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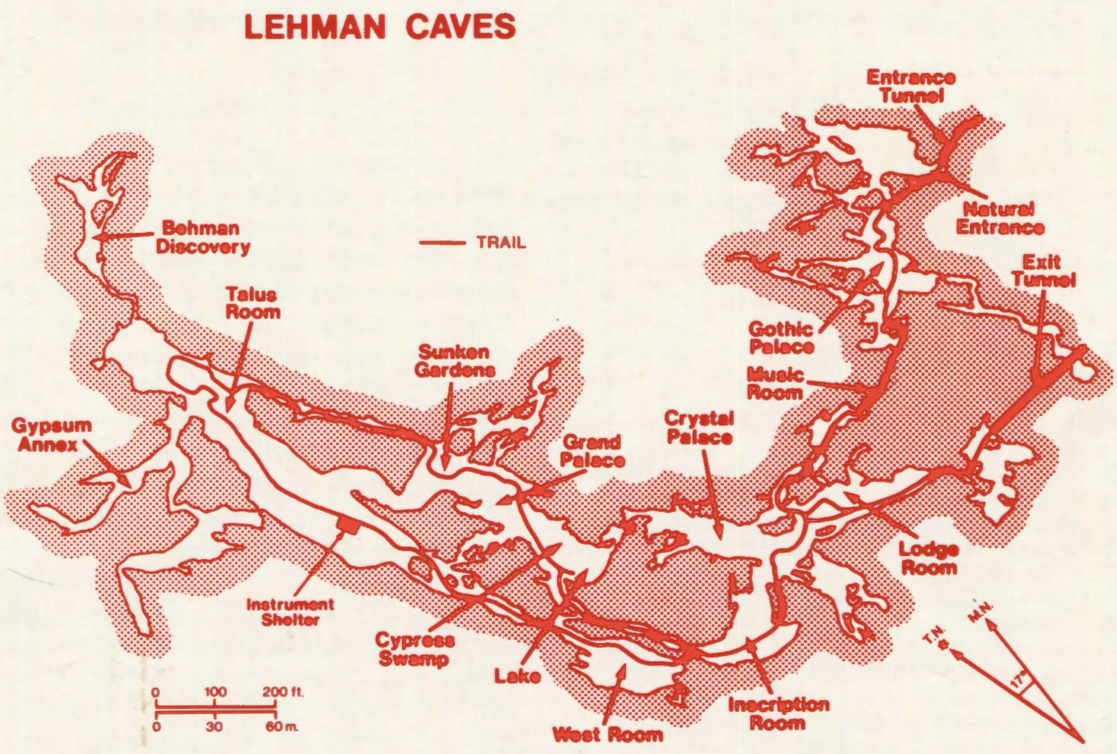
*Journal of Caves and Karst Studies*

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Cover: See Quinn, page 59.

Roy, W. R.—Preliminary Assessment of the Solution Equilibria of Sulphur River, Parker Cave, Kentucky: *NSS Bulletin* 50: 37-41.

# PRELIMINARY ASSESSMENT OF THE SOLUTION EQUILIBRIA OF SULPHUR RIVER, PARKER CAVE, KENTUCKY

W. R. Roy*

*This study is a preliminary assessment of the solution equilibria of Sulphur River, Parker Cave, Kentucky. Aqueous samples were collected and chemically characterized. The chemical composition of the Phantom, a small waterfall flowing into Sulphur River, was similar to Mississippian oil-field brines in Illinois. Thermodynamic modeling of aqueous samples indicated that the reduced, saline solution was supersaturated with respect to gypsum and amorphous iron disulfide. When the Phantom waters mix with Sulphur River, gypsum precipitates and represses the solubility of carbonates. Thermodynamic modeling also predicted the precipitation of elemental sulfur and an aluminum sulfate phase, and that both the Phantom effluent and the receiving waters appeared to be in equilibrium with chalcedony.*

## Introduction

Parker Cave, part of the Turnhole Springs drainage basin in central Kentucky, is located near Park City, 16 km south of Green River. Sulphur River is one of five subterranean streams in this system (see Thompson and Olson, 1988). Approximately 167 m upstream from the downstream access to Sulphur River via Parker Cave, there is a small waterfall (referred to as "The Phantom") that drops 6 m into Sulphur River (Fig. 1). Sulphur River has a base flow of less than 100 $m^3/hr$ (Quinlan and Rowe, 1978). The chemical composition of the Phantom is very different from that of the receiving waters, and has had a major impact on the chemical composition and microbiology downstream. This paper is the second in a series of three presentations describing a preliminary, multidisciplinary study to characterize the geochemistry and biology of Sulphur River.

Quinlan and Rowe (1978) concluded that the Phantom was oil-field brine diluted with meteoric waters, and cited as evidence the existence of shallow, uncased oil wells near the Parker Cave System. Approximately ten shallow oil wells were drilled within a kilometer of Sulphur River (Quinlan, 1988). Quinlan and Rowe (1978) found that aqueous samples of the Phantom were saline, and contained dissolved sulfide species. Gas analyses of the air in the passage in proximity of the Phantom indicated the presence of $H_2S$, and the $CO_2$ content was as high as 2.8% in some locations.

In this study, aqueous samples were collected along a 202-m traverse from the downstream access of Sulphur River to an area upstream from the Phantom (Fig. 1). The samples were chemically characterized. The data were treated by the equilibrium-thermodynamic model WATEQ2 (Ball et al., 1980) to attempt to generalize the aqueous geochemistry of Sulphur River.

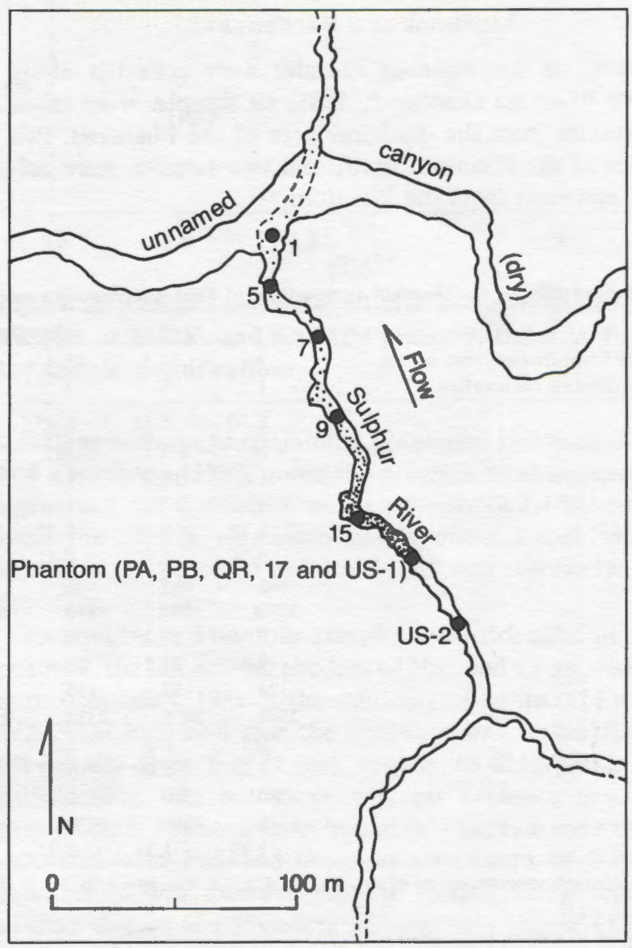


***Figure 1.*** **Location of the study area and the water sample stations. All of the area shown is subterranean. The Phantom enters Sulphur River from an upper passage (not shown).**

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This computer program calculates the ionic strength of each solution from the input chemical data. The calculated ionic strengths were used to determine single-ion activity coefficients (via the Davies equation) that were used to convert solution concentrations to thermodynamic activities. The calculated activities were plotted on mineral stability diagrams to illustrate solution equilibria. Chemical-equilibrium models can lead to useful insights into the geochemistry of aqueous systems such as Sulphur River. However, the results of such modeling must be interpreted cautiously because of kinetic barriers, nonequilibrium conditions and mixed-phase solids. Moreover, the experimental uncertainty associated with some solubility constants for mineral phases can make the assessment of equilibrium controls difficult. It cannot be assumed that the samples were at chemical equilibrium; they were collected from a flowing system. However, if the rates of the reactions are rapid relative to the velocity of the water in contact with the mineral phases, steady-state concentrations may develop.

## METHODS AND PROCEDURES

A total of ten aqueous samples were collected along Sulphur River on October 5, 1985; six samples were taken downstream from the discharge area of the Phantom, two samples of the Phantom itself, and two samples were collected upstream from the Phantom.

The pH and Eh (redox potential) of each sample were determined in the field by electrode. Eh measurements were reported relative to a standard ZoBell solution (ZoBell, 1946). An aliquot of each sample (20 mL) was diluted with an equal volume of a sulfide anti-oxidant buffer (80 g NaOH, 320 g sodium salicylate, and 72 g ascorbic acid diluted to 1 L) to minimize the oxidation of sulfides prior to analysis. Sulfide and chloride determinations were conducted by electrode, sulfate was determined turbidimetrically and alkalinity by titration (American Public Health Association, 1985). Another aliquot of each sample was acidified in the field with $HNO_3$ and analyzed later for solution concentrations of Al, As, B, Ba, Be, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, Sb, Se, Si, Sn, V, and Zn by inductively coupled argon plasma emission spectrometry (ICAP) using a Jarrell-Ash Model 975 Plasma AtomComp.

## RESULTS AND DISCUSSION

The Phantom effluent was a very saline solution having an ionic strength exceeding 0.25 mole/L. The samples were dominated by Na and Cl (Table 1) and were reduced (Eh $\leq$ 5 mV). The sulfide-rich solution altered the chemical composition of the receiving waters; primary indicators of this impact included the occurrence of elevated concentrations of Al, Ca, Cl, Fe, K, Mg, Na, sulfide, and sulfate downstream from the point source.

**Table 1. Summary of the chemical composition of field samples collected at Sulphur River, Parker Cave, on Oct. 5, 1985[1].**

| | Downstream | | | | | | Phantom Waters | | | Upstream | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance from downstream access (meters) | 2.7 | 24.4 | 53.3 | 75.0 | 129.8 | 169.5 | 171.0 | 171.0 | — | 174.0 | 201.5 |
| Station designation | 1 | 5 | 7 | 9 | 15 | 17 | PA | PB | QR[3] | US-1 | US-2 |
| pH | 6.30 | 6.45 | 6.45 | 6.45 | 6.40 | 6.40 | 6.45 | 6.70 | 7.20 | 6.50 | 7.98 |
| $Eh_z$(mV)[2] | +285 | +237 | +285 | +137 | +185 | +205 | −5 | −30 | NM[4] | +211 | +430 |
| EC (mmhos/cm) | 11.6 | 11.2 | 11.5 | 11.8 | 11.3 | 11.0 | 20.0 | 20.5 | >26.0 | 10.6 | 2.68 |
| Alkalinity (mg/L $CaCO_3$) | 254 | 257 | 259 | 257 | 265 | 248 | 137 | 157 | NM | 141 | 210 |
| Al (mg/L) | 0.17 | 0.23 | 0.27 | 0.19 | 0.22 | 0.31 | 0.51 | 0.71 | NM | 0.35 | <0.07 |
| B | 0.76 | 0.70 | 0.71 | 0.81 | 0.79 | 0.91 | 0.95 | 0.90 | NM | 0.71 | <0.05 |
| Ca | 685 | 665 | 624 | 725 | 950 | 1140 | 1635 | 1095 | 1450 | 781 | 109 |
| $Cl^-$ | 3290 | 3290 | 4390 | 4400 | 4400 | 4400 | 8890 | 10100 | 8170 | 3600 | 163 |
| Fe | 0.36 | 0.29 | 0.30 | 0.30 | 0.21 | 0.32 | 0.37 | 0.35 | 0.11 | 0.21 | <0.03 |
| K | 19.6 | 21.7 | 22.6 | 24.9 | 37.0 | 25.3 | 36.5 | 29.5 | 36.0 | 38.0 | 2.68 |
| Mg | 174 | 169 | 156 | 160 | 158 | 183 | 311 | 281 | 360 | 181 | 26.1 |
| Na | 2540 | 2475 | 2324 | 2335 | 1990 | 2275 | 4860 | 4640 | 4200 | 2317 | 121 |
| $S^{2-}$ | 0.3 | 0.5 | 0.3 | 0.3 | 0.3 | 0.9 | 11.0 | 21.0 | 50.0 | 0.7 | <0.05 |
| Si | 6.36 | 5.60 | 5.65 | 6.40 | 7.10 | 6.80 | 4.75 | 3.80 | NM | 5.72 | 4.64 |
| $SO_4^{2-}$ | 1180 | 1200 | 1220 | 1220 | 1220 | 1180 | 2550 | 2540 | 2750 | 1230 | 118 |
| TDS[5] | 8740 | 8060 | 9070 | 9190 | 9090 | 9520 | 20250 | 18900 | — | 8330 | 806 |
| C/A[6] | 1.23 | 1.31 | 0.94 | 0.98 | 0.95 | 1.13 | 1.27 | 0.81 | — | 1.21 | 1.16 |

[1]The solution concentrations of As, Ba, Be, Cd, Cr, Cu, Mn, Mo, Ni, P, Pb, Sb, Se, Sn, V, and Zn were below analytical detection limits, values no greater than 0.09 mg/L.

[2]Relative to a standard ZoBell solution.

[3]Data from Quinlan and Rowe (1978).

[4]Not measured; a value of −50 mV was used in the modeling.

[5]Total dissolved solids (calculated).

[6]Ratio of cations to anions (equivalents).

It is not clear whether the occurrence of the Phantom is caused by oil exploration or if it is a formation brine whose occurrence is not related to petroleum production. In a study by Steele and Cline (1987), shallow Pennsylvanian brines were differentiated from deeper, Mississippian brines that were associated with oil production in the Illinois Basin. On the basis of analyses of 78 brine samples, the two types of brine were differentiated by canonical discriminant analysis; Mississippian brines were characterized by lower Na/Cl ratios. In the study reported here, discriminant function scores were calculated on the basis of the ratios of Ca/Cl, Mg/Cl, Na/Ca, and Na/Mg using the data given in Table 1. These scores were within the population of oil-producing Mississippian systems given by Steele and Cline (1987), suggesting that the Phantom samples resembled the Mississippian brines in the Illinois Basin. Thus, albeit a tenuous argument, these results support the conclusion of Quinlan and Rowe (1978) that the Phantom is a diluted oil field brine. However, the study area lies just outside the Illinois Basin.

Quinlan and Rowe (1978) noted the presence of gypsum in the Sulphur River system. Results from the thermodynamic model WATEQ2 indicated that the Phantom waters were supersaturated with respect to gypsum; the saturation indices of the samples were 0.186 and 0.313 (a saturation index (SI) in the logarithm of the ratio of the observed ion-activity product to the solubility ion-activity product). The downstream samples (stations 1, 5, 7, and 9) may have attained gypsum equilibrium (Fig. 2) suggesting that gypsum precipitates in the mixing zone and controls the aqueous concentrations of $Ca^{2+}$ and $SO_4^{2-}$. Olson and Thompson (1988) noted the presence of gypsum needles adjacent to the Phantom. The solubility of carbonates may be repressed by gypsum through mass-action effects (Akin and Lagerwerff, 1965). The Sulphur River and Phantom samples were undersaturated with respect to calcite, aragonite, dolomite, and magnesite. Thus, it appeared that gypsum was repressing carbonate solubility in the study area.

Olson and Thompson (1988) presented evidence for the presence of elemental sulfur on artificial substrates made of mylar that had been placed beneath the Phantom waterfall for 112 days. Modeling results indicated that, on the basis of all of the samples collected (i.e., Table 1) were vastly supersaturated with respect to orthorhombic sulfur. The origin of the sulfur may also be related to sulfur-forming bacteria identified on substrates, but this relationship has not been studied (Olson and Thompson, 1988). This study suggests that the presence of elemental sulfur was reasonable from a thermodynamic point of view as an intermediate product in the oxidation of sulfide.

The modeling results also indicated that all of the samples (with exception of station US-2) were supersaturated with respect to $Al_4(OH)_{10}SO_4$ and alunite ($KAl_3(SO_4)_2(OH)_6$). Alunite is usually formed by the interaction of sulfuric-acid solutions with rocks containing potassium feldspars. Olson and Thompson (1988) noted the presence of aluminum and sulfur but not potassium on mylar substrates. Therefore, while the specific aluminum sulfate mineral could not be identified, its presence was consistent with thermodynamic modeling.

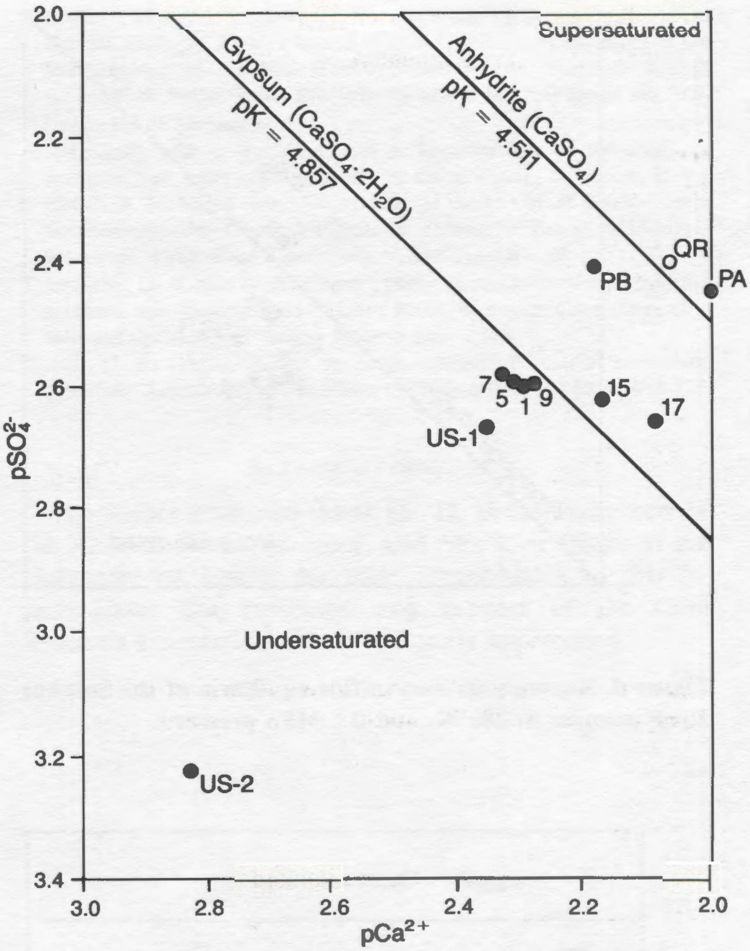


*Figure 2.* **Calcium sulfate equilibria of the Sulphur River samples at 285°K, and 0.1 MPa pressure. Refer to Table 1 for sample identifications.**

Although the Phantom samples were brinelike in composition, the ion activity product of $Na^+$ and $Cl^-$ represented approximately 0.13% of the solubility of halite. The model WATEQ2 indicated that the Phantom was supersaturated (SI greater than 0.113) with respect to amorphous iron sulfide (Fig. 3), but there was no evidence that FeS precipitated. The samples collected downstream were undersaturated with FeS and the near attainment of $Fe(OH)_3$ equilibrium was indicated by the model. These data indicated that as the Phantom effluent was mixed with the receiving waters, sulfide was oxidized to sulfate and some of the Fe (II) in solution was converted to Fe (III) as expected. A concomitant increase in the oxidation-reduction potential (Eh) downstream was also detected (Table 1) but it was

