mL volume was carefully measured each month and the evaporation rate in mm/day was determined from the volume lost divided by the pan area and number of days between measurements. Using these methods, evaporation rates could be determined with an accuracy of ±1 mL/m<sup>2</sup>/day. The distribution of these measurements is shown in Figure 3. Average evaporation in the cave is 9.4 mL/m<sup>2</sup>/day. Values less than zero represent a gain in the volume of water in the pan due to condensation onto the water surface. Evaporation measurements indicated that most areas have evaporation rates near zero. Figure 2 shows that rates of evaporation and condensation at this location follow the shape of the air temperature curve. As air temperature falls, moisture in the air condenses onto cooler surfaces. As air temperatures rise, evaporation increases.

RELATIVE HUMIDITY

Relative humidity is defined as the percentage of moisture contained in the air compared to the maximum amount of moisture that the air can hold at a given temperature. Most caves have high relative humidity, often approaching 100%. At 100% relative humidity, the air contains the maximum amount of moisture it can hold at that temperature and is said to be saturated. The amount of moisture contained in a volume of air can be computed from the relative humidity and temperature (Zimmerman & Lavine 1964).

A relative humidity (RH) decrease of a few percent will have a major impact on moisture conditions within the cave as the rate of evaporation is largely determined by the relative humidity. Higher humidity results in lower evaporation. For example, if the relative humidity changes from 99.5% to 99.0%, the evaporation rate will double.

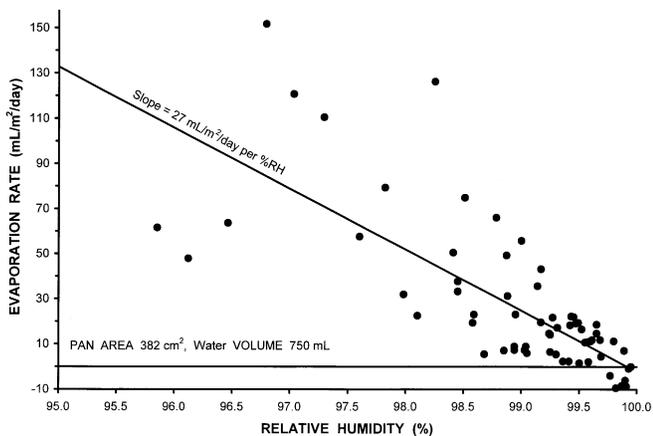
Initially RH measurements in Kartchner Caverns were per-



**Figure 4. Distribution of precise relative humidity measurements.**

formed with hand-held sling psychrometers. These instruments have a maximum accuracy from  $\pm 0.7\%$  to  $\pm 2.5\%$  at high humidity levels. Experience showed that this method is not accurate enough to assess moisture conditions and flux within the cave. Sling psychrometers almost invariably measure the RH at 100% even in areas where there are obvious changes in moisture conditions. Therefore, a switch was made to a dewpoint microvoltmeter to precisely measure RH. This instrument, typically used for measuring soil moisture content, is capable of measuring the relative humidity and dewpoint temperature with a accuracy of  $\pm 0.05\%$  RH. Throughout the cave, 318 measurements were taken with the dewpoint meter. RH varied from 96.32% to 100.00%, averaging 99.42% (Fig. 4). The distribution is highly skewed toward relative humidities approaching 100%.

High RH also means that only a very small drop in air temperature is needed to condense water out of the air. For the majority of conditions observed within the cave, a temperature drop of  $< 0.1^\circ\text{C}$  will bring the air to saturation, and any additional cooling of the air will cause condensation to occur. A



**Figure 5. Pan evaporation rates versus average precise relative humidity.**

rise in air temperature has the opposite effect, lowering the RH and increasing the evaporation rate.

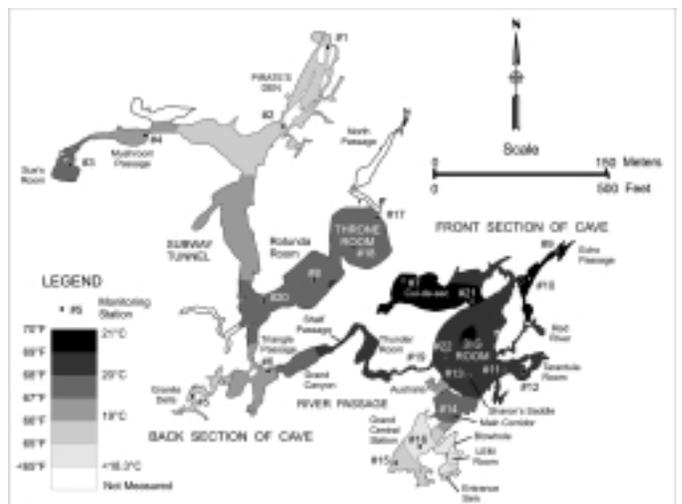
A significant amount of moisture can be lost from a cave by evaporation and air exchange with the surface (McLean 1971; 1976). Due to the arid Arizona climate, the outside air almost always contains less moisture than the cave air. As a consequence, exchange of outside air for cave air will usually result in drying out the cave.

The greatest numbers of precise relative humidity measurements were taken at five monitoring stations in the Big Room. Evaporation decreases with increasing RH, although there is considerable scatter (Fig. 5). A straight-line fit of the data has a slope of 27 mL/m<sup>2</sup>/day of evaporation for each 1% RH change below 100%. As mentioned previously, cave surfaces become dry at an evaporation rate of  $> 12.4$  mm/yr. Using the above relationship, this evaporation rate corresponds to a RH of 98.7%. Thus, an apparently small change from 99.4% RH to 98.7% would allow the cave to dry out.

**EVAPORATION FROM CAVE SURFACES**

The total amount of evaporation from all surfaces within the cave can be estimated based on the measured values from the environmental stations. The surface area and volume of the cave was determined from the survey data and passage cross sections. Total evaporation estimates were made for the two regimes: (1) the cave entrance area where evaporation rates are high; and (2) remote areas where evaporation rates are much lower.

The entrance area includes the entrance passages, Grand Central Station, Main Corridor, Mud Flats, and the Tarantula Room (Fig. 6). The floor area of these passages totals 3,710 m<sup>2</sup>. The annual average evaporation rate in this area is 23 mL/m<sup>2</sup>/day which is equivalent to 8.4 L/m<sup>2</sup>/yr. The floor of remote areas of the cave is 25,100 m<sup>2</sup>. The evaporation in this



**Figure 6. Map of the distribution of soil temperatures in Kartchner Caverns.**

area is estimated at 5.8 mL/m<sup>2</sup>/day, equivalent to 2.1 L/m<sup>2</sup>/yr.

