

THE NSS BULLETIN

Journal of Caves and Karst Studies



Volume 57 December, 1995 Number 2

Published by

The National Speleological Society

ISSN 0146-9517

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METATYUYAMUNITE FROM SPIDER CAVE, CARLSBAD CAVERNS NATIONAL PARK, NEW MEXICO

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Metatyuyamunite [$\text{Ca}(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 3\text{-}5\text{H}_2\text{O}$], a hydrated uranyl vanadate, has precipitated as decimicron to millimeter-sized crystals in Spider Cave, Carlsbad Caverns National Park. Crystals are canary yellow and plate-like; they commonly consist of laths shaped like "playing cards" standing upright. *Metatyuyamunite* occurs as a druse in association with botryoidal opal coatings. X-ray diffraction and optical and scanning electron microscopy were used to identify *metatyuyamunite*. *Tyuyamunite* was not found to be present in the samples analyzed. The *metatyuyamunite* was found to have unit-cell dimensions of $a = 10.397(4)\text{\AA}$, $b = 8.403(2)\text{\AA}$, $c = 16.692(12)\text{\AA}$.

Spider Cave has developed within dolostones and siltstones of the Yates Formation. Uranium and vanadium compounds were probably concentrated and deposited along an oxidation-reduction front during the (sulfuric acid) dissolution of bedrock which formed the cave. Association of *metatyuyamunite* with secondary opal on breakdown blocks, floor deposits, and speleothems indicates that *metatyuyamunite* mineralized from vadose solutions after speleogenesis and lowering of the water table.

INTRODUCTION

Spider Cave, Carlsbad Caverns National Park, New Mexico (Fig.1), is one of four caves within the Guadalupe Mountains in which pale yellow to bright canary yellow mineral deposits have been found. Yellow deposits, identified as sulfur, are known to occur in Carlsbad Cavern, Cottonwood and Lechuguilla caves (Davis, 1973; Hill, 1987), and yellow druses on breakdown, gypsum crusts, and floor deposits in the Ghost Room of Spider Cave were also suspected of being sulfur. X-ray diffraction (XRD), and optical and scanning electron microscopy (SEM) revealed that the crystals were *metatyuyamunite*, a hydrated uranyl vanadate mineral.

This is the first reported occurrence of *metatyuyamunite* [$\text{Ca}(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 3\text{-}5\text{H}_2\text{O}$] in a cave, although *tyuyamunite* [$\text{Ca}(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 5\text{-}8\text{H}_2\text{O}$] has been previously reported from Tyuya-Muyun Cave in the former USSR, in Horse Thief Cave in Wyoming (Hill and Forti, 1986, and citations contained therein), and in a Montana cave (Bell, 1963). *Metatyuyamunite* is the dehydration product of *tyuyamunite* (Stern et al., 1956) and is likely to occur with *tyuyamunite* in cave settings.

The presence of uranium-vanadium compounds in caves of the Guadalupe Mountains offers new insight into the geologic history of these caves.

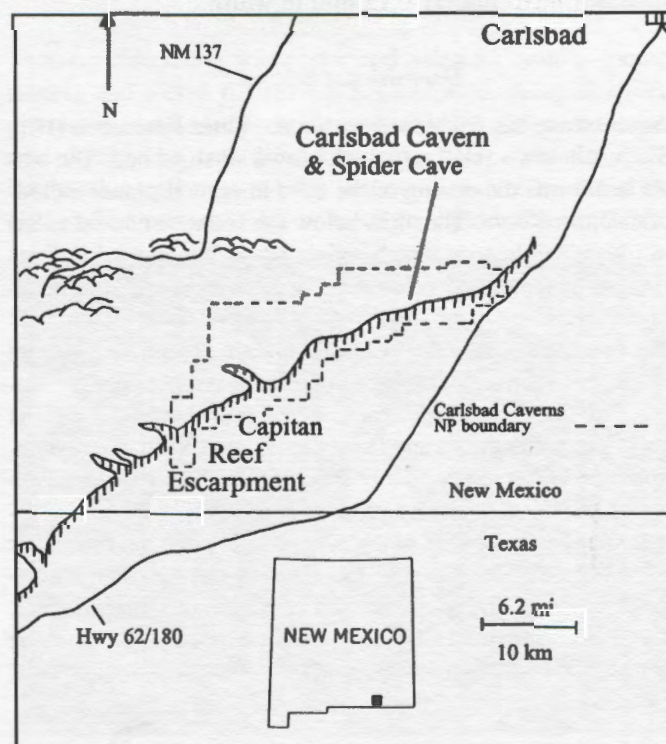


Figure 1. Location map showing the Carlsbad Caverns National Park in the Guadalupe Mountains of New Mexico. Spider Cave is located near Carlsbad Cavern in the park.

RESULTS

Physical and Optical Descriptions

In Spider Cave, metatyuyamunite occurs as lath-shaped crystals, 0.1 to 0.5 mm across, which resemble playing cards standing upright (Figs. 2 & 3). The crystals are interpreted as having formed originally as tyuyamunite, subsequently dehydrating to the present species. They are canary yellow, occasionally with a greenish tinge, and they have an adamantine luster. Optical microscopy shows perfect rectangular cleavage, with parallel extinction (Fig. 2). The crystals examined are biaxial negative and very faintly pleochroic. Birefringence, mostly masked by the yellow color of the mineral, appears to be first or second order.

The opal which coats the metatyuyamunite is botryoidal or spheroidal (Fig. 4). Botryoid diameters range from 5 to 50 μm .

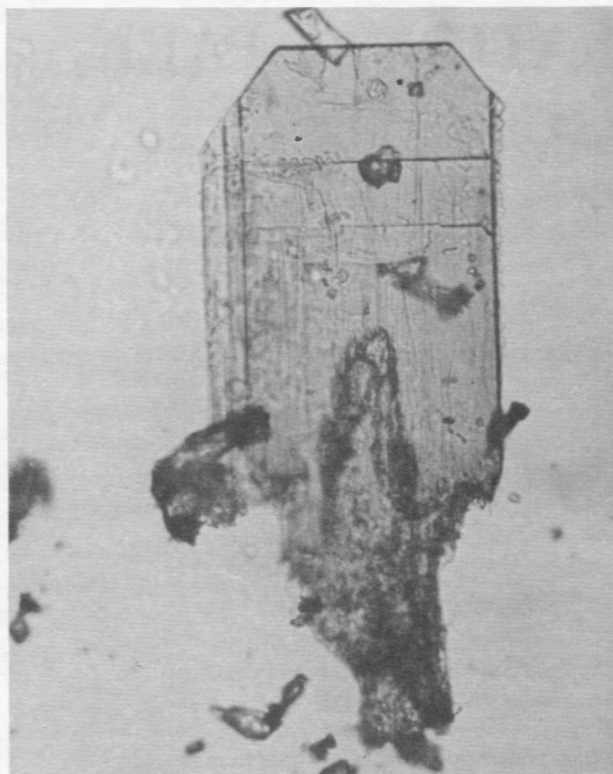


Figure 2. Photomicrograph of metatyuyamunite lath showing rectangular cleavage and well-formed crystal faces. The crystal is approximately 0.15 mm in width.

Depositional Setting

Spider Cave has developed within the Yates Formation (Hill, 1987) just below a relatively thick brown siltstone bed. The siltstone bed forms the ceiling of the cave in several places including the Ghost Room. The units below the siltstone consist mostly of pisolitic dolostone which appear silt-rich in many localities within the cave. Metatyuyamunite deposits were found in bone-yard passage three meters below the Ghost Room.

In the study area below the Ghost Room, carbonate speleothems such as stalactites, columns, cave popcorn, moon-milk, and crusts are numerous. Sulfate speleothems consist mostly of gypsum crusts and flowers. Canary yellow metatyuyamunite was observed on the bedrock surface of a large breakdown block, on gypsum crusts on the same block, and on clay-rich floor sediments. One patch of yellow crystals on this block measured 2 cm by 5 cm. The most striking druse, which measured 7 cm by 20 cm, was observed on clay-rich floor sediment. Metatyuyamunite druses are associated with botryoidal opalline coatings, and both have precipitated late in the genetic history of Spider Cave.

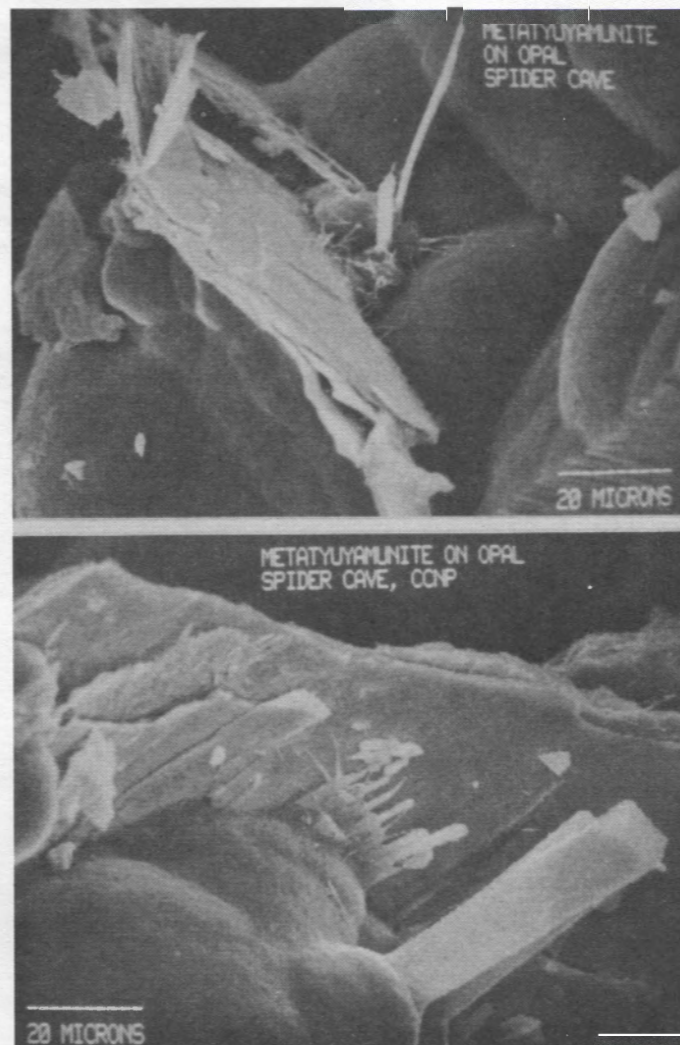


Figure 3. SEM image of a plate-like metatyuyamunite crystal and botryoidal opalline coating. There appears to be an intimate association between the two precipitates.

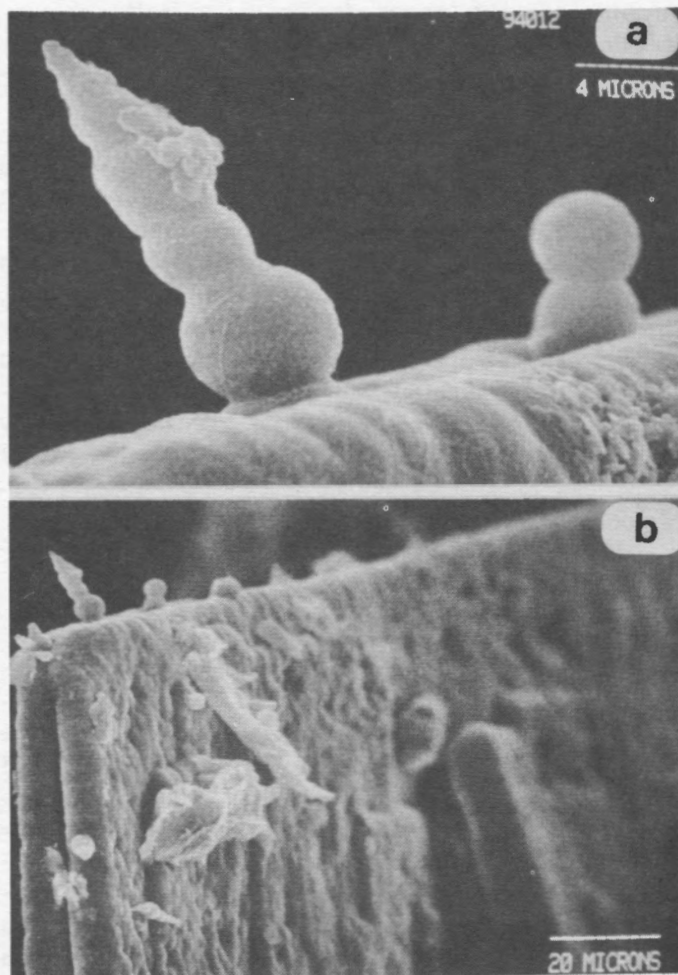


Figure 4. SEM image showing a metatyuyamunite platelet entirely coated with opal. (a) Attached to the coated platelet are features that resemble "stacked" spheres. Energy dispersive X-ray microanalysis of the spheres indicates they are also composed of silicon and oxygen (opal). (b) Note the way in which opal has precipitated along the edge of the metatyuyamunite crystal.

Spheres of opal are usually associated with filaments (Fig. 5). The spheres are generally less than 5 μm in diameter and sometimes exhibit a "stacked" appearance (Fig. 4a). Nucleation of opal is evident along uranyl vanadate crystal corners, and consequently two parallel sets of botryoids have developed along platelet edges (Fig. 4b). The opalline coatings are transparent.

External Radiation Detection

Naturally occurring uranium isotopes emit alpha radiation, and several daughter products of uranium decay are alpha, beta and/or gamma radiation emitters. Gamma radiation is easily detected using portable Geiger-Mueller or scintillation detectors; however, gamma-emitting daughter products would probably not be present in significant quantities in relatively recent efflorescent uranium mineral deposits. Therefore, portable scintillation survey meters designed to measure alpha radiation would be the most effective means of detecting recent efflorescent uranium mineral deposits in caves. An alpha detector can also be used to crudely measure relative concentrations of radon gas (an alpha-emitting daughter product of uranium) in cave passages. There should be an enrichment of radon in air in areas where the bedrock or cave deposits contain higher concentrations of uranium.

