THE NSS BULLETIN

Journal of Caves and Karst Studies

SALAMANDER CAVE   Monroe Co., Indiana

BREAKDOWN MOUNTAIN

Levias Member

Indian Creek Beds

Spar Mountain Member

10 Ft.
3.05 M.

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Cover: Stratigraphic section for Salamander Cave
(see Conner, page 4).

STRATIGRAPHIC SECTIONS IN THE STE. GENEVIEVE FORMATION (MIDDLE MISSISSIPPIAN) EXPOSED IN GARRISON CHAPEL KARST AREA CAVERNS—WESTERN MONROE COUNTY, INDIANA

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The Ste. Genevieve Formation and related strata in the Blue River Group comprise more than 250 feet of Middle Mississippian carbonate deposition across the Indiana flank of the Eastern Interior Basin in Valmeyeran seaways. Karst outcrop and cavern exposures of these strata occur in the strike-oriented Crawford Upland physiography. Karst valleys are a striking topographic feature along the margin of this rugged escarpment of Chester clastic strata.

Twenty-five miles of surveyed subterranean passages lie beneath the Garrison Chapel karst area occupying a western portion of a karst valley in the headlands of Indian Creek; an area of fifteen square miles. Descriptions of drainage and cavern systems extending from sinkholes to springs have been the focus of more previous investigations.

The bedrock floor of this karst valley is locally accordant with a continuous horizon of lithographic limestone ranging nine to fifteen feet in thickness; within the lower Levias Member as indicated by structure mapping at five measured cavern sections. This lithographic unit is a decisive structural reference for mapping thickness and continuity variations in algal, breccia, and sandy facies in the overlying Paoli and Popcorn Beds and the subjacent Rosiclare Member.

INTRODUCTION

The Garrison Chapel karst area in western Monroe County, Indiana, has been a popular area of subterranean exploration and scientific investigations pertaining to cavern origin and development. More than 40 kilometers of subterranean streams and canyons have been surveyed from water catchment sinkholes and blind valleys downward to the spring resurgences. These caverns lie along the western margin of a distinctive karst erosional valley occupying 35 square kilometers located southwest of Bloomington, Indiana, in the Crawford Upland physiographic division (Malott, 1922, p. 197–203). The Garrison Chapel karst area of about 10 square kilometers and the karst valley at the headlands of Indian Creek are illustrated in Figure 1.

The bedrock host or floor of this karst valley consisting of sinkholes and downstream segments of sinking streams is locally accordant with a solutionally incised horizon of lithographic limestone that is laterally continuous throughout the headland area of Indian Creek. The lithographic limestone beds are generally 3 to 5 meters thick, thin

and evenly bedded cryptocrystalline micrite. They are white with tan and green clay stains. Clay intercalations occur along bedding planes and vertical fractures are filled with clay and recrystallized calcite. Styolites are observed at some exposures coinciding with bedding planes. Stratified nodular chert may be present at some exposures. The lithographic texture distinguishes these strata essentially comprising the lower half of the Levias Member of the Ste. Genevieve Formation. The Ste. Genevieve Formation in the Blue River Group is Middle Mississippian in age. These lithographic beds are named the Indian Creek Limestone Beds (Conner, 1986: Fig. 2).

Recognition of the Indian Creek Beds as a mappable unit is attributed in part to exposures in cavern sections in the Garrison Chapel karst area and comparison to established surface exposures described in the literature. Five measured stratigraphic reference sections in cavern exposures associated with the karst valley are presented with this investigation and illustrate the cycle of subterranean cavern development and related surface valley drainage in accordance with the structural form of the Indian Creek Beds (Fig. 3).