The area of effective evaporation is assumed to be twice the area of the floor to account for the irregular nature of the floor and walls. Evaporation from the ceiling is assumed to be zero as moisture enters at the ceiling and RH is higher in the less dense air. Potential total evaporation is calculated as follows:

entrance areas    8.4 L/m<sup>2</sup>/yr · 3,710 m<sup>2</sup> · 2 = 62,300 L/yr  
 deep cave        2.1 L/m<sup>2</sup>/yr · 25,100 m<sup>2</sup> · 2 = 105,000 L/yr

While the above estimation for the entrance area is potentially 62,300 L/yr, evaporation cannot exceed the available moisture supply. Since the amount of moisture reaching the cave has been estimated to be 7.9 mm/yr, over the area of the entrance passages (3,710 m<sup>2</sup>), this amounts to 29,300 L of available water. Thus, evaporation in the entrance passages will be limited by the available moisture supply to 29,300 L/yr. Total evaporation from the entire cave based on measured evaporation rates and available moisture supply is estimated as 135,000 L/yr. The total average amount of water which reaches the cave is 7.9 mm/yr or a total of 230,000 L/yr. Thus, in an average year the cave receives less than twice as much moisture as it can lose by evaporation. Therefore, a succession of several dry years would begin to dry the cave out.

These calculations were made to illustrate how a small opening, such as the natural entrance, can dramatically increase evaporation in a large portion of the cave. Creation of another opening of similar size, such as an artificial entrance, would cause enough additional evaporation to use up the available moisture supply unless evaporation control measures are implemented.

#### CAVE TEMPERATURE

The temperature of a large cave is generally considered the same as the mean local surface temperature at the cave's elevation (Moore & Sullivan 1978). A comparison of measurements made in 54 Arizona caves (Buecher 1977) indicates that the temperature of a cave at Kartchner's elevation (1420 m) should be about 15.4°C

Kartchner Caverns does not have a constant temperature but varies from 20.9°C (69.7°F) to 18.6°C (65.5°F) throughout the cave. Temperatures at all locations inside the cave are always 1.7°C (3.0°F) to 4.0°C (7.2°F) higher than the mean surface temperature (Fig. 7). The mean temperature of the whole cave is 19.8°C as compared with 16.9°C for outside the cave. Why these differences in mean cave and surface temperatures?

The most likely reason is geothermal heating. The 1982 Geothermal Resources Map of Arizona (Witcher *et al.* 1982) indicates that the San Pedro Valley east of the cave is an area of geothermal water. Near Tombstone, heat flow from the earth ranges from 74 to 85 mW/m<sup>2</sup>, equivalent to a thermal gradient that would increase the cave temperature by 2.8°C at a depth of 30 m.

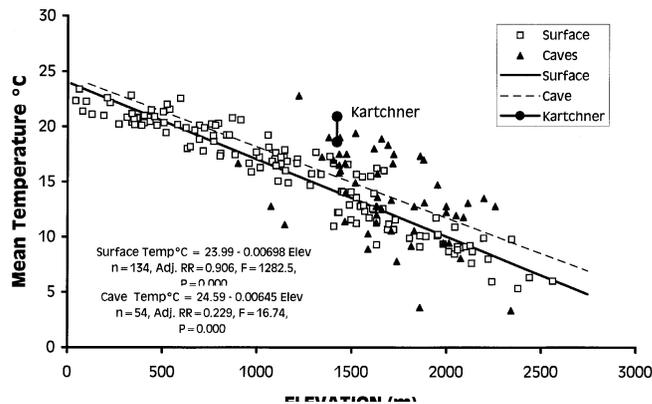


Figure 7. Arizona cave and surface station temperatures versus elevation.

A temperature profile log of a nearby water well (Graf 1999) provides further evidence that geothermal heating causes the elevated temperature in Kartchner Caverns. In measurements conducted in July and November 1991, temperature asymptotically approached 19.6°C just above the water level, ~15 m below the surface. Figure 8 shows the measured temperature profiles and the mean surface temperature of the Kartchner well (Cropley 1965; Lee 1965; Whitaker 1977). The maximum well temperature of 19.6°C is 2.7°C (4.9°F) warmer than the mean surface temperature. This well temperature at 15 m depth is exactly the mean temperature of Kartchner Caverns, 19.6°C. Other wells on the park also show slightly elevated water temperatures (Graf 1999, Table 1).

While geothermal heating explains why the cave is warmer than expected, it does not explain the variations in temperature in different sections of the cave. The warmest part of the cave is the Big Room at 20.9°C. The coldest parts of the cave are in the Back Section (18.6°C) and in the entrance passages (averaging ~17.8°C). Temperatures in the entrance passages

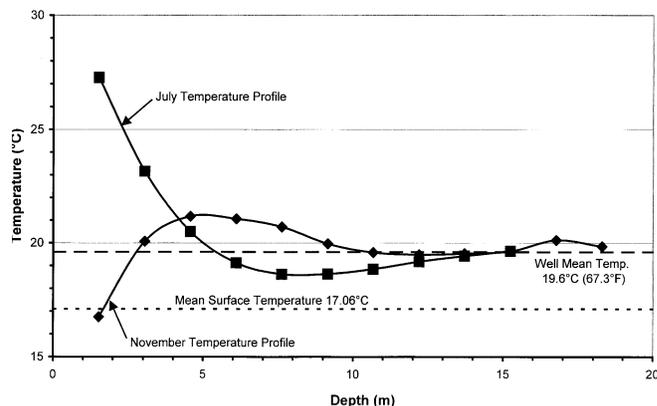


Figure 8. Temperature profiles of the Kartchner well in June and November converge to a stable temperature of 19.6°C, 2.6°C above the mean surface temperature, at a depth of 15 m.

are almost the same as the mean surface temperature due to air exchange. Why the other two areas of the cave have such different temperatures is more problematic. Flooding of the cave during the winter months provides the most likely reason for the cold temperatures in the Back Section. Although flooding does not occur every year, when it does flood, there is apparently insufficient time for the Back Section to completely return to the ambient temperature. The pattern of depressed soil temperatures appears to match the flooded area.

Warmer temperatures in the Big Room may result from air stratification. Cool dry surface air entering the cave remains near the Big Room floor while warmer air rises towards the ceiling. A thin layer of condensation fog forms at the interface between these two masses of air. This fog is frequently seen along the Main Corridor during the winter months. Condensation releases heat which warms the overlying air mass (the upper areas of the Big Room), and condensation droplets fall into the cooler, drier air near the floor. The droplets evaporate, further cooling the incoming air while raising the relative humidity of that air. Condensation-corrosion weathering and the popcorn "line" on the walls leading into the Big Room is evidence of this stratification effect.

#### ENTRANCE PASSAGE TEMPERATURE AND HUMIDITY

The existing natural entrance to Kartchner Caverns is the only known connection to the surface. Early observations indicated that the natural entrance has a profound influence on conditions throughout the cave, prompting an intensive program of data collection. Seven dry and wet bulb temperature probe stations were connected to a computer data logging system. Temperatures were recorded each hour from March 1989 to June 1990. Relative humidity was calculated from the difference between the unventilated dry and wet bulb temperatures. Figure 9 shows the temperature measurements and calculated RH in the LEM Room, which is located 25 m from the entrance.