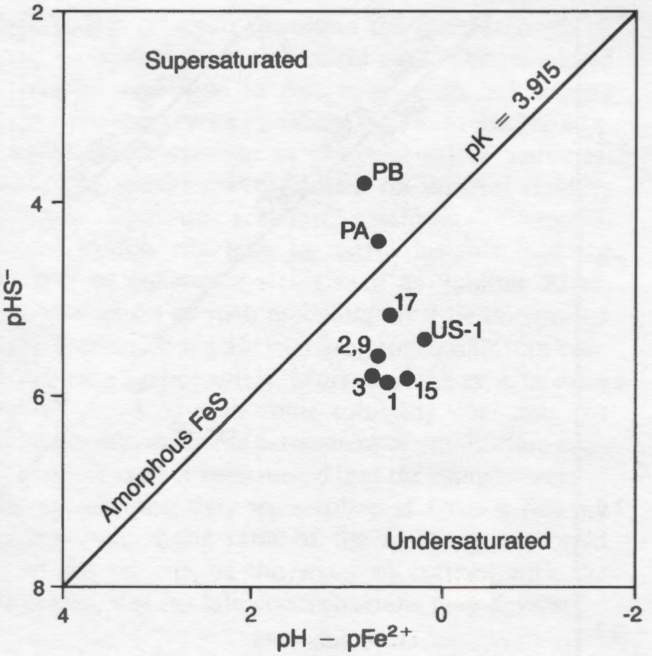


*Figure 3.* **Amorphous iron sulfide equilibria of the Sulphur River samples at 285°K, and 0.1 MPa pressure.**

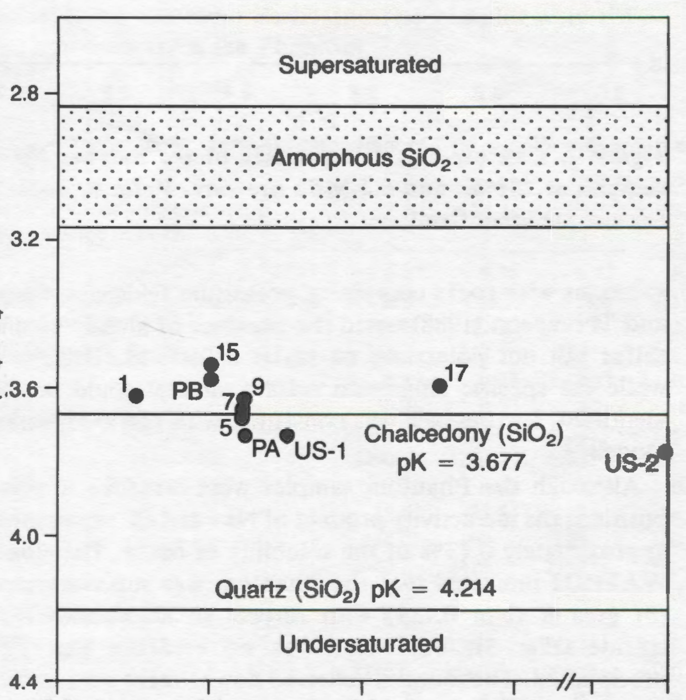


*Figure 4.* **Silica equilibria of the Sulphur River samples at 285°K, and 0.1 MPa pressure.**

uncertain as to which redox couple was dominating the system. The Eh values calculated from the $HS^-/SO_4^{2-}$ couple were lower than the electrode-derived measurements that were used in modeling efforts. The difficulties in interpreting Eh measurements in mixed-potential systems is well known (Lindberg and Runnells, 1984).

According to the models, all of the samples appeared to be in equilibrium with chalcedony, a fibrous form of quartz (Fig. 4). Saturation indices ranged from −0.027 to 0.097. Other solutions collected in Mammoth Cave were also found to be in equilibrium with chalcedony (Roy and Olson, unpublished data). Chalcedony occurs in sedimentary rocks possibly forming from the dissolution of clay minerals (Jenne, 1988). However, for the purposes of this paper, chalcedony is presented as a theoretical "model" mineral; its occurrence has not been verified.

## SUMMARY

This preliminary study indicated that the major solution equilibria of the Phantom-Sulphur River system may be relatively simple. Thermodynamic modeling suggested that the aqueous activities of dissolved constituents were influenced by the solubility of common mineral phases. The presence of some of the mineral phases has been verified in a related study indicating that the predicted equilibria were reasonable for generalizing the aqueous geochemistry of Sulphur River. Because of the limited scope of this investigation, much work remains to be done. For example, the influence of phosphate and other sulfate solid phases could not be evaluated because the solution concentrations of some constitutents (such as Ba and P) were below analytical detection limits (see also Olson and Thompson, 1988). Moreover, it is not known how the chemical composition and equilibria of the study area vary with time. This report should provide a foundation for future studies. Because of the potential health risks associated with the $H_2S$, future investigators should consider using respirators and goggles.

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Thompson, D. Bruce and Olson, Rick—A Preliminary Survey of the Protozoa and Bacteria from Sulphur River, in Parkers Cave, Kentucky: *NSS Bulletin* **50: 42-46.**

# A PRELIMINARY SURVEY OF THE PROTOZOA AND BACTERIA FROM SULPHUR RIVER, IN PARKERS CAVE, KENTUCKY

D. BRUCE THOMPSON* AND RICK OLSON**

*Parkers Cave is located in the Turnhole Spring drainage basin near Mammoth Cave in central Kentucky. One passage, Sulphur River, contains an input of reduced sulfur water. At least two species of sulfur oxidizing bacteria are present in a thick bacterial mat that covers the floor of the stream passage. In addition, thirteen genera of protozoa were identified. The main energy source appears to be the reduced sulfur laden water which is utilized by sulfur oxidizing bacteria which in turn can support a wide variety of protozoa and higher organisms.*

## INTRODUCTION

Parkers Cave is part of the Turnhole Springs drainage basin in the central Kentucky karst and lies several miles southwest of Park City, Kentucky (Quinlan and Ray, 1984). Sulphur River lies toward the eastern end of the cave and is one of five streams in this system (Fig. 1). The passage containing Sulphur River, when entered near its downstream terminus, is approximately 5 feet wide by 8 feet high with steep mud banks along the walls. Base flow is less than 1 cfs, and the stream bottom is covered several centimeters thick with a white bacterial mat (Figs. 2 and 3). In addition, hydrogen sulfide is present in the air and water (Quinlan and Rowe, 1978). Approximately 550 feet upstream from the downstream access to Sulphur River is a small waterfall which drops 20 feet into the stream and is the input for hydrogen sulfide laden water, with 11 to 21 mg $S^{2-}$/L. Upstream from this waterfall the bacterial mat covering the streambed disappears and hydrogen sulfide measurements are 0.05 mg $S^{2-}$/L (Roy, personal communication).

Hydrogen sulfide is known from caves in both the eastern and western United States and is of interest for several reasons. Based on observations in Wyoming caves, Egemeir (1981) proposed a theory of cavern development in which hydrogen sulfide is oxidized to sulfuric acid which replaces the limestone with gypsum. The gypsum is then removed by solution. This theory of limestone replacement and solution has also been invoked to explain cave development in the Guadalupe Mountains (Hill, 1987). In addition, others have suggested that cave streams with hydrogen sulfide may be useful model systems for the study of industrial waste contamination of karst aquifers (Herman *et al.*, 1986).

Reduced sulphur compounds can act as energy sources for a number of organisms (Paull *et al.*, 1984, Grassle 1985). Certain species of bacteria such as the colorless sulfur bacteria (Leucothiobacteria) are capable of deriving energy from the oxidation of sulfide to sulfate (Fjerdingstad, 1979; Jannasch and Wirsen, 1981; Young and Maw, 1958). In certain environments, such as deep sea hydrothermal vent communities sulphur oxidizing bacteria replace photosynthetic organisms in the production of organic carbon and serve as primary producers (Ruby, Wirsen, and Jannasch, 1981; Jannasch and Taylor, 1984). Although the hydrothermal vent communities are localized around vents with discharge temperatures of 8–350°C, similar sulfide based communities have been found at the Florida escarpment where temperatures remained around 4°C (Paull *et al.*, 1984). Recently, it has been demonstrated that mitochondria in some higher eukaryotes are also capable of oxidizing sulfides and coupling this to the production of ATP (adenosine triphosphate), suggesting that sulfide utilization may not be a limited phenomena (Powell and Somero, 1986).

Since the early work on protozoa in Mammoth Cave (Tellkamph, 1845; Kofoid, 1900), there have been a number of different surveys of protozoa and bacteria from caves the world over (Gittlesen and Hoover, 1969; Caumartin, 1963). The results of Gittleson and Hoover's review suggest that most of the protozoa found in caves tend to fall into eight main orders which parallel protozoa found on the surface. Their survey of Mammoth Cave also suggested this relationship (Gittleson and Hoover, 1970). Considering the high sulfide concentration and the absence of light in Sulphur

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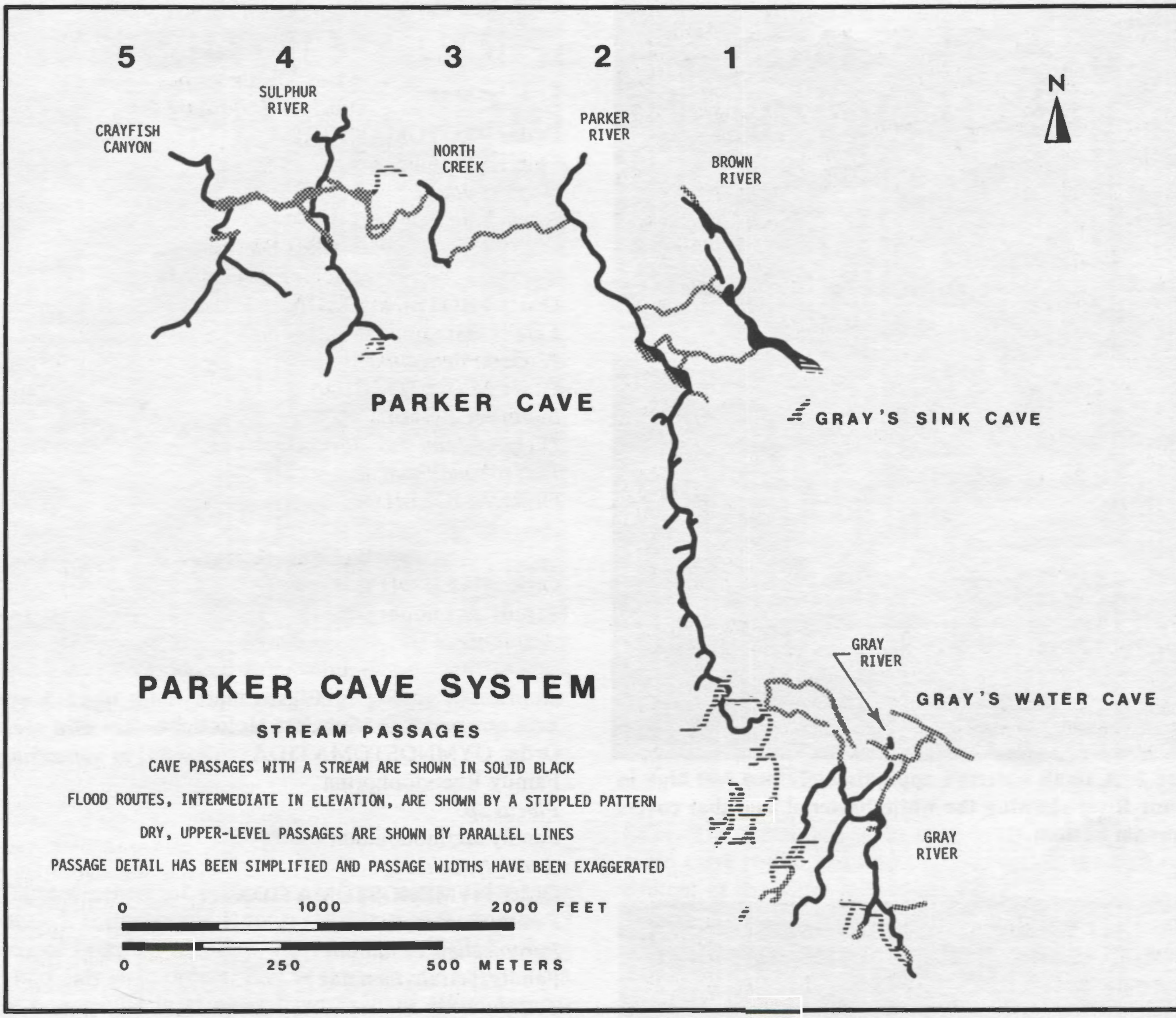


***Figure 1.*** **The map of Parkers Cave showing the main stream passages. Reprinted with permission from Ewers and Quinlan 1984.**

River, a preliminary survey of the bacteria and protozoa of this chemolithotrophic environment was of interest.

## MATERIALS AND METHODS

Three trips covering the period from September 1985 through February 1986 were made to Sulphur River in Parkers Cave. Samples of stream water and bacterial mat from the bottom of Sulphur River were collected in sterile 50 ml screw top centrifuge tubes. Upon exiting the cave the samples were placed on ice and maintained at 4°C until analyzed. Samples were generally analyzed within 48 to 72 hours of collection. Whole wet mounts were prepared and observed using an Olympus microscope equipped with Normarski optics. All bacteria and protozoa were photographed with either Kodak Ektachrome 200 or Technical Pan 2415, and additional drawings were made. Scanning electron micrographs were prepared according to standard procedures. Several taxonomic sources were used in the morphological identification of protozoa and bacteria (Kudo, 1966; Grittleson and Hoover, 1970; Holt, 1977).

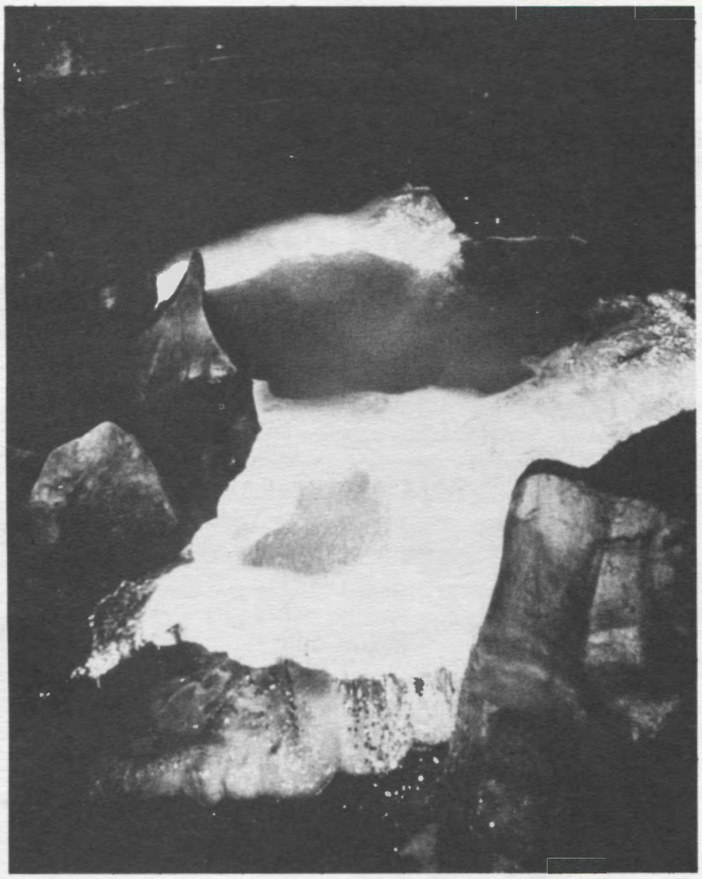

*Figure 2.* **A small waterfall approximately two feet high in Sulphur River showing the white bacterial mat that covers the stream bottom.**

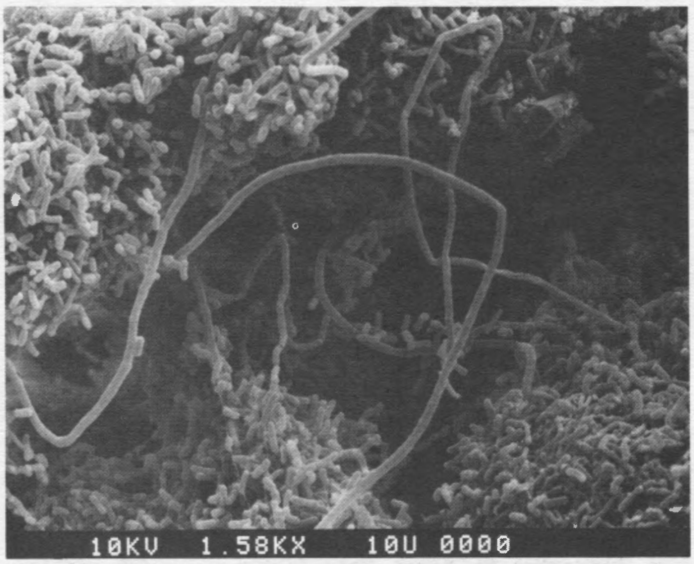


***Figure 3.* Scanning electron micrograph of the bacterial mat from Sulphur River. Large filamentous bacteria resembling *Beggiatoa* imbedded in a matrix of smaller bacteria. Scale bar represents 10 microns.**

## RESULTS

Phylum Protozoa
Class Mastigophora
Subclass Zoomastigia
Order PROTOMASTIGIDA
Family Bodonidae
*Bodo caudatus*
*Rhynchomonas sp.*
Class Scaridona
Subclass Rhizopoda
Order PROTEOMYXIDA
Family Aspidiscidae
*Nucleria delicatula*
Order MYCETOZOIDA
Suborder Acrasina
*Dictyostelium discoideum*
*Polysphondylium sp.*
Order AMOEBIDA
*Amoeba sp.*
Subclass Actinopoda
Order HELIZODA
Family Actinophryidae
*Actinophrys sol*
Subphylum Ciliophora
Class Ciliata
Subclass Holotricha
Order GYMNOSTOMATIDA
Family Rhabdophorina
*Placus sp.*
Family Actinobolinida
*Actinobolinida sp.*
Order HYMENOSTOMATIDA
Family Parameciidae
*Paramecium caudatum*
Family Tetrahymenidae
*Tetrahymena sp.*
Subclass Spirotricha
Order HYPOTRICHIDA
Family Euplotidae
*Euplotes patella*
Family Aspidiscidae
*Aspidica sp.*
Division Protophyta
Class Schizomycetes
Order BEGGIATOALES
Family Beggiatoaceae
*Beggiatoa alba*
Family Leucotrichaceae
*Thiothrix tenuissima*