Bob Buecher (pers. comm., 1994) has scanned several areas in Spider Cave with a portable radiation survey meter equipped with an alpha window. Results of the survey indicate significant increases in counts per minute (cpm) in areas adjacent to metatyuyamunite deposits. Results are as follows:

Background in Spider Cave	15 cpm
Ghost Room	15 cpm
Metatyuyamunite passage	35 cpm
Floor deposit of metatyuyamunite	47 cpm

X-ray Diffraction Analysis of Metatyuyamunite

X-ray diffraction was performed using a Gandolfi (powder) camera and nickel filtered Cu-K α radiation. A small sliver of aluminum was added as an internal standard with metatyuyamunite during the last diffraction run. XRD data fits the orthorhombic cell reported for metatyuyamunite by Stern et al. (1956). The orthorhombic unit-cell for Spider Cave metatyuya-

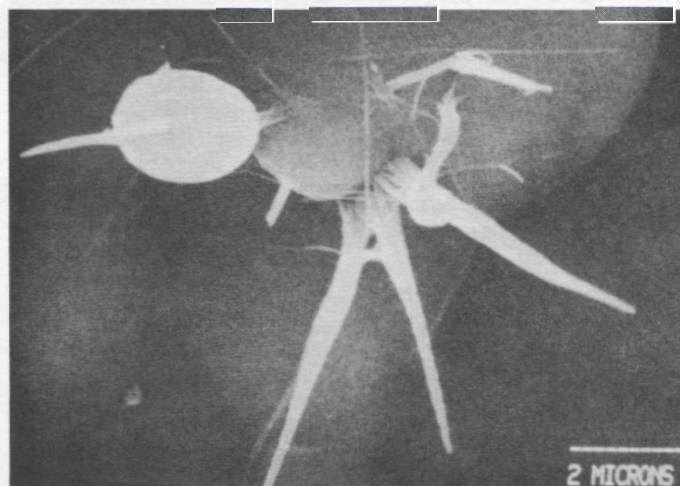


Figure 5. SEM image showing the relationship between opal spheres and filaments.

munite generated using Appleman and Evans (1973) least squared indexing program modified for the PC by Benoit (1987) has the parameters $a = 10.397(4)\text{\AA}$, $b = 8.403(2)\text{\AA}$, and $c = 16.692(12)\text{\AA}$. The XRD powder data is available upon request from the authors. Opal botryoids associated with metatyuyamunite crystals also were X-rayed with the Gandolfi camera. XRD data for the botryoidal material indicates the presence of opal-A and opal-CT. Opal-A is indicated by a broad indistinct reflection of the Gandolfi film at $4.2\text{\AA}$ (Senkayi, et al., 1985). Opal-CT is indicated by reflections at 4.33, 4.12, and $2.50\text{\AA}$ (Drees, et al., 1989).

Chemical Analysis of Bedrock

One sample of bedrock with metatyuyamunite was collected from a 0.5 meter diameter breakdown block. The carbonate bed from which the breakdown block had fallen lies directly under a thick siltstone bed. A fragment of carbonate bed on which metatyuyamunite has crystallized and two samples of siltstone from the Ghost Room were analyzed for elemental chemistry and mineral content. Trace element analyses were performed by Chemex Labs. The carbonate bedrock consisted of calcite with minor quartz and dolomite. The siltstone consisted of quartz with minor amounts of illite and dickite and/or kaolinite. The results of the chemical analyses are listed in Table 1. In the carbonate bedrock sample, 26 ppm vanadium and 20 ppm uranium were detected, and in the siltstone samples, 9 ppm vanadium and <10 ppm uranium were detected.

Microanalysis of Metatyuyamunite and Opal

Semi-quantative elemental analysis of both metatyuyamunite and opal were provided by SEM energy dispersive spectroscopy

Table 1: Chemical analysis of siltstone and limestone bedrock from the Ghost Room area in Spider Cave.

SAMPLE NUMBER	93026 siltstone	93027 siltstone	93030 carbonate bedrock
Al (%)	0.16	0.27	0.15
Ba (ppm)	70	40	<10
Ca (%)	0.88	0.24	>15.00
Co (ppm)	24	7	<1
Cu (ppm)	5	2	<1
Fe (%)	2.14	1.58	0.08
K (%)	0.04	0.12	0.03
Mg (%)	0.08	0.10	5.01
Mn (ppm)	1750	485	<1
Ni (ppm)	98	27	1
P(ppm)	220	670	80
Pb (ppm)	8	4	<2
Sr (ppm)	7	8	85
U (ppm)	<10	<10	20
V(ppm)	9	9	26
W (ppm)	<10	<10	20
Zn (ppm)	16	38	4

Sample 93026 was collected from a thin Mn-rich horizontal zone.

(EDS). EDS confirms that the metatyuyamunite consists of Ca, O, U, and V. All of the opal analyses consisted only of Si and O; impurities were not detected.

DISCUSSION

This is the first report of uranium/vanadium minerals from Guadalupe Mountains caves. However, Hill (1987) reported high concentrations of uranium in montmorillonite and cave raft deposits in Carlsbad Cavern. Uranium compounds in black amorphous hydrocarbon material have also been reported from a prospect approximately 20 km west north-west of Carlsbad, New Mexico (Waltman, 1954). Within the same area, a yellow powdery deposit suspected to be tyuyamunite was reported in Tansill surface outcrops by Bell (1963). Hill (1993) has reported concentrations of vanadium above 100 ppm from many prospects and mines within the Guadalupe Mountains; most of these occurrences were within the Seven Rivers, Yates, or Tansill formations.

Significance of Hydrated Uranyl Vanadate Occurrence

Allen and Thomas (1984) reported tyuyamunite in sandstones of the Permian Rush Springs Formation in southwestern Oklahoma. They attributed the occurrence to deposition of uraninite caused by the interaction of uraniferous ground waters with H_2S which was generated from migrating hydrocarbons or from reduction of sulfates by hydrocarbons; the uraninite later contributed to the formation of tyuyamunite. This mode of formation may apply to the metatyuyamunite of Spider Cave. Oxidized ground water within the Yates siltstones and dolostones could have interacted with H_2S -bearing solutions migrating from hydrocarbon fields in the Delaware Basin as proposed by Hill (1987; 1990). This would have provided an oxidation-reduction front along which the uranium and vanadium could have precipitated. Uranium and vanadium compounds may have been deposited by the solutions which were ultimately responsible for development of Spider Cave. After development of cave passages and lowering of the water table, most uranium compounds would probably become mobilized because solutions enriched with respect to carbonate and bicarbonate ions favor solubility of uranium in the oxidized, hexavalent or uranyl state (Bell, 1963; Langmuir, 1978; Young, 1984). The vanadate ion is an especially effective precipitant for uranyl ions (Dongarra, 1984; Smith, 1984), so areas enriched in vanadium could favor precipitation of uranyl vanadates. This would explain why uranyl vanadates are the uranium minerals most commonly found in carbonate caves (Bell, 1963; Smith, 1984).

Uranium could be derived from any of the Permian rocks of or adjacent to the Guadalupe Mountains, such as siltstones, dolostones, and internal sediments of the Capitan Reef Complex, or shaley sandstones and limestones of the Delaware Basin.

Sources of vanadium, however, are more likely to be bituminous marine sediments. Vanadium concentrations have been reported as high as 5000 ppm in some shales and 3000 ppm in some bituminous carbonates, while limestones in general contain about 10-80 ppm (Wedepohl, 1978). Concentrations of vanadium greater than 100 ppm have been reported in crude oils (Fairbridge, 1972), and as much as 50% vanadium has been reported in the ash of petroleum (Wedepohl, 1978). Hill (1993) reported 211 ppm vanadium and 70 ppm uranium from oil tar along the eastern margin of the Delaware Basin, and 292 ppm vanadium from a prospect in the Lamar Member of the Bell Canyon Formation near the contact with the Capitan Limestone fore reef facies. We postulate that the source of vanadium found in rocks of the Capitan Reef Complex is basinal shaley and/or bituminous sandstones and limestones, or residual of petroleum deposits.

If deposition of uranium and vanadium and native sulfur are related to development of Guadalupe caves, then it is important that yellow deposits be properly identified and documented. Absolute identification of each yellow deposit will provide additional insight as to the origin of sulfur and uranyl vanadates, respectively. Sulfur occurrences have been related to speleogenesis and many yellow mineral occurrences may have been misidentified as sulfur, because the mineralogy was not verified. Reexamining each yellow deposit to verify mineralogy may help clarify future geologic interpretations.

Significance of Opal Occurrence

Opal has precipitated as botryoidal coatings adjacent to, and on, the metatyuyamunite crystals. Bell (1963) reported tyuyamunite in caves of the Pryor Big Horn Mountains of Wyoming and Montana in association with siliceous sinters, and the setting of these sites is similar in description to that of Spider Cave. There appears to be a direct relationship between uranyl vanadates and siliceous coatings/crusts in carbonate caves. In addition to the cave occurrences, relatively high concentrations of uranium have been noted in association with siliceous precipitates in other depositional environments. Hein, et al. (1987) reported values three to eight times above crustal average of uranium in circum-Pacific marine diatomite-porcelanite rocks; they found that organic-rich biosiliceous sediments were mostly responsible for uranium enrichment. Zielinski (1980) reported relatively high uranium concentrations within secondary silica precipitates such as chalcedony in carbonate rocks of the Shirley Basin in Wyoming. Zielinski suggested that uranium was adsorbed by uranyl-silica-hydroxyl complexes and subsequently incorporated in silica gel. The association of siliceous coatings/crusts with uranyl vanadate minerals in caves is significant as an indicator of the mechanism of mineralization.

The presence of opal with metatyuyamunite probably indicates an elevated pH ground water environment because the solubility of amorphous and crystalline silica increase rapidly above pH 9 (Drees, et. al, 1989) and solubility of uranyl vana-

dates increase above pH 8 (Langmuir, 1978). Uranyl minerals such as metatyuyamunite are the most stable at low CO_2 pressures (Langmuir, 1978), so it is expected that ground water seeping into the cave would degas CO_2 to seek equilibrium with the cave atmosphere and thus favor precipitation of uranyl minerals. The following mechanism is suggested for the precipitation of opal and metatyuyamunite in Spider Cave: (1) uranium is mobilized in the oxidized ground water as uranyl carbonate and uranyl-silica-hydroxyl complexes, (2) upon evaporation and CO_2 degassing, evaporative carbonate speleotherms such as popcorn and moonmilk precipitate at the rock-cave interface which further concentrates the solutions with respect to uranyl and silica complexes, and vanadate ions, and (3) precipitation of opal and uranyl vanadate minerals occur as surface coatings and efflorescence. Slow seepage rates, evaporation, and removal of CO_3^{2-} and SO_4^{2-} ions by precipitation of aragonite, Mg-calcite, hydromagnesite, or gypsum are probably critical to the final enrichment and precipitation mechanism.

SUMMARY

Two samples of canary-yellow deposits were collected from the Ghost Room area of Spider Cave, Carlsbad Caverns National Park and were identified as metatyuyamunite. The yellow crystals, millimeter-sized and smaller, occur as euhedral platelets and are closely associated with a clear botryoidal opalline coating.

Uranium compounds were initially concentrated in the Yates Formation along an oxidation-reduction front probably during the formation of Spider Cave. Sometime after development of the cave passages and lowering of the water table, uranium compounds were remobilized and in the presence of vanadates, precipitated as metatyuyamunite on breakdown, gypsum crusts, and clay-rich floor deposits. Opalline crusts also precipitated in association with metatyuyamunite druses.

ACKNOWLEDGEMENTS

We thank Michael Goar and Richard Knapp for bringing to our attention the canary yellow deposits near the Ghost Room, and for field assistance. Gratitude is expressed to Dale Pate and Jason Richards of the Carlsbad Caverns National Park Service for arrangement of permits necessary to conduct this study. We are grateful to Dr. Necip Güven of Texas Tech University for providing use of the X-ray and electron microscope labs, and to Dr. Nancy McMillan of New Mexico State University for help with abstract preparation. We are also very grateful to Carol A. Hill, a consulting geologist in Albuquerque, for editing drafts of this paper, and to the reviewers Paolo Forti of the University of Bologna, Italy, and Peter B. Leavens of the University of Delaware. We also thank Bob Buecher for discussions related to yellow deposits in Spider Cave and other possible cave occurrences. Chemex Labs performed the trace-element analyses.

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Manuscript Received by the Society 4/11/95.

Manuscript Accepted for Publication 8/30/95.

A SUBTERRANEAN CHEMOAUTOTROPHICALLY BASED ECOSYSTEM

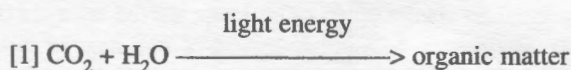
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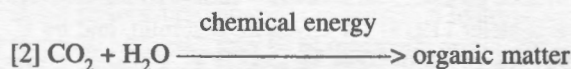
An unusual invertebrate fauna has recently been discovered in Dobrogea, southern Romania. This fauna inhabits the deep recesses of an extensive cave system that has been isolated from the surface for several million years. The numerous species discovered in the cave, most of them previously undescribed, live in an atmosphere that is very poor in oxygen and very rich in carbon dioxide. The most peculiar characteristic of this ecosystem is that it derives its energy from the oxidation of hydrogen sulfide present in the thermal waters that flood the lower level of the cave. Microbial mats consisting of fungi and chemoautotrophic bacteria occur on the walls of the cave and are also found floating on the surface of the sulfidic water in the cave. This appears to be the first known subterranean ecosystem that is completely chemoautotrophically based. In this regard it shares much in common with the deep sea vent communities discovered in the 1970's.

INTRODUCTION

Generally life on earth depends, directly or indirectly, on the energy of the sun for carbon fixation in the process of photosynthesis [1]. However, in the late 1970's R.D.



Ballard (1977) and other oceanographers and marine biologists discovered rich communities of deep-sea organisms thriving around thermo-mineral vents on the bottom of the Pacific Ocean near the Galapagos Islands, at several thousand meters depth. Studies performed by H. W. Jannasch (1985) and others showed that chemolithoautotrophic sulfur-oxidizing microorganisms use energy from the oxidation of hydrogen sulfide dissolved in the thermal waters to fix carbon [2].



The autotrophic microorganisms are the base of the trophic chain and supply the energy requirements of the entire vent ecosystem. Numerous other diverse deep-sea vent communities were later discovered on the bottom of the oceans. Although there are important differences among them, they all have one essential trait in common: by means of chemoautotrophic microbes, they use chemical energy rather than solar energy in the process of carbon fixation.

The discovery of another chemoautotrophically based ecosystem, located underground rather than on the floor of the

ocean, has provided a more accessible example of this type of system for study and comparison. In 1986, geologist C. Lascu discovered a 240 m long network of cave passages at the bottom of a 25 m well dug in the limestone plateau of southeastern Dobrogea, Romania (Fig. 1). The cave is partially flooded by ther-



Figure 1. Map of Dobrogea (Romania) and the location of the recently discovered Movile Cave.

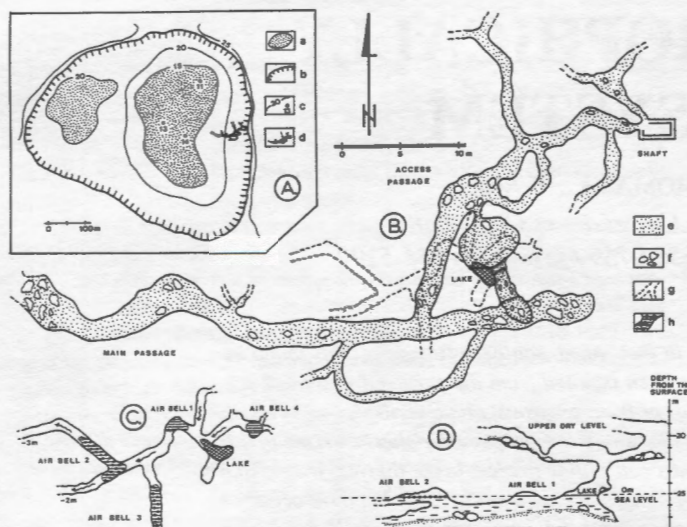


Figure 2. Movile Cave. A. Location of the cave in the "Obanul de la Movile" sinkhole: a. bottom of the sinkhole; b. edge of the sinkhole; c. altitude in meters; d. cave; B. Plan of the upper level of the cave: e. clay; f. breakdown; g. lower level; h. airbells containing floating mats. C. Plan of the submerged level of the cave. D. profile of the Lake Room area.

mal waters that contain hydrogen sulfide (H_2S). Movile Cave (Fig. 2), the only known human access to this system, contains a rich cave adapted invertebrate fauna that depends on the food produced *in situ* by chemoautotrophic sulfide-oxidizing microbes. This represents the first known subterranean ecosystem primarily, if not entirely, based on chemoautotrophic carbon fixation.