It is clear from these plots that temperature and RH follow an annual cycle. The temperatures at even this short distance into the cave do not mimic those on the surface but rather have a sawtooth shape. The peak temperature in the LEM Room occurs during late September and early October, indicating a lag of 3 months behind the surface. The lowest temperatures are in December, January and February and occur at approximately the same time as low temperatures on the surface. The annual cycle is markedly asymmetric. Temperatures rise from March to September (7 months) and fall from October to January (4 months). The rise in air temperature is much slower than the decline.

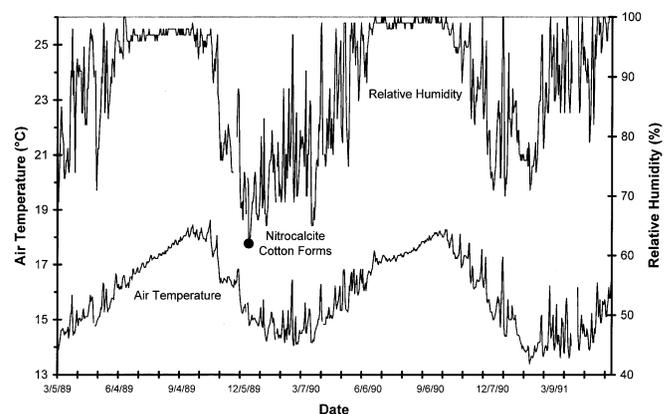
The annual cycles of RH in the LEM Room reveal a pattern where RH is highest from mid-June to mid-September when it is typically at or near 100%. During this time RH stays remarkably constant. The remaining months of the year show numerous short periods of RH fluctuations as dry, high-pressure weather systems move through the region. The lowest relative humidity occurs during December, January and February.

The lowest RH was recorded between 10-16 December 1989 and this very low RH allowed nitrocalcite cotton to form in the entrance passages (Hill 1999).

The annual patterns of temperature and relative humidity can be explained partially by the predominant direction of airflow observed in the entrance passages. During the winter months, cold dry air flows into the cave. This quickly lowers the temperature in the entrance passages. Large fluctuations occur because storms and short-term surface weather changes cause reversals in airflow direction. During the summer, from mid-June to mid-September, the airflow reverses and warm, moist air blows out of the natural entrance. Because the deep-interior cave temperature is at a near-constant temperature, air from the interior maintains this uniform temperature in the entrance when air is blowing out of the cave. Likewise, the high RH results from air moving from the interior of the cave. Slight cooling of this air in the entrance passages further raises the RH. The uniform rate of temperature rise and steady flow of air out of the natural entrance during the summer months maintains a constant high relative humidity. In summary, the entrance passages operate under two distinctly different seasonal modes.

#### SOIL TEMPERATURE

Soil temperatures taken on a monthly basis at each of the monitoring stations were identical to the air temperature (Table 1). In order to determine how temperature varies between the stations, a comprehensive survey of soil temperatures throughout Kartchner Caverns was conducted during April 1990. Temperatures were measured approximately every 15 m to 30 m along the trails throughout the cave to provide detailed information between monitoring stations. The results of the survey (Fig. 9) show a surprisingly large variation in soil temperature throughout the cave.



**Figure 9. Average daily temperature and relative humidity in the LEM Room, ~25 m from the cave entrance. Temperatures show a sawtooth pattern that peaks in October. RH has a flat plateau near 100% during the summer months.**

The purpose of the survey was to: (1) determine the temperatures of those areas poorly represented by the environmental monitoring stations; and (2) identify areas of anomalous temperature. Areas of unusually high or low temperatures can be indicative of outside air entering or leaving the cave. The average of 119 individual soil temperature measurements was 19.3°C. The areas near the natural entrance are unusually cool and bias this average. A better representation of the true interior temperature of the cave obtained by averaging all areas of the cave exclusive of the entrance passages is 19.6°C.

Wigley and Brown (1971) developed a mathematical model of temperature and RH profiles at cave entrances. An important aspect of this model is the use of the relaxation length,  $X_0$ , to describe these profiles.

$$\text{Relaxation length (m)} = X_0 = 100r^{1.2} V^{0.2}$$

where  $r$  = passage radius in meters and  $V$  = air velocity in m/min.

The relaxation length is a measure of the rate of exponential damping of temperature differences as one proceeds deeper into conduit, in this case a cave. Temperatures should remain constant year-round a distance of 4 to 5 times the relaxation length. The model predicts the relaxation length under assumptions of uniform air velocity and passage geometry where passages are considered to be essentially circular pipes with moist walls. Air entering the passage gradually comes to thermal equilibrium with the walls through conduction, and gain or lose of water by evaporation or condensation.

Based on known entrance passage geometry and measured airflow rates in Kartchner Caverns, the anticipated relaxation length was calculated using an airflow of 10 m/min and passage areas of 0.30 m<sup>2</sup> and 1.0 m<sup>2</sup>. Calculated relaxation lengths are 39 m and 80 m, respectively. Based on the soil tempera-

tures measured in April 1990, a relaxation length of 44 m provided the best fit to the measured temperatures (Fig. 10). The profile of soil temperatures in the entrance passages shows an exponential decay, and the observed relaxation length is in good agreement with that predicted by the Wigley-Brown model. The best fit to the measured profile is a small average passage cross-section and daily air volume of 4,300 m<sup>3</sup>.

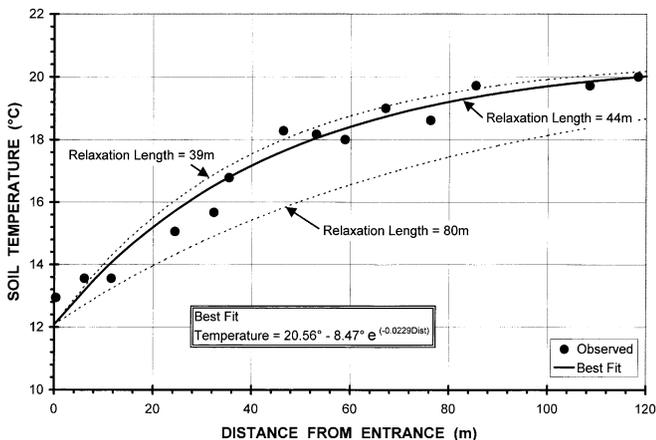
The soil temperature survey shows that the natural entrance has the largest horizontal temperature gradient of any area in the cave. The effect of the natural entrance on soil temperatures extends for at least 120 m from the entrance (Fig. 10). Approximately 100 m from the entrance, a temperature gradient of 0.018°C/m exists. Examining the soil temperature map for large horizontal temperature gradients should identify areas of the cave that are near even a small entrance. Other than the entrance passages, only the Pyramid Room/Granite Dells area have temperature gradients in excess of 0.018°C/m. The steep gradient in this area is more likely the result of cooling by floodwater than from entrance airflow. The lack of high soil temperature gradients in other areas of the cave indicates that it is unlikely there are additional entrances that draw appreciable outside air into the cave. However, there may be other small openings where air is being expelled from Kartchner Caverns.