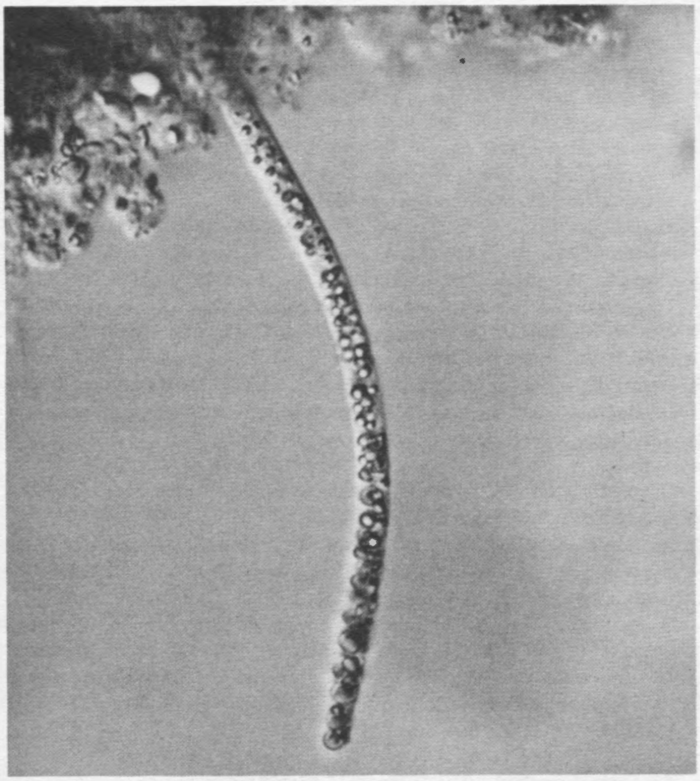

*Figure 4.* **Light micrograph of a large gliding filamentous bacteria with sulfur inclusions identified as *Beggiatoa alba.* Magnification is 10000X.**

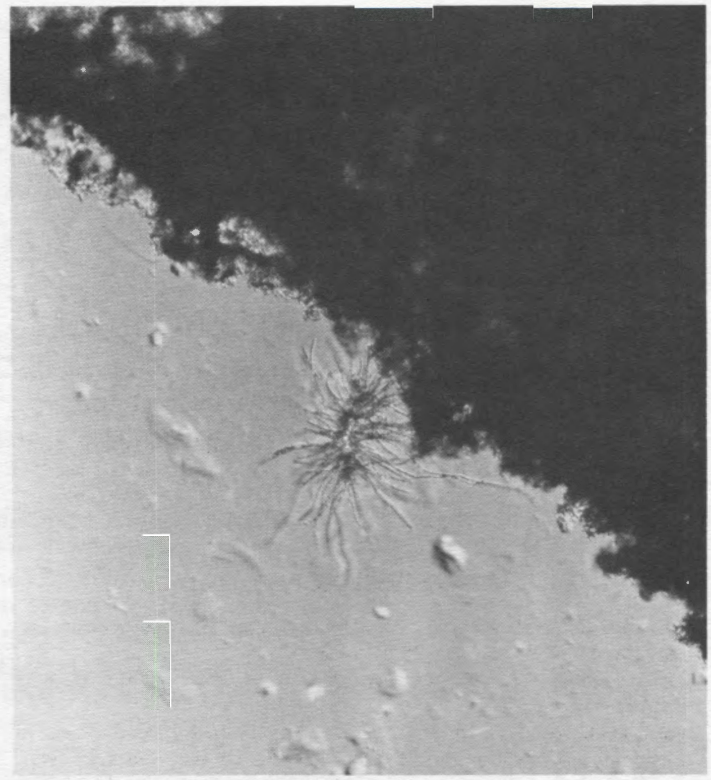

*Figure 5.* **Light micrograph of a rosette of filamentous bacteria characteristic of *Thiothrix*. Magnification is 400X.**

## DISCUSSION

Thirteen genera of protozoa covering eight order were identified. Gittleson and Hoover (1970) noted that of the 29 orders of protozoa reported, 82% of the identified species fall into only eight orders. Five of those orders of protozoa were represented in samples from Sulphur River and included Gymnostomatida, Amoebida, Hymenostomatida, Hypotrichida, and Protomastigida. The two slime molds from the order Mycetozoida (Dictyostelium and Polysphondylium) were identified from cultured samples and may not necessarily represent free living forms, but some investigators have reported free living amoeba that feed on bacteria (Vandel, 1965), suggesting that the free living amoeboid forms of slime molds may exist in caves. Representatives of the final two orders, Proteomyxida and Helizoda, have been reported from several caves.

Representatives of the genera *Bodo, Rhynchomonas* and *Amoeba* occurred more frequently than representatives of any other genera. Every sample examined contained these three genera and this generally parallels the frequencies seen in streams in Mammoth Cave (Gittelson and Hoover, 1970). At least six species of protozoa we identified (*Bodo, Rhynchomonas, Amoeba, Actinophrys, Paramecium,* and *Euplotes*) have been previously reported from Mammoth Cave. The remaining seven species are new for the Mammoth Cave region and may partially reflect the high sulfide content of the water in Sulphur River.

Two bacteria, *Beggiatoa* and *Thiothrix* were identified, based on their morphology (Figs. 4 and 5). Further identification of other bacteria required culturing and was beyond the scope of this investigation. Although only *Thiothrix* is an obligate sulfur oxidizer, both bacterial species are capable of utilizing reduced sulfides as energy sources, oxidizing sulfide to sulfur and then to sulfate (Young and Maw, 1958; Fjerdingstad, 1979). Both *Beggiatoa* and *Thiothrix* like bacteria have been observed in samples from deep sea hydrothermal vent communities (Jannasch and Wirsen, 1981).

Higher eukaryotes also occur in the Sulphur River passage and include annelids, five species of collembolans, a psocopteran, a staphylinid, a cave carabid, several species of mites, and a large number of linyphiid spiders, *Phanetta subterranea* (Lisowski *et al.*, 1985). Drops of water suspended from the webs of *P. subterranea* also contain numerous rod shaped bacteria similar in morphology to those found in the bacterial mat along the streambed of Sulphur River (unpublished observations).

Considering the renewed interest in chemolithotrophic environments since the discovery of the deep sea hydrothermal

vent systems, an analogous system within caves should help provide insight into these unique ecosystems. In addition, Sulphur River provides an opportunity to explore the relationships between microorganisms and their roles in speleogenesis and speleothem development.

## ACKNOWLEDGEMENTS

We would like to thank Dr. David Nanny whose laboratory assisted with some of the identifications and the Cave Research Foundation for personnel and support. Finally, to Dr. Quinlan for assistance and permission to reprint the map of Parkers Cave.

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# SCANNING ELECTRON MICROSCOPY AND ENERGY DISPERSIVE X-RAY ANALYSIS OF ARTIFICIAL AND NATURAL SUBSTRATES FROM THE PHANTOM FLOWSTONE OF SULPHUR RIVER IN PARKER CAVE, KENTUCKY

RICK A. OLSON* AND D. BRUCE THOMPSON**

*In order to sample its biological and mineral constituents in a nondestructive manner, two mylar artificial substrates were placed on a flowstone mass in Sulphur River known as "The Phantom," in Parker Cave, Kentucky. The substrates were retrieved for study after 112 days and found to be encrusted with a layer of flowstone approximately 1 mm thick. Scanning electron microscopy (SEM) and energy dispersive x-ray analysis (EDX) showed that the flowstone consisted of mineral precipitate and bacteria. The lack of significant cation peaks in the EDX spectra indicated that sulfur in this flowstone was predominantly elemental rather than complexed as sulfates or sulfides. The presence of orthorhombic sulfur was later verified by x-ray diffraction. Possible sulfur-metabolizing bacteria were observed in association with the sulfur. In order to compare the artificial with natural substrates, two unattached gypsum needles were also collected. SEM and EDX showed that bacteria, sulfur crystals, and calcium phosphate were present on the surfaces of the needles.*

*The Phantom Flowstone and downstream Sulphur River is a subterranean sulfuretum that is unique in the approximately 450 miles of mapped cave passage in the Mammoth Cave Region. Whether this sulfuretum is a natural phenomenon or a result of oil well pollution is an important question that remains to be answered.*

## INTRODUCTION

Parker Cave is located beneath the Sinkhole Plain of the Mammoth Cave Region a few miles southwest of Park City, Kentucky. For detailed descriptions of Parker Cave and the surrounding area, see Quinlan and Rowe (1978), Quinlan et al. (1983), Meiman (1989), and Thompson and Olson (1988). The cave contains five separate streams of which Sulphur River is strikingly unusual because of the overpowering presence of hydrogen sulfide gas, resultant thick bacterial mats in the stream, and an enriched terrestrial invertebrate fauna. This paper is concerned primarily with two flowstone masses deposited in Parker Cave by the Phantom Waterfall, a tributary of Sulphur River and the main source of its high solute, sulfurous water. One flowstone mass is located in a room above the stream canyon (Fig. 1), and the other, in the canyon below, forms a natural bridge over the stream. The confluence of the Phantom Waterfall and Sulphur River marks the beginning of bacterial mats in the stream. However, unlike the stream below, the flowstone masses do not have an obvious biological component. It was therefore of interest to investigate what, if any, microflora were present and to determine the chemical constituents of the flowstone.

## METHODS AND MATERIALS

Two square mylar[1] substrates measuring 2.5 cm on a side were placed in the Phantom Waterfall on October 5, 1985. Both were anchored with nylon string tied to projections on the upper and lower flowstone. Retrieval was delayed until January 25, 1986 (112 days after placement) because of heavy rainfall and consequent dangers of flooding. The substrates were preserved immediately upon collection in Parducz' Fixative (Parducz, 1967) for transport to the laboratory. Two natural substrates, in the form of unattached gypsum needles found on a ledge which receives secondary spray from the lower flowstone bridge, were also collected and preserved.

Upon arrival in the laboratory, the samples were proc-

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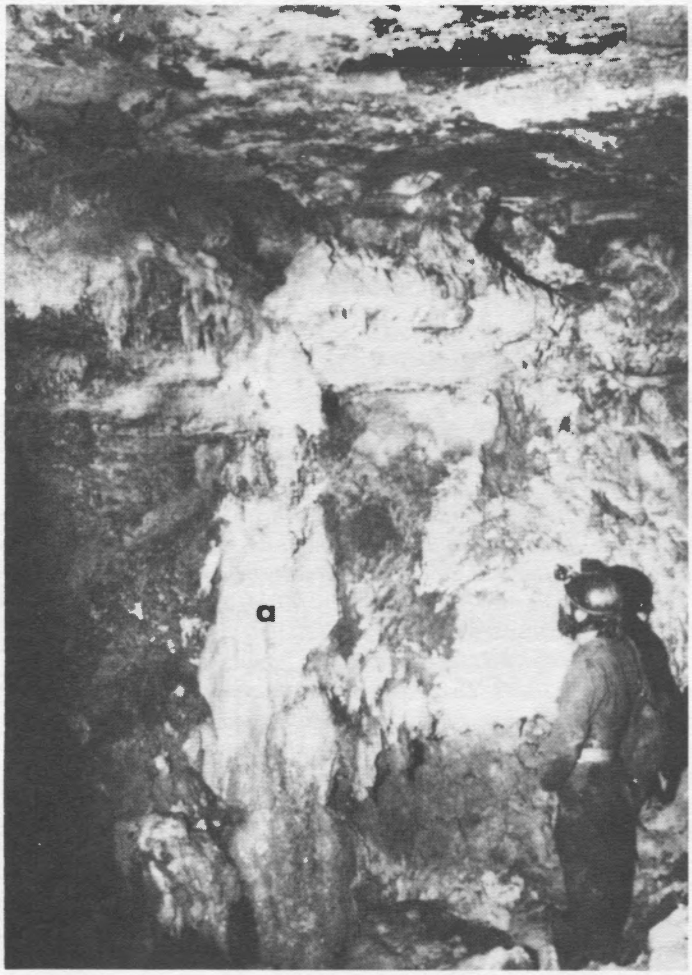


*Figure 1.* **Bruce Thompson standing next to the upper Phantom Flowstone. The letter "a" marks the location of the artificial substrate placement.**

essed through an ethanolic dehydration series (10, 25, 50, 75, 85, 95, 100%) and critical-point dried in a Tousimis Samdri 700. The specimens were mounted on aluminum stubs with colloidal carbon and coated with a few nanometers of carbon in a Denton vacuum evaporator. Energy dispersive x-ray analysis (EDX) was performed with a Tracor Northern TN-2000 spectrometer on an International Scientific Instruments (ISI) DS-130 scanning electron microscope operating at 10 kV. The identity of sulfur and gypsum phases was verified with a Scintag ISO 1001 x-ray diffractometer. After x-ray analysis, a thin coating of gold/palladium (60/40) was applied in a Structure Probe sputter coater. Secondary electron images of specimen surfaces were then micrographed with the DS-130 and with an ISI-40 (also operating at 10 kV). Unstained whole-mounts of bacteria suspended in water collected with flowstone material were prepared using carbon-coated formvar membranes on 300 mesh copper grids. The grids were examined in a Hitachi H-600 transmission/scanning-transmission electron microscope equipped with a Tracor-Northern TN-5500 x-ray spectrometer.

## RESULTS AND DISCUSSION

An unexpected heavy accumulation of material approximately 1 mm thick was found on both substrates, and the lower Phantom mylar had become partially embedded in the flowstone. Scanning electron microscopy (SEM) and EDX showed that both the upper and lower masses are composed of mineral precipitate and bacteria (Figs. 2 and 3).

The EDX spectrum obtained from the upper mass was noteworthy because of its conspicuous sulfur peak and lack of any prominent cation peak (Fig. 2A). These data indicate that the Phantom Flowstone is composed predominantly of native sulfur; x-ray diffraction confirmed that orthorhombic sulfur is the primary constituent of the flowstone with some gypsum present as well. The Phantom was previously believed to be composed of sulfates and sulfides (Quinlan and Rowe, 1978), probably because gypsum is abundant immediately adjacent to the upper half of the waterfall and because aqueous deposition of elemental sulfur occurs under such a narrow range of conditions that it is quite rare (Seeman, 1982).

Most non-volcanic elemental sulfur is produced by the biological reduction of sulfate to hydrogen sulfide (Postgate, 1984) followed by chemical and/or biological oxidation of hydrogen sulfide to sulfur. Sulfides are readily oxidized by molecular oxygen (Sato, 1960, Fenchel and Blackburn, 1979), and this is the pathway suggested by Subba-Rao (1949) in the interpretation of sulfur-bearing clay on the coast of India; by Davis and Kirkland (1970) in their study of deep sulfur deposits in the Rustler Springs district of west Texas; by Kirkland and Evans (1976) in their description of a sulfur encrusted pit in a limestone butte also located in the Rustler Springs area; by Egemier (1981) in the presentation of his replacement-solution mechanism of speleogenesis by sulfurous, thermal waters for caves in the Bighorn Basin of Wyoming; and by Hill (1987) in her analysis of sulfur in the caves of Carlsbad Caverns National Park, New Mexico. Jones and Starkey (1956), along with Feely and Kulp (1957), proposed that sulfur in the caprock of salt domes in Texas and Louisiana is formed through oxidation of hydrogen sulfide by sulfate ions in this deep anaerobic environment. Davis (1973), in his description of sulfur in New Mexico's Cottonwood Cave, includes both the molecular oxygen and ionic sulfate oxidation pathways. There are inconsistencies, however, with either mechanism: the spatial distribution of sulfur in Cottonwood does not support the oxygen hypothesis, but laboratory experiments by Davis, et al. (1970) failed to confirm the sulfate hypothesis. Seeman (1982), in his interpretation of sulfur-

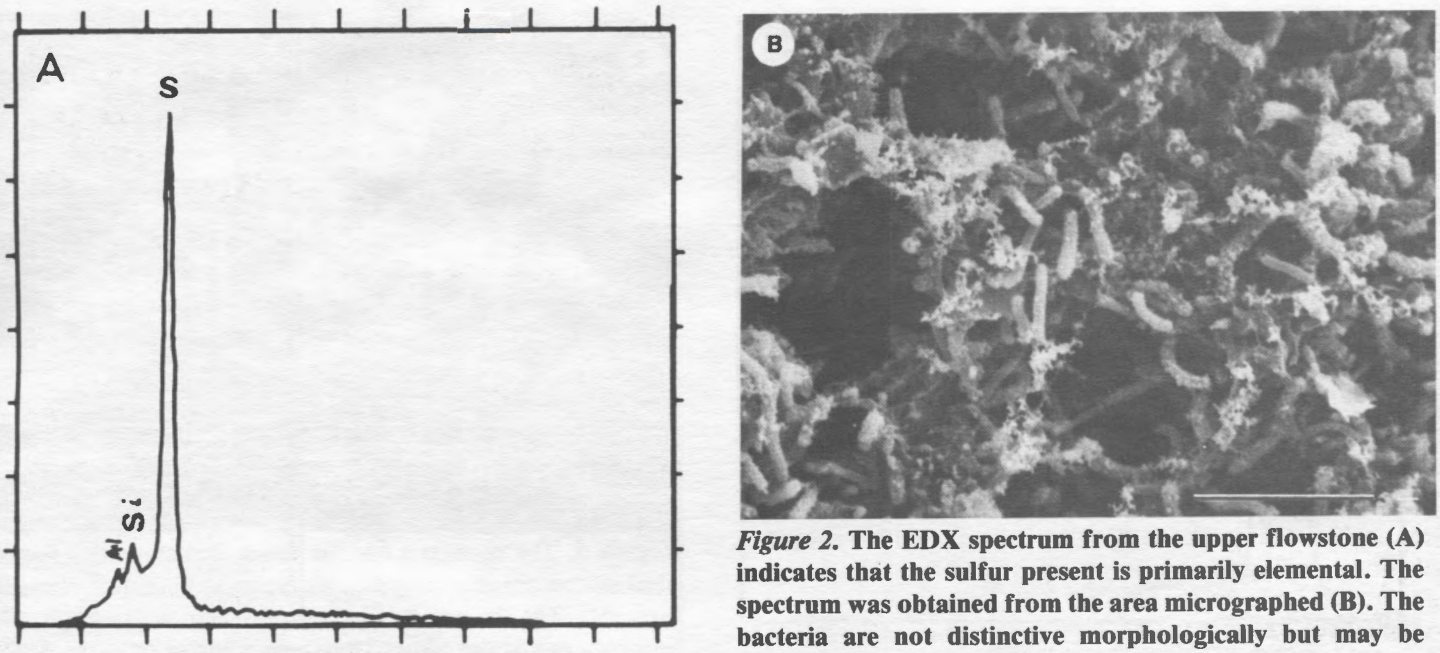


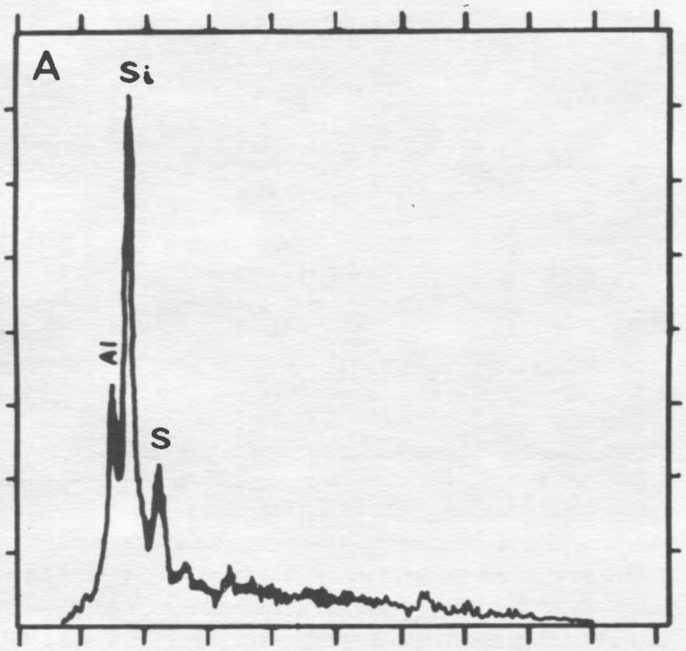

*Figure 2.* **The EDX spectrum from the upper flowstone (A) indicates that the sulfur present is primarily elemental. The spectrum was obtained from the area micrographed (B). The bacteria are not distinctive morphologically but may be sulfur-metabolizers. Scale bar is 10 μm.**

containing nodules from Dachstein-Mammuthöhle in Austria, reported that in an anaerobic, acidic, weakly reducing environment with a high sulfate concentration (such as may have existed in Cottonwood Cave), elemental sulfur is produced as a first reaction product before sulfides. These conditions exist in Parker Cave at the Phantom Waterfall; water analysis and thermodynamic modeling by Roy (1989) revealed that the Phantom waters are vastly supersaturated with respect to orthorhombic sulfur.