How was such an ecosystem formed? How does it function? Is it a unique case, or were there certain peculiar conditions in the geological past that led to the formation of numerous such ecosystems that are yet to be discovered? The geological and biological investigations that have been performed for the last seven years provide answers for some of these questions. In order to better understand how such an ecosystem was formed, one needs to place the recently discovered cave in its geological context.

GEOLOGY AND HYDROLOGY OF MOVILE CAVE

Movile Cave is located on a karst plateau, at a depth of 20 meters beneath the surface. It does not have a natural entrance and the only access to it is the artificial well dug in 1986. It consists of a network of passages developed in Sarmatian Limestone (12.5 million years old). The upper level of the cave is dry whereas the lower level is partially flooded by thermal sulfide-rich waters. Several air-bells are present in the lower level of the cave. The atmosphere of the air-bells is poor in oxygen (7-10%), rich in carbon dioxide (2-3.5%) and contains small amounts of

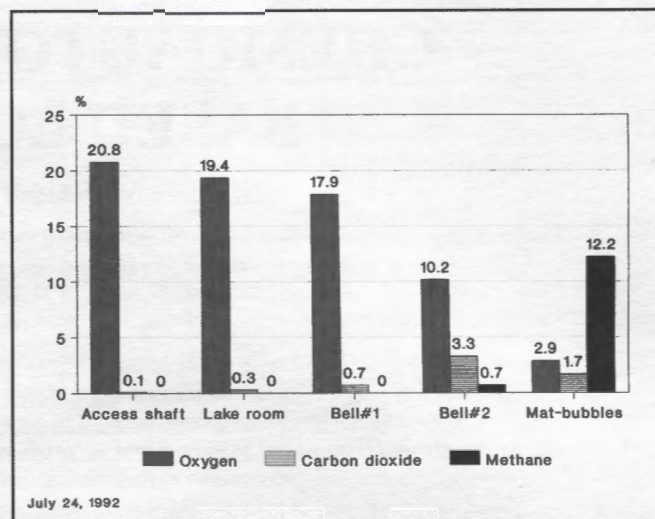
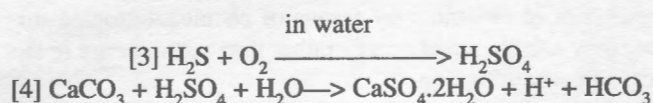


Figure 3. Chemical composition of the atmosphere in various parts of Movile Cave.

Table 1. Physico-chemical characteristics of the water in Movile Cave.

IONS	amounts in mg/l
Ca^{2+}	47.9
Mg^{2+}	27.7
Na^+	201.8
K^+	8.8
Cl^-	230.0
HCO_3^-	330.8
H_2S	8.4
Temperature	20.9°C ($\pm 0.3^\circ\text{C}$)
pH	7.29
Redox potential	-341 mV

methane (1-2%) (Fig. 3). Higher amounts of methane (up to 13.5%) are found in the small gas bubbles that keep the microbial mats afloat. The water temperature is 21°C and the amount of dissolved hydrogen sulfide varies between 8 and 12 mg/l (Table 1). The cave walls of the lower level have been extensively corroded by chemical processes similar to those described by S. J. Egemeier (1973) for caves in Wyoming and by C. A. Hill (1990) for caves in New Mexico (e.g., Carlsbad Caverns, Lechuguilla Cave). Hydrogen sulfide from the cave water reacts with oxygen from the air to form sulfuric acid [3] which in turn reacts with the limestone walls of the cave [4]. The byproduct of this reaction is gypsum (calcium sulfate) which is deposited on the cave walls.



What is the origin of this subterranean water? The carbonate deposits reach a thickness of up to 800 meters in the Dobrogean plateau and consist of marine deposits of Jurassic [205 to 135 million years ago (mya)], Cretaceous (135 to 65 mya), Eocene (53 to 34 mya), and Sarmatian (12.5 mya) age, laying on a thick layer of Paleozoic sediments. Numerous deep wells have been dug in the region during the last 20 years, intercepting thermal H_2S -rich waters with physicochemical characteristics resembling those of the water present in Movile Cave. Hydrogeological studies performed by M.U. Feru and A. Capota (1991) have shown that these waters come from a captive aquifer (with pressures of 1 to 1.7 atmospheres) lodged in the Jurassic and Cretaceous limestones, that extends 15 km north and 50 km south of Mangalia. In the Mangalia region the H_2S -rich water ascends to the surface through a system of faults that extend deep into the limestone layers. Consequently, numerous sulfide-rich springs are present in this region. Some springs are located a few kilometers inland, but most of them are located along the Black Sea shore. There are also numerous submarine springs in shallow waters on the continental platform of the Black Sea at Mangalia. Some of the springs have been known for a long time and have been utilized for therapeutic purposes for over 2,000 years. The presence of a highly productive aquifer in such an arid region as Dobrogea has long been a mystery for Romanian hydrogeologists. Isotopic studies performed in the 1980's by A. Tenu, F. D. Davidescu, and A. Slăvescu (1987) showed that the waters of the deep Jurassic-Cretaceous aquifer (200–400 m of depth) come from regions in the west and southwest at distances of 100 to 200 km after having spent up to 25,000 years underground. Our recent oxygen and hydrogen stable isotope analyses show that these waters are lighter than the present precipitation input for both oxygen and hydrogen thus supporting the hypothesis that these waters have a considerable subterranean age. While ascending toward the surface through faults, the waters flow through the superficial Sarmatian Limestone, get dispersed in the networks of fissures and their temperature decreases. Eventually they mix with superficial oxygenated Sarmatian waters, and hydrogen sulfide is oxidized to form elemental sulfur and sulfate.

What is the origin of the hydrogen sulfide? The results of sulfur stable isotope ratio analyses suggest that hydrogen sulfide in the waters at Mangalia may be of magmatic origin, similar to hydrogen sulfide in the water of deep-sea vents. The hydrogen sulfide present in Movile Cave is characterized by $\delta^{34}S$ values of +3.5 to +4.2‰ as opposed to the $\delta^{34}S$ values of -40‰ characteristic of hydrogen sulfide from the deep waters of the Black Sea. This contradicts the hypothesis that the hydrogen sulfide is produced by sulfate-reducing microorganisms living in anoxic conditions, as happens in the deep anoxic waters of the Black Sea. On the other hand, these $\delta^{34}S$ values are similar to those of magmatic sulfides, suggesting that the source of reduced sulfur may be a mass of hot magmatic rock located deep under the Dobrogean sedimentary deposits. This hypothesis is also supported

by the presence of a positive geomagnetic anomaly in southeastern Dobrogea that was identified by S. Airinei (1980). This would explain the presence of large amounts of hydrogen sulfide in the water, as well as the increased water temperature.

Although overall the environmental characteristics of Movile Cave resemble those of most other caves (absence of light, constancy of temperature and relative humidity), there are certain peculiarities that directly influence the cave's fauna. The mean temperature of the cave, which is highly constant throughout the entire year ($20.9^\circ C \pm 0.3$), is significantly higher than the mean annual temperature of caves located in temperate climates (4° to $12^\circ C$); thermal H_2S -rich waters are present; cave walls are corroded by sulfuric acid; and finally, due to the impermeable silt layers above the cave, there is no infiltration of surface waters into the cave and air exchange between the cave and the surface is reduced.

What data support the hypothesis that Movile Cave is well isolated from the surface? Flowstone formations such as stalactites or stalagmites are completely absent in Movile Cave. Such formations are the result of redeposition of calcium carbonate from waters percolating through the limestone strata. Their absence suggests a lack of surface water infiltration. The reduced oxygen concentrations and the increased amounts of carbon dioxide in the cave, especially in the air-bells, indicate a reduced gas exchange between the cave and the surface, an additional consequence of the impermeability of the rock layers above the cave. This is particularly interesting given the fact that the cave is located only 20 meters below the surface. A careful examination of the cave walls shows that they are covered by a thin layer of clay that fills all the interstices of the limestone. Following the 1986 Chernobyl accident, high amounts of artificial nuclides ($^{90}Strontium$ and $^{137}Cesium$) were released in the atmosphere and spread by winds all over Europe. High concentrations of these nuclides were found throughout Romania, in the soil, in lakes, in the Black Sea, and in sediments of other caves. Investigations performed by I. Oswath and F. Baci (unpublished) showed that artificial nuclides were completely absent in Movile Cave thus supporting the hypothesis that the cave is well isolated from the surface. Additional support for the isolation of the Movile Cave ecosystem from the surface is offered by the absence of other natural and artificial indicators such as diatoms, fecal streptococci, and pesticide residues in the cave water and sediments. Carbon stable isotope data support the hypothesis that there is no input of organic matter of photosynthetic origin into the subterranean ecosystem. Several samples of organic matter from the cave were analyzed and all yielded very low $\delta^{13}C$ values (-36‰ to -45.5‰) showing a significant depletion in the heavy carbon isotope (^{13}C). If organic matter was transported into the cave by surface waters infiltrating from surface lakes, its expected $\delta^{13}C$ value would be of about -26‰ to -23‰ reflecting its origin from photosynthetically fixed carbon from the surface. The isotopically light organic carbon found in the cave appears to be produced by chemoautotrophic

sulfide oxidizing bacteria which are known to fractionate carbon to a greater extent than photoautotrophs. The source of inorganic carbon appears to be the large amount of isotopically light CO_2 resulting from the oxidation of methane which ascends along with the sulfidic waters from the deep aquifer (Fig. 4).

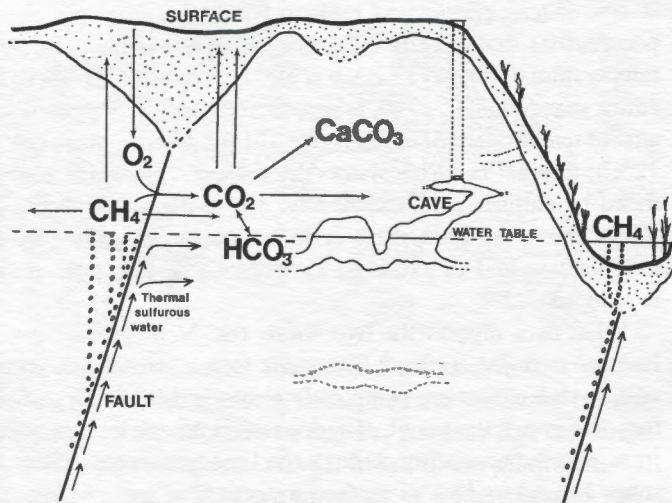


Figure 4. Hydrogeologic profile through the Movile region. Warm H_2S -rich waters ascend along faults and disperse into the superficial Sarmatian Limestone. Along with the water, methane of biogenic origin (δD -195 to -112 ‰; $\delta^{13}\text{C}$ -55‰) also ascends along these faults. Upon reaching the water table methane is oxidized to produce isotopically light CO_2 .

THE FAUNA

These peculiar physicochemical conditions produce a unique ecosystem. Forty-six species of terrestrial and aquatic invertebrates have been discovered in the cave so far, of which 31 are previously undescribed. Twenty-two new species of terrestrial invertebrates (Table 2) collected only in the lower level of the cave in the vicinity of the H_2S -rich waters are included in this group. They are all endemic to the subterranean ecosystem associated with the thermal waters at Mangalia. The vast majority are arthropods belonging to four classes: Arachnida, Crustacea, Myriapoda, and Insecta. These species are obligate cave-dwellers (i.e., troglobites), well adapted to the peculiar environment in which they live. They lack eyes and pigment, and their appendages (legs and antennae) are elongated, traits that are important in an environment in which light is absent and tactile and chemical sensory systems are important in perceiving the environment.

Eighteen aquatic species have been collected in the lower submerged level of the cave (Table 3). They belong to six phyla: Platyhelminthes (flatworms), Nematoda (round worms), Rotifera (microscopic animals related to round worms), Annelida

Table 2. Terrestrial troglobites found in Movile Cave.

Oligochaeta	
Lumbricidae	- <i>Allolobophora</i> sp.
Pseudoscorpiones	
Chthoniidae	- <i>Chthonius monicae</i> Boghian, 1989 *
	- <i>Roncus dragobete</i> Ćurčić, Poinar & Sarbu, 1993 *
	- <i>Roncus ciobanmos</i> Ćurčić, Poinar & Sarbu, 1993 *
Araneae	
Theridiidae	- <i>Marianana mihaili</i> Georgescu, 1989 *
Linyphiidae	- <i>Lepthyphantes constantinescui</i> Georgescu, 1989 *
Clubionidae	- <i>Agracina cristiani</i> (Georgescu, 1989) *
Nesticidae	- <i>Nesticus</i> n.sp. *
Hahniidae	- <i>Iberina caeca</i> Georgescu & Sarbu, 1992 *
Acarina	
Nicoletiellidae	- <i>Labidostoma motasi</i> Iavorschi, 1992 *
Isopoda	
Armadillidiidae	- <i>Armadillidium tabacaru</i> Gruia, Iavorschi & Sarbu, 1994 *
Trachelipidae	- <i>Trachelipus troglobius</i> Tabacaru & Boghian, 1989 *
Trichoniscidae	- <i>Caucasonethes</i> n.sp. *
	- <i>Haplophthalmus</i> n.sp. *
Chilopoda	
Cryptopidae	- <i>Cryptops anomalans</i> Newport, 1844
Geophilidae	- <i>Geophilus</i> sp. (<i>insculptus</i> L. Koch ?)
	- <i>Clinopodes trebevicensis</i> (Verhoeff, 1898)
Symphyla	
Scolopendrellidae	- <i>Symphynella</i> sp.
Diplopoda	
Iulidae	- <i>Archiboreoiulus</i> n.sp. *
Collembola	
Onychiuridae	- <i>Onychiurus movilae</i> Gruia, 1989 *
Entomobriidae	- <i>Heteromurus cf nitidus</i> (Templeton) 1835 *
Cyphoderidae	- <i>Onchopodura vioreli</i> Gruia, 1989 *
Diplura	
Campodeidae	- <i>Plusiocampa isterina</i> Condée, 1993 *
	- <i>Plusiocampa</i> n.sp. *
Coleoptera	
Staphylinidae	- <i>Medon dobrogicus</i> Decu & Georgescu, 1994 *
Pselaphidae	- <i>Tychobythinus</i> n.sp. *
	- <i>Decumarellus sarbui</i> Poggi, 1994 *
Clivinidae	- <i>Clivina subterranea</i> Decu, Nitzu & Juberthie, 1994 *

* - Species that are endemic to the subterranean ecosystem associated with the thermal waters at Mangalia.