#### CAVE AIRFLOW

Air exchange to the surface causes moisture loss from the cave. Controlling the air exchange rate is one of the most important concerns in commercial cave development. Airflow is also strongly related to other processes within the cave, such as the concentration of carbon dioxide and radon gas. Management of these gases may contradict the most effective means of controlling cave moisture. Increasing air exchange rates would lower gas concentrations but also would increase evaporation, drying of the cave, and potentially damage the beauty of the cave. A knowledge of how these three parameters- evaporation rate, carbon dioxide concentration, and radon concentration- relate to airflow facilitates predicting the likely effect of development.

The most reliable method for determining the rate of air exchange is by directly measuring the quantity of air entering and leaving the cave. Unfortunately, the entrance passages are in a breakdown complex with many small (inaccessible) openings, so that air follows many different paths. Furthermore bats entering and leaving the cave during the summer use these passages, restricting the time for winter measurements. Thus, no single passage in the front part of the cave seems appropriate. Airflow measurements at a few locations can only give us a lower limit on the rate of air exchange.

The equipment used to measure airflow consisted of a sensitive hotwire anemometer, airflow direction indicator, wet and dry bulb temperature sensors, and an atmospheric pressure sensor, all connected to a datalogger. One-minute averages of each parameter downloaded to a computer. Airflow was mea-



**Figure 10.** Profile of soil temperatures near the natural entrance in April 1990. An exponential curve fit to the temperatures has a relaxation length of 44 m.

sured at the interior end of the Blowhole crawlway and at the entrance to the River Passage. Airflow was measured 22 times, yielding a total of 22.7 days worth of data.

Selected data from the Blowhole provided an understanding of airflow near the entrance of Kartchner. Measurements taken during the winter of 1989 and 1990 were selected because they represent a nearly continuous record of airflow over several days (Table 2). The Blowhole area at the measurements station has a cross-sectional area of 0.47 m<sup>2</sup>. Using the average of the measurements in Table 2, the volume of air that entered the cave averaged 4,000 m<sup>3</sup>/day during the coldest part of the winter. But the Blowhole is not the only known route for airflow. Air also enters through the Babbitt Hole and other small openings in the LEM and Crinoid Rooms. Based on the cross-sectional area of these other openings, the roughly estimated total airflow is about three times that entering through the Blowhole, or 12,000 m<sup>3</sup>/day.

**Table 2. Airflow Measurements at Blowhole.**

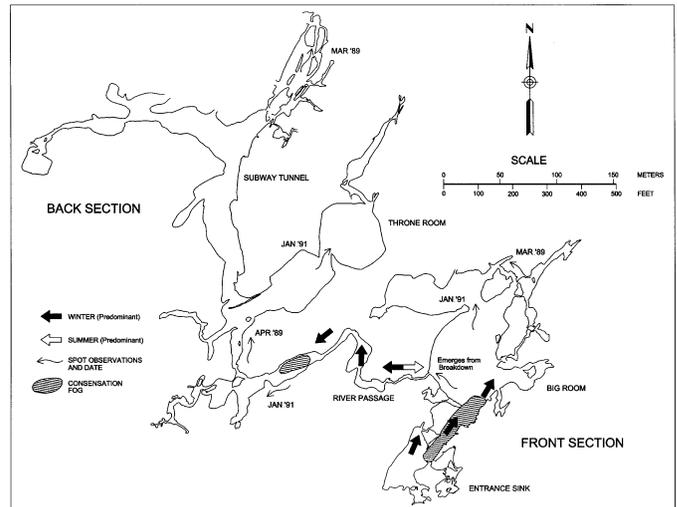
| Start Date | Sample Duration | Air Movement* | Airflow Rate/Day |
|------------|-----------------|---------------|------------------|
| 12/23/89   | 0.44 days       | 3,288 m (IN)  | 7,470 m/day      |
| 12/27/89   | 0.26 days       | 2,069 m (IN)  | 7,956 m/day      |
| 12/29/89   | 0.35 days       | 3,383 m (IN)  | 9,666 m/day      |
| 12/31/89   | 0.18 days       | 3,453 m (IN)  | 19,185 m/day     |
| 01/12/90   | 1.74 days       | 14,552 m (IN) | 8,363 m/day      |
| 01/14/90   | 1.39 days       | 9,261 m (IN)  | 6,662 m/day      |
| 01/16/90   | 1.71 days       | 15,612 m (IN) | 9,130 m/day      |
| TOTALS     | 6.07 days       | 51,616 m (IN) | 8,503 m/day      |

A minor amount of air moved out of the cave during these measurements. The total airflow out was 1,788 m or 3.4% of the inflow.

The most surprising finding of the airflow measurements is that during the winter months, the direction of airflow is overwhelmingly (97%) into the cave. Direct observations of airflow direction confirm that air is moving almost exclusively into the cave at the Blowhole during the winter. The simplest explanation for this airflow pattern is that the cave functions as a “chimney”. During the winter, colder, denser air enters at the natural entrance, becomes warmer, and rises out of openings at a higher elevation. The naturally induced airflow into the lowest entrance is strongest in the winter, weakening and reversing direction during the summer. The airflow measurements provide strong evidence that other small entrances to the cave exist at elevations higher than the natural entrance. No higher, second opening has been found, but the inferred opening must be smaller than the natural entrance to create the observed pattern of air movement. Such an opening may be comprised of several smaller openings or be covered by loose soil.

**CAVE AIRFLOW PATTERNS**

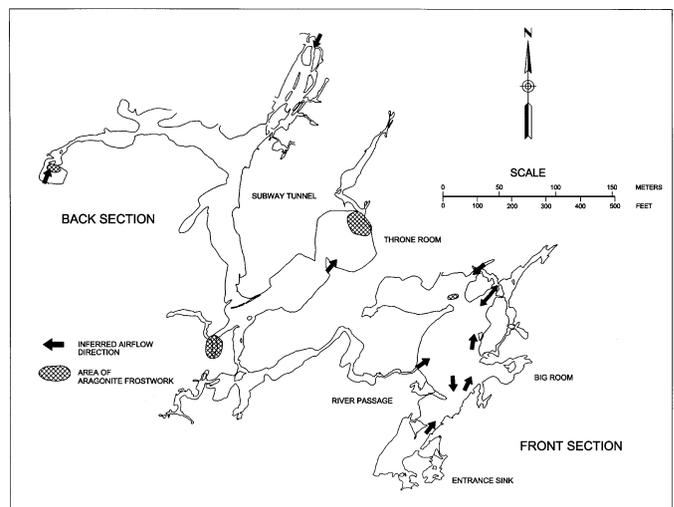
The pattern of airflow through the cave was mostly deduced by two methods. Airflow direction can be felt in constricted passages if there is sufficient air movement (Fig. 11). An indirect method is to observe the growth patterns of certain cave deposits (speleothems) known as “popcorn”. The growth,