Biological and chemical oxidation of hydrogen sulfide to elemental sulfur was suggested by Porch (1917) in his description of shallow sulfur deposits in the aforementioned Rustler Springs region. This combination of biological and chemical oxidation was later confirmed by Butlin and Postgate (1954) in a study of spring-fed, sulfurous lakes in the Lybian desert; by Baas-Becking and Kaplan (1955) in their research on sulfur containing nodules on the shore of Lake Eyre in Australia; by Ivanov (1962) in his research on large sulfur deposits in the Soviet Union; and by Sokolova and Karavaiko (1968) in their work on production of sulfur from hydrogen sulfide using bacterial reactors.

Prior to this investigation, sulfur bacteria had not been isolated from a cave sulfur deposit (Hill and Forti, 1986). The Phantom Flowstone masses, however, harbor an abundant bacterial population. The rod-shaped cells from the artificial substrate placed on the upper flowstone mass (Fig. 2B) are not morphologically distinctive in secondary electron imaging and the biochemical assays necessary for taxonomic determinations are beyond the scope of this investigation. However, because the substrate they rest upon is orthorhombic sulfur precipitated from the Phantom Waterfall, the waters of which contain greater than 10 mg/l $H_2S$ (Roy, 1988), it is reasonable to suspect that they may be sulfur-metabolizing bacteria. The rapid growth rate of the Phantom Flowstone masses is reminiscent of surface travertine deposits where the majority of calcite deposited may be bacterially precipitated (Chafetz and Folk, 1984). The role of bacteria in the deposition of sulfur on the Phantom Flowstone masses may be twofold: biochemical oxidation of hydrogen sulfide to elemental sulfur and entrapment of chemically precipitated sulfur in glycocalyx material. Transmission electron microscopy of unstained wholemounts of bacteria suspended in water collected with flowstone specimens yielded a wide variety of cell types including some rods with dense inclusions. EDX of these inclusions performed in scanning-transmission mode produced spectra indicative of polyphosphate bodies rather than sulfur inclusions.

The mud floor in the vicinity of the upper flowstone mass is coated with a thin, white to pale yellow layer that is heaviest near the flowstone. EDX spectroscopy of this microcrystalline crust yielded a lone sulfur peak so it too is probably elemental sulfur. In October 1985, Dr. Norm Pace of Indiana University, measured the pH of this mud at 0.13 (pers. comm.). Sulfur oxidizing bacteria of the genus *Thiobacillus* are known to produce sulfuric acid, and gram-negative, motile, rod-shaped bacteria in the proper size range (0.5 x 1–2 μm) were observed by Dr. Pace using phase contrast light microscopy. The sulfur crust may result from the action of *Thiobacillus*-like organisms or it may be from direct reaction of hydrogen sulfide with atmospheric oxygen.



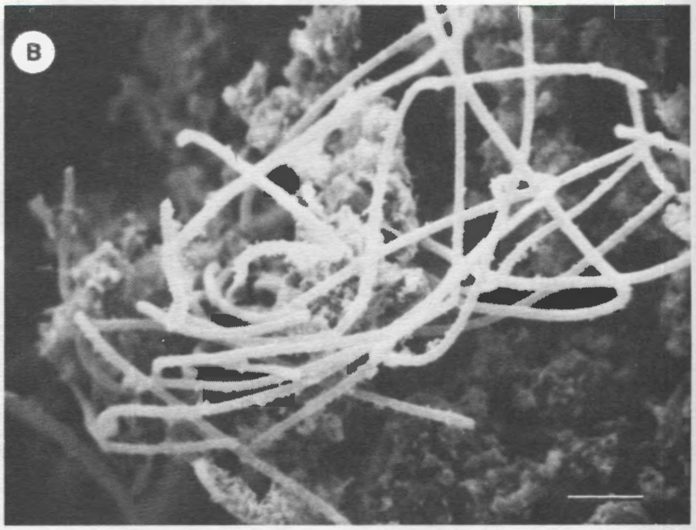
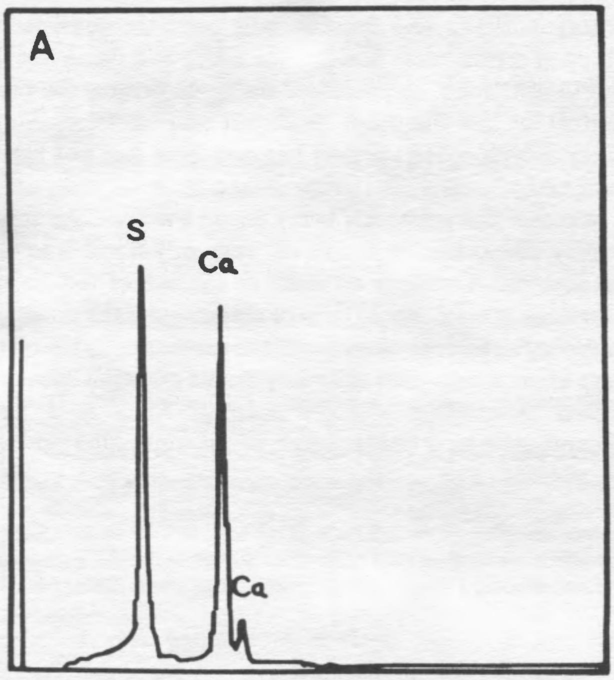




***Figure 3.*** **The spectrum for the lower flowstone (A) shows that silicon supercedes sulfur as the most abundant element present. The bacterial filaments in the micrograph (B) possibly are of the genus *Thiothrix*, a sulfur oxidizer. Scale bar is 10 $\mu$m.**

The EDX spectrum from the lower Phantom Flowstone (Fig. 3A) is interesting because of the relative increase in silicon and decrease in sulfur, as compared to the upper flowstone. EDX spectra taken from rough bulk surfaces are difficult to interpret quantitatively (Goldstein, 1981). Nonetheless, since repeated spectral acquisitions over several areas of the substrate always yielded the same large relative peak intensities, it is clear that silicon was more abundant than sulfur. EDX spectra from subsequent samples of both the upper and lower flowstone masses have had highly variable silicon peaks. Whether this is a consequence of silt deposition during floods or precipitation of chalcedony from the Phantom Waterfall is unknown. The aluminum peaks in both the upper and lower spectra are likely attributable to aluminum sulfate (alum); the water was determined to be supersaturated with respect to $Al_4(OH)_{10}$ $SO_4$ (Roy, 1989). Alum was also documented by Ivanov (1962) at Shor-su and other sulfur mining sites in the Soviet Union. Another consistent difference between the spectra of the two substrates was total detectable x-ray signal. Both spectra were collected for 1000 seconds, yet the signal intensity for the upper substrate was four times greater than that for the lower sample. The lower count rate may reflect a greater organic content in the lower flowstone mass. Unfortunately, conventional EDX detectors cannot record elements lower in atomic number than sodium.

The bacterial filaments from the artificial substrate on the lower flowstone mass (Fig. 3B) may be of the genus *Thiothrix* based upon their habitat and distinctive morphology. *Thiothrix* filaments are typically 2–3 $\mu$m in diameter, over 100 $\mu$m long, and tend to develop in groups as a result of their dispersal mechanism. They are sulfur oxidizers that are commonly found in sulfur springs with a high hydrogen sulfide concentration and are well adapted to flowing water (Buchanan and Gibbons, 1974, Starr *et al.*, 1981). As part of its life cycle, *Thiothrix* filaments form rosettes, a characteristic that is considered unique among bacteria in fresh water habitats. Using phase contrast microscopy, one of these rosettes was positively identified in a sample from Sulphur River (Thompson and Olson, 1988). Poorly defined rosettes and dense groupings of filaments were also common on the natural substrates described in the following paragraph.

Unattached crystalline needles up to 2 cm in length were abundant on ledges which receive secondary spray from the lower flowstone mass. An EDX spectrum taken from a fresh fracture surface (Fig. 4A) yielded sulfur and calcium peaks, indicating that they are gypsum; this was later verified by x-ray diffraction. Abundant bacterial filaments, described above, were attached to the surface of the crystals (Fig. 4B). Also attached to the surface of the gypsum needles were occasional clusters of subangular microscopic crystals (Fig. 5B). The EDX spectrum of these crystals had only a single sulfur peak (Fig. 5A), indicating that they are elemental sulfur. These sulfur crystals were rarely near any bacterial filaments and so were most likely formed by direct oxidation of hydrogen sulfide. Additionally, there were poorly defined masses composed of phosphorus and calcium (Fig. 6A). Clearly visible crystals, with the same EDX signature (Fig. 6B), were found adhering to an artificial substrate placed in



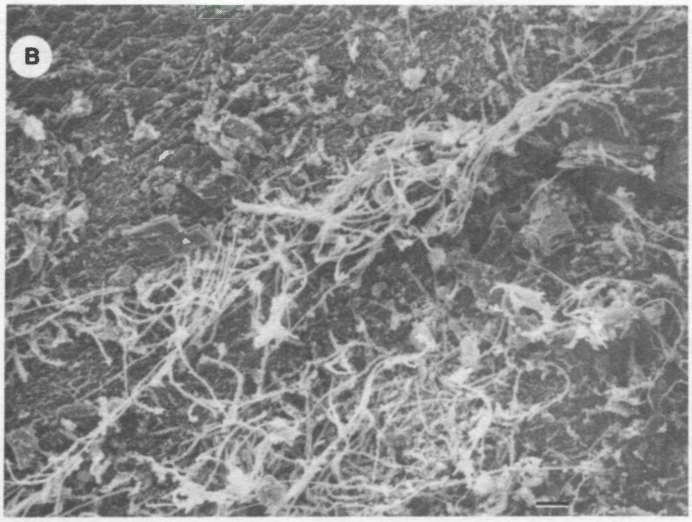
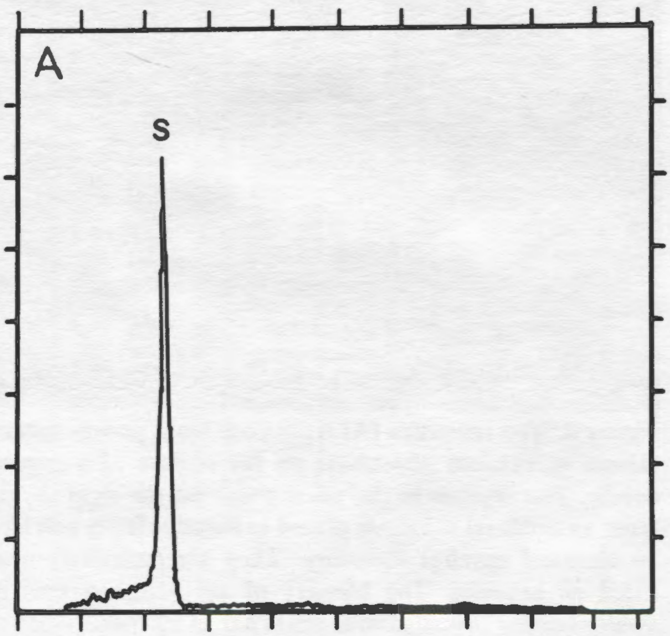




*Figure 4.* **This spectrum (A) was obtained from a clean fracture surface of the gypsum needle shown in the accompanying micrograph (B). Note the attachment of *Thiothrix*—like filaments to the original crystal surface in the middle left of the image. Scale bar is 10 $\mu$m.**

Sulphur River during an earlier, unpublished investigation in 1983. Of the diverse phosphate minerals described in caves, these crystals are most similar to brushite (Hill and Forti, 1986) because of their plate-like morphology and the acidic (pH 6.4) environment in which they were found. Normally, however, brushite is found in association with guano deposits which do not exist in Sulphur River. The source of the phosphate is not known with certainty, but phosphorus is commonly present in carbonate rocks (avg. 400 ppm) and in shales (avg. 700 ppm) (Hill, 1981).

## GEOLOGICAL AND HYDROLOGICAL CHARACTERISTICS OF NATIVE SULFUR DEPOSITION

Elemental sulfur deposits are most common in areas where oil and gas are found, where abyssal brines mix with sulfate-calcium mineralized waters, where sulfate rock adjoins carbonate rock, where there are tectonic fissures and where there are elevated and subsided tectonic units (Ivanov, 1964). These conditions exist in the Parker Cave area where abandoned, uncased oil wells are abundant and



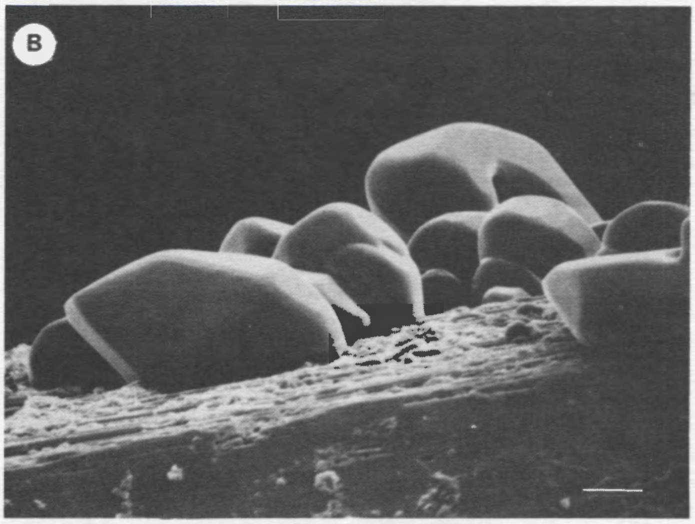




*Figure 5.* **The spectrum (A) was taken from the subangular crystals of elemental sulfur (B) which are attached to the surface of a gypsum needle. Scale bar is 10 $\mu$m.**

where artesian conditions might cause a natural rise of brine (Quinlan and Rowe, 1978). On its upward path, the brine would pass through evaporite beds in the lower and middle St. Louis limestone, which contain gypsum and anhydrite (Palmer, 1981; McGrain and Helton, 1964; Freeman, 1951). A lineament analysis of the Parker Cave area was performed by Angelo George, a geologist of George Consultants, using Lansat 4 imagery. Lineaments are the surface expression of deep structural fractures that may enhance vertical hydraulic conductivity (George, 1984). Three of these were found to form an open triangular intersection just south of Parker Cave. One vertex is located approximately 400 meters up-dip of the Phantom. Finally, Parker Cave is coincident with a structural monocline (Quinlan et al., 1983, Figs. 4 and 10), or bending of the bedrock with which increased fracturing would be associated.

## CONCLUSIONS

The rapid accumulation of material on the artificial substrates and the abundance of bacteria indicate that, for a cave environment, the Phantom Flowstone is a site of dynamic chemical and biological activity. The microbiology of the Phantom needs much more work but it does appear that the biological richness of the Phantom and Sulphur River downstream from the waterfall is based upon chemoautotrophic sulfur metabolism; i.e., it is a sulfuretum (Postgate, 1984). Two additional observations support this hypothesis: milky bluish turbidity in the rimstone pools of Sulphur River is likely due to colloidal sulfur (Butlin and Postgate, 1954); and floating rafts, with the consistency of whipped cream, were positive for sulfur in a flame test (Pace and Olson, 1983, unpublished data). However, the organic content of the Phantom Waterfall and upstream Sulphur River, which could support heterotrophs, has not been determined.

Whether the sulfurous brine enters Parker Cave through nearby abandoned or active oil wells or natural fractures is not known. A reliable estimate of the age of the Phantom flowstone masses would help to determine if the mineralized water began to enter the cave at the same time as the oil wells were abandoned. This is an important question because the answer determines whether Sulphur River is a natural phenomenon or a consequence of oil well pollution.

## ACKNOWLEDGEMENTS

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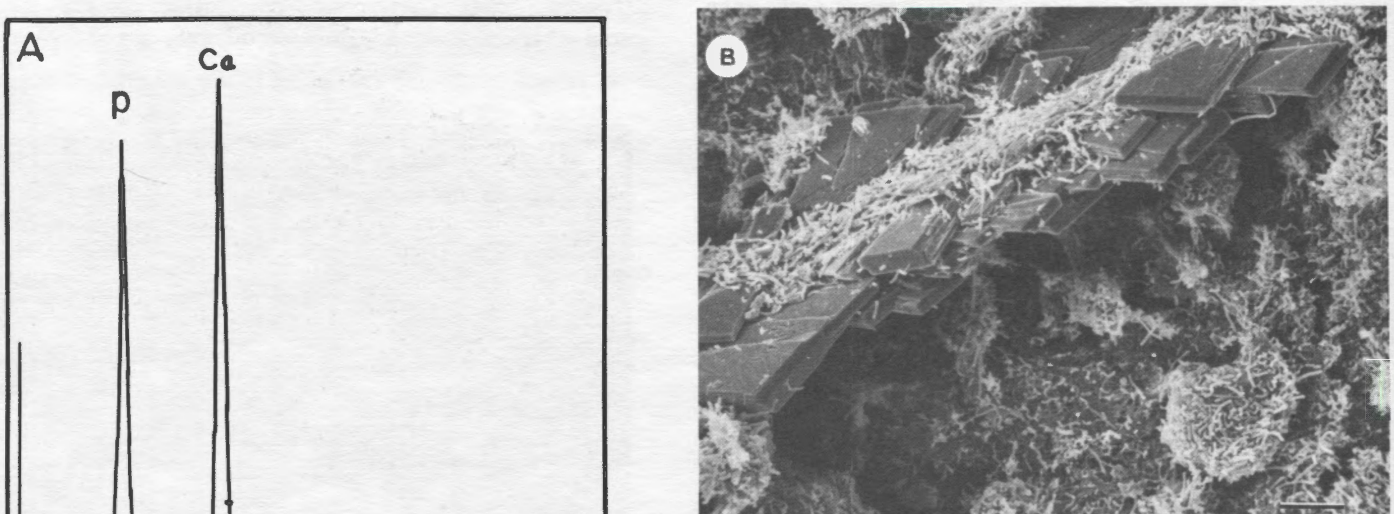


***Figure 6.*** **The spectrum (A) was taken from poorly defined masses of calcium phosphate on the surface of a gypsum needle. The crystals in the micrograph on the right (B) are from an artificial substrate placed in Sulphur River and have an identical spectral signature. They are tentatively identified as brushite. The identity of the attached bacteria awaits further investigation. Scale bar is 10 μm.**

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[1] Polyethylene terephthalate made by DuPont.