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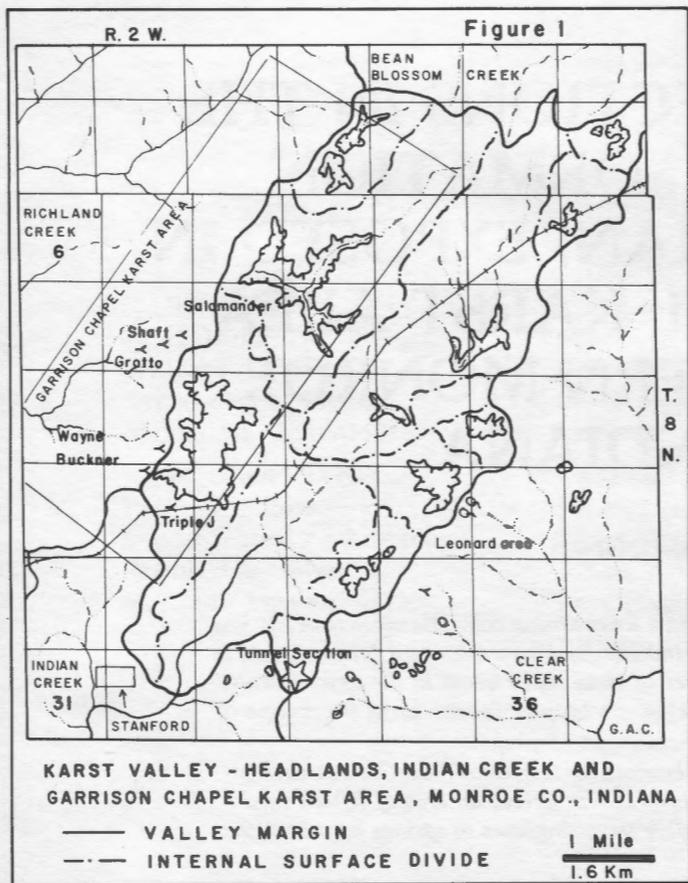
Figure 1. Karst Valley—headlands, Indian Creek and Garrison Chapel karst area.
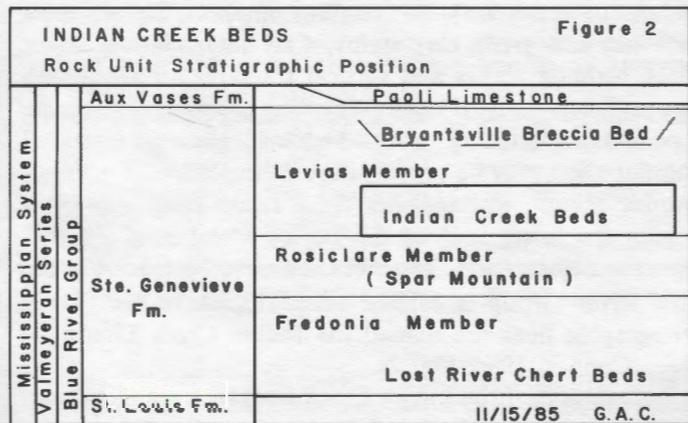
Figure 2. Stratigraphic column indicating position of the Indian Creek Beds.
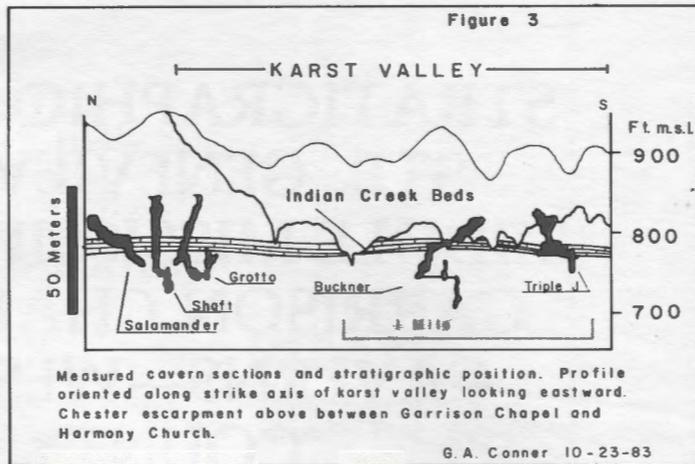
Figure 3. Cross-section illustrating measured cavern sections and their position relative to the Indian Creek Beds.