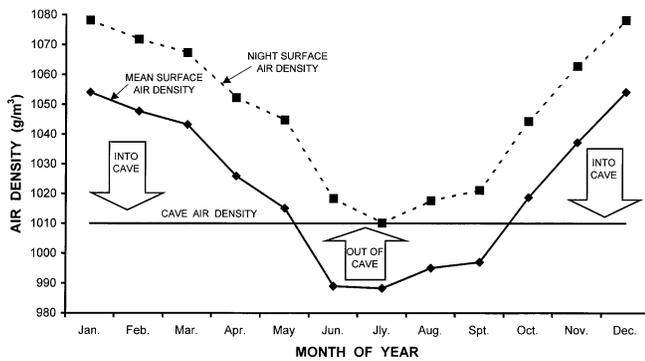
**Figure 11. Observed airflow direction in Kartchner Caverns.**

orientation, and type of popcorn are influenced by long term patterns of airflow (Fig.12). Using these methods, the following pattern of winter airflow is hypothesized.

The natural entrance is the only (known) point where air enters the cave. In the Anticipation Room, air entering the cave divides, part going into Main Corridor and the remainder going to Grand Central Station (Fig. 11). Outside air that enters the cave is cooler, drier and denser than the cave air so it flows along the floor. This displaces the warmer, more humid air in the Big Room and results in the stratification of air with the warm, moist cave air forming a layer starting about 1 m above the floor. The air that enters Grand Central Station flows under the breakdown of the Big Room and exits at the start of the River Passage. During the winter, a steady breeze



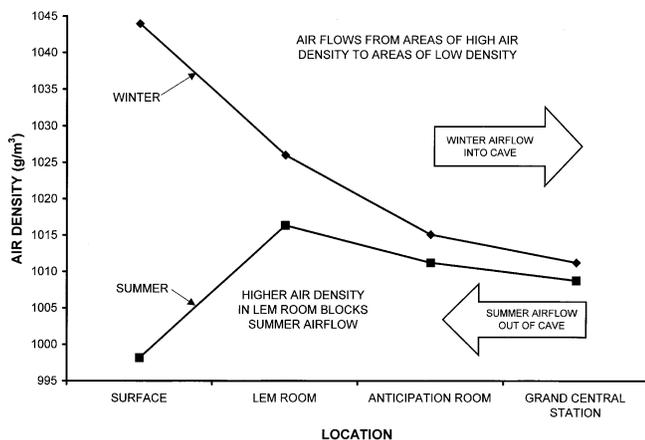
**Figure 12. Airflow pattern deduced from the orientation of popcorn speleothems.**



**Figure 13. Direction of airflow estimated from mean monthly surface air density.**

can be followed along the River Passage to the Grand Canyon Passage. A continuation of this airflow is seldom noticeable in the crawlway at the west end of Grand Canyon. Condensation fog is also frequently visible in the Grand Canyon. The bedrock in the Grand Canyon passage is quite fractured. It is not difficult to envision small cracks and fissures continuing to the surface. In the summer, the airflow pattern appears to stagnate or perhaps weakly reverse. Moist air frequently flows out of the natural entrance but this pattern is not as strong or consistent as the dry air that enters in the winter. Infrequently, airflow has been felt in the Triangle Passage crawl blowing into the cave toward the Subway Passage. Airflow has also been observed entering the Throne Room from the Rotunda Room. The observed popcorn growth is consistent with this airflow pattern (Fig. 12), as popcorn grows into the direction of dry, cool air movement (Hill & Forti 1997).

The annual pattern of air exchange can be quantitatively understood by comparing the density of surface air and cave air (Fig. 13). During winter months, surface air is colder and



**Figure 14. Winter and summer air density profile of entrance passages. In the summer, air in the LEM Room has greater density than air at the surface or deeper in the cave, thus restricting airflow.**

denser than cave air and therefore flows into the cave. During the summer, the surface air is warmer and less dense than air in the cave and so air would tend to flow out the natural entrance. Two other effects complicate this simple relationship. First, as discussed previously, the cave is several degrees warmer than the average surface temperature. As a result the density difference driving winter air exchange is twice as great as it is during the summer. The geothermal warming also lowers the air density in the cave causing the summer airflow out of the cave to last for only 4 months. This asymmetric pattern of airflow creates the second effect. Air will move along a gradient of decreasing air density, as shown in the winter profile of Figure 14. But because a greater volume of air enters the cave during the winter, the entrance passages become quite chilled. In the summer, air moving out of the cave is cooled as it approaches the entrance. This creates a pocket of cool dense air that partially blocks the summer airflow out of the natural entrance.

CARBON DIOXIDE

Measurement of carbon dioxide concentrations consisted initially of collecting “grab” samples in a number of locations throughout the cave. Then, beginning in the summer of 1990, CO<sub>2</sub> was intensely monitored on a monthly basis at two locations - the Throne Room and the Big Room at Sharon’s Saddle. The results of these measurements are given in Table 3. CO<sub>2</sub> concentrations are highest during the summer and can reach 5400 ppm.

**Table 3. Monthly CO<sub>2</sub> Measurements.**

| Upper Throne |      | Sharon’s Saddle |      |
|--------------|------|-----------------|------|
| DATE         | Room | DATE            | Room |
| 07/18/90     | 2910 | 07/26/90        | 3610 |
| 08/26/90     | 3925 | 08/23/90        | 4680 |
| 09/30/90     | 5400 | 09/27/90        | 4100 |
| 10/30/90     | 4935 | 10/23/90        | 2220 |
| 11/24/90     | 3827 | 12/05/90        | 1130 |
| 12/19/90     | 3296 | 12/19/90        | 1132 |
| 01/15/91     | 2430 | 01/17/91        | 852  |
| 02/14/91     | 1690 | 02/21/91        | 1147 |
| 03/24/91     | 2620 | 03/31/91        | 1190 |
| 05/05/91     | 2167 | 04/23/91        | 1746 |
| 05/29/91     | 1660 | 05/29/91        | 1190 |
| 06/11/91     | 2650 | 06/10/91        | 2130 |

Measurements in ppm by Drager diffusion tubes, corrected to 854 Mb pressure.

The measurement of CO<sub>2</sub> is important for a number of reasons. First, high levels of CO<sub>2</sub> in Kartchner Caverns during late summer and autumn raise some concerns regarding the levels that may be present after the cave is open to the public. Visitors to the cave will add more CO<sub>2</sub> to the air, possibly raising it to unacceptable levels (Cabrol 1997). Second, the concentration of CO<sub>2</sub> is an important parameter in determining if

the water percolating into the cave will deposit or dissolve calcite. The growth of carbonate speleothems (such as helictites) depends on the concentration of CO<sub>2</sub> entering the cave via vadose seeping dripwater and equilibrating with the cave air (Hill & Forti 1997).