Fischer, Hans—Etymology, Terminology and an Attempt of Definition of Mondmilch: *NSS Bulletin* **50: 54-58.**

# ETYMOLOGY, TERMINOLOGY, AND AN ATTEMPT OF DEFINITION OF MONDMILCH

HANS FISCHER*

*The historical term Mondmilch (=calcite moonmilk) is related to the proper type locality, the cave Mondmilchloch from South-Pilatus near Lucerne (Switzerland). Moreover, an attempt has been made to define Mondmilch* sensu stricto *(>90% $CaCO_3$) more precisely in order to distinguish mondmilch-like carbonate speleothems (=moonmilk, < 90% $CaCO_3$) and other subterranean deposits, e.g., sulphates, phosphates and silicates from pure calcite Mondmilch.*

## HISTORY AND TYPE LOCALITY

Mondmilch (Latin: lac lunae) was first mentioned by Agricola (1546, p. 194) and described by Gesner (1555), after visiting the cave Mondmilchloch ("moonmilk hole") at South-Pilatus near Lucerne (Switzerland). He characterized the spongy, limy and white substance as Mondmilch. This was in agreement with a popular expression and without consideration of the actual mineral composition, how almost all speleothems have been named. To some extent, the cave Mondmilchloch can be considered to be the type locality for Mondmilch (Fischer, 1987a; 1988a, d). Later, Mondmilch became well known throughout Europe (Scheuchzer, 1752) and was especially used as a medicament. The first sketch map of the Mondmilchloch was prepared by Kappeler (1767) and the first detailed cave map originates from Schär (1894). The most recent measurements from this cave have been published by Fischer (1987a; 1988b) and Fischer and Militzer (1988).

## ETYMOLOGY OF MONDMILCH AND MONDMILCHLOCH, RESPECTIVELY

The origin of the word Mondmilch (calcite moonmilk) is contradictory and has been ambiguously interpreted in the past. Early reports discussed two contrasting origins: one derived from the similar-sounding expression "montmilch" (Latin: mons = mountain), therefore mountain-milk (German: Bergmilch) (Kyrle, 1923; Trimmel, 1965); and the other as being related to the moon. Sidler (1939/40; 1940) discussed the influence of the moon, and its position relative to the deposits, on the medicinal properties of Mondmilch. However, the actual origin of the term Mondmilch is most likely derived from a completely different root. According to Lutz (1956), the expressions Mondmilch and Mondmilchloch, respectively, have their origins in the cult of the earth (German: Erdkult). Many legends were created from this cult which include myths and stories about little earth men (Swiss-German: Erdmannli), similar to dwarves or gnomes who dwelled in hollows or "manholes" (dialectial: Mannliloch, Manloch, Maloch). In one pharmacy in Central Switzerland the "product" Mondmilch was offered under the name "manmilk" ("Mannlimilch") as late as of the beginning of the 20th century. This popular expression may reflect the original meaning of the word. Due to differences in the pronunciation of the various Swiss dialects this term "Mannlimilch" may have been mistaken for the word Mondmilch (Gesner, 1555), thus transposing the word man into moon. Therefore, Mondmilch seems more likely to be derived from "earth-man milk" ("Erdmännlimilch" "Erdleutemilch") or little earth-man (gnome) hole ("Erdmännliloch"), rather than from the moon or mountains.

This schematic development of the term Mondmilch was recorded for the first time by Bernasconi in 1959. Fischer (1988c) has presented the parallel development of the cave name "Mondmilchloch" and the speleothem "Mondmilch" (Table 1). Moreover, it has been shown that "Montmilch" and "Bergmilch" are historically and etymologically false expressions.

## TERMINOLOGY: FACIES TERM VERSUS MINERALOGICAL TERM

Numerous synonyms in the different languages (see Appendix) exist for mondmilch-like or moonmilk-like speleothems. Many of the descriptions listed by Heller (1966) are not only related to calcite growth, but also of clayey, marly or silicaceous deposits in caves. The original term Mondmilch or "Mannlimilch" from the cave Mondmilchloch refers to calcite precipitation and does not originally represent the phenomenon for speleothems in general.

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**Table 1. Etymological development of the term "Mondmilch."**

| cave Mondmilchloch: | | speleothem Mondmilch: |
|---|---|---|
| cult of the earth<br>(Erdkult) | | |
| ↓ | | |
| little earth-man<br>(Erdmännli) | | |
| ↓ | | |
| little earth-man hole<br>gnome hollow<br>(Erdmännliloch) | ↔ | earth-man milk<br>(Erdmännlimilch)<br>(Erdleutemilch) |
| ↓ | | ↓ |
| manhole<br>(Mannloch) | ↔ | manmilk<br>(Mannmilch)<br>(Mamilch)<br>(Mannlimilch)<br>(Mandlimilch) |
| ↓ | | ↓ |
| moonhole<br>(Mondloch) | | |
| ↓ | | |
| moonmilk hole<br>(Mondmilchloch) | ↔ | moonmilk<br>(Mondmilch) |
| | | ↓ |
| | | montmilk<br>(Montmilch) |
| | | ↓ |
| | | mountain milk<br>(Bergmilch) |

(In parenthesis the German or dialectial Swiss-German expressions.)

*Figure 1.* **In situ formation of wet Mondmilch (in center) surrounded by older and desiccated.**

In the course of time, the term Mondmilch has been applied to all subterranean occurrences of white, plastic material in the two-phase system of water and calcite. The term has changed continuously from one of limited use to a widely used facies term (Gèze & Pobeguin, 1962). Hill and Forti (1986) even suggested that texture and not composition is implied by the term "moonmilk" (not "Mondmilch"!). As a result, not only carbonates, but also sulphates, phosphates and silicates have been designated as Mondmilch or mountain milk (German: Bergmilch), respectively, in the literature. Roda and Rajman (1976) have proposed the use of "soft sinter" instead of Mondmilch for calcite two-phase systems. On the other hand, Bernasconi (1980) suggests that the description "white plastic masses" be employed as a facies term and that the term Mondmilch be exclusively used for white plastic masses with a solid phase of more than 90% mineralogically determined calcite (see attempt of a definition).

## Mineralogy and Genesis of Mondmilch

Mondmilch *sensu stricto* is a microcrystalline or cryptocrystalline calcite cave deposit and can be well determined by optical methods and X-ray analysis. In a humid or wet state Mondmilch is spongy and plastic (Fig. 1), desiccated Mondmilch is white and hard (approx. hardness 3 on the Mohs-scale). Macroscopically, it has often a cauliflower-like appearance and is formed either by accumulation in layers on older Mondmilch deposits (Fischer, 1987b; 1987c,d) or by one of the numerous hypotheses described by Gèze (1961), Pochon et al., (1964), Bina (1981), Cabrol and Coudray (1982), and summarized by Bernasconi (1981). Since an increased calcite precipitation results either from a rise of temperature or from a decrease in $CO_2$-content in the atmosphere, the sheet-like Mondmilch structure (Fig. 2) may, by all means, correspond to rhythmic accretion.

The X-ray diffraction pattern (Fig. 3) confirms that Mondmilch from the cave Mondmilchloch at Pilatus is calcite carbonate (>95% $CaCO_3$) (Fischer, 1987c). The microcrystalline structure can be easily confirmed by scanning electron microscope methods (SEM) (Fig. 4).

## Attempt of a Definition

With respect to the historical importance and according to mineralogical findings, the proposition of Bernasconi (1981) that the term Mondmilch should be reserved exclusively for calcite deposits, is generally to be supported. Since Mond-

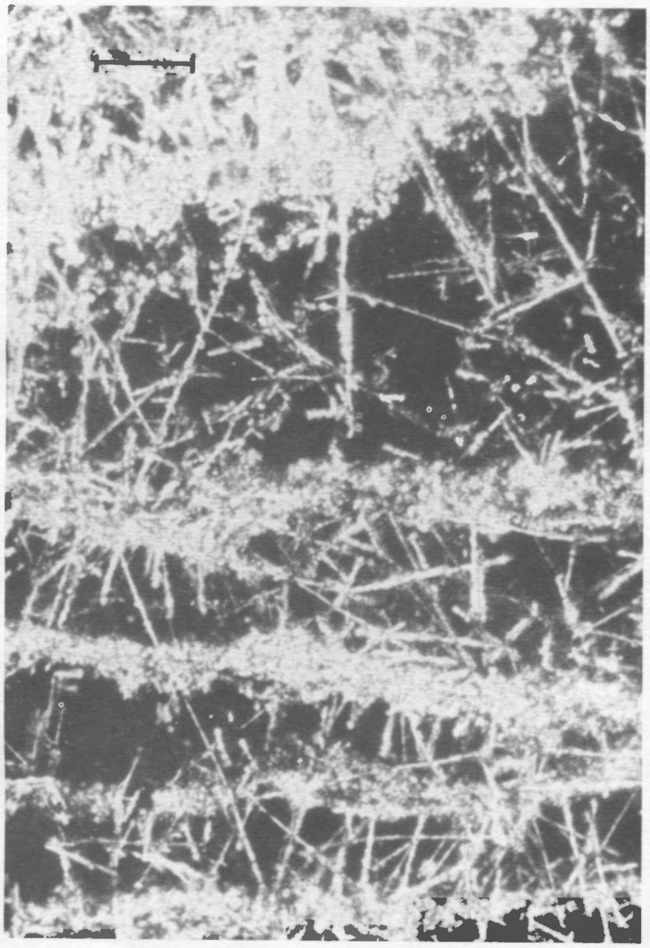


*Figure 2.* **The photograph from a thin-section gives clear evidence for an accumulation in layers of small calcite crystals (error bar = 0.1 mm).**

milch is formed primarily in a two-phase system (liquid/solid), but subsequently appears quite desiccated, it is necessary to include a precise specification for desiccated Mondmilch as well. In addition, criteria to unequivocally determine Mondmilch must be simple and measurable.

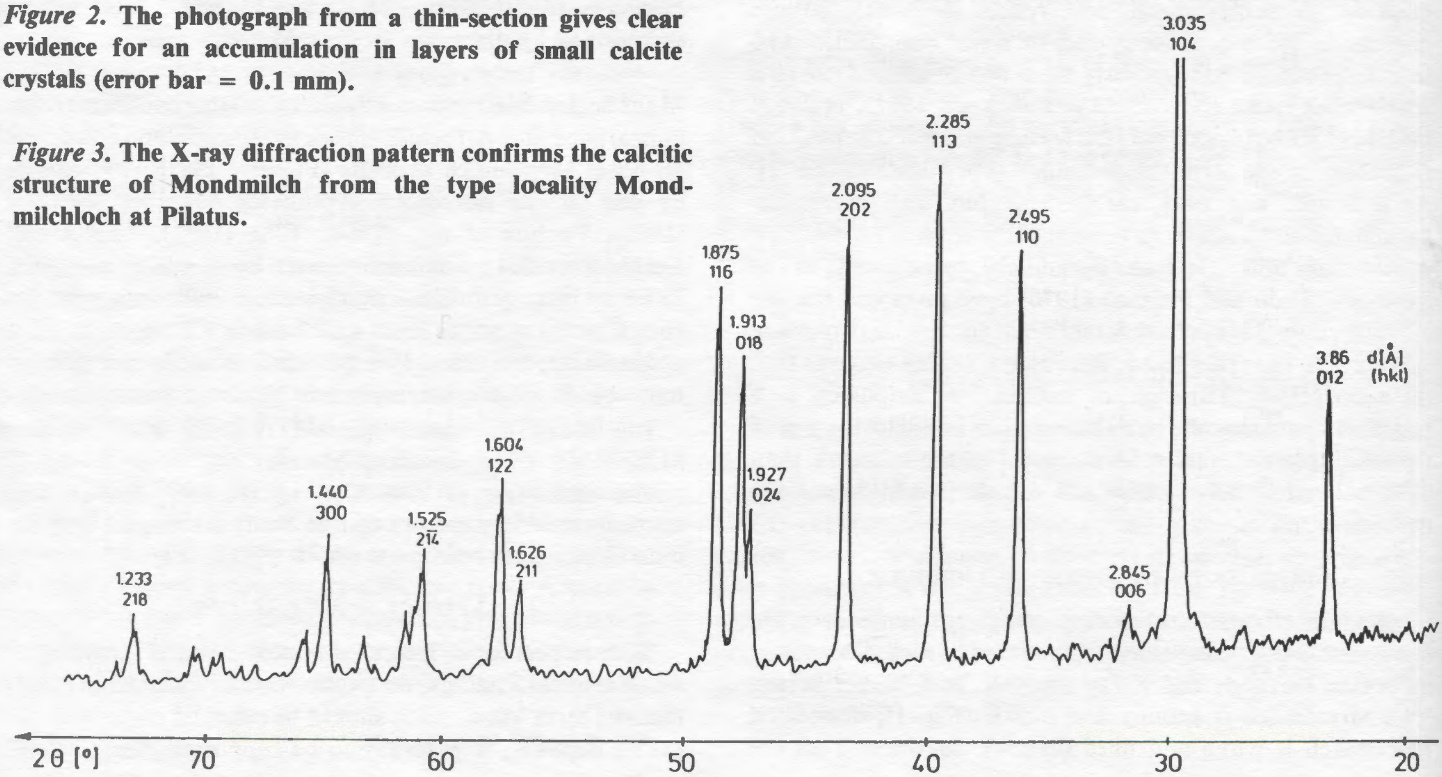
SUGGESTION:

Mondmilch *sensu stricto* (= calcite moonmilk) is a calcite, microcrystalline or cryptocrystalline speleothem, which is formed primarily as a two-phase system (liquid/solid) with a minimum calcite content of 90 weight%. A carbonate speleothem of less than 90% calcite should be designated as a mondmilch-like deposit or as moonmilk. All other subterranean deposits, e.g., sulphates, phosphates and silicates, should not be related to the word Mondmilch nor to moonmilk.

REASON:

In practice cavers can first call white pasty masses as moonmilk until it is analyzed to be Mondmilch, moonmilk or even another subterranean deposit such as sulphates, phosphates or silicates. The mineralogical nature of Mondmilch can be easily confirmed by the mineralogical methods mentioned above. In order to take into account small impurities and a certain mixture of more or less pure limestone and dolomite, the limit of 90% calcite seems to be reasonable. Moreover, the quantitative criteria of a 90% calcite content is easily determined. By dissolving desiccated Mondmilch in hydrochloric acid (HCl), the undissolved residue must be less than 10% by weight.

*Figure 3.* **The X-ray diffraction pattern confirms the calcitic structure of Mondmilch from the type locality Mondmilchloch at Pilatus.**



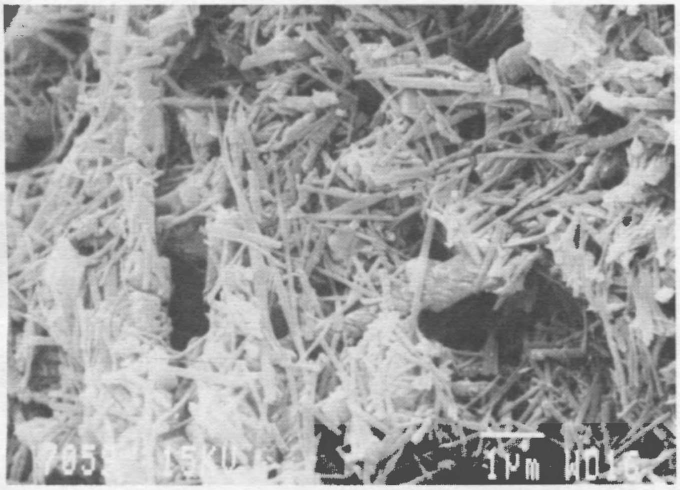
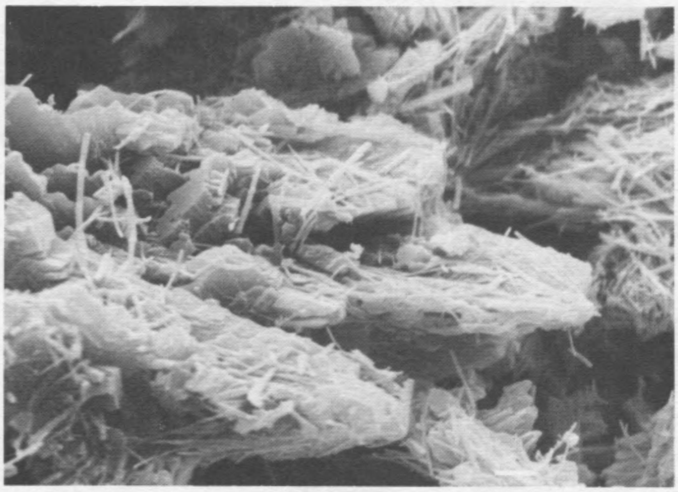
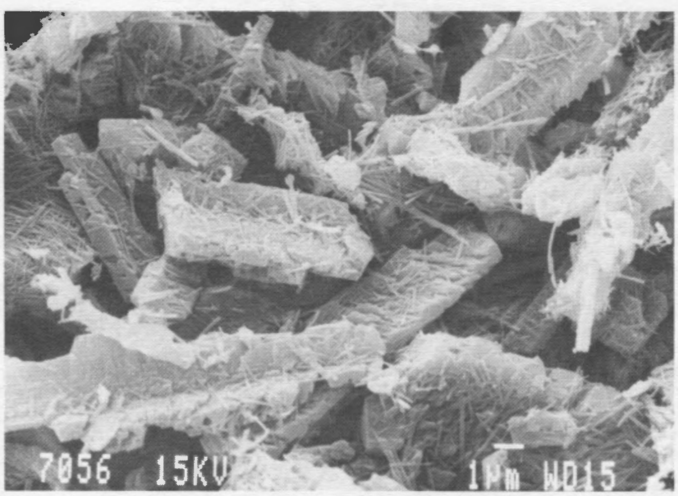



*Figure 4.* **By means of scanning electron microscope investigations, several kinds of calcite crystals can be observed:**

**a) needlelike**



**b) skeletal**




**c) ledgy**

## CONCLUSIONS

1. The type locality for Mondmilch *sensu stricto* is the cave Mondmilchloch at Pilatus (Switzerland).
2. The origin of the word Mondmilch is not originally related to the moon (milk) nor to mountain (milk) but, on the contrary, to "little earth-man" (German: Erdmannli) and little earth-man milk (German: Mannlimilch), respectively.
3. The term Mondmilch *sensu stricto* should not be applied as a facies term, but only as a term for calcite speleothems.
4. Mondmilch is a calcite, microcrystalline cave deposit, which is formed primarily in a two-phase system (liquid/solid) with a minimum calcite content of 90 weight%. Carbonate deposits of less than 90% calcite are mondmilch-like speleothems or moonmilk. All other subterranean deposits, e.g., sulphates, phosphates and silicates, should not be related to the word "Mondmilch" nor to moonmilk.

## ACKNOWLEDGEMENTS

Gretchen Früh-Green improved the English. The manuscript has benefitted from critical comments of two anonymous reviewers.

**APPENDIX: Synonyma of Mondmilch**

| | | |
|---|---|---|
| **German:** | **French:** | **Italian:** |
| Mamilch | lait de lune | latte di luna |
| Mahmilch | lait de roche | latte di roccia |
| Maamilch | lait de montagne | latte di monte |
| Maanmilch | lait de caverne | latte di montagna |
| Mannlimilch | | latte dell'uomo |
| Mandlimilch | **English:** | latte dello gnomo |
| Moonmilch | moonmilk | |
| Monmilch | mountain milk | **Latin:** |
| Monnmilch | mondmilk | lac lunae |
| Montmilch | rock milk | lac montanum |
| Milchstein | gnomes milk | lithomarga |
| Bergmilch | | stenomarga |
| Steinmilch | **Spanish:** | |
| Steinmergel | leche de luna | **Greek:** |
| | leche de roca | speleogala |
| **Russian:** | | |
| mleko gornego | **Czech:** | **Yugoslav:** |
| kamennoe moloko | nickaminek | grosko mlijeko |
| **Turkish:** | | |
| dik karstik kalinti | | |

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Quinn, Joyce A.—Relationship between Temperature and Radon Levels in Lehman Caves, Nevada: *NSS Bulletin* **50**: 59-63.