THE GARRISON CHAPEL KARST AREA

The Garrison Chapel karst area (Fig. 4) described in the Convention Guidebook of the National Speleological Society (1973, p. 16–34), refers generally to four major cavern systems. These westward draining caverns are oriented along the strike axis of the karst valley from Garrison Chapel southward to the Illinois Central Railway grade. The northern most cavern system considered here is comprised of the hydrologically integrated streams flowing through Salamander, Shaft, Grotto, and Coons Caves. Wayne and Buckner Caves lie to the south as separate hydrological drainage systems. Farthest south is the Blair Springs system comprised of Triple J, Brinegar, Trap Door, and King Blair Caves. Many smaller caves are related to these systems. Other major systems lie to the north and east of this area of the karst valley, but were not included in this investigation. Powell (1960) published a statewide survey of known caverns in Indiana. The periodical Newsletter of the Bloomington Indiana Grotto is an important source for articles and maps pertaining to caverns of the Garrison Chapel area.

RECOGNITION OF THE KARST VALLEY

The fifteen minute topographical map of the Bloomington quadrangle (Marshall, 1910) revealed the karst landforms in the headlands of Indian Creek. J. W. Beede (1911) investigated the origin of the karst valley there with description of the area including the Garrison Chapel area while focusing on the eastern side of the valley in the area of Leonard Springs. The springs and related landforms were illustrated with photographs and a pen sketch revealing Beede's interpretation of subterranean stream piracy. Sinkholes above the caverns intercept surface waters from short segments of Indian Creek diverting them downward and southwestward under the Garrison Chapel area through cave streams discharging into Richland Creek. Trending in

Monroe County, Indiana   Figure 4

Base modified 1973 Convention Guidebook,
National Speleological Society

Contours —Ft. mean sea.
— — — Out-crop of Indian Creek Beds based on
altimeter readings, G. A. Conner

I Kilometer

Figure 4. **Topographic map of the Garrison Chapel karst area with structure contours on the Indian Creek Beds.**

the opposite direction other cave streams flow southeastward below the Leonard area discharging waters into Clear Creek to the east.

C. A. Malott (1922) described the landforms and drainage related to the karst valley of Indian Creek and the related phenomenon of subterranean stream piracy. Malott's sketch map outlined the entire karst valley showing internal surface drainage divides and sinkholes in the blind valleys similar to the outlines of Figure 1. The origin and age of the karst valley are related to the Kirksville peneplain discussed by Malott (1919, p. 23). Stratigraphic names Paoli and Ste. Genevieve Limestone were in use at that time, but Malott's reference to the strata employed the earlier terms Mitchell Limestone and the overlying Coal Measures of the Carboniferous strata.

W. J. Wayne (1949) described a karst plain or sinkhole plain as a region underlain by limestone in which all of the drainage is underground. Wayne's map illustrated principally the same area as Malott's map. Wayne discussed the

jointed and oolitic nature of the Paoli and Ste. Genevieve limestones; stating the operational stream piracy of the headwaters of Indian Creek by Richland and Clear Creeks.

STRATIGRAPHIC NOMENCLATURE FOR THE CAVERN SECTIONS

Stratigraphic names employed in the illustrations of the measured rock sections in the caverns (Fig. 2) represent units of current use in rock-unit stratigraphy in Indiana. Emphasis on the word member in the stratigraphic sense, used here for measured sections rather than the words limestone or sandstone following a proper name is intended to maintain conformity with established nomenclature for the Blue River Group in Indiana while omitting an exiguous and reiterative discussion of the attendant nomenclatural revisions over past decades.

The Blue River Group established by Gray et al (1960), includes in ascending order the St. Louis and Ste. Genevieve Formations succeeded by the Paoli Limestone. Divisions of the Ste. Genevieve Formation include the Fredonia Member, with the Lost River Chert Bed, the Rosiclare Member, and the Levias Member including the Indian Creek Beds and the Bryantsville Breccia Bed at the top. The term Spar Mountain Member of Illinois use has been synonymously substituted for the Rosiclare Member of Indiana which has been accepted by most investigators.