Third, changes in the concentration of CO<sub>2</sub> gas in the cave air can be used to approximate the rate of air exchange between the cave and the surface. The outside air contains approximately 300 ppm CO<sub>2</sub>. Within the cave, CO<sub>2</sub> concentrations vary seasonally from approximately 1000 ppm in late winter to over 5000 ppm in late summer. The amount and rate of CO<sub>2</sub> entering the cave follows an annual cycle, being dependent on the rate of drip water entering the cave and the biologic activity in surface soils. The measured concentration of CO<sub>2</sub> in Kartchner Caverns varies by a factor of 3 to 5 over the course of a year. If we make two simplifying assumptions that the rate at which CO<sub>2</sub> enters the cave is constant, and that ventilation with outside air is the primary method of removal, we can make a simple estimation of the ventilation rate. The equation for the time-dependent concentration of a tracer being removed at a constant rate is:

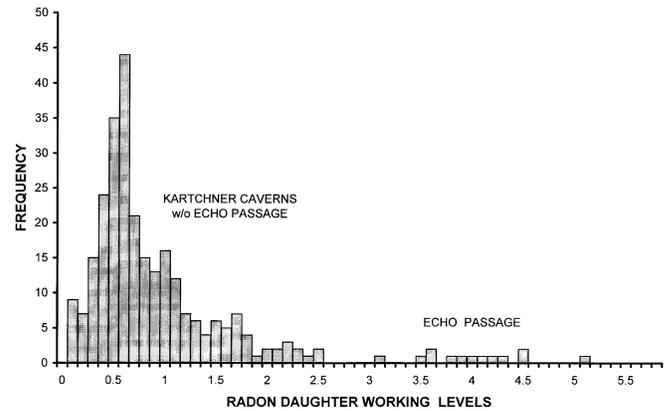
$$\text{Concentration} = \text{Starting Concentration} \exp(-Kt)$$

Where: K = flow rate/ Volume (air exchanges per day)  
t = time (days)

For the Throne Room measurement station, CO<sub>2</sub> levels decreased from 5400 ppm on 9/30/90 to 1690 ppm on 2/14/91, a period of 137 days. For this station K was determined to be 0.0085; the reciprocal is the time for a complete air exchange, or 118 days. For the Big Room at Sharon's Saddle, CO<sub>2</sub> levels decreased from 4100 ppm on 9/27/90 to 1130 ppm on 12/5/90, a period of 69 days. For this station K was determined to be 0.0187 and the ventilation rate 54 days. These ventilation rates (118 and 54 days) are equivalent to air exchange rates of 1,100 to 2,400 m<sup>3</sup>/day, respectively.

#### RADON

Radon<sup>222</sup> gas is an intermediate product in a chain of radioactive decays that begins with uranium and ends with lead. Radon gas is present in caves as a result of the liberation of radon from low concentrations of uranium in bedrock or sediments. Radon is an inert gas and, unlike all other uranium-series decay products, does not form chemical bonds. As a result, radon atoms can move freely through the pore spaces of porous materials like bedrock or sediments without bonding to other substances. Radon<sup>222</sup> has a half-life of 3.82 days, and decays into a series of atomic-sized particles known as radon decay products or radon daughters. A few seconds after formation, the daughters may become attached to airborne dust and condensation particles in cave air. If the radon daughters are inhaled, their further disintegration by radioactive decay releases a high-energy alpha particle that can be injurious to



**Figure 15. Distribution of radon daughter “Working Level” measurements. All of the measurements above 3 WL are in the Echo Passage during the winter.**

healthy lung tissue. It is important to measure radon in caves for two reasons: (1) at high levels radon decay products have been shown to cause increased incidence of lung cancer, and (2) it is useful as a natural tracer gas in understanding the movement of air.

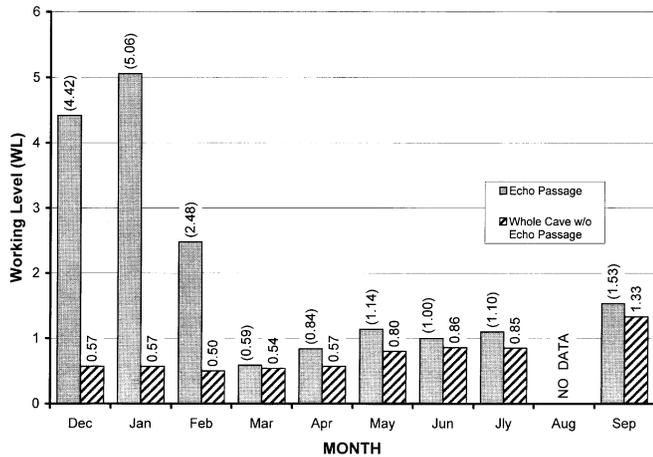
Radon<sup>222</sup> gas is measured in picoCuries per liter of air (pCi/L) but its decay products, radon daughters, are commonly reported in “Working Levels” (WL), a unit of exposure. Under ideal conditions 1 pCi/L of radon<sup>222</sup> will decay and produce a total exposure of 0.01 WL from radon daughters. This conversion is only approximate since we are comparing radon gas with the sum of the decay products, some of which may have been removed from the air prior to measurement.

Radon daughters in Kartchner Caverns were first measured by OUL during September and December of 1989, (Aley 1989, 1990). These measurements demonstrated that alpha radiation levels from radon daughters were high enough to possibly be of concern for the long-term health of employees spending a lot of time in the cave. However, the OUL measurements were taken only twice and did not provide an adequate picture of radon variations over an entire year. Nor were the OUL measurements sufficiently detailed so as to be useful in characterizing the reasons for the variations found in different areas of the cave.

ACPI followed up with a more comprehensive study. This study included measurements on:

- (1) Radon Working Levels,
- (2) Radon<sup>222</sup> gas, and
- (3) Individual radon daughters.

The distribution of all 275 radon daughter measurements by ACPI and OUL is shown in Figure 15. The most of the measurements (263) are below 3 working levels and average 0.77 Working Levels. A second group of 12 measurements clusters at higher values, averaging 3.96 Working Levels. These measurements all came from near the start of the Echo



**Figure 16.** Average monthly radon daughter “Working Levels” for all of Kartchner Caverns excluding the Echo Passage, and for only the Echo Passage.

Passage during the winter months. Measured radon daughter concentrations in the cave appear to exhibit a seasonal pattern, with lower levels in the winter and higher levels in the late summer (Fig. 16). The Echo Passage has the largest variation, ranging from a high of 5.09 WL in January to a low of 0.59 WL in March. The rest of the cave varies from a high of 1.33 WL in September to a low of 0.50 WL in February.