# RELATIONSHIP BETWEEN TEMPERATURES AND RADON LEVELS IN LEHMAN CAVES, NEVADA

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*Concentrations of radon gas in caves are partially controlled by temperature differences between the cave and the surface. Although there is a significant correlation between exterior temperature and radon in Lehman Caves, Nevada, large standard errors prevent prediction of radon levels with any precision. Discriminant analysis, using mean or minimum temperature of the day prior to sampling, can be used to predict with 90% accuracy whether radon working levels will be above or below .300, a critical level for health.*

## INTRODUCTION

It is well known that radioactive gases such as radon (Rn 222) are common in mines, and attention recently has focused on radon in homes and workplaces. Radon daughters, which are natural decay products of uranium and radon, become attached to airborne particulates and thus pose a potential threat to health when inhaled into the lungs. Several federal agencies [Mining Enforcement and Safety Administration (Mesa), Environmental Protection Agency (EPA), and Occupational Safety and Health Administration (OSHA) ] have set standards for radiation exposures and require that radon concentrations be monitored and that high levels be corrected in all mines. The existence of similar radiation in natural caves was first discussed at length in 1967 by Breisch, but it was not until the mid-1970s that further studies by Wilkening and Watkins (1976) and by Trout (1975) drew attention to the problem of radiation in caves by reporting radon 222 concentrations in Carlsbad Caverns. The National Park Service (NPS) immediately expressed concern and, with the help of MESA officials, confirmed the existence of rather high radon levels in Carlsbad. As a result of those concentrations, weekly monitoring programs were initiated at Carlsbad in September 1975 and, subsequently, at other NPS caves where radon approaches potentially hazardous levels (Ahlstrand, 1977). Previous ignorance of potentially hazardous radon gas is illustrated by the fact that cave air with WL .5–.6 at Mammoth Cave, Kentucky, was routinely pumped up into the Administration Building for year-round "natural" air conditioning until late April 1976 (Yarborough, 1978).

High radiation levels in mines can be lowered through ventilation systems, but the installation of an artificial air exchange system in a cave would disrupt the natural cave microclimate and ecosystem. Radon monitoring in NPS caves is done not to provide grounds for corrective measures but rather to compile data on the cumulative exposure of personnel to radiation. Radon levels are generally not hazardous to the occasional visitor but may be so to personnel such as guides who spend a considerable amount of time underground. Exposure is measured in working levels (WL) and cumulative exposure in working level months (WLM). "One WL is defined as any combination of short-lived radon and/or thoron daughters in one liter of air which will result in the ultimate emission of 1.3 x $10^5$ MeV [million electron volts] of potential alpha energy. [WLM is] defined as the exposure received from breathing air at one WL concentration for 173 working hours per month (40 hrs./work week)" (Yarborough, 1977). According to OSHA standards, an employee may not exceed 4 WLM in any calendar year; thus, records are kept of radon WL and employee exposure time. The measured WL multiplied by the number of hours an employee spends in the cave calculates cumulative working level hours (WLH) for that employee. WLM is then calculated by dividing WLH by 173.

## PROBLEM

Since 1976 NPS has been required to monitor radon daughter concentrations in its natural cave systems (Yarborough, 1977). If the WL is found to be greater than .300, sampling must be done weekly. With lower concentrations sampling can be done less frequently. Levels between .200 and .300 require quarterly samples; between .100 and .200, annual samples; and less that .100, no action. A WL of .300 is critical because there appears to be a greater incidence of lung cancer, up to three times as many cases, for persons continually exposed to .300 WL and above (Yarborough et al., 1979). The need for continual monitoring of radon in NPS cave systems would be greatly reduced if radon concen-

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trations could be predicted from some other parameter. The problem has two parts. One, since concentration of radon in caves depends partially on air exchange with the surface, can radon working levels be correlated with some atmospheric parameter that controls or contributes to airflow? Two, is there an atmospheric parameter which will predict the level of radon to be above or below the critical .300 point?

Several studies have indicated a direct relationship between radon levels and atmospheric conditions. Radon levels fluctuate with air flow in and out of caves. Air moves in direct response to spatial variations in air pressure, which in turn is partially controlled by variations in temperature. Cold air is heavy and creates high pressure, in contrast with lighter warm air which results in low pressure. Air always flows from areas of high pressure to areas of low pressure. Temperature is a more easily obtainable meteorological variable and is often indicative of pressure conditions. Radon working levels have been shown to be positively correlated with minimum daily, weekly or monthly temperatures (Ahlstrand, 1977; Yarborough, 1977; Yarborough et al., 1979; Ahlstrand & Fry, 1979; Wilkening, 1979; Ahlstrand, 1980). In caves where most passageways are below the entrance (called right-side-up—RSU), there is a distinct seasonal variation in radon levels associated with annual march of temperature. In winter, cold outside air sinks into the cave, diluting the radon concentration. Conversely, in summer when outside temperatures are high, colder, denser cave air stagnates and radon accumulates (Yarborough, 1977). Pressure-induced air flow resulting from passage of cyclonic systems plays a minor secondary role in radon levels. These synoptically-related pressure changes create diurnal air flows which more readily affect caves with configurations different from RSU (Yarborough, 1978; Ahlstrand, 1980).

Lehman Caves best fits the criteria for RSU caves. The majority of its passageways are on one level, about 50 feet below the natural entrance. Although there is only one known large natural entrance to Lehman Caves, small, undiscovered openings also probably contribute to and complicate air flow. The entrance and exit constructed by NPS are equipped with airlock doors, minimizing artificial air exchange between the outside and cave interior.

## METHODS

Radon concentrations are monitored in Lehman caves weekly, following the Kusnetz method (Budnitz, 1974). Beginning at 7:00 a.m., eleven 5-minute samples, a combination of stationary and walking, are taken to approximate the time spent in various areas of the cave on a routine tour (Fig. 1, Table 1). In order to avoid daily sampling, the mean of these samples is the "cave average" WL for the following seven days and is used to calculate WLM for each employee who spends time in the cave during that period.

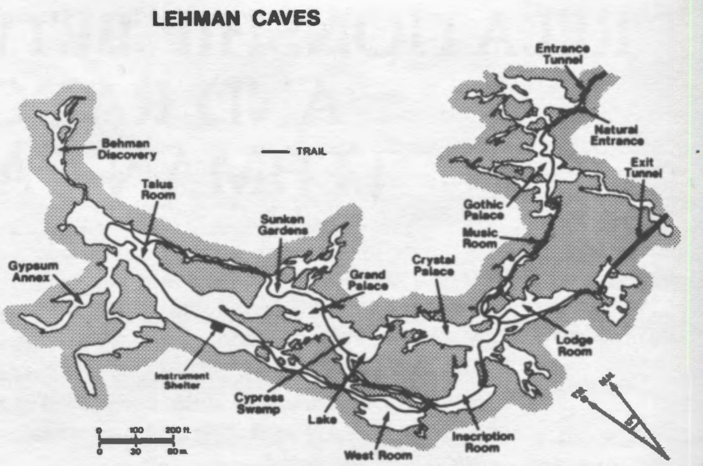


*Figure 1.* **Radon monitoring locations in Lehman Caves, Nevada.**

**Table 1. Radon Sampling Locations in Lehman Caves.**

| | |
|---|---|
| 1. | SS#1—Gothic Palace |
| 2. | WS#1—Entrance Tunnel to Lodge Room |
| 3. | WS#2—Lodge Room to Sunken Gardens |
| 4. | SS#2—Grand Palace |
| 5. | WS#3—Sunken Gardens through Talus Room |
| 6. | SS#3—Talus Room—Benches |
| 7. | SS#4—Talus Room—Billboard Wall |
| 8. | WS#4—Southwest end of Talus Room to Exit Tunnel |
| 9. | SS#5—Lodge Room |
| 10. | SS#7—West Room |

SS = Stationary sample
WS = Walking sample

Radon is sampled by drawing a known volume of air through a filter attached to a battery-operated hand-held pump. Cave air is sampled for exactly five minutes (minimum of 10 liters), with one minute lapse between samples to change filters and locations. Radon daughters on the filters are then counted for 4 minutes on a scintillation-type detector with digital readout within 40 to 90 minutes of sampling.

A standard weather station shelter housing maximum and minimum thermometers for compiling official National Weather Service (NWS) data is located 100 m outside the cave entrance. Temperature data were taken from NWS and NPS records. Weather instruments are read daily at 4:00 p.m., meaning that the weather "day" runs from 4:00 p.m. to 4:00 p.m. Radon measurements are taken between 7:00 and 8:00 a.m. on Mondays. The maximum temperature from the day before sampling, therefore, would have occurred sometime Sunday afternoon, generally between 2:00 and 4:00 p.m. The minimum temperature of the day prior to sampling was considered to be the Sunday night/Monday morning low temperature, because Sunday's low

temperature would actually have occurred late Saturday/early Sunday. This may be construed as previous-day high temperature and same-day low temperature, but these readings represent temperatures closest to, but not after, the time of radon sampling. Other temperature variables may be useful, but preliminary investigations indicated no significant difference in results when various temperature combinations were correlated with radon.

Although atmospheric pressure differences would be a better measure of probable air flow, it was believed that the continuous traces of pressure as measured with barographs inside and outside the cave were too crude to show the minor pressure differences that may create air exchange. Weekly maximum and minimum pressures for a year's time (1982) were compared, using pressure data obtained from barograph charts inside and outside the cave. From January to August both high and low pressures averaged .22 inch higher inside the cave, with most values between .18 and .24 inch. In contrast, differences from September to December of the same year were minimal, with the cave pressure averaging .02 inch above or below the exterior pressures. The difficulty of precise calibration of barographs together with the fact that the abrupt change in measurements coincides with a time when the Park Service typically undergoes a shift in personnel invalidates the pressure data. A simple correlation of radon with exterior high pressure proved valueless, producing a correlation coefficient of .033. Although it is readily acknowledged that pressure differences are the inducements to air exchange and dilution or concentration of radon, little is known either about pressure differences or air flow in Lehman Caves.

Temperature is the only reliably accurate atmospheric variable available for Lehman Caves, and temperature has been successfully correlated with radon concentrations in previous studies elsewhere. Because temperature is easily measured and available, its usefulness in prediction is believed to exceed that of atmospheric pressure, in spite of pressure being the underlying cause of air exchange with the cave.

All data used are from January 1981 to July 1983, for a total of 100 weeks. Winter 1981-82 was omitted from analysis because radon measurements taken during that time are suspected to be erroneous. An error in instrumentation or calculation is suspected because the records for that time period vary consistently from comparable time periods by an order of magnitude.

## ANALYSIS

### *Regressions*

Simple linear regressions were run (BMDP1R) (Dixon, 1985) using six temperature measurements as independent variables (maxima, minima, and means for both the 7-day week and for the day previous to sampling) against the weekly radon WL as the dependent variable. No multiple regression was attempted because of the highly intercorrelated nature of the temperature variables. Even if reliable pressure data were available, the high correlation between pressure and temperature would preclude the inclusion of pressure as an independent variable in multiple regression with temperature. There was little variation in results (Table 2). Correlation coefficients varied from .810 to .852, with 68–75% of the variation in radon WL explained by variation in exterior temperature. Standard errors were consistently high, about .100 WL.

**Table 2. Correlations of Radon WL with Temperature.**

| | $R^2$ | $S_{\hat{y}}$ |
|---|---|---|
| Day Mean | .726 | .093 |
| Day Max | .719 | .096 |
| Day Min | .680 | .101 |
| Week Mean | .715 | .095 |
| Week Max | .656 | .105 |
| Week Min | .715 | .095 |

$p < .001$, $n = 100$ $S_{\hat{y}} = \sqrt{MSE}$

Although there is positive correlation of any of the temperature variables used, the standard errors are so large (between 15% and 50% of the measured radon level) that such regression models would be of limited use in accurate prediction of actual radon WL in Lehman Caves. The correlation coefficient may be acceptable, but the scatter of points around the regression line is not (Figs. 2 and 3).

### *Discriminant Analysis*

A second part of the study was to determine if radon levels below or above .300, a critical point for health, could be predicted from temperature parameters. As discussed above, the regression models are of no use because the

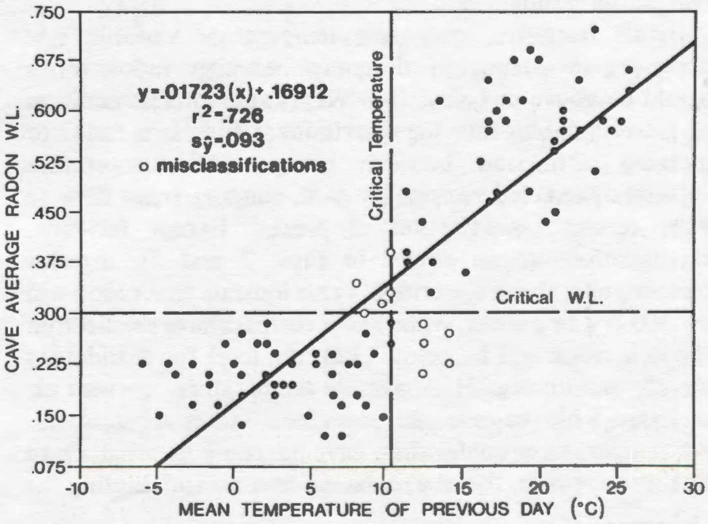


*Figure 2.* **Correlation of radon WL with mean temperature of day prior to sampling. Open circles denote misclassifications.**

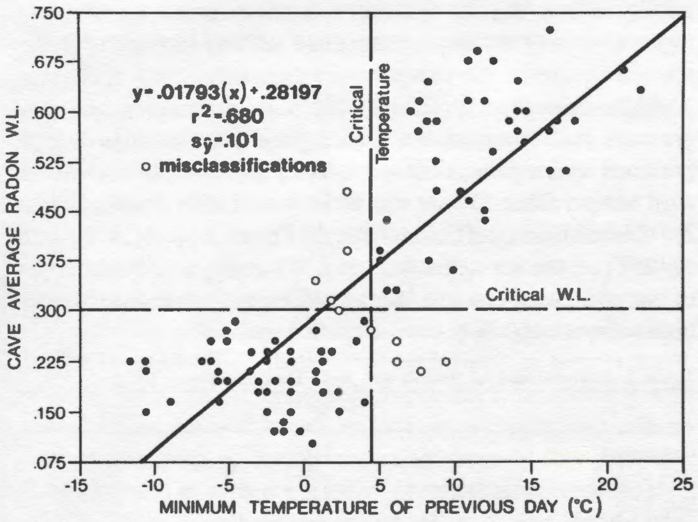


*Figure 3.* **Correlation of radon WL with minimum temperature of day prior to sampling. Open circles denote misclassifications.**

margin of error is too great. Discriminant analysis (BMDP7M) (Dixon, 1985) was used to determine whether any combination of the above temperature variables could accurately separate the potential radon hazard into two groups, those weeks when radon averaged above .300 and those weeks when it averaged below .300. The jack-knifed method of classification, as an accepted alternative to using a new data set, was used to check the accuracy of the discriminant function (Morrison, 1977). On the jack-knifed method, each week's data is eliminated in turn, and a new discriminant function calculated. That week is then classified according to the discriminant function calculated when it was omitted from analysis. This method decreases bias in the results.

In all instances, only one temperature variable was necessary to adequately determine whether radon levels would be above or below .300 WL (Table 3). The addition of more variables into the discriminant functions failed to increase distinction between groups. All temperature variables predicted reasonably well, ranging from 82% to 91% correct classification of weeks. Except for misclassifications (open circles in Figs. 2 and 3), exterior temperatures above the critical value indicate that radon will be .300 WL or greater, while lower temperatures predict that radon content will be below .300, the level for mandatory weekly monitoring. High outside temperatures prevent air exchange with the cave and, therefore, radon accumulates. Air temperatures colder than cave air cause external air to sink into the cave, thereby replacing cave air and diluting the radon.

The best predictor variables are mean and minimum temperatures of the previous day (Day Mean and Day Min) (Figs. 2 and 3) and minimum temperature of the previous

**Table 3. Classification Matrix.**

| Variable | Critical Temp. (°C) | Number of Cases Misclassified: To Below .300 | To Above .300 | % Correct Classifications |
|---|---|---|---|---|
| Day Mean* | 11-12 | 5 | 5 | 90 |
| Day Max | 17-18 | 6 | 6 | 88 |
| Day Min* | 4-5 | 5 | 5 | 90 |
| Work Mean | 11-12 | 7 | 6 | 87 |
| Week Max | 21-22 | 7 | 11 | 82 |
| Week Min* | 0-1 | 6 | 3 | 91 |

(n = 100) *Best predictors

week (Week Min). Both Day Mean and Day Min correctly classify 90% of the weeks, with 10 misclassifications, 5 each to the two groups, above and below .300. Minimum temperature of the previous 7 days (Week Min) correctly classifies 91%, but that slight improvement is the result of fewer misclassifications to the above .300 group. Misclassifications to the above .300 WL group when temperatures are above the critical point present no problem because higher temperatures would indicate that radon concentrations would most likely be above .300 WL and weekly sampling would be done. It is more important for potential health reasons to minimize misclassifications to below .300 when lower temperature would suggest radon levels to be below the critical point that necessitates weekly monitoring. In addition, in the interest of simplicity, a daily mean or minimum temperature is more readily identified than a weekly minimum. There is such minor difference, though, in the results of Day Mean, Day Min, and Week Min that little argument can be made in favor of one over the others.

Four out of the 5 weeks misclassified to below .300 WL are consistent for either mean or minimum temperature of the day before monitoring, indicating perhaps a more complex relationship between synoptic meteorology and air exchange with the cave. Most of the misclassifications according to any temperature parameter fell during spring and fall months when synoptics could change very quickly with passage of frontal systems. More accurate correlations and predictions may be possible using precise pressure data, and this avenue should be explored, but at present, NPS is not equipped to monitor pressure with the precision required. More information is also needed in determining air flow and residence time of air in Lehman Caves.

## SUMMARY AND CONCLUSION

Although there is a significant correlation of temperature with radon WL in Lehman Caves, Nevada, the standard error is too large for precise prediction of radon levels from temperature. Mean or minimum temperature of the day preceding radon sampling, however, can be used to accurately predict whether the WL will be above or below .300, a critical level for health and mandatory weekly

monitoring. If one allows for a buffer to minimize error, the following temperatures become critical. If mean above-ground temperature is below 7-10°C or the minimum temperature is below -1-+4°C, NPS should be justified in foregoing sampling because radon WL should be less than .300 and hazard from radon should be at a minimum.

These results are specific to Lehman Caves and should not be applied to other cave systems. It is interesting to note, however, that the critical mean temperature is about 10°C, which approximates the interior year-round temperature of Lehman Caves. If similar temperature and radon relationships exist in other cave systems, the key to predicting hazardous radon levels may be whether the exterior temperature for a given week or day averages above or below the mean temperature inside the cave.