(segmented worms), Mollusca (snails), and Arthropoda (ostracod, copepod, isopod, and amphipod crustaceans, and insects). Among the new aquatic species found in the cave is a small (1-3 mm long) snail (*Heleobia dobrogica*), a blind leech, and a blind water-scorpion (Fig. 5). The new species of water-scorpion discovered in Movile Cave represents the first cave adapted aquatic heteropteran in the world and the first species of cave adapted heteropteran to be found in the temperate region.

ECOSYSTEM FUNCTION IN MOVILE CAVE

We are interested in understanding the trophic structure of the community. A detailed examination of the region appears to pre-

Table 3 Aquatic troglobites found in Movile Cave.

Turbellaria	
Dendrocoelidae	- <i>Dendrocoelum</i> sp.
Nematoda	
Rhabditidae	- <i>Protorhabditis</i> n.sp. *
Panagrolaimidae	- <i>Panagrolaimus</i> n.sp. *
Leptolaimidae	- <i>Chronogaster troglodytes</i> Poinar & Sarbu, 1994 *
Aphanoneura	
Aeolosomatidae	- <i>Aeolosoma hyalinum</i> Bunke, 1967
	- <i>Aeolosoma litorale</i> Bunke, 1967
Hyrudinea	
Haemopidae	- <i>Haemopsis</i> n.sp. *
Rotatoria	
Habrotrochidae	- <i>Habrotrocha rosa</i> Donner, 1949
	- <i>Habrotrocha bidens</i> Gosse, 1851
Gasteropoda	
Moitessieriidae	- <i>Heleobia dobrogica</i> (Grossu & Negrea, 1989) *
Ostracoda	
Cyprididae	- <i>Pseudocandona</i> sp. aff. <i>eremita</i> (Vejd.)
Cyclopoida	- <i>Eucyclops subterraneus sythicus</i> Pleša, 1989 *
	- <i>Tropocyclops prasinus</i> (Jur.)
Harpacticoida	- <i>Parapseudoleptomesochra italica</i> Pesce & Petkovski, 1980
Amphipoda	
Gammaridae	- <i>Niphargus</i> cf. <i>stygius</i>
	- <i>Pontoniphargus racovitzae</i> Dancau, 1970 *
Isopoda	
Asellidae	- <i>Asellus aquaticus</i> (L.)
Heteroptera	
Nepidae	- <i>Nepa anophthalma</i> Decu, Gruia, Keffer & Sarbu, 1994 *

* - Species that are endemic to the subterranean ecosystem associated with the thermal waters at Mangalia.

clude the possibility of significant input of organic matter from the surface (there are no lakes, rivers or swamps in the region to provide organic matter that could infiltrate the system). This is supported by carbon stable isotope data presented previously. Further, the annual mean precipitation in southeastern Dobrogea is less than half of the evapo-transpiration capacity of the soil, suggesting that precipitation does not infiltrate the ground and reach the H_2S rich aquifer. Despite the lack of a significant food input from the surface however, the terrestrial and aquatic cave communities are very rich, both in number of taxa present and in the population sizes of these species.

What is the source of the food base for this system? The answer appears to lie in the microbiota inhabiting the lower level of Movile Cave. Microbial mats occur floating on the surface of the water and covering the limestone cave walls in the remote air-bells where the cave's atmosphere is depleted in oxygen and enriched in carbon dioxide. The thickness of these mats varies between 0.3 and 3 mm. Examination of these mats by P. Febbroriello (unpublished) revealed a network of fungal hyphae with an average diameter of 3 μm composed of several species of fungi (*Plasmophora* sp., *Gliocladium* sp., *Penicillium* sp., *Tri-*

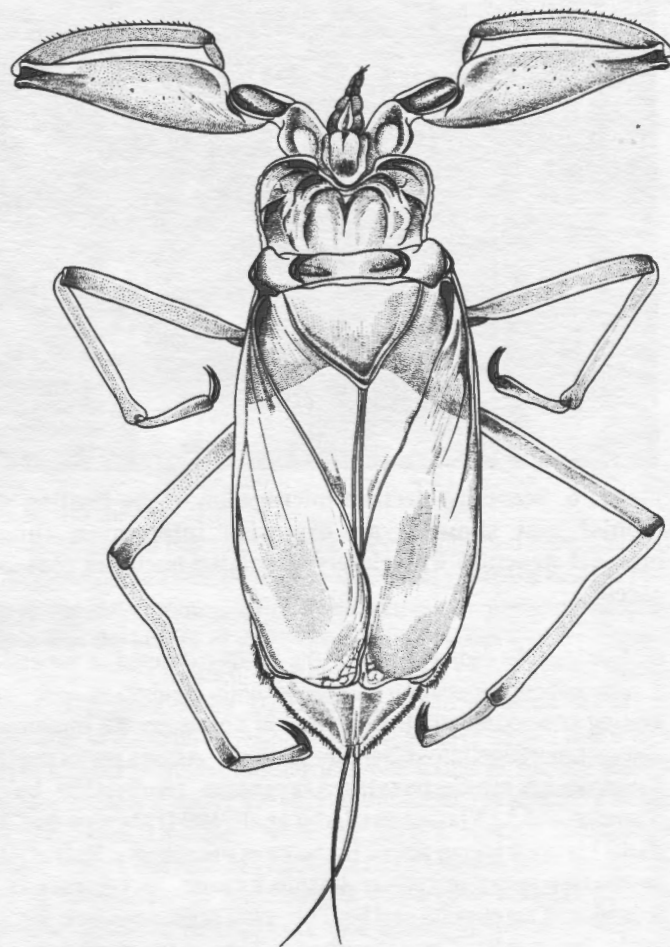


Figure 5. *Nepa anophthalma*, the first known aquatic cave adapted water scorpion in the world inhabits the H_2S -rich waters of Movile Cave (drawing by M. Gruia and M. Georgescu).

choderma sp.). The hyphae form a matrix which is colonized by bacteria (Fig. 6). The bacteria are essential for the functioning of the ecosystem: they are chemoautotrophic organisms belonging to the genera *Beggiatoa*, *Thiobacillus*, and *Thiomicrospira*. These microorganisms use the energy derived from the oxidation of H_2S [see equation 3] that exists in high concentrations in the cave water to fix carbon. Elemental sulfur which may result from this reaction can accumulate as small granules within bacterial cells. If the oxidation process goes further, sulfate results as the byproduct of this oxidation. The microbes can use energy released by the exergonic sulfide-oxidation reaction to fix carbon dioxide and to produce organic molecules [see equation 2]. The use of oxygen in this process could explain the oxygen depletion of the atmosphere in the air-bells.

Samples of floating microbial mat collected in the air bells in the lower level of Movile Cave were incubated with radiolabeled bicarbonate ($H^{14}CO_3^-$), to determine if the cave microbiota is able to incorporate inorganic carbon into organic

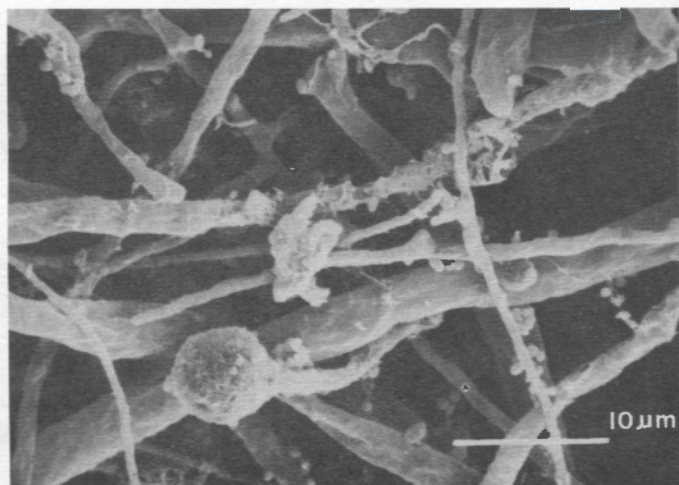


Figure 6. Scanning electron micrograph of the floating microbial mat showing an extensive interwoven fungal mycelial structure with closely associated bacterial rods and cocci.

molecules. The radioactivity of the lipids extracted at the end of a time course incubation increased with incubation time suggesting chemolithoautotrophic carbon uptake by the microbiota and incorporation into metabolic products. Assays performed for Ribulose-1,5-bis-Carboxylase/Oxygenase (RuBisCO) by P. Sheridan and L. Vlasceanu (Sarbu et al., 1994) showed that RuBisCO is present and active in the cave microbiota. RuBisCO is an enzyme active in carbon dioxide fixation. Its presence is an indicator of autotrophy and heterotrophic organisms lack this enzyme. The results of recent carbon stable isotope studies support the hypothesis that organic carbon is being produced *in situ* in the cave. The $\delta^{13}\text{C}$ of -39.5 to -39.7‰ values for the organic matter in the floating mat are consistent with the expected carbon isotope fractionation by sulfide-oxidizing bacteria. The $\delta^{13}\text{C}$ value of the bicarbonate in the cave water on average is -15‰ . The depletion in ^{13}C of approximately -24.6‰ measured in Movile Cave is similar to values previously reported for sulfur-oxidizing chemoautotrophic bacteria by E. T. Degens (1969) and by E. G. Ruby, H. W. Jannasch and W. G. Deuser (1987).

The chemoautotrophic microbiota living in the mat and in the water, represent the first level (i.e., primary producers) in the trophic chain of the Movile Cave ecosystem. Heterotrophic bacteria and fungi feed upon the chemoautotrophic bacteria and the organic molecules that they excrete. In the aquatic community, the primary consumers include the large populations of ciliates, nematodes, annelid worms, rotifers, and copepod crustaceans living under the floating mats where they graze on the mat bacteria and fungi. The gastropods, isopods and amphipods are detritivorous and feed on the floating mats as well. Three predators are present in the aquatic community: the flat worm *Dendrocoelum* sp., the blind leech *Haemopsis* n.sp., and the troglobitic water scorpion *Nepa anophthalma*.

Direct observations show that the aquatic fauna is present only at the surface of the water, and no specimens are found at depths greater than 5 cm due to the very small concentration of dissolved oxygen (less than 0.03 mg/l) at depths exceeding 5 cm. Large populations of cyclopoid copepods, which are excellent swimmers, are present in the Lake Room and in the first air-bell, where the floating mats are absent, whereas the second and third air-bells, where floating mats cover the water surface, are dominated by harpacticoid copepods, which crawl on floating mats.

The terrestrial community primary consumers: collembola, terrestrial isopods, and millipedes crawl on wall mats and on floating mats and feed on the rich microbiota. Numerous predators occur in the terrestrial community (spiders, pseudo-scorpions, centipedes, beetles) and feed upon the rich populations of primary consumers. The results of recent stable carbon isotope studies helped confirm the position of several of the terrestrial troglobites in the cave's food web. In carbon stable isotopic terms it is accepted that "you are what you eat plus 1.5‰ ." The $\delta^{13}\text{C}$ values obtained for *Armadillidium tabacarui* (-38.2 to -38.3‰) are approximately 1.3‰ heavier than the $\delta^{13}\text{C}$ values obtained for the floating microbial mats (-39.5 to -39.7‰) suggesting that the terrestrial isopods feed on the mats. Furthermore the centipede *Cryptops anomalans*, the top terrestrial predator in this ecosystem, shows $\delta^{13}\text{C}$ values (-36.1 to -36.6‰) that are approximately 2‰ heavier than *A. tabacarui*, suggesting that the centipede preys upon the isopods or on other mat-feeding invertebrates inhabiting the cave.

BIOGEOGRAPHY AND EVOLUTIONARY ORIGIN OF THE FAUNA

Some of the species discovered in Movile Cave also inhabit some of the old wells dug by peasants in the town of Mangalia and in villages nearby. Thus, this fauna is not limited to Movile Cave, but is distributed throughout an extensive network of fissures and cave passages located in the Mangalia region. The extensive nature of this network is supported by the presence of high concentrations of carbon dioxide (2.5 - 3%) at the bottom of some of the old hand-dug wells. The aquatic isopod *Asellus aquaticus* inhabits surface lakes and springs throughout southern Dobrogea, but all the surface populations have eyes and are normally pigmented, whereas the populations found in Movile Cave and in old hand-dug wells are blind and depigmented. Some of the species of spiders and beetles have their closest relatives in tropical climates as shown by M. Georgescu (1989) and by R. Poggi (1994). The spider *Agraeocina cristiani* is related to spiders living in the Canary Islands and in northern Africa (Weiss and Sarbu, 1994). Nearly 75% of the terrestrial species discovered in Movile Cave are endemic to the subterranean environment associated with the thermal H_2S -rich waters at Mangalia. This degree of endemism is much higher than the degree of endemism classically observed in the subterranean environment. This appears to be the consequence of a long isolation of this fauna from ancestors which lived on the surface.

Paleogeographical and geological studies performed by C. Lascu (1989) suggest that a part of the Movile Cave fauna invaded the network of fissures and cave passages and became isolated in this environment as early as the Upper Miocene, about 5.2 mya. The Black Sea, as well as the Mediterranean Sea, are remnants of the ancient Tethys Sea which separated Africa from Europe and connected the Atlantic to the Indian Ocean. About 20 million years ago, the movement of the African plate to the north divided the Tethys into a southern part that occupied today's Mediterranean basin and a northern part known as the Paratethys. The latter extended from the Hungarian basin in the west to the Aral Sea in the east, and it included southeastern Europe, the Black Sea and the Caspian Sea. About 5.5 to 5.2 mya, the Mediterranean basin underwent one of the most spectacular changes in its history: the "Messinian Crisis". The northward movement of Africa caused the uplifting of the Gibraltar area, closing the Mediterranean's communication with the Atlantic. During the next millennia, the huge amounts of water lost by evaporation led to a severe drop in the level of the Mediterranean Sea which was reduced to several small lakes containing hypersaline waters. Deep drillings performed by the Glomar Challenger expedition in the Black Sea in 1970, showed the existence of deep sedimentary deposits dated at 5.2 million years, typical of shallow waters. Based on these findings, K. J. Hsü (1978) concluded that the water level in the Black Sea had dropped over 3,000 m compared with today's level. After the Black Sea was drained, the subterranean waters infiltrated deeper underground in search of a new water table. Consequently, numerous large cave passages were formed at depths of about 200 m below the surface. Later these caves were inundated by H_2S -rich waters.

What happened to the tropical fauna that inhabited the Dobrogean region before the Messinian event? During the crisis, the climate of southern Dobrogea became extremely dry leading to the extinction of the majority of the species that used to inhabit this region. Some species that may have also become established in the fissures and cracks of the underground substratum could have survived on the food produced in situ by the chemoautotrophic microbiota. Over evolutionary time these species became cave adapted, losing eyes and pigment in the process.