The Paoli Limestone and lower sandy beds were considered by N. M. Smith (Shaver and others, 1970, p. 125–128), to be the outcrop equivalent of the Renault Formation. The lower sandy beds were consistently recorded at Indiana exposures under the name Aux Vases Formation by Malott (1952) and by Perry and Smith (1958). Later an exposure of this unit in Lawrence County Indiana was named Popcorn Sandstone Bed by Swann (1963, p. 31, 32). The Popcorn Bed is continuous through the Garrison Chapel area as a calcareous sandstone and shale, but is less than 2.5 cm. in thickness in many exposures there. Illustrated on the figures it is not labeled at its position overlying the Bryantsville Breccia Bed.

DESCRIPTION OF THE CARBONATE AND RELATED LITHOLOGIES

A legend of the lithologic and stratigraphic characteristics of the Blue River Group exposed in the caverns is illustrated in Figure 5. Legend symbols represent the main lithotypes, bedding, and jointing characteristics which allow the beds to be recognized and correlated among isolated exposures.

Carbonate rocks were classified by relative size of crystallinity, grainstone component, and cementation. Sparite generally refers to a cementing material or cavity filling. Crystal size was not directly measured during microscopic examination of hand samples. Granular is a term applied to dolostones, but also to certain calcite and partially dolomitized beds. Micrite was recognized in crystalline and detrital modes, but this detail was omitted from the descriptions substituting the terms crystalline or granular.

Figure 5

Limestone breccia.
Algal & subaerial laminar crust.
Crystalline sparry limestone.
Oolite.
Lithographic limestone.
Sandstone.
Dolostone, sucrosic, vuggy, or chalky.
Granular limestone.
Shale.
Nodular limestone.
Fossiliferous limestone.
Chert.
Steeply inclined joints.
Cross bedding.

Legend of characteristics of the Ste. Genevieve Formation exposed in the Garrison Chapel karst area.

Figure 5. Explanation for stratigraphic sections (Figures 6-10).

Algal structures and related sub-areal laminated crust were frequently observed in the top of the Levias associated with the Bryantsville Breccia Bed. Low and steeply-inclined joints were commonly exhibited in the oolitic and bioclastic beds in the upper half of the Levias Member and the Paoli Limestone. Thin laminar and cross laminar bedding is characteristic of the sandy beds in the Spar Mountain Member. Massive argillaceous detrital limestones with nodular chert and silty laminations are typical of the Fredonia Member including dolostone beds.

DESCRIPTION OF MEASURED CAVERN SECTIONS

Description and measurement of the carbonate rock sections in the caverns were made at Breakdown Mountain in Salamander Cave (Fig. 6); the entrance and lower offset pit in Shaft Cave (Fig. 7); the entrance and offset chambers in Grotto Cave (Fig. 8); entrance, Signature Room, and waterfall in Buckner Cave (Fig. 9); and the entrance crevice in Triple J Cave (Fig. 10).

Bedrock surfaces exposed in cavern walls and shafts are frequently more amenable to recognition of various lithologies than corresponding surface exposures. Surface frost wedging, vegetation, and direct sunlight are not a major influence on modification of cavern walls that are sculptured by water or gravity fall of jointed blocks.