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Richards, Ronald L. and Munson, Patrick J.—Flat-headed Peccary (*Platygonus*) and Recovered Quaternary Vertebrate Fauna of Indun Rockshelter, Monroe County, Indiana: *NSS Bulletin* **50: 64-71.**

# FLAT-HEADED PECCARY (PLATYGONUS) AND RECOVERED QUATERNARY VERTEBRATE FAUNA OF INDUN ROCKSHELTER, MONROE COUNTY, INDIANA

RONALD L. RICHARDS* AND PATRICK J. MUNSON**

*Archaeological investigation of a sandstone rockshelter in Monroe County, south-central Indiana has produced remains of 45 vertebrate species. Noteworthy is the extralimital occurrence of the eastern woodrat (*Neotoma floridana*) and spotted skunk (*Spilogale putorius*), and the recovery of teeth of an extinct late Pleistocene peccary (*Platygonus sp.*). The fauna suggests temperate deciduous woodlands during accumulation of the deposit. The activities of aboriginal man at the site appear not to be related to the presence of peccary.*

## INTRODUCTION

Indun Rockshelter is located about 15 km from Bloomington, in southern Monroe County, south-central Indiana (the exact location is on file at the Glenn A. Black Laboratory of Archaeology). The shelter lies at an elevation of about 171 m asl and is located near the top of a southward-facing, nearly vertical sandstone cliff. The poorly drained floodplain of Salt Creek (now inundated at this location by Monroe Reservoir) is 15 m below the rockshelter and extends for 0.8 km to the south. Behind and above the rockshelter is the dissected Mitchell Plain.

The Mitchell Plain is a moderately dissected peneplain formed on westward-dipping Mississippian limestones of the Blue River and Sanders groups of the Valmeyeran Series (Malott, 1922). Upland elevations in the vicinity of Indun Rockshelter range from *ca*. 200 to 245 m asl. Salt Creek and its major tributaries have entrenched as much as 90 m into this peneplain, exposing in their valley walls sandstones and siltstones of the Borden Group. The eastern edge of the Crawford Upland lies 6.5 km to the west of the shelter, and the western edge of the Norman Upland is immediately to the east; these two highly dissected uplands rise to elevations as great as 300 m asl.

The Mitchell Plain, Crawford Upland, and Norman Upland comprise a group of unglaciated highlands that extend northward from the Ohio River in south-central Indiana. Lobes of the Illinoian glacier extended along both the western and eastern margins of this highland mass. The eastern lobe of the Illinoian over-rode the Norman Upland some 30 km northeast of Indun Rockshelter, and Salt Creek served at this time as a minor sluiceway for glacial meltwater. At the Wisconsinan maximum, *ca*. 20,000–18,000 ybp, the ice-front lay 45 km to the north of the shelter (Thornbury, 1950; Wayne, 1963; Delcourt & Delcourt, 1981).

Present average annual precipitation for the area is 110 cm and mean annual temperature is 11.3° C. Modern vegetation of the upland areas is Western Mesophytic, with beech, sugar maple, oak, and hickory making up about 80% of the tree species. At the top of the cliff in which Indun Rockshelter is located is a small area of white oak-juniper barrens. The poorly drained floodplain of Salt Creek immediately below and to the south of the shelter supports a mixture of upland species and such lowland trees as silver maple, boxelder, sycamore, and willow. Animals that might be expected within a 0.5 km radius of the rockshelter include aquatic and semi-aquatic species (creek and marsh habitats) and upland deciduous forest species, as well as those species that prefer the relatively xerophytic conditions that result from the steep slope, exposed rock, and southward exposure of the cliff in which the shelter is located.

## DESCRIPTION AND EXCAVATION OF THE SHELTER

The rockshelter (Fig. 1) is approximately 18 m long east-west, with a maximum overhang of 2.4 m. Maximum ceiling height above the bedrock floor is 4.0 m, and ceiling height in most of the shelter exceeds 3.0 m (Fig. 2). The bedrock floor slopes down toward the front of the shelter (south) at an angle of approximately 30°. Floor deposits exceed 65 cm in depth near the front of the shelter and consist of unsorted detritus from the ceiling and back wall; particle sizes range from silt and sand to breakdown slabs weighing over 100 kg.

The rockshelter, which was discovered in 1976 during an archaeological survey of the shoreline of Monroe Reservoir, has been designated as archaeological site 12M0350 in the

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*Figure 1.* **Indun Rockshelter, Monroe County, Indiana, at the beginning of excavations (viewed from the east).**

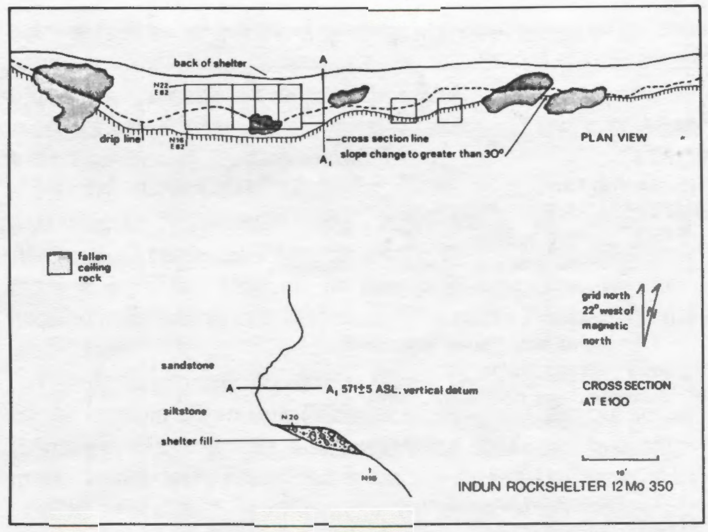


*Figure 2.* **Plan and cross-section views of Indun Rockshelter, Monroe County, Indiana.**

files of the Glenn A. Black Laboratory of Archaeology (Indiana University). Excavations were carried out during the summer of 1978 by an Indiana University archaeological fieldschool directed by Cheryl Ann Munson. Approximately 8.4 m² of the area within the shelter was excavated at this time, primarily from behind the dripline in the widest portion of the shelter. Excavations were conducted in *ca.* 0.9 X 0.9 m (3 x 3 ft) squares in arbitrary *ca.* 15 cm (0.5 ft) levels down to bedrock or massive breakdown. All excavated deposits were dry-screened through *ca.* 6 mm (¼ in) mesh, and a 5% subsample, after dry-screening, was water-screened over window mesh (*ca.* 1.0 mm).

A relatively small quantity of archaeological material was recovered in the excavations. The majority of these items consist of hunting and butchering implements, plus tiny chert flakes that resulted from the sharpening and repair of these implements. Temporally diagnostic artifacts of the Late Archaic (*ca.* 5000–3000 ybp) and Late Woodland (*ca.* 1400–900 ybp) periods were recovered. The rockshelter appears to have functioned as a temporary, intermittently occupied hunting camp for peoples of these periods. No natural strata were discernable in the profiles excavated through the deposits, and analysis of the archaeological materials has demonstrated that artifacts of both periods occur in all levels. Furthermore, remains of an extinct Pleistocene peccary (*Platygonus* sp.) were recovered in levels as much as 30 cm above Late Woodland artifacts. Although no animal burrows were observed in the dry, unconsolidated deposits, it is assumed that bioturbation was the primary cause of the apparent vertical mixing.

The recovered archaeological and faunal materials are curated at the Glenn A. Black Laboratory of Archaeology, Indiana University, Bloomington, under Accession Number 6853.

Abbreviations that are used in the following section are: L, left; R, right; dI/1, dI/2, dI/3, lower first, second and third deciduous incisors, respectively; dP2/, upper second deciduous premolar; dP4/, dP/4, upper and lower fourth deciduous premolars, respectively; M1/, M/1, upper and lower first permanent molars; mm, millimeters; m, meters; ybp, radiocarbon years before present (A.D. 1950).

## SYSTEMATIC PALEOZOOLOGY

A total of 704 bones and bone fragments were identified from Indun Rockshelter (Table 1). These represent a minimum of 72 individual animals of 45 species. Hundreds of small bone scraps of large mammals (most probably of white-tailed deer) were without identifiable characters. To better understand the habitat preference of the extinct flat-headed peccary (*Platygonus*), we have reviewed habitat information on all of the recovered species. Habitat information is primarily from Minton, 1972 (amphibians and reptiles) and Mumford and Whitaker, 1982 (mammals).

### FISHES

Two sections of fin rays and a ctenoid scale of unidentified fishes were recovered.

### AMPHIBIANS

Order Caudata: Salamanders. Four species of salamanders (marbled salamander, *Ambystoma opacum*; spotted salamander, *A. maculatum;* slimy salamander, *Plethodon glutinous*, and the newt, *Notopthalmus viridescens*) were identified on vertebral characters (Tihen, 1958; Holman, 1964, 1968; Davis, 1973), and confirmed with comparative material. The three terrestrial salamanders are rather secretive, the marbled and spotted occupying both upland and bottomland woods, with the slimy common on

**Table 1. Vertebrate materials recovered from the Indun Rockshelter, Monroe County, Indiana.**

| Species | Min. No. Individuals | (No ident. Pieces) |
|---|---|---|
| FISHES | | |
| Indet. fish sp. | 1 | ( 3) |
| AMPHIBIANS | | |
| Family Ambystomidae | | |
| *Ambystoma opacum*, Marbled Salamander | 1 | ( 4) |
| *Ambystoma maculatum*, Spotted Salamander | 1 | ( 3) |
| *Ambystoma* sp., "Mole Salamander" | 1 | ( 5) |
| Family Salamandridae | | |
| *Notopthalmus viridescens*, Newt | 1 | ( 1) |
| Family Plethodontidae | | |
| *Plethodon glutinosus*, Slimy Salamander | 1 | ( 2) |
| Indet. plethodontidae | — | ( 1) |
| Indet. salamander sp. | — | ( 3) |
| Family Bufonidae | | |
| *Bufo americanus*, American Toad | 2 | ( 2) |
| Family Ranidae | | |
| *Rana* cf. *R. palustris*, Pickerel Frog | 1 | ( 1) |
| *Rana* cf. *R. sylvatica*, Wood Frog | 1 | ( 1) |
| *Rana* sp., Frog | 4 | ( 32) |
| Indet. anura, Frogs and Toads | — | ( 85) |
| REPTILES | | |
| Family Emydidae | | |
| Indet. turtle sp. (?*Pseudemys* sp.) | 1 | ( 4) |
| Family Scincidae | | |
| *Eumeces fasciatus/laticeps*, Five-lined or Broad-headed Skink | 1 | ( 2) |
| Indet. lizard sp. | — | ( 1) |
| Family Natricidae | | |
| *Storeria dekayi/occipitomaculata*, Brown or Redbellied Snake | 1 | ( 2) |
| *Thamnophis cf. T. sirtalis*, Garter Snake | 1 | ( 12) |
| Family Colubridae | | |
| *Coluber constrictor*, Racer | 1 | ( 2) |
| *Elaphe obsoleta*, Black Rat Snake | 1 | ( 2) |
| *Lampropeltis triangulum*, Milk Snake | 1 | ( 1) |
| *Diadophis punctatus*, Ringneck Snake | 1 | ( 12) |
| Colubridae cf. *Carphophis amoenus*, Worm Snake | 1 | ( 4) |
| Indet. small colubridae | — | ( 7) |
| Family Viperidae | | |
| *Agkistrodon contortrix*, Copperhead | 1 | ( 3) |
| Indet. viperidae | 1–2 | ( 7) |
| Indet. snake sp. | — | ( 21) |
| BIRDS | | |
| Indet. large bird sp. | 1 | ( 2) |
| Indet. bird sp. (2+species) | 3 | ( 9) |
| MAMMALS | | |
| Family Didelphidae | | |
| *Didelphis virginiana*, Virginia Opossum | 1 | ( 2) |
| Family Soricidae | | |
| *Blarina brevicauda*, Short-tailed Shrew | 6 | ( 36) |
| Family Talpidae | | |
| *Scalopus aquaticus*, Eastern Mole | 1 | ( 1) |
| Indet. mole sp. | — | ( 1) |
| Family Vespertilionidae | | |
| Indet. large bat sp. | 1 | ( 2) |
| Indet. medium-sized bat sp. | 1 | ( 1) |
| Indet. bat sp. | — | ( 2) |
| Family Leporidae | | |
| *Sylvilagus floridanus*, Eastern Cottontail | 1 | ( 1) |
| Rabbit cf. *S. floridanus*, Eastern Cottontail | 1 | ( 9) |
| Family Sciuridae | | |
| Sciuridae cf. *Tamias striatus*, Eastern Chipmunk | 1 | ( 2) |
| *Marmota monax*, Woodchuck | 1 | ( 1) |
| *Sciurus carolinensis*, Gray Squirrel | 1 | ( 1) |
| *Sciurus* cf. *S. niger*, Fox Squirrel | 1 | ( 4) |
| *Sciurus* sp., Tree Squirrel | — | ( 31) |
| Sciuridae cf. *Sciurus* sp., Tree Squirrel | — | ( 12) |
| Indet. small sciurid sp. | — | ( 1) |
| Family Cricetidae | | |
| *Peromyscus* sp., "White-footed Mouse" | 4 | ( 17) |
| *Neotoma floridana*, Eastern Woodrat | 2 | ( 4) |
| *Microtus pinetorum*, Woodland Vole | 8 | ( 12) |
| *Microtus* sp., Vole | — | ( 58) |
| Rodent cf. *Ondatra zibethicus*, Muskrat | 1 | ( 1) |
| *Synaptomys* sp., Bog Lemming | 1 | ( 1) |
| Indet mouse sp. | 2 | (123) |
| Indet. rodent sp. | — | ( 13) |
| Family Procyonidae | | |
| *Procyon lotor*, Raccoon | 1 | ( 2) |
| Carnivore cf. *Procyon lotor*, Raccoon | — | ( 2) |
| Family *Mustelidae* | | |
| *Mephitis mephitis*, Striped Skunk | 1 | ( 1) |
| *Spilogale putorius*, Eastern Spotted Skunk | 1 | ( 2) |
| Indet. mustelid sp. | — | ( 1) |
| Indet. carnivore sp. | 1 | ( 2) |
| Family Tayassuidae | | |
| Platygonus cf. *P. compressus*, Flat-headed Peccary | 1 | ( 9) |
| Family Cervidae | | |
| *Odocoileus virginianus*, White-tailed Deer | 1 | ( 5) |
| Artiodactyla cf. *O. virginianus*, White-tailed Deer | — | ( 14) |
| Artiodactyla cf. *Cervus elaphus*, Elk | 1 | ( 1) |
| Family Bovidae | | |
| *Capra hircus*, Domestic Goat | 1 | ( 1) |
| Indet. artiodactyl sp. | — | ( 31) |
| Indet. mammal cf. artiodactyl sp. | — | ( 7) |
| Indet. mammal sp. | — | ( 56) |
| 45 species | 72 | 704 |

wooded hillsides, especially along streams. The newt is found in woodlands with ponds or marshes.

Order Anura: Frogs and Toads. Ranid frogs were common. Both the wood (*Rana sylvatica*) and pickeral (*R. palustris*) frogs were identified by ilial characters (Holman 1965; Davis, 1973; Lynch, 1965). The American toad (*Bufo americanus*) was identified by ilial characters (Holman, 1967) and by the large size of the tibiofibula. Both the wood and the pickeral frogs occur in rocky, shaded gorges and forested bottomland, the latter also occurring near springs and caves. The American toad prefers grasslands and sparse woods.

## REPTILES

Order Testudinata: Turtles. A relatively thick-shelled turtle (?*Pseudemys*) was represented by four small bone scraps.

Order Squamata: Lizards and Snakes. A right dentary and trunk vertebra represents either the five-lined (*Eumeces fasciatus*) or the broad-headed (*E. laticeps*) skink. Both are woodland species.

A diversity of snake vertebrae were recovered, with each species represented by only a few elements. Vertebrae were identified by characters cited in the following reports: *Storeria dekayi/occipitomaculata,* brown or redbellied snake (Holman, 1962); *Thamnophis sirtalis*, garter snake (Holman, 1962, supplemented by inferences from distribution); *Coluber constrictor*, racer (Auffenberg, 1963); *Elaphe obsoleta,* black rat snake (Auffenberg, 1963); *Lampropeltis triangulum,* milk snake (Holman, 1963); *Diadophis punctatus,* ringneck snake (Auffenberg, 1963; Hill, 1971); *Carphophis amoenus,* worm snake (Auffenberg, 1963); and *Agkistrodon contortrix,* copperhead (Holman, 1963; Rogers, 1976).

The black rat snake inhabits woodlands, both on ridgetops and in lowlands. The ringneck and worm snakes prefer damp, shaded, rocky situations. The milk snake can be found in wooded ravines and on rocky hillsides, as well as in overgrown fields. The copperhead is usually found in dry, rocky terrain in oak-hickory forest. In contrast, the garter snake frequents damp, open grassy areas, and the racer prefers dry, open or forest-edge habitat with good undergrowth. The *Storeria* vertebrae could represent the redbellied snake of the dry, forested upland or the brown snake of various habitats, especially those of open grass country. Bones of aquatic snakes such as *Nerodia sipedon*, the banded watersnake, were not present.

## BIRDS

Eleven fragmented pieces of bird bone (and an eggshell scrap) represented at least three species, possibly including the wild turkey, *Meleagris gallopavo* (L femur, proximal articulation).

## MAMMALS

Family Didelphidae: Opossums. The Virginia opossum (*Didelphis virginiana*) occurs in a variety of habitats, favoring wooded areas. It is a relatively recent arrival into the area from the south in the past three or four thousand years (Guilday, 1958).

Family Soricidae: Shrews. The short-tailed shrew (*Blarina brevicauda*) is one of the most abundant of Indiana mammals, and occurs in most Indiana habitats. Its most common associate is the white-footed mouse (*Peromyscus leucopus*) and, where the moist woods have soft soils, the woodland vole (*Microtus pinetorum*) (Mumford and Whitaker, 1982).

Family Talpidae: Moles. The eastern mole (*Scalopus aquaticus*) was identified by an isolated molar; this mole is found in most Indiana habitats.

Family Vespertilionidae: Bats. Both a large (*Eptesicus fuscus/Lasiurus* sp.) and a medium-sized (?*Myotis* sp.) bat were represented by two teeth.

Family Leporidae: Rabbits. The eastern cottontail (*Sylvilagus floridanus*) was represented by small or fragmented remains. Two minute deciduous premolars were from a juvenile. Cottontails are most abundant in overgrown fields and brush, although they occur sparingly in the woodlands.

Family Sciuridae: Squirrels. Given the abundant activity of the eastern chipmunk (*Tamias striatus*) on the site today (Munson, observation), it is surprising that only two chipmunk bones were recovered from the deposits. Chipmunks inhabit woodlands and brushy or open areas bordering woodlands, and are common in rocky areas and about cave entrances in south-central Indiana. The woodchuck (*Marmota monax*), represented by only one tooth, is presently most abundant in open situations (Mumford and Whitaker, 1982), although it may have originally inhabited the woodlands (Lyon, 1936).

Bones of both the gray (*Sciurus carolinensis*) and the fox (*S.* cf. *S. niger*) squirrels were recovered. A gray squirrel maxilla was identified by the presence of a small premolar alveolus anterior to the molariform toothrow. Fox squirrel was suggested by the large size of several adult postcranial elements. Both squirrels inhabit deciduous woodlands, the gray squirrel occupying denser, more extensive tracts with a heavier understory than the fox squirrel. The two often occur together, one usually far outnumbering the other (Mumford and Whitaker, 1982). Notably the red squirrel (*Tamiasciurus hudsonicus*), common on eastern late Pleistocene sites (Guilday, Parmalee, and Hamilton, 1977), was absent from the assemblage.