Many of the species discovered in Movile Cave are relics from that period. Hence, the spiders *Agraeocina cristiani*, *Iberina caeca*, and *Nesticus* n.sp., the terrestrial isopod *Trachelipus troglolobius*, and the new genus of pselaphid beetle show an advanced degree of troglomorphy (extreme depigmentation, absence of eyes, elongation of appendages), indicating a long history of underground evolution. There are also some species that have not yet acquired all the characteristics of true troglolobites. Among these are the collembolan *Heteromurus nitidus* and the centipede *Cryptops anomalans*, that are also found at the surface, in the soil, as well as in other caves in the region. They may have colonized the cave during the Quaternary. During the latest

glaciation, about 15,000 years ago (Würm), the water level of the Black Sea dropped 65 to 70 meters, leading to the formation of a new series of caves. This probably triggered a new wave of invasions into the cave by surface species.

What appears true for the terrestrial fauna, is not necessarily true for the aquatic fauna. The aquatic species living at the surface could have continuously invaded the aquifer through its points of discharge at springs located along the shore of the Black Sea and on the bottom of the H_2S -rich lakes present in the region. Besides the very old species that inhabit Movile Cave such as the amphipod *Pontoniphargus racovitza* there are also species that invaded the aquifer very recently, during the Würm glaciation and even later. The aquatic isopod *Asellus aquaticus* has a very recent presence in Europe in general (Magniez, personal communication). Several of the ciliate protists are probably also more recent colonists along with the nematodes, the leech, and the copepods.

Adaptation of colonizers to the specific physico-chemical and biological parameters of Movile Cave was clearly a critical factor in the development of this ecosystem. Of particular importance was the ability of these organisms to adapt to the presence of high concentrations of hydrogen sulfide. Physiological investigations performed by D. Danielopol and R. Popa (1994) at Mondsee in Austria, on *Asellus aquaticus* have shown that under oxygen concentrations similar to those found in surface waters (approximately 8 mg/l) the cave animals behave similarly to the surface forms. However, when the oxygen concentrations drop below 1 mg/l, the rate of ventilation decreases in cave forms but not in surface forms indicating that the cave animals possess specific adaptive mechanisms that enable them to survive in anoxic conditions. Other adaptations may be physiological and biochemical in nature. Since hydrogen sulfide is a highly toxic substance, the development of resistance to its toxicity has undoubtedly been a key factor in the colonization of this unique environment. Studies performed by R. Popa (unpublished) show that some of the species living in Movile Cave are highly resistant to poisoning by hydrogen sulfide. The body of the water-scorpion *Nepa anophthalma*, for example, is covered by a thick layer of filamentous sulfur-bacteria that may be an important means of protection against the poisonous gas.

Research on the Movile Cave ecosystem is far from completion. Unfortunately, the cave passages are very narrow and the ecosystem is extremely fragile. Even minor modifications of one of the physicochemical parameters of the cave environment (e.g., temperature, humidity, composition of the atmosphere) could adversely affect the ecosystem and lead to the extinction of some of the species inhabiting the cave. Thus we have tried to minimize our impact in order to preserve as much as possible of this unique ecosystem. We have recently completed the construction of a research station at the surface. By piping H_2S -rich thermal water into this laboratory from drilled wells in the area we can reproduce the physicochemical parameters of the cave environment and perform experimental work that cannot be ac-

completed in Movile Cave itself. Thus we will be able to investigate quantitatively the process of chemoautotrophic carbon fixation, to study microbial ecology and eco-physiology, and study the ecology and behavior of the Movile Cave fauna without destroying it.

ACKNOWLEDGEMENTS

This research was supported by the National Geographic Society (4639-91; 5460-95), the National Science Foundation (DEB9420033), the Cave Research Foundation, and the National Speleological Society (two grants from the Research Awards Committee and the Ralph Stone Award for 1993).

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Revised Manuscript Received 7/10/95.

Manuscript Accepted for Publication 8/30/95.

BONES OF *PUFFINUS LHERMINIERI* LESSON (AVES: PROCELLARIDAE) AND TWO OTHER VERTEBRATES FROM CUEVA DEL AGUA, MONA ISLAND, PUERTO RICO (WEST INDIES)

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ABSTRACT.- From a dive in Cueva del Agua, Mona Island, Puerto Rico, twelve un-mineralized bones of *Puffinus lherminieri* Lesson, one of *Cyclura stejnegeri* Stejneger, and one of *Moormops blainvillii* Leach were collected. The subfossil evidence confirms that *P. lherminieri* was a common species on Mona Island. *Cyclura stejnegeri* and *M. blainvillii* probably became trapped and died in the pool chamber.

RESUMEN.- De una buceada en Cueva del Agua, Isla de Mona, Puerto Rico, doce huesos no mineralizados de *Puffinus lherminieri* Lesson, uno de *Cyclura stejnegeri* Stejneger y uno de *Moormops blainvillii* Leach fueron colectados. La evidencia subfósil confirma que *P. lherminieri* fue una especie común en Isla de Mona. *Cyclura stejnegeri* y *M. blainvillii* probablemente quedaron atrapados y murieron en la cámara del estanque.

Caves are among the most important places for the preservation of animal remains, and they have contributed greatly to our knowledge of the paleo- and neontology of the Antilles. Early studies of fossil and subfossil vertebrates from Puerto Rican caves began with reports on birds (Wetmore, 1922), mammals (Anthony, 1925), and reptiles (Williams, 1952). More recent studies include Choate and Birney (1968), Woods (1972) and Pregill (1981). Herein we document the presence of bones of Audubon shearwater, *Puffinus lherminieri* Lesson and two other vertebrates in an underwater section of a cave in Mona Island, Puerto Rico. This represents the first report of subfossil evidence from an underwater cave on the island.

The study area was Cueva del Agua (18°03'N, 67°53'W), located at Playa Brava, Mona Island (Fig. 1). This cave is located in a sea cliff composed of Miocene Lirio Limestone (Kaye, 1959). From the entrance, the cave extends down and inland through smaller passages cut first through the Pleistocene facies, then back into the Lirio Limestone again. The underwater portion extends to the north for approximately 30 m, through a series of three water-filled chambers, and a partially water-filled chamber. The water in the cave is that of the local water table

and is brackish. Piles of debris and breakdown form the rough floor of the cave. A detailed description of the cave's geomorphology appears in Frank (1993).

At two localities (Fig. 2, letters and arrows), the senior author collected the bones and placed them in two 75 ml plastic cylinders. Bones were identified by reference to the comparative collection of the Joint Science Department, The Claremont Colleges, and the Natural History Museum of Los Angeles County, California. Three species were identified from the samples:

1. Audubon Shearwater, *Puffinus lherminieri* Lesson. **Material.**-Five distal humeri, 5.5 to 5.7 cm long x 0.8 to 1 cm wide; two proximal humeri, 4.7 cm long x 1 cm wide, and 2 cm long x 0.7 cm wide, incomplete; two distal tibia, 5.8 cm long x 0.6 cm wide, and 3.7 cm long x 0.6 cm wide, fragmented; one proximal ulna 2.7 cm long x 1.1 cm wide, incomplete; one distal radius, 4.1 cm long x 0.4 cm wide, fragmented; and one distal femur, 3.3 cm long x 1.4 cm wide, incomplete (Fig. 3C). **Modern distribution.**- Occurs in islands of the Atlantic, Pacific, and Indian Oceans. It is a common bird in the Greater and Lesser Antilles, but is rare in Puerto Rico.

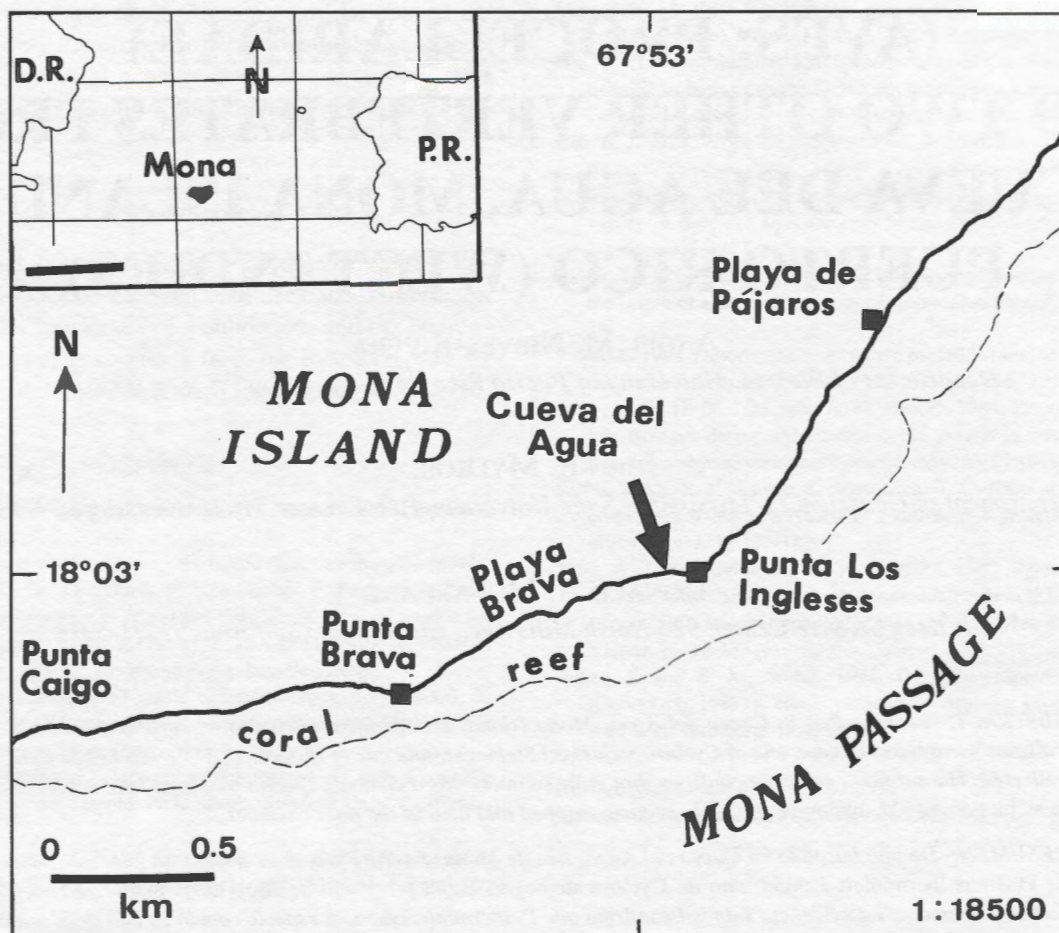


Fig. 1. Map of the study area in southwestern Mona Island, Puerto Rico. Shown on the inset is the location of the Mona and neighboring islands (D.R. = Dominican Republic; P.R. = Puerto Rico). Scale bar = 45 km.

2. Mona Island Ground Iguana, *Cyclura stejnegeri* Stejneger.

Material.- One femur belonging to a young specimen was collected, 3.3 cm long x 0.8 cm wide (Fig. 3B). **Modern distribution.**-Restricted to Mona Island.

3. Blainville's Leaf-chinned Bat, *Moormops blainvillii* Leach.

Material.- Only a partial lower jaw with no teeth was obtained, 8 mm long x 9 mm wide, from the spaces of teeth, the dentary formula is I, 2-2 x C, 1-1 x PM, 1-2 x M, 0-0 = 9 (Fig. 3A). **Modern distribution.**- Very common in Cuba, Haiti, Jamaica, and Mona Island, rare in Puerto Rico.

Specimen ages cannot be directly determined. However, their lack of mineralization and deposition in the fine silt of the underwater passages leads to the conclusion that their ages can probably be measured in tens, rather than hundreds of years. Bones of literally hundreds of birds are contained in the chamber floor.

Bones of the Audubon Shearwater were observed from Cueva Negra by Kaye (1959) and it has been suggested that early Taino settlers ate these birds. Today it is unclear if this species still nests on Mona (Pérez-Rivera and Bonilla, 1983; Raffaele, 1989). The bird spends the day at sea and returns at night to attend nest burrows. Nests are located in steep cliff crevices or inaccessible caves, making it difficult to evaluate the bird's status (Raffaele, 1973).

Remains of *Puffinus lherminieri* and *Cyclura stejnegeri* are also known from Cueva Negra on the west coast, Cueva del Caballo, Cueva de Chito, and Cueva de los Lirios on the east coast (Nieves-Rivera, pers. obs.). Anthony (1925) reported *Noctilio leporino* (Dahl) and *Moormops blainvillii* from Mona Island. Of these, *M. blainvillii* is a common bat on the island, and is frequently seen at night hunting insects (Wiedwandt, 1973; Nieves-Rivera, pers. obs.).

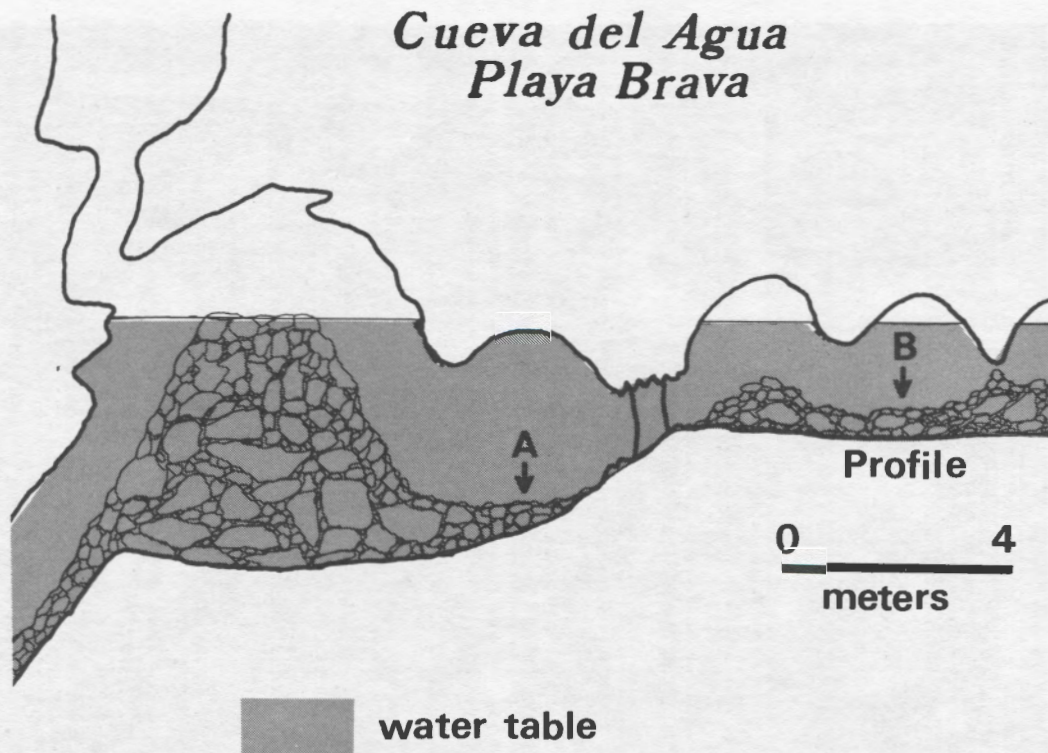


Fig. 2. Map of the underwater passages in Cueva del Agua, Playa Brava, Mona Island. The arrows (↓) and letters show collection sites. A = Station 1 (7 m from entrance); B = Station 2 (14 m from entrance).