Irregularities and surface relief exposed on the cavern walls results from solution features which are generally smooth and curved or from breakdown falls which leave straight and angular fracture surfaces. Both types of features reveal some degree of surficial leaching as a response to differential moisture after the bed is left above the high water level of the cave stream.
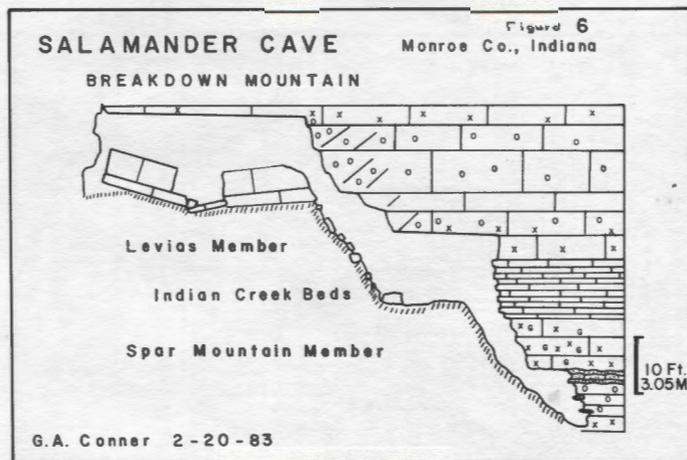
Figure 6. Stratigraphic section for Salamander Cave. See Figure 5 for key.
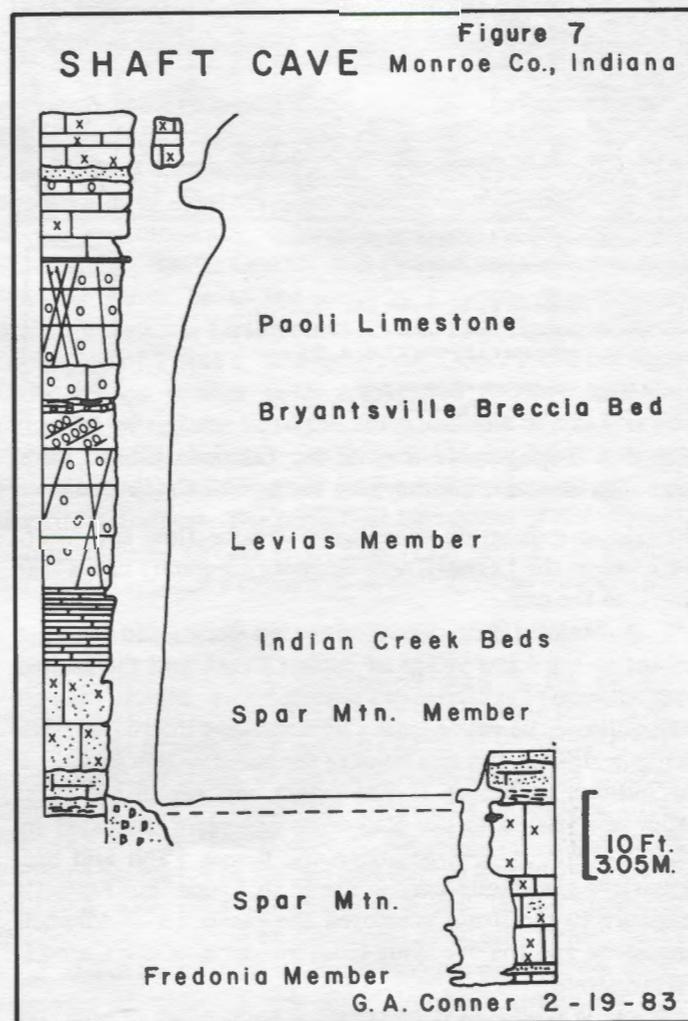
Figure 7. Stratigraphic section for Shaft Cave. See Figure 5 for key.
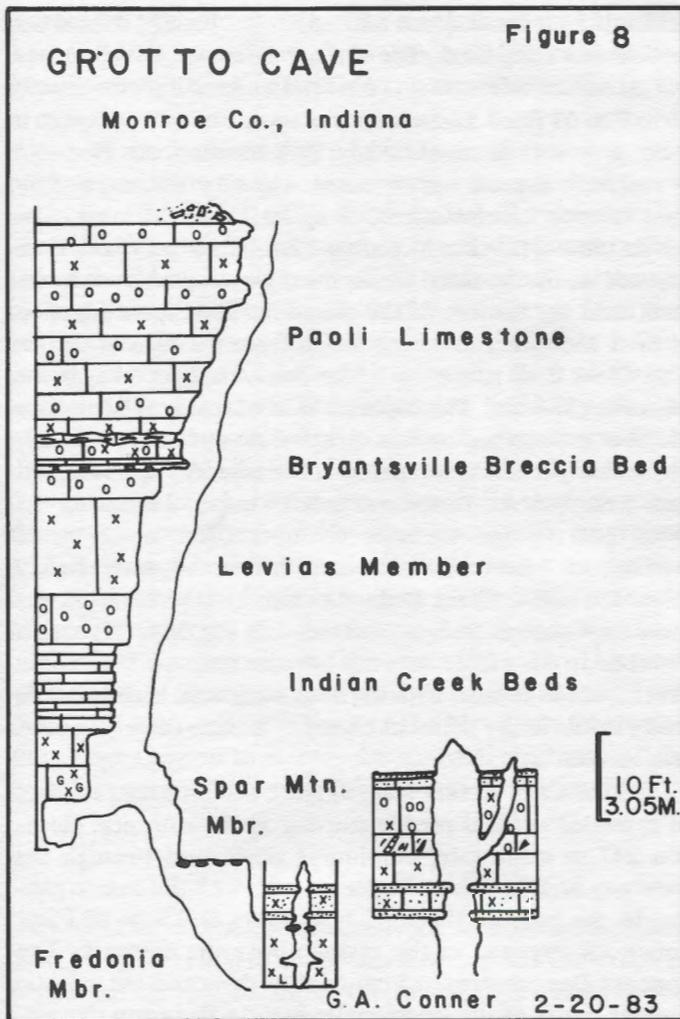
Figure 8. Stratigraphic section for Grotto Cave. See Figure 5 for key.