Family Cricetidae: New World Mice. *Peromyscus* remains were common, but the recovered M/1's were too worn for species determination (Guilday, Martin and McCrady, 1964; Ray, 1967). Both the white-footed (*Peromyscus leucopus*) and the deer mouse (*P. maniculatus*) are common in Indiana today. The white-footed mouse, perhaps the most abundant mammal in the state, is found in many (primarily woodland) environments, including caves. *Peromyscus* bones are usually the most abundant of non-bat vertebrate remains in cave deposits (Richards, 1972), but at Indun Rockshelter were only half as abundant as those of the woodland vole (*Microtus pinetorum*).

Four bones of the eastern woodrat (*Neotoma floridana*) were recovered at Indun Rockshelter (juvenile maxilla; adult R and fragmentary L dentaries, and fragmentary humerus). The R dentary bears carnivore/scavenger punctures. Today the woodrat occurs in Indiana only in the caves and bluff-crevice escarpments of Harrison and Crawford counties, some 100 km to the south of Indun Rockshelter (Mumford

and Whitaker, 1982). Many other caves in Monroe and nearby counties have yielded woodrat bones, indicating a major reduction of its former distribution (Richards, 1972, 1987). Monroe County remains date back to the Sangamonian interglacial (Parmalee, Munson and Guilday, 1978).

The most abundant vertebrate in the deposit was the woodland vole (*Microtus pinetorum*). Teeth of *M. pinetorum* are very similar to and usually indistinguishable from those of *M. ochrogaster*, the prairie vole. Johnson (1972), however, was able to separate the two species in Iowa with two measurements ("neck" width and posterior length) of the M/1. This method was tested on modern Indiana specimens (47 *M. pinetorum*, 40 *M. ochrogaster*) with similar results (Figs. 3 & 4). Eight of the Indun Rockshelter M/1's fell into the *M pinetorum* size range, while three occurred in the "gray area" between species. None occurred in the *M. ochrogaster* size area (Fig. 4). This suggests that most, if not all, of the M/1's from Indun Rockshelter represent *M. pinetorum*. The woodland vole is primarily an inhabitant of deciduous forests with soft soil and a leaf mold that allows it to burrow easily. However, it also lives on rocky hills and about cave entrances (Hahn, 1908). Its major associates in the woodlands are the short-tailed shrew and white-footed mouse, both common in the Indun Rockshelter deposits.

A section of muskrat (*Ondatra zibethicus*) incisor indicates nearby marshes or streams with emergent vegetation. One grooved upper incisor (fragmented) of a bog lemming (*Synaptomys* sp.) was recovered. *Synaptomys cooperi,* the southern bog lemming, is commonly recovered in grassy fields of Indiana today, and is usually trapped with the prairie vole (*Microtus ochrogaster*), meadow vole (*Microtus*

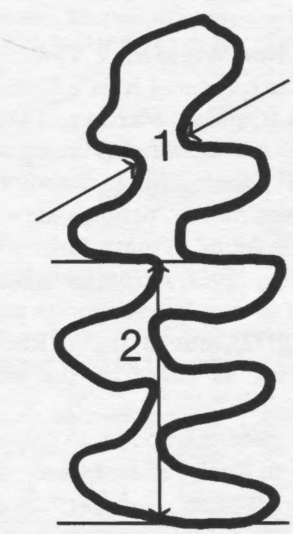


***Figure 3.*** **"Neck" (1) and posterior length (2) measurements, M/1 of *Microtus pinetorum* and *M. ochrogaster* (after Johnson, 1972).**

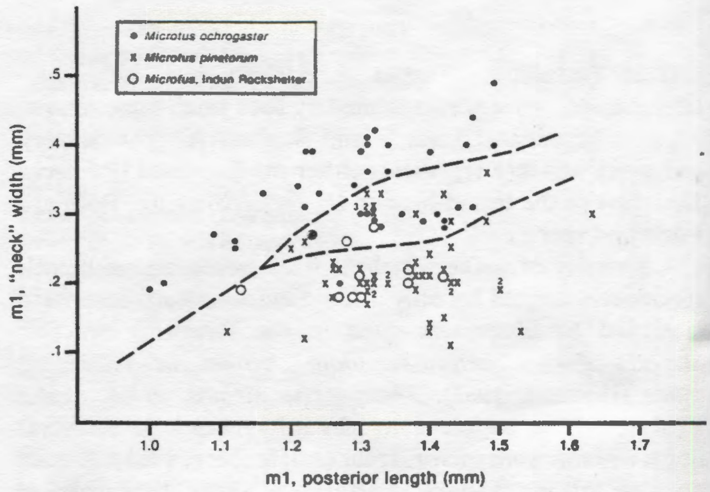


***Figure 4.*** **Separation of *Microtus pinetorum* and *Microtus orchrogaster* by dimensions of the M/1. Modern Indiana sample: 40 *M ochrogaster*; 47 *M. pinetorum.* Indun Rockshelter sample: 11 teeth. Numbers indicate superimposed symbols. Dashed lines suggest distinct and overlapping size zones.**

*pennsylvanicus*) and the masked shrew (*Sorex cinereus*) (Mumford and Whitaker, 1982), none of which were identified from the Indun Site fauna.

Family Procyonidae: Raccoons. Three teeth (2 burned) and a tibia fragment were referred to the raccoon (*Procyon lotor*). The burned teeth indicate aboriginal consumption of raccoon or the incidental scorching of previously deposited remains by heating or cooking fires. Raccoons frequent wooded areas, commonly traveling along waterways, and enter caves.

Family Mustelidae: Weasels and Skunks. The striped skunk (*Mephitis mephitis*), represented by one tooth (L M1/), occurs in a variety of habitats, including woods and fields, and is known to enter caves. Recovery of two elements (radius and L ulna, proximal end) of the spotted skunk (*Spilogale putorius*) is noteworthy. Historic accounts in Indiana date prior to about 1920 and are confined to the southwestern counties. Skeletal remains, however, have been recovered from cave deposits in Harrison, Lawrence and Monroe counties (Bader and Hall, 1960; Richards, 1985) and are known from the Sangamonian of the latter county (Parmalee, Munson and Guilday, 1978). While throughout much of its range the spotted skunk is usually an animal of the prairies and brushy or sparsely wooded areas (Burt and Grossenheider, 1964) present Kentucky populations inhabit the cliffs and rocky areas in the rugged hill country, denning in crevices at the base of cliffs or among boulders (Barbour and Davis, 1974).

Family Tayassuidae: Peccaries. The extinct flat-headed peccary (*Platygonus* cf. *P. compressus*) is represented by

**Table 2. Deciduous tooth measurements (mm), Platygonus cf. P. compressus, Indun Rockshelter, Monroe County, Indiana.***

| TOOTH | ANTEROPOSTERIOR DIAMETER | TRANSVERSE DIAMETER |
|---|---|---|
| L dI/1 | — | 3.48 |
| R dI/1 | 5.51 | 3.48 |
| L dI/2 | — | 4.28 |
| R dI/2 | — | 4.30 |
| R dI/3 | 3.22 | 2.60 |
| L dP2/ | 8.90 | 4.62 |
| R dP4/ | 12.42 | 11.49 |
| L dP/4 | — | ca 9.20** |

*Note: incisor diameters include root, premolars the crown.

**Width of posterior loph.

nine deciduous teeth (left dI/1, dI/2, dP2/, dP/4, posterior fragment; right dI/1, dI/2, dI/3, dP4/, and a broken lower dP crown; R. W. Graham, letter 8 Mar 1988 to R. L. Richards). Measurements are presented in Table 2. The lack of duplication suggests one individual. With all teeth positioned in their alveoli, a juvenile of perhaps 6–40 weeks is indicated by modern collared peccary (*Tayassu tajacu*) tooth eruption (Kirkpatrick and Sowls, 1962). The left dP/4 has a small stylid on the labial side between the second and third transverse lophs (noted by R. W. Graham). No postcranial material could be identified.

Remains of *Platygonus* have, until recently, been uncommon in Indiana. The late Irvingtonian-early Rancholabrean species, *Platygonus vetus* (= *cumberlandensis*), is known from Lawrence (Hay, 1912, 1923; Lyon, 1936; material lost) and Monroe Counties (Parmalee, Munson and Guilday, 1978; Munson, Parmalee and Guilday, 1980; Volz, 1977). *Platygonus compressus,* the Rancholabrean species, is known from Allen (Griswold, 1917; specimen lost), Wabash (Cope and Wortman, 1885; Hay, 1912, 1923; Lyon, 1936; specimen lost), Marion (Munson, in prep.) and Crawford (Richards, in prep.) counties.

The Indun Rockshelter specimen is referred to *Platygonus* cf. *P. compressus* because of the late Quaternary age of the accompanying fauna. *Platygonus compressus* has been recovered from over 80 localities throughout much of the United States below 45° latitude, including California, Arizona, Colorado, Nebraska, Kansas, Texas, Arkansas, Missouri, Iowa, Illinois, Indiana, Michigan, New York, Pennsylvania, Ohio, Kentucky, Virginia, Tennessee, Georgia, and Florida (Kurten and Anderson, 1980; Lundelius, *et al.,* 1983). It is thought to have inhabited open country, sometimes in a peri-glacial environment (Guilday, Hamilton and McCrady, 1971; Guilday, 1971; Ray, Denny and Rubin, 1970). Remains of *Platygonus,* often representing numerous individuals, are frequently found in caves (Guilday, Hamilton and McCrady, 1971; Davis, 1969; Slaughter, 1966; Simpson, 1949; Hood and Hawksley, 1975; Hawksley, Reynolds and Foley, 1973; Hawksley, 1986). This suggests the use of caves and rockshelters for shelter or farrowing. The youngest reliable date for *Platygonus compressus* may be 12,950±550 ybp (Welsh Cave, Kentucky, Meltzer and Mead, 1983). *Platygonus compressus* has not been recovered in archaeological context (Kurten and Anderson, 1980).

Family Cervidae: Deer. Several scraps of metatarsal and other limb bones and small pieces of teeth were attributed to the white-tailed deer (*Odocoileus virginianus*). The remains were extensively broken, burned and rodent-gnawed and appear to represent the refuse of aboriginal meals. Hundreds of unidentified bone scraps of similar taphonomy are also likely of deer. In the eastern United States, deer were often an important food item when animals were extensively exploited by prehistoric peoples. White-tailed deer inhabit woodlands, woodland borders, brushy areas and swamps, and are often found near a water source. Presence of the elk (Artiodactyla cf. *Cervus elaphus*) is suggested by a carnivore/scavenger punctured proximal rib section (R, *ca.* #9). Elk inhabit woodlands, forest edge situations and brushy areas (Mumford, 1969).

Family Bovidae: Bovids. A gnawed left astragalus has been referred to the domestic goat, *Capra hircus* (letter, 8 Mar 1988, R. W. Graham to R. L. Richards). This suggests that the activity of modern scavengers has contributed some of the remains to the deposit.

## DISCUSSION

In general, the small, burrowing and secretive forms (frogs, some snakes, shrews, voles) are represented by multiple elements, suggesting rapid burial in their natural habitat. Larger forms (some snakes, birds, larger rodents, and carnivores) are represented by fewer elements. Some of these bear tooth punctures and may represent parts of prey dragged into the shelter by carnivores and scavengers. Constant movement along the bluffs by carnivores and scavengers would have resulted in the reworking of any freshly deposited, unburied animal remains. Woodrats undoubtedly pilfered unburied bones, carrying them back to their dens in the bluff crevices. Fresh, exposed bone was readily gnawed by most rodents (e.g., mice, porcupine) frequenting the shelter. The food processing of carcasses of deer and perhaps large birds and carnivores by native Americans contributed much of the burned, broken bone to the assemblage.

Because of most of the remains occurred in an expected habitat (e.g., remains of salamanders, frogs, most snakes, shrews, most rodents and some carnivores), and in typical relative proportions (e.g., abundant rodents and few carnivores), it is believed that most of the assemblage represents natural accumulation in the rockshelter, augmented by the activities of man. Species that inhabited upland deciduous woodlands are strongly represented. The white-footed mouse/short-tailed shrew/woodland vole component represents the most abundant animals on the site, and is par-

ticularly indicative of moist deciduous woodlands during deposition. Although some species do indicate open glades in the vicinity (American toad, racer, garter snake, eastern cottontail and striped skunk), only a few individuals are represented. The absence of such grassland and old field species as the prairie vole (*Microtus ochragaster*) and least shrew (*Cryptotis parva*), presently common in south-central Indiana, also suggests the minor role of open areas in the rockshelter area during deposition. Although some aquatic forms are represented (fish, newt, turtle, muskrat), their remains are particularly sparse, suggesting perhaps that the steepness of the bluffs and height of the rockshelter above the former stream channel of Salt Creek may have limited their accumulation.

While the majority of species recovered suggest an environment during accumulation similar to that at the site today, the extralimital occurrence of woodrat and spotted skunk and the presence of the extinct peccary raise doubts. The reduction of range of both the woodrat and spotted skunk, however, took place in relatively recent times, as evidenced by historic observations of the spotted skunk and by a radiocarbon date of 2,315±65 ybp from Freeman's Pit, Monroe County, where both species were present (Richards, 1983, 1985).

Stratigraphic mixing within the deposit seriously limits the interpretation of environmental change. The presence of flat-headed peccary indicates a late glacial/early Holocene environment. Just how that environment differed (if at all) from that in the area today is not discernible from the recovered microfauna, which indicates moist, deciduous woodlands. The majority of the previously described fossils of *Platygonus compressus*, in contrast, have been recovered in contexts that suggest prairie-plains, spruce parkland, or tundra conditions (e.g., Eshelman, Evenson and Hibbard, 1972; Lewis, 1970; Ray, Denny and Rubin, 1970; Slaughter, 1966), environments that are markedly more open and/or cooler than those indicated by the fauna recovered at Indun Rockshelter.

## ACKNOWLEDGEMENTS

We wish to thank Cheryl Ann Munson, Glenn A. Black Laboratory of Archaeology, Indiana University for making the fauna available for study. Russell W. Graham, Quaternary Studies Center, Illinois State Museum, Springfield, kindly identified the *Platygonus* teeth and *Capra* astragalus, and J. Alan Holman, The Museum, Michigan State University, East Lansing, identified the *Lampropeltis* vertebra. John O. Whitaker, Jr., Dept. of Life Sciences, Indiana State University, helpfully loaned crania of *Microtus pinetorum* and *M. ochrogaster* for the M/1 study. John Wyatt, Indiana State Museum, produced Figs. 3 and 4, and the Indiana State Museum Society kindly provided project support.

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# BIBLIOGRAPHY OF INDIANA KARST AND KARST-RELATED LITERATURE

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Indiana contains one of the major areas of karst development in the United States. Solution features associated with the karst of Indiana are restricted to two regions of limestone exposures in southern Indiana. The major and more extensively studied karst region lies within the thick sequence of Mississippian limestones in south-central Indiana. This region includes portions of the Crawford Upland and the Mitchell Plain. The other region is located in southeastern Indiana where the karst features are developed in Devonian and Silurian carbonates but are obscured by a cover of glacial drift.

The purpose of this bibliography is to present a compilation of the descriptive and scientific studies concerning Indiana karst and karst-related papers. The literature search was primarily restricted to general geology and geography journals, master's and Ph.D. theses, and speleological publications. The references have been separated into five categories: speleology, cave descriptions, karst hydrology/hydrochemistry, carbonate geology, and peripheral references. By its very nature, grouping of references into categories is somewhat arbitrary. Many of the references address subject matter which may overlap into more than one category.

"Note: Until the latter 1980's, master's theses at Indiana University, Bloomington, were labelled as A.M., rather than M.A."

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# Index to Volume 50 of the National Speleological Society Bulletin

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This index contains references to all articles and other items of importance published in volume 50 parts 1 and 2 including the abstracts from the 1987 N.S.S. convention. These abstracts are identified by an "(ABS)" preceding the title in the citation.

The index consists of three parts. The first of these is a **keyword index** which starts on **page 78.** Keywords include: unique words from the article title, cave names, geographic names, and descriptive terms. The second part is a **biologic names index** begining on **page 87.** These terms are Latin names of organisms discussed in articles. The third part is an alphabetical **author index** starting on **page 89.** Articles with multiple authors are indexed under each author.

Citations are of the following form: names of all authors in the order which they appear in the journal; title of the article or abstract; volume number and part number (separated by a colon); beginning and ending page (separated by a dash); and year of publication from the cover of the issue. Volume number and year are included in the citation so that their format will match that of the cumulative index of volumes 1 through 45 which was recently published. Within an index group, such as Archaeology, the earliest article is cited first, followed by consecutive articles.

Index data was input on an IBM-PC using the SDI-Soft front-end program designed by Keith Wheeland. The index was prepared on an IBM 4341 computer running a VM/CMS operating system. Indexing was performed by the IBM KWIC/KWOC program as modified by William H. Verity at The Pennsylvania State University Center for Academic Computing. Formatting was accomplished using the SCRIPT text formater, and Generalized Markup Language, with camera-ready copy produced on a Xerox 2700 laser printer.

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# Keyword Index

# Biologic Names Index

# Author Index

## Guide To Authors

The *NSS Bulletin* is a multidisciplinary journal devoted to speleology, karst geomorphology, and karst hydrology. The *Bulletin* is seeking original, unpublished manuscripts concerning the scientific study of caves or other karst features. Authors need not be associated with the National Speleological Society.

Manuscripts must be in English with an abstract, conclusions, and references. An additional abstract in the author's native langauge (if other than English) is acceptable. Authors are encouraged to keep in mind that the readership of *The Bulletin* consists of both professional and amateur speleologists.

For general style refer to the present *Bulletin* and the following guides: "Suggestions to Authors" (U.S. Geological Survey), "Style Manual for Biological Journals" (American Institute of Biological Sciences), and "A Manual of Style" (The University of Chicago Press). For assistance in writing an abstract see "A Scrutiny of the Abstract" by K. Landes, Bulletin of the American Association of Petroleum Geologists, vol. 50 (1966), p. 1992. Because good figures are an essential part of any paper, authors are encouraged to see what bad figures look like in the editorial on figures by K. Rodolfo in the *Journal of Sedimentary Petrology*, vol. 49 (1979), p. 1053-60.

Each paper will contain a title with the author's name and address. This will be followed by an abstract and the text of the paper. Acknowledgements and references follow the text. References are alphabetical with senior author's last name first, followed by the date of publication, title, publisher, volume, and page numbers. See the current issue of *The Bulletin* for examples.

Authors should submit two copies of their manuscript (include only copies of the illustrations) to the appropriate specialty editor or the senior editor. The manuscript must be typed, double space on one side of the page. Authors submitting manuscripts longer than 15 typed pages may be asked to shorten them. All measurements will be in Système Internationale (metric). Other units will be allowed where necessary if placed in parentheses and following the SI units.

Figures and lettering must be neat and legible. Figure captions should be on a separate sheet of paper and not within the figure. Most figures will be reduced, hence the lettering should be large. Once the paper has been accepted for publication, the original drawings (with corrections where necessary) must be submitted to the editor. Black-and-white photographs must be sharp, high contrast, and printed on glossy paper. Color prints will be printed at authors expense only.

All submitted manuscripts are sent out to two specialists for review. Reviewed manuscripts are then returned to the author for consideration of the referee's remarks and revision (where necessary). Revised manuscripts are returned to the appropriate editor who then recommends acceptance or rejection. Upon acceptance, the author should submit all photographs and original drawings to the editor.

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## CONTENTS




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