In conclusion, *C. stejnegeri* and *M. blainvillii* are common extant species on Mona, and probably became trapped and died in the pool chamber. The abundance of *P. lherminieri* bones in Cueva del Agua and other Mona caves is more notable. Although the local extinction of this species on Mona is not certain, the birds no longer nest in Cueva del Agua, Cueva Negra, Cueva del Caballo, Cueva de Chito, or Cueva de los Lirios. The sub-fossil evidence confirms that *P. lherminieri* was formerly a common species on Mona.

ACKNOWLEDGMENTS

Support was provided by the Department of Natural and Environmental Resources, Commonwealth of Puerto Rico (collection permit DRN-95-13). We thank the U. S. Geological Survey personnel (Caribbean District, Water Resources Division), Dr. J. A. Rivero, Dr. C. Delannoy, E. F. Frank, R. A. Pérez-Rivera and J. Muñoz-Vázquez for their help in the field and laboratory work. Corrections made to the text offered by various colleagues are most appreciated.

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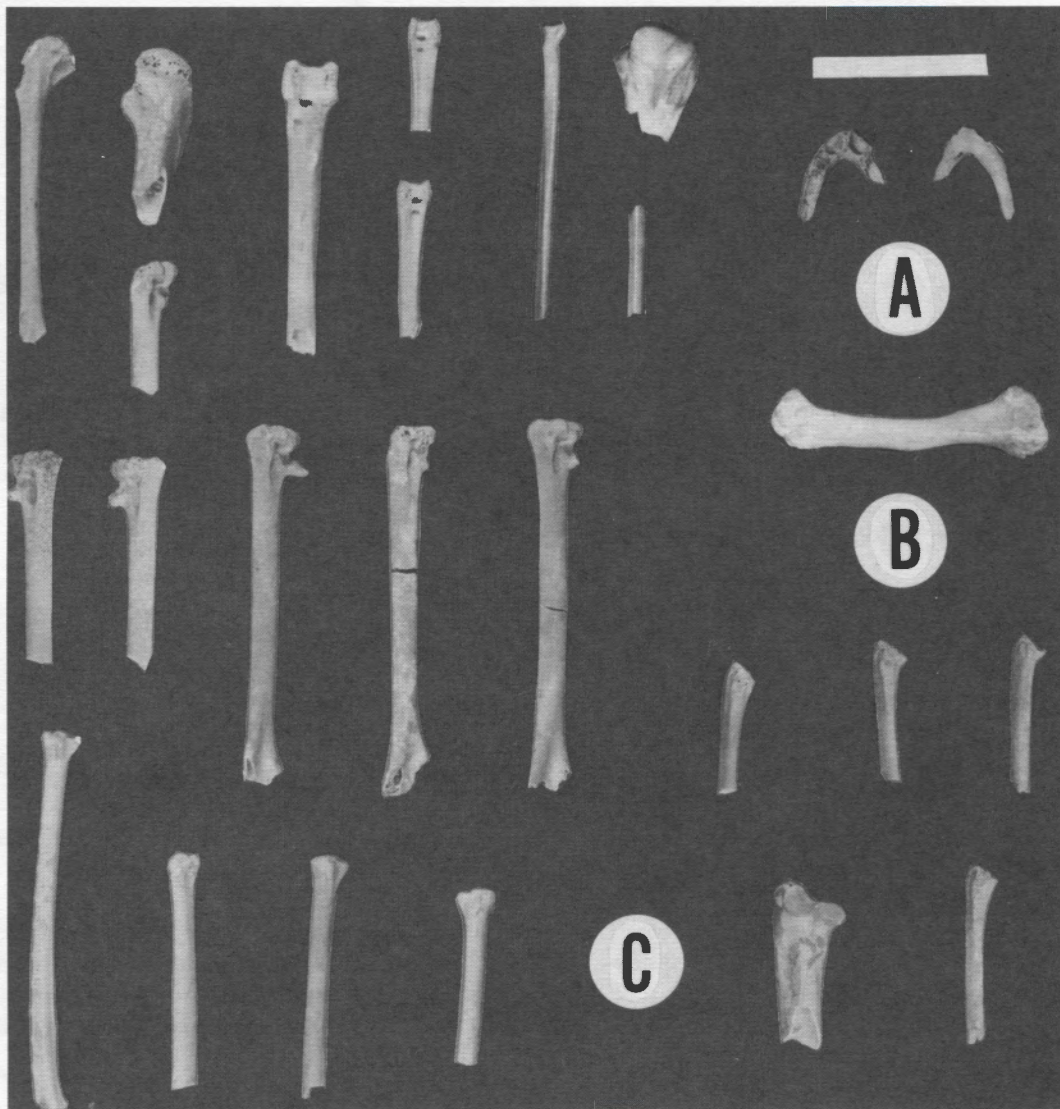


Fig. 3. Vertebrate bones from Cueva del Agua, Mona Island. A. *Moormops blainvillii* Lesson, jawbone on front (left) and back (right). B. *Cyclura stejnegeri* Stejneger, femur. C. *Puffinus Iherminieri* Lesson, bones as detailed in the text. Scale bar = 1.5 cm for A; 1.8 cm for B and 3 cm for C.

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Revised Manuscript Received 6/23/95
Manuscript Accepted for Publication 8/30/95

EFFECTS OF FEEDING REGIME ON PREY CONSUMPTION AND WEIGHT CHANGE RATES IN CAPTIVE SOUTHERN CAVEFISH, *TYPHLICHTHYS SUBTERRANEUS* GIRARD (PISCES: PERCOPSIFORMES: AMBLYOPSIDAE)

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*Relatively little is known of the feeding ecology of the southern cavefish, *Typhlichthys subterraneus*, particularly in captivity. This study examined prey consumption and weight change rates in 15 individuals maintained in the laboratory at 17°C. The prey used were epigeal amphipods, *Hyaella azteca*, provided ad libitum. Two contrasting feeding regimes were employed, one involving daily assessment of consumption rates and prey replenishment (daily assessment technique), the other involving variably longer intervals between assessment and replenishment (multi-day assessment technique). The latter technique, which resulted in slight increases in the mean daily rates of relative weight change, appears to be superior for captive maintenance, probably because it subjects the fish to less frequent disturbance. Prey consumption rates were low under both experimental regimes, consistent with suggestions that cavefish have evolved a relatively low metabolic rate in their food-poor subterranean environments. These data provide benchmarks for assessing routine prey consumption and for monitoring the health and vigor of captive individuals.*

INTRODUCTION

The southern cavefish, *Typhlichthys subterraneus* Girard, is a small, blind, troglomorphic species found in subterranean waters of the Ozark Plateau in southern Missouri and northeastern Arkansas, and of the Cumberland and Interior Low plateaus from central Kentucky through Tennessee and into northern Alabama and northwestern Georgia (Brown and Willis, 1984; Cooper, 1980). *Typhlichthys* habitats are threatened by ground-water contamination, water table lowering, forest clearing for agriculture, and other disturbances, prompting the species' listing in various jurisdictions (Schmidt, 1990). A minority of these populations characteristically yield sightings of more than a few individuals (Ramsey, 1986).

Despite its status, little is known of the southern cavefish's feeding ecology, beyond identifying specific prey types (Cooper, 1974; Cooper and Beiter, 1972; Poulson, 1960). Because laboratory research and/or future conservation efforts may eventually involve captive rearing, a more thorough understanding of the feeding requirements of this fish is desirable. Consequently, we herein examine prey consumption rates and weight changes

in southern cavefish maintained in the laboratory under two contrasting feeding regimes.

MATERIALS AND METHODS

Collection and Maintenance

The 15 specimens studied here (presumably including both sexes) were collected from a spring-fed sink hole system in Wayne County, Missouri, on 30 June 1991, and ranged from 36 to 57 mm total length when measured on 19 August 1991. While a potentially atypical locale (see Discussion), specimens were obtained from this site because removals were less likely to impact the large population there.

Preceding and during testing, the fish were maintained individually at the University of Missouri-Columbia in bare 37.5-l aquaria (50 x 25 cm bottom area) containing 31 l of water. Single air stones situated mid-depth provided continuous light aeration. The aquaria were routinely cleaned of feces, and received weekly 1/4-volume water changes. The chemical parameters of the dechlorinated well water used in the aquaria closely resem-

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bled those of the collection site (Schubert, 1993). The laboratory temperature ($17 \pm 2^\circ\text{C}$) matched that of the collection site at the time of capture.

ACCLIMATION AND FEEDING

Each cavefish was acclimated to laboratory conditions for at least four months before beginning the feeding experiments. During this time, the fish were provided post-juvenile (3-5 mm body length) freshwater amphipods, *Hyaella azteca*, *ad libitum*, from laboratory cultures. All 15 cavefish remained disease free during the experiments, no mortalities occurred among them, and all consumed food regularly throughout the experiments. All trials were conducted under constant darkness, except for the prey counting/reprovisioning periods.

MEAN DAILY CONSUMPTION RATE

Daily Assessment Technique: Cavefish prey consumption rates were assessed in two ways, the first of which involved one trial each of a daily assessment technique conducted on six separate cavefish (fish 1-6). Each trial began by supplying each fish with 25 amphipods (several times more than any fish had ever consumed in a day). Twenty-four hours later, any live and dead amphipods remaining in each tank were counted and recorded as uneaten. Amphipod disappearances were assumed to represent consumption since escapes and/or non-detections in the bare aquaria were highly unlikely. Any dead amphipods were removed, after which live amphipods were added to return their numbers to between 15 and 25. This process was repeated until 40 days' consumption data had been obtained for each fish. An individual's mean daily consumption rate was then determined by summing the total number of amphipods consumed during the trial, then dividing by 40. These trials were conducted during a 58-day period between 21 August and 17 October 1991, with non-simultaneous trial starts and minor discontinuities in data collection accounting for the difference. By testing for an association between daily amphipod consumption and availability in each trial, these data also allowed us to confirm that prey were truly available in excess.

Multi-Day Assessment Technique: The second prey consumption rate assessment technique was devised to reduce the potential impact of disturbances caused by the daily monitoring and amphipod restocking described above. This involved variably lengthening the interval between amphipod counts in each trial by allowing their numbers to drop to between 5 and 10. Only then was a tally made of the numbers left alive or dead, after which replacements were introduced. Using this technique, mean daily consumption rate data were collected for fish 1-6 over a period of 95 days (29 October 1991 to 22 January 1992), and for the 9 remaining fish (7-15) for 85 days (19 October 1991 to 22 January 1992). For each trial, mean daily consumption rates (amphipods/day) were determined for every provision/re-

provision interval by dividing the decrease in amphipod numbers within each interval by that interval's duration. These within-interval means were then averaged across all the intervals comprising a trial to generate each fish's overall mean daily consumption rate. In the absence of daily counts, we tested for a correlation between amphipod consumption and availability within each trial by respectively averaging the consumption and availability data within sequential 5-day periods to smooth the highly variable consumption responses.

WEIGHT MEASUREMENT

Each fish's total weight (± 0.01 g) was measured just before (pre-trial), during (mid-trial), and just after (post-trial) each feeding trial by adding the lightly blotted fish to a tared water-filled beaker and determining its weight by difference. This procedure minimized the potential for handling-related injury or consequent development of disease, other specimens from this site having shown susceptibility to the latter. For the daily assessment trials, weight measurements were made on 19 August, 30 September, and 24 October 1991. For the multi-day assessment trials, weighings occurred on 24 October and 3 December 1991, and on 29 January 1992. Lengths were also assessed, but did not vary beyond the limits of measurement error. Hence, the weight changes we detected can also be construed as assessments of changing condition/robustness.

MEAN DAILY RELATIVE WEIGHT CHANGE RATE

For all feeding trials, we determined the rate of each fish's mean daily relative weight change (mg weight change/g fish/day) as per Hayward (1990). This involved calculating the regression relating a fish's pre-, mid-, and post-trial weights and the trial day numbers on which the weights were measured, determining the respective slope and intercept values, and calculating the quotient of the latter to derive the rate of daily mean relative weight change.

RESULTS

Mean Daily Consumption Rate

Daily Assessment Technique: Using the daily assessment technique for six specimens (Table 1, third column), the fish's daily mean consumption rates ranged from 0.98 to 4.15 amphipods/fish/day, averaging 2.34 ± 1.09 ($\bar{X} \pm \text{S.D.}$). For each of the six trials, the lack of significant correlation between the number of amphipods a fish consumed and the number available each day (Table 1, fourth column) indicated that prey supplies had indeed exceeded *ad libitum* rations. Analysis of the pooled data ($r=0.095$, $n=240$, $p>0.10$) corroborated this. The correlation here between mean daily consumption rate and fish mean weight

Table 1. Results of monitoring the daily amphipod consumption rates of six southern cavefish for 40 days using the daily assessment technique. Mean weight is of each fish's pre-, mid-, and post-trial weights. For correlation between daily numbers of amphipods consumed vs. available, ns=non-significant, $p>0.05$ ($n=40$ for each).

Fish ID	Mean Weight (g)	Mean Daily Consumption Rate (# amphipods/fish/day)	# Consumed versus # Available Correlation (r)	Mean Daily Relative Weight Change Rate (mg wt change/g fish/day)
1	0.497	0.98	-0.152 (ns)	-2.856
2	0.640	1.73	0.197 (ns)	-3.316
3	0.677	2.28	0.071 (ns)	-0.697
4	0.443	4.15	0.290 (ns)	-1.490
5	0.557	2.90	0.000 (ns)	-1.548
6	0.690	2.03	0.384 ($p<0.05$)	-3.195
$\bar{X} \pm S.D.$	0.584 ± 0.101	2.34 ± 1.09	n/a	-2.184 ± 1.082

was not significant ($r=-0.407$, $n=6$, $p>0.20$; data from Table 1), indicating that consumption rate did not consistently increase with increasing fish size over the size range examined.

Multi-Day Assessment Technique: Using the multi-day assessment technique for 15 specimens (Table 2, third column), the fish's mean daily consumption rates ranged from 1.70 to 4.53 amphipods/fish/day, averaging 2.79 ± 0.74 ($\bar{X} \pm S.D.$). While this value slightly exceeded that from the daily assessment technique, the multi-day trials were conducted on fish of slightly greater average weights (daily assessment fish: 0.584 ± 0.101 g; $\bar{X} \pm S.D.$; multi-day assessment fish: 0.725 ± 0.317 g). However, between the techniques, neither the fish's mean daily consumption rates nor their weights differed significantly (ANOVAs, both $F<1.20$, both $p>0.25$). Here, as before, there were no significant correlations among the fish between the amphipod consumption and prey availability data (Table 2, fourth column), indicating that prey had again been supplied in numbers that exceeded their demand. Analysis of the pooled data (repeat-tested Wayne County fish 1-6: $r=0.032$, $n=114$, $p>0.50$; singly-tested Wayne County fish 7-15: $r=0.000$, $n=152$, $p>0.50$) confirmed this. The correlation here between mean daily consumption rate and fish mean weight was not significant ($r=-0.050$, $n=15$, $p>0.50$; data from Table 2), once more indicating that consumption rate did not consistently increase with increasing fish size over the range of sizes considered.