A series of radon<sup>222</sup> gas measurements were made utilizing alpha track detectors that maintain a high degree of sensitivity even at high humidity levels. The detector is a small plastic film that is damaged by the track of a particle of alpha radiation. By counting the number of alpha tracks and knowing the length of exposure, the average radon gas concentration was determined. Detectors were left in the cave for three to four weeks. These tests gave a long-term average of the radon gas concentration in the cave. The results of the alpha track radon measurements are given in Table 4. While only a limited number of measurements were made, these show that in the Big Room the concentration of radon<sup>222</sup> is highest in summer and decreases by a factor of 2.5 during the winter. In the Throne Room, which is far from the natural entrance, the concentration of radon dropped 11% from summer to winter. The Echo Passage was found to have the highest concentration of radon gas in the cave.

**Table 4.** Alpha Track Radon Gas Measurements.

| Location             | Start Date | End Date | Radon (pCi/L) |
|----------------------|------------|----------|---------------|
| Big Room near Bishop | 05/05/89   | 07/10/89 | 162.0         |
| Big Room near Bishop | 03/07/90   | 03/31/90 | 66.0          |
| Throne Room EMS 18   | 05/05/91   | 05/29/91 | 58.5          |
| Throne Room EMS 18   | 12/19/90   | 01/15/91 | 52.1          |
| Echo Passage EMS 10  | 12/05/90   | 12/18/90 | 368.7         |
| Average (all)        |            |          | 141.5 ±135    |
| Average (w/o Echo)   |            |          | 84.7 ±52      |

A total of 17 additional measurements were made in order to determine the concentration of three of the individual radon daughters; radon A (Po<sup>218</sup>), radon B (Pb<sup>214</sup>), and radon C (Bi<sup>214</sup>). The method used was the modified Tsivoglou method (Harley 1988; Nazaroff & Nero 1988). The results of these measurements are shown in Table 5. The average concentration for the first radon daughter, Radon A, was 101 pCi/L. Radon A has a short half-life of approximately three minutes. Because of the short half-life, it is likely to be in equilibrium with the parent radon gas. The fact that the average Radon A (101 pCi/L) is within the range of measured radon gas concentrations reinforces this conclusion. The second radon daughter, Radon B, has a half-life of 27 minutes. The average concentration of Radon B was found to be 73 pCi/L. The third radon daughter, Radon C, has a half-life of 20 minutes. The average concentration of Radon C was found to be 60 pCi/L.

**Table 5.** Individual Radon Daughter Measurements.

| Date    | Location                 | Sample # | Radon-A | Radon-B | Radon-C | Comments             |
|---------|--------------------------|----------|---------|---------|---------|----------------------|
|         |                          |          | pCi/lp  | Ci/l    | pCi/l   |                      |
| 3/31/91 | Echo Passage             | 2        | 208     | 219     | 210     | Equilibrium          |
| 3/31/91 | Big Rm-Kartchner Towers  | 3        | 66      | 61      | 61      | Equilibrium          |
| 2/24/91 | Big Rm-Main Corridor     | 5A       | 39      | 32      | 40      | Equilibrium          |
| 2/24/91 | Big Rm-Overlook          | 1        | 59      | 48      | 51      | Equilibrium          |
| 2/24/91 | Big Rm-Mud Flats         | 1        | 61      | 62      | 64      | Equilibrium          |
| 5/29/91 | Throne Rm-Upper          | 1A       | 57      | 53      | 40      | Equilibrium          |
| 3/24/91 | Big Rm-River Passage     | 4        | 46      | 35      | 33      | Non-equilibrium      |
| 3/31/91 | Big Rm-Traverse          | 1A       | 62      | 43      | 38      | Non-equilibrium      |
| 3/31/91 | Throne Rm-Lower          | 2A & 3A  | 84      | 58      | 50      | Non-equilibrium      |
| 5/5/91  | Big Rm-Bat House         | 2        | 143     | 118     | 97      | Non-equilibrium      |
| 5/16/91 | River Passage-Grand Cny  | 2        | 84      | 60      | 49      | Non-equilibrium      |
| 5/16/91 | Big Rm-Fallen Shield     | 5        | 83      | 51      | 36      | Non-equilibrium      |
| 5/29/91 | River Passage-Grand Cny  | 2        | 99      | 61      | 42      | Non-equilibrium      |
| 5/29/91 | River Passage-Thunder Rm | 1        | 241     | 153     | 93      | Non-equilibrium      |
| 6/25/91 | River Passage-Grand Cny  | 2        | 175     | 66      | 33      | Non-equilibrium      |
| 5/16/91 | Grand Central            | 1        | 66      | 53      | 43      | Outside Air Dilution |
| 6/21/91 | Entrance Passages-Pop-up | 5A       | 147     | 63      | 34      | Outside Air Dilution |

If air exchange or other processes remove none of the radon daughters, then the concentration of each radon daughter will be in equilibrium with the parent and all should be equal. This is true in the case of six of the measurements. This indicates that for some areas of Kartchner there is little or no removal of radon daughters other than by radioactive decay. The remaining measurements for other areas of the cave show that the concentration of each successive daughter is generally smaller than the preceding daughter. This indicates that some process is actively removing the successive radon daughters from these areas. Two mechanisms that can remove radon daughters are air exchange and attachment to surfaces. In order for air exchange to be a significant factor in removing radon daughters, the exchange rate must be relatively large compared to the half-life of the radon. Because the half-life of each radon daughter is less than half an hour, the air exchange rate must be greater than once per hour to remove a significant quantity of radon daughters. High rates of air exchange have been found only in the entrance passages and may account for the reduction in radon daughter concentrations in two of the samples. For the remainder of the samples, it appears that the

individual radon daughters are being removed by plate-out onto aerosols or cave surfaces.

#### CONCLUSIONS

- (1) The amount of water reaching the cave from surface precipitation is estimated to be 7.9 mm/yr. This is less than 2% of the annual precipitation at Kartchner Caverns State Park.
- (2) The average rate of evaporation for the whole cave is 9.4 mL/m<sup>2</sup>/day, while areas of the cave far from the natural entrance have a rate of evaporation as low as 3 mL/m<sup>2</sup>/day. Evaporation rates are highly skewed toward very low rates that approach no evaporation at all.
- (3) Relative humidity averages 99.4% for the whole cave. The distribution is highly skewed toward RH values above 99.5%.
- (4) Comparison of RH and evaporation rates shows that, as expected, the rate of evaporation is proportional to the RH difference from 100%. Evaporation increases by 27 mL/m<sup>2</sup>/day for each additional 1% RH below 100%.
- (5) Using the measured evaporation rates, the amount of moisture being lost from cave surfaces is estimated at 134,700 L/yr. This represents over half of the 7.9 mm of water that infiltrates into the cave. During a dry year the cave will lose more moisture by evaporation than is resupplied by surface precipitation.
- (6) The soil and air temperatures in the cave are in equilibrium. The temperatures within the cave are always above the mean surface temperature. This is due to regional geothermal heating. The slightly warmer cave temperatures have a profound influence on the air exchange rate.
- (7) Annual temperature and RH measurements in the entrance passages of Kartchner indicate that during the winter cold air enters the cave, and during the summer warm moist air is expelled.
- (8) A profile of the cave soil temperature from the entrance shows that the influence of the small natural entrance extends 120 m into the cave. This profile agrees well with theoretical predictions and is supporting evidence for the volume of air entering the cave.
- (9) Measurement of airflow near the cave entrance shows that during the winter the direction of airflow is overwhelmingly into the cave. This is taken to be evidence that the cave has unidentified small openings at a higher elevation than the natural entrance. The volume of air that enters the cave during the coldest part of the winter is estimated to range from 4,000 to 12,000 m<sup>3</sup>/day.
- (10) Seasonal fluctuations in CO<sub>2</sub> concentrations collected in the fall in two areas of the cave were used to make