Technique Comparison: Considering the data from fish 1-6 alone (Tables 1 and 2), a paired sample t-test revealed that the mean daily consumption rates from the two assessment techniques did not differ significantly ($t=-1.42$, $p=0.22$). This indicates that both approaches yielded comparable consumption rate estimates (but see below).

Table 2. Results of monitoring the daily amphipod consumption rates of 15 southern cavefish for 95 (fish 1-6) and 85 (fish 7-15) days using the multi-day assessment technique. Notation is as in Table 1. For correlations (column 4), $n=19$ for fish 1-6; $n=17$ for the remainder except fish 15 where $n=16$.

Fish ID	Mean Weight (g)	Mean Daily Consumption Rate (# amphipods/fish/day)	# Consumed versus # Available Correlation (r)	Mean Daily Relative Weight Change Rate (mg wt change/g fish/day)
1	0.480	2.77	0.032 (ns)	1.997
2	0.657	2.50	0.055 (ns)	3.365
3	0.710	1.98	-0.148 (ns)	0.414
4	0.517	3.41	0.045 (ns)	4.569
5	0.570	3.18	0.084 (ns)	1.061
6	0.707	4.53	0.089 (ns)	2.938
7	0.707	1.97	-0.173 (ns)	2.149
8	0.500	3.10	-0.468 (ns)	-0.561
9	1.157	3.45	0.084 (ns)	0.542
10	0.677	3.50	0.109 (ns)	-0.280
11	1.713	2.46	0.349 (ns)	-1.371
12	0.703	1.70	0.148 (ns)	-1.581
13	0.617	2.47	0.000 (ns)	4.674
14	0.520	2.53	-0.126 (ns)	-1.760
15	0.640	2.32	0.032 (ns)	-2.400
$\bar{X} \pm S.D.$	0.725 ± 0.317	2.79 ± 0.74	n/a	0.917 ± 2.298

MEAN DAILY RELATIVE WEIGHT CHANGE RATE

Daily Assessment Technique: All six fish tested using the daily assessment technique exhibited negative rates of mean daily relative weight change (Table 1, fifth column). These weight losses suggest that disturbances caused by the daily amphipod counting might have impaired the fish's foraging, or that the stress increased their metabolic rates.

Multi-Day Assessment Technique: From the multi-day assessments (Table 2, fifth column), the fish's mean daily relative weight change rates ranged from -2.400 to 4.674 mg weight change/g fish/day. While these fish gained weight at an average rate of 0.917 mg weight change/g fish/day over the course of the experiment, a t-test revealed that these growth rates did not differ significantly from zero ($t=1.55$, $p=0.14$). Interestingly, all six specimens that yielded negative rates of mean daily relative weight change using the daily assessment method (Table 1) exhibited positive rates during the multi-day assessment (Table 2) (paired sample t-test, $t=-5.01$, $p=0.0041$).

DISCUSSION

Acclimation and Feeding

Regarding our choice of prey, we recognize that *Hyaella azteca* is a non-troglobite, and thus is unlikely to be a species encountered by our specimens in nature. Nonetheless, *H. azteca*

could conceivably be more susceptible to predation by *T. subterraneus* than would troglobitic prey: sighted prey held under aphotic conditions might be disadvantaged, and would also lack the morphological/neurophysiological/behavioral adaptations that troglobitic prey would have evolved in the presence of troglobitic predators (Cooper, pers. comm.). In contrast, our use of bare aquaria might have made it easier for the amphipods to escape and harder for the fish to forage on them, since amphipods tend to congregate beneath rocks and cavefish tend to concentrate their foraging there (Poulson, pers. comm.). However, the amphipods did congregate along the junction between the aquarium walls and bottom, and cavefish predation attempts were most often seen here during prey enumerations. The scale and confines of our aquaria, and the higher than natural prey densities we employed (Poulson, pers. comm.), might also have influenced the predator-prey interactions involved.

Regardless, the cavefish's ability to maintain weight (Table 2), and their ready consumption of these prey from the onset of captivity through the extended acclimation/experimental period, suggest that *H. azteca* so provided were indeed acceptable prey. Poulson (1960) likewise used *Hyalella* in his sustained culturing of various amblyopsid species, and both Weise (1957) and Jenio (1980) used amphipods in rearing and feeding experiments involving *Chologaster agassizi*. In addition, *H. azteca* is readily cultured using established techniques (USEPA, 1994), and is not a species at risk.

Mean Daily Consumption Rate

Volumetrically, amphipods (including eyed species) can comprise a significant part of the southern cavefish's diet in caves (e.g. Barr, 1968; Bechler, 1980; Cooper and Beiter, 1972; Garman, 1889; Poulson, 1960), and the *H. azteca* consumption rates we recorded (range 1 to 5, mean ca. 2.5 amphipods/fish/day) may thus represent a rough "rule of thumb" for establishing prey provisioning rates and/or densities for captive southern cavefish. A caveat, however, is that the food supplies at the specimen collection site are particularly rich, with the growth and perhaps metabolic rates of the fish therein being correspondingly high (Poulson, pers. comm.). As such, the values we derived may more closely approximate upper limits for the species. Between-site comparisons would be in order.

For neither the daily assessment (prey numbers maintained daily between 15 and 25 in 31 l) nor the multi-day assessment (prey numbers not allowed to drop below 5-10 in 31 l over a series of days) trials were there significant correlations between the prey availability and prey consumption data (Tables 1 and 2). These findings suggest that density-dependent prey consumption rate reductions did not accompany the decreases in prey density that occurred within the prey provision/reprovision intervals.

Mean Daily Relative Weight Change Rate

The slight positive average of the rates of mean daily relative weight change obtained from the multi-day assessment trials (Table 2, bottom) is consistent with literature indications that growth in southern cavefish is slow relative to many epigeal species (Poulson, 1960, 1963). Consistent with this, southern cavefish metabolic rates are sufficiently low (Poulson, 1960, 1963) that captive specimens have been maintained alive without food for extended periods.

The evidence in fish 1-6 of weight losses during the daily assessment trials (Table 1), and subsequent weight gains during the multi-day assessment trials (Table 2), indicates that the latter, with its lessened frequency of disturbance, is a superior feeding regime. An alternative explanation for the weight losses observed could involve residual relocation effects, given that the daily assessment trials (August-October 1991) where all fish lost weight were the first to be conducted after the fish were captured on 30 June 1991. Contrary to this thinking, relocation effects do not appear to explain the negative rates of mean daily relative weight change observed in the six of nine individuals among fish 7-15 from the multi-day assessment trials (Table 2): while these fish had also been relocated shortly before trials commenced (from the Midwest Science Center to Stephens Hall on 22-29 October), a paired sample t-test revealed no difference in each fish's mean daily relative consumption rate during the first 15 and last 40 days of this feeding experiment ($t=1.748$, $p>0.05$). This indicates that their recent relocation had not resulted in diminished feeding early in these trials. Since this latter information suggests that the effects of pre-trial relocation were minimal, a within-trial disturbance effect seems to better explain the poorer growth achieved in our daily assessment trials.

An alternative reason why fish 1-6 improved their rates of daily mean relative weight change between the daily and multi-day assessment trials may involve learning: four of the six individuals increased their daily mean consumption rates in the subsequent multi-day trials, suggesting that their foraging efficiency might have improved with practice (Poulson, pers. comm.). However, all the fish used in these experiments had been maintained in the same-sized tanks, under comparable conditions, using the same prey, since their capture on 11 April 1991. Hence, fish 1-6 had been acclimated for more than 4 months before the daily assessment trials began, and fish 7-15 had been acclimated for more than 6 months before the multi-day trials began, periods likely sufficient for learning-based improvements in foraging efficiency to have occurred.

ACKNOWLEDGMENTS

Funding for this project was provided by the Missouri Department of Conservation (MDC) and the Missouri Agricultural Experiment Station to the senior author (DBN), and by a Paul K. Wehmiller Fellowship to ALSS. Holding facilities and/or equip-

ment in Columbia were furnished by The School of Natural Resources, the Missouri Cooperative Fish and Wildlife Research Unit, and the U.S. National Biological Service's Midwest Science Center. The U.S. Forest Service allowed us to collect specimens from the Mark Twain National Forest District. Dennis Figg, MDC Endangered Species Coordinator, provided the collection permit, logistical support in obtaining the specimens, and an abiding interest in the project. D. Figg, R. Gleidt, K. Lister, K. Olsen, D. Porter, and J. Rathert participated in the field collections. E. Greer, E. Little, and M. Nelson granted us use of Midwest Science Center amphipod cultures. Drs. E. Little, D. Galat, C. Gerhardt, R. Hayward, and T. Poulson contributed important suggestions along the way. The perceptive reviews of Drs. J. Cooper, R. Hayward, and T. Poulson greatly improved the manuscript. This publication is a contribution from the Missouri Cooperative Fish and Wildlife Research Unit (the U.S. National Biological Service, Missouri Department of Conservation, The School of Natural Resources of the University of Missouri-Columbia, and the Wildlife Management Institute cooperating), and from the Missouri Agricultural Experiment Station, Journal Series No. 12,385.

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Manuscript Received by the Society 7/10/95

Revised Manuscript Received 8/17/95

Manuscript Accepted for Publication 8/30/95

THE ISKENDER-I-BIRKILIN CAVES IN THE 9TH AND 12TH CENTURIES B.C.

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A visit to caves near the source of the Tigris River by the Assyrian king, Shalmaneser III, in 853 B.C. is commemorated pictorially on contemporary bronze decoration on his palace gates which now are in the British Museum. One of the relevant scenes has been explained as showing stalagmites in a cave, or alternatively as a line of posts across a valley. This paper examines both interpretations, giving reasons for and against each. The documented history of the cave begins in 1100 B.C.

As presently known, cave history emerges from prehistory at the Iskender-I-Birkilin resurgence cave ("Tigris Tunnel," "Birkilin-su Cave") in central Turkey. The year 2000 A.D. will mark 3,100 years of written documentation here, recently reviewed by Kusch (1993) and by others before him. In the year 1100 B.C., conqueror-king Tiglath-Pileser of Assyria ordered his picture inscribed on a limestone face just outside the resurgence cave. With it is a cuneiform inscription that mentions that he had been there (or thereabouts) on three separate occasions.

250 years later, in 851 or 852 B.C., another great Assyrian king followed in his footsteps: Shalmaneser III. Shalmaneser's portrait is inscribed in the resurgence cave, with a cuneiform inscription about 10 m long. A similar inscription may be seen in a nearby dripstone cave. Seven years later, Shalmaneser returned, and added to the inscription in the dripstone cave. Perhaps by this time, an error of his artisans had become evident: the inscription in the resurgence cave was incised in the seasonal flood zone. It has suffered considerably from erosion and solution in the subsequent centuries.

Shalmaneser left other accounts of his visits to the cave. As recounted by King (1915) and others, in his capital city of Nimrud his artisans inscribed a tall black stone obelisk with these and other events of his reign:

In the seventh year of my reign (858-824 B.C. - authors) I marched to the source of the Tigris; the place where the water comes forth. I cleansed the weapon of Asher therein; I took (? sacrificed - authors) victims for my gods; I held a joyful feast. A mighty image of my majesty I fashioned; the glory of Asher, my lord, my deeds of valor, all I had accomplished in the lands, I inscribed thereon and I set it up (? - authors) there.

An inscription on a huge carved bull was much the same.

After the fall of Assyria and the destruction of Nimrud, the obelisk and bull remained hidden for 25 centuries in the ruins of collapsed buildings. Then came British Assyriologists. Today the black obelisk stands central in a noble hall of the British Museum, for all the world to learn of these remote caves in the first glimmering days of written history. All that is necessary is a bus ticket and the ability to read Assyrian cuneiform.

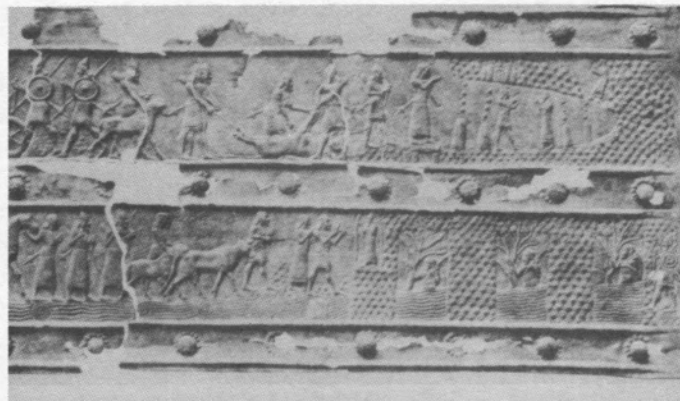


Figure 1. Scenes on the gates of the royal palace at Balawat, showing one or more caves visited about 853 B.C. (British Museum). The upper scene has been interpreted variously as a valley with incense burning on posts, or a cutaway view of a cave. The lower scene shows workers or priests in an underground stream illuminated by three skylights. At the entrance of the cave, an artisan is preparing a royal inscription. Sacrifices are about to occur at the mouth of the cave, on the bank of the stream which emerges from the cave.

Other evidences of ancient esteem of these long-forgotten caves are on display in the British Museum, including a depiction of at least one of the caves. During a field season lasting from 1878 to 1880, a young native of Mosul, Harmuzd Rassam, discovered two sets of hammered and engraved bronze bands from huge wooden gates of a palace of Shalmaneser. In vertically paired sequences somewhat like today's comic strips, the bands show many scenes from Shalmaneser's triumphs. Accompanying them are explanatory cuneiform texts. As translated by Unger (1913, cited by King, 1915 and by Kusch, 1993), one inscription accompanying a river scene recounts:

I entered the sources (? source - authors) of the river; I offered sacrifices to the gods; my royal image I set up.

Above the river scene is a companion panel which is not as readily interpreted. The scenes in the bands are so representational that most of them are immediately comprehensible today. But they also made use of Assyrian artistic conventions and perspective which changed even during Assyrian times.

There is universal agreement on the depiction of the river scene in the lower panel. As King wrote in 1915:

A bull and ram are being led forward for sacrifice before the image of Shalmaneser, which is being carved on the rockface of the grotto, in front of the tunnel's mouth, by a sculptor standing on a block in the stream. The subterranean course of the river is conventionally shown by means of rectangular openings, through which men can be seen wading waist-deep and carrying plants or torches. The trees, which appear to be growing in the stream and protruding from the openings (or growing alongside the stream in the huge skylight room of the cave - authors) explain the convention: at a point near its mouth the roof of the tunnel has fallen in, and one can still look down on to the stream from above, through a wide opening (which may have been three smaller openings 2500 years ago - authors) on the steep sides of which brushwood and small trees have found a

footing. A sentry on the hill above the natural tunnel closes the register.

The upper scene is a different matter. King (1915) wrote:

The sacrificial scene in the Upper Register is taking place at the head of a neighboring valley. The objects which are usually explained as four rows of posts across the valley may perhaps be altars of incense, the rising smoke from which is represented conventionally by discs.

An alternative interpretation flashes into the minds of speleologists on viewing the bronze panel or published photographs thereof: a cutaway view of a cave, with droplets of water falling



Figure 2. A cuneiform account of Shalmaneser's cave visit on the Black Obelisk at Nimrud (841 B.C., British Museum).

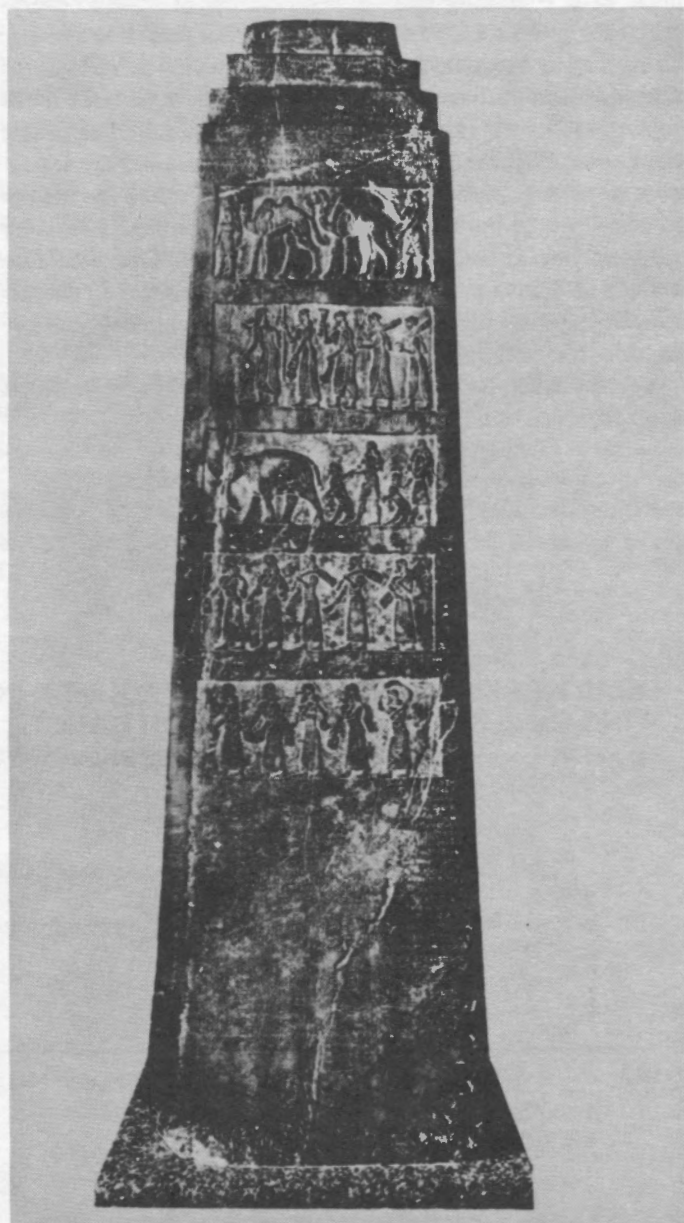


Figure 3. The Black Obelisk of Nimrud (841 B.C., British Museum).

onto stalagmites (Opitz, 1929; Shaw 1976, 1992). In favor of this view is the existence of the dripstone cave and its inscription, a short distance up the valley from the resurgence cave (Waltham, 1976). It is especially easy to accept this viewpoint from review of published photographs of the panel.

In an attempt to resolve the divergent interpretations, the authors recently studied the original panel and minutely accurate hammered copper copies of it in the British Museum. We concluded that direct observation brings out some details that are not well seen on photographs. A building or small village is seen near the left upper end of the cave or valley. Either it is on the valley floor at the edge of the hillside, or it is perched on the roof of the cave, extending into the bedrock, out of scale to everything else in the scene, as some kind of unexplainable symbol. Also a man is seen, standing on what King would identify as the hillside around the curve of the valley head, or in bedrock in the cutaway roof of the cave. There is progressive diminution of size in the scene; this man is smaller than the men amid the stalagmites or incense posts (who in turn are smaller than the men in the main part of the panel). The building or village is smaller still, implying artistic handling of perspective. This would be relevant in depiction of a valley, not a cutaway cave. The accompanying inscription gives no clue, and it is unlikely that the question ever will be fully resolved.

Beyond doubt, however, the lower panel is the world's oldest dated depiction of a cave.

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Manuscript received by the society 12/10/94.

Manuscript accepted for publication 9/26/95.

ERRATA

HELICITITE BUSH FORMATION AND AQUIFER COOLING IN WIND CAVE, WIND CAVE NATIONAL PARK, SOUTH DAKOTA

Edward J. Larock and Kimberly I. Cunningham, *NSS Bulletin* V. 57 #1 43-51

1) Page 43, The last sentence in the Introduction should read "Calcite *Lake* lies at the lowest elevation. . ."

2) Table 1, page 45. The following sample description was missing from the bottom of Table 1:

Sample No.	Survey Station	Locality	Speleothem Description
H4A	LB4	Emperor Maximus	Boxwork consisting of calcite spar overgrowth on vein calcite.

DISCUSSION: COMPARISON OF CAVE PASSAGEWAYS WITH FRACTURE TRACES AND JOINTS IN THE BLACK HILLS REGION OF SOUTH DAKOTA

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In their paper "Comparison of Cave Passageways with Fracture Traces and Joints in the Black Hills Region of South Dakota," *NSS Bulletin* 56(2)96-103, Tariq J. Cheema and M. R. Islam apply a K-S statistical test to distributions of cave-passage, fracture-trace, and bedrock-joint directions in their study area. They conclude, for instance, that with 95 percent confidence the distributions of fracture-trace and cave-passage directions are "from the same population," i.e., that the true distributions sampled by the data are the same. This indicates a serious misunderstanding of the nature of this or any similar statistical test. Such a test is intended to demonstrate, to a particular level of statistical confidence, that two distributions that might conceivably be the same are in fact different. If it fails to do so, then all that can be said is that some combination of the degree of similarity of the distributions and lack of sufficient data has precluded statistical detection of a difference. Such tests might properly be applied, for instance, to determine whether some experimental treatment has altered a distribution of results as compared to a control group, or to compare the sexual habits of two different social groups.

Manifestly, the distributions of directions of fracture traces and cave passages cannot be the same, because they are distri-

butions, in fact, of different things. They could only be the same if the directions of the two phenomena were in fact affected only by exactly the same causes acting in exactly the same ways. A larger quantity of data would inevitably have permitted the test to demonstrate that, in fact, the distributions are different.

The authors do conclude, with regard to joint and passage directions, that the test fails to confirm that their distributions are the same. What in fact the test has done is to show, with 95 percent confidence, that those distributions are different. That is, of course, obvious from a glance at the rose diagrams. Furthermore, it is hardly surprising to find that those distributions, like any distributions of different things, are different. If the distributions of joint and passage directions were really the same, then absolutely nothing other than the bedrock joints could have influenced the formation of the caves, which would be astounding.

The data gathered and presented by Cheema and Islam are interesting, at least if one is willing to pay attention to subjective things like fracture traces. But the statistical treatment would have been better omitted.

COMPARISON OF CAVE PASSAGEWAYS WITH FRACTURE TRACES AND JOINTS IN THE BLACK HILLS REGION OF SOUTH DAKOTA: REPLY

T. J. CHEEMA*

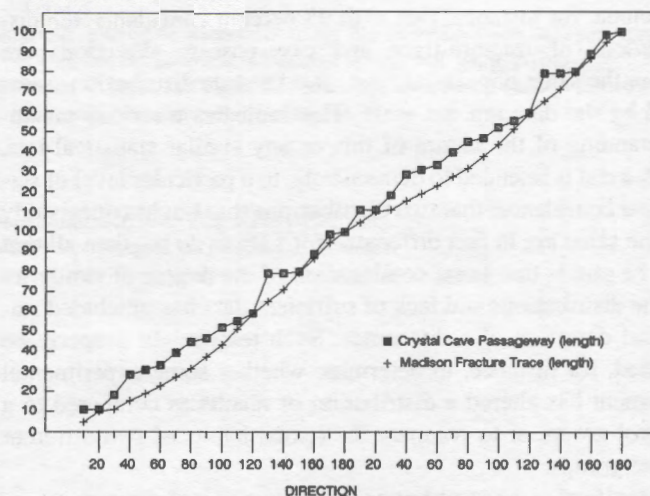
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We read with interest the comments of Bill Mixon on our paper entitled "Comparison of Cave Passageways with Fracture Traces and Joints in the Black Hills Region of South Dakota" (Cheema and Islam, 1994). Mr. Mixon painstakingly describes the limitations of the K-S test. He, however, does not offer an alternative to the K-S test. In fact, the K-S test has been shown to be the most suitable statistical method for the purpose of this study (Barlow and Ogden, 1984; Siegel, 1956). In our case, the two distributions are fracture traces and cave passageways. However, we fail to understand why distributions of fracture traces and cave passageways cannot be the same. Fracture traces are nothing but the surficial expressions of underlying planes of weaknesses and the paleokarstic features present in the Black Hills are, in fact, zones of structural weaknesses that can be observed on aerial photographs.

Mr. Mixon postulates that a large quantity of data would support his claim that two distributions are different. To the contrary, our study demonstrates that a larger data set results in smaller observed D values (Cheema, 1995). For Crystal Cave, total length of the cave passageways was 562 meters. For Black Hills Caverns, this length is 493.2 meters. The observed D value for K-S tests for Crystal Cave and Black Hills Caverns is 14. Figure 1 is a cumulative percent plot of Crystal Cave passageways and fracture traces. However, when fracture trace data were plotted against cave passageways of Crystal Cave and Black Hills Caverns combined, the observed D value drops to 7. This can be seen in Figure 5 of our paper. The only restriction is to compare data of fracture traces and cave passageways that come from the same structural domain. For instance, cave passageways of Jewel Cave (located on the western block of the Black Hills domal uplift) cannot be combined with the cave passageways of Crystal Cave and Black Hills Caverns (located on the eastern block of Black Hills domal uplift).

Distributions of cave passageways and bedrock joints are different, partly because of the scarcity of bedrock joint data, and partly because of the influence of many other structural inhomogeneities involved in the formation of Black Hills caves. Some



of the cave passageways are influenced by the joints while others are controlled by the bedding planes. The absence of reasonable joint measurements makes it hard to find how many cave passageways are joint-controlled. In our study area, the Madison Formation is present in the form of cliffs and not many localities are accessible for joint measurements. It would be interesting to separate joint controlled cave passageways and then, compare joint distribution with the distribution of cave passageways.

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BOOK REVIEW

LANDFORM REPLICATION AS A TECHNIQUE FOR RECLAMATION OF LIMESTONE QUARRIES by John Gunn, Debra Bailey and Peter Gagen 1992, Department of Environment, 38p. + 7pgs. of appendices. About \$24.00 plus postage.

Available from: Her Majesty's Stationary Office
P. O. Box 276
London SW8 5DT
England

This book was produced for the British government by members of the Limestone Research Group under the leadership of Dr. John Gunn of Huddersfield University. There are a few small handbooks and dozens of articles published on the topic of the restoration of damage inside of caves, some of which are in a language other than English. This text is one of the few devoted to the mitigation of the damage done by surface mining to karst landscapes.

This book presents a step-by-step description of how to restore a large limestone quarry wall to a natural looking limestone slope typical of the local area. In addition, the original vegetation sequence is also replicated. Two quarries were selected for study and mitigation. Natural cliff faces nearby the quarries were studied in order to understand the geology, soils, micro-climate and vegetation common to the two locations in order to duplicate these factors.

The first chapter is an introduction to limestone quarries and the concepts behind landscape replication. The objectives of the project are set forth and the two quarries are briefly described.

Chapter two is the longest in the book. It describes the technology used for the replication of the landforms by blasting. The authors give details on proper blast design for sculpting the bare rock to the proper slope needed for restoration.

The climate, soils and vegetation of the test sites are presented in chapter three. This chapter explains what is needed for proper vegetation restoration on the prepared sites. Details of experiments with different vegetation and soils are also presented. Thorough descriptions of procedures used are illustrated in charts and sixteen color plates vividly show the progression of work on the sites. The plates raise the cost of the text, but are invaluable in understanding the process of restoration.

Chapter four details the actual work of establishing the landform and vegetation sequence in the quarries. An eleven step program is given to guide those interested in implementing similar restoration projects. The authors provide time estimates (in man-days) for each of the eleven steps for their specific projects. Also included is the actual cost of each project broken down to cost per square meter. The total cost was about \$20,000 or less for each site. This is actually quite inexpensive for an environmental restoration project. Of course, these costs can vary greatly, based on such things as the amount of donated time and ma-

terials, as well as the total size and vertical relief of the area to be restored.

The cost of long-term maintenance of the revegetated site is also discussed. Such items considered are the need to protect browse from rabbits, the necessity for fertilizers and the occasional watering during dry periods.

This chapter ends with a consideration of greater economic and technical factors in the project. Most aspects of a complete cost-benefit analysis of these types of projects are presented. Environmental and safety factors in the use of explosives and blast design are also explained.

The final chapter summarizes the project objectives and how well they were met. As monitoring of the sites proceeds, more reports will be produced to report on the success or failure of the methodologies used. It is also expected that a complete technical manual will be published to provide more detailed guidelines to those wishing to try similar efforts. Finally, some consideration is given to future projects with modifications learned from these two pilot sites.

Appendices provide detailed information on blast hole geometry, depth, charge size and sequence used to create the proper landform shape. A short glossary is included.

This short book is packed with information useful in attempting a quarry restoration project. Some detailed contour maps (before and after restoration) might have been useful in better describing the work done at the sites. However this is only a small shortcoming in an otherwise excellently presented text. I am looking forward to the forthcoming books, and in particular, the technical manual.

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INDEX TO VOLUME 57 OF THE NSS BULLETIN

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The index includes all articles and abstracts published in volume 57 parts 1 and 2. The proceedings (abstracts) for the 1994 Society meeting in Bracketville, Texas, are contained in this volume. Readers should note that because volume 56 was a one-part theme issue, no annual index of that volume was published. Volume 56 will, however, be included in upcoming cumulative indices.

The index consists of three sections. The first is a **Keyword** index, containing general and specific terms from the title and body of an article. This includes cave names, geographic names, etc. The second section is a

Biologic names index. These terms are Latin names of organisms discussed in articles. The third section is an alphabetical **Author** index. Articles with multiple authors are indexed for each author.

Citations include only the name of the author, followed by the page numbers. Within an index listing, such as "Bats", the earliest article is cited first. Articles containing extensive lists of cave or organism names are listed under List, Cave and List, Fauna, respectively.

Thanks to Keith D Wheeland for the use of his KWISOFT indexing program.

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