independent estimates of the ventilation rate. These measurements indicate that air was moving into the cave at 1,100 to 2,400 m<sup>3</sup>/day.

- (11) High radon levels in the cave were found to be a possible health concern for long-time workers in the cave. Radon levels are not high enough to cause concern for the viewing public. Radon<sup>222</sup> concentrations average 90 pCi/L and radon daughters average 0.77 WL in the main cave. The Echo Passage has radon levels that are as much as seven times higher than this during the winter. This is due to the stable microclimate and limited air movement in this passage. Natural removal of radon daughters occurs predominantly by plate-out onto cave surfaces or aerosols, while removal by ventilation seems to be a minor factor.

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# Kartchner Caverns Photo Gallery





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Robert H. Buecher is a registered professional engineer and land surveyor. He has a bachelors degree in civil engineering from the University of Arizona. He was project manager of the baseline studies of Kartchner Caverns for Arizona Conservation Project, Inc.

Gary Tenen is one of the two discoverers of Kartchner Caverns and was the first person to enter the main cave. With his wife Judy, he owns and operates an "Alphagraphics" quick-print franchise in Tucson, Arizona. Tenen is a Fellow of the National Speleological Society.

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David H. Jagnow is a consulting petroleum geologist in Albuquerque, and also does venture capital financing. He is a life member of the NSS, NSS Conservation Chairman, NSS Conservation Award recipient, NSS Fellow, and has explored and studied the caves of New Mexico and Arizona for the past 28 years.

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Ronnie Sidner has conducted field studies of bat populations since 1980 for various state and federal agencies and for her

graduate research on bat demography. She received a Ph.D. at the University of Arizona, where she is currently teaching a course as an adjunct assistant professor in ecology. Also a self-employed, consulting mammalogist, she has been monitoring cave roosts and activities of endangered nectar-feeding bats in Arizona for ten years for the US Army.

Debbie Buecher has been exploring caves and supporting scientific cave research for 29 years. Her interest in bats led her to complete a degree in biology at the University of Arizona. She volunteered hundreds of hours of work on the Kartchner Caverns baseline studies as cartographer and field technician.

Dr. Owen Kent Davis is a Professor in the Department of Geosciences, University of Arizona. He teaches classes on Environmental Geology and Palynology, and has written 4 books and 178 other publications. He was born March 13, 1949, in Nampa, Idaho, and received his Ph.D. in Ecology.

**PHOTO CREDITS****Front Cover**

Debbie Buecher next to "Kartchner Towers", a group of large stalagmites in the Big Room of Kartchner Caverns. Photo by K.L. Day, A.C.P.I./Arizona State Parks Department.

**Back Cover**

Randy Gruss admiring the stalactites hanging from the ceiling of the Throne Room Overlook of Kartchner Caverns. Photo by K.L. Day, A.C.P.I./Arizona State Parks Department.

**Title Page**

Debbie Buecher next to a wall of stalagmites and draperies in the Big Room of Kartchner Caverns. Photo by K.L. Day, A.C.P.I./Arizona State Parks Department.

**Kartchner Caverns Photo Gallery**

Soda Straws and helictites hang from the ceiling of the Rotunda Room. Photo by K.L. Day, A.C.P.I./Arizona State Parks Department (top left).

Stalactites with crystalline tips in Sue's Room at the end of Kartchner Caverns. Photo by K.L. Day, A.C.P.I./Arizona State Parks Department (bottom left).

Translucent draperies hand from the ceiling of the Throne Room Overlook. Photo by K.L. Day, A.C.P.I./Arizona State Parks Department (top right).

Caver, Steve Holland, peers through the Blowhole. This hole was enlarged by Gary Tenen and Randy Tufts and led to the discovery of Kartchner Caverns. Photo by K.L. Day, A.C.P.I./Arizona State Parks Department (bottom right).

**Previous Page**

Roland Browne admires the Angel Wing shield in a side passage off the Subway Tunnel in Kartchner Caverns. Photo by K.L. Day, A.C.P.I./Arizona State Parks Department.



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# Speleogenesis

## Evolution of Karst Aquifers

January 2000 Edition

Alexander B. Klimchouk  
Derek C. Ford  
Arthur N. Palmer  
Wolfgang Dreybrodt  
Editors

With Members of the Commission on Karst Hydrogeology and Speleogenesis  
International Union of Speleology



### Contents

- Part 1 Introduction
- Part 2 Historical Perspective
- Part 3 Geologic and Hydrogeologic Controls of Speleogenic Development
- Part 4 Theoretical Fundamentals of Speleogenetic Processes
- Part 5 Development of Cavities and Cave Systems in Various Settings
- Part 6 Meso- and Microphology of Caves
- Part 7 Speleogenesis in Noncarbonate Lithologies
- Part 8 Some Implications of Speleogenetic Studies

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### The Editors

**Alexander B. Klimchouk**—Senior Scientist, Institute of Geological Sciences, National Academy of Science, Ukraine.  
**Derek C. Ford**—Emeritus Professor of Geography and Geology, McMaster University, Canada.  
**Arthur N. Palmer**—Distinguished Teaching Professor and Director, Water Resources Program, State University of New York at Oneonta.  
**Wolfgang Dreybrodt**—Professor of Experimental Physics, University of Bremen, Germany.  
**The Authors**  
Forty-four authors from 15 countries, members of the Commission on Karst Hydrogeology and Speleogenesis, International Union of Speleology.

### Overview

This book is a pioneer attempt by an international group of cave scientists to:

- Summarize modern knowledge about the origin of caves in various settings.
  - Examine the variety of approaches that have been adopted.
  - Outline the role of speleogenesis in the evolution of karst aquifers.
- Along with some well-established theories and approaches, the book contains new concepts and ideas emerging in recent years.

We hope that this approach will stimulate further development and exchange of ideas in cave studies and karst hydrogeology.

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- Evolutionary typology of karst.
- Geologic and hydrogeologic controls.
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