Figure 9. Stratigraphic section for Buckner Cave. See Figure 5 for key.

Individual beds or groups of beds are observed to stand in relief from the plane of the wall or are reentrant. The reentrant zones are recessed behind the wall plane. Harder and more indurated carbonates and those high in insoluble grains as well as the more coarsely crystalline beds tend to stand in relief from walls in contrast to the oolitic and bioclastic beds. Clayey shales tend to be more reentrant where plastic flow, pressure unloading, and differential moisture influence them.

Sandstones and silty shales usually are exposed in relief from the walls, but are not always conspicuous. Dolostone is usually found in relief and is often sculptured into erosional forms extending across the entire width of canyons as bridges because of its lower solubility rate and a propencity to become coated with precipitated carbonate and manganese dioxide. Where dolostone is not coated, it typically develops a soft chalky surface. Carbonate precipitated on cavern walls results in various forms referred to as speleothems and frequently covers silty or sandy beds where porosity permits water seepage. Wall forms are important in recognizing the textural types of carbonate strata when tracing from one reference section to the next.

Breakdown Mountain in Salamander Cave (Fig. 6) is located about 150 m upstream from the entrance and is generally accessible except for rapid short term crest during thunderstorms. The section profile is drawn facing outward or downstream. A floor elevation of 227 m mean tide was established by Paulin altimeter. The lower canyon walls reveal the top sandy beds of the Spar Mountain Member exposed 2.7 m above the floor. The Indian Creek Beds in the lower Levias Member above measure 2.9 m in thickness with the base resting on the Spar Mountain. Above in the breakdown chamber the oolitic, bioclastic and jointed beds of the upper Levias Member are well exposed in the ceiling. The Bryantsville Breccia Bed was not observed, but would lie several meters above the ceiling.

The entrance pit to Shaft Cave (Fig. 7) is located about 180 m southwest of Breakdown Mountain in Salamander Cave. The entrance lies at an elevation of 251 m mean tide and drops 23 m to a canyon developed in the middle of the

TRIPLE J CAVE

Figure 10

Paoli Limestone

Levias Member

Indian Creek Beds

Spar Mountain Member

10 Ft.
3.05M

G. A. Conner 2-19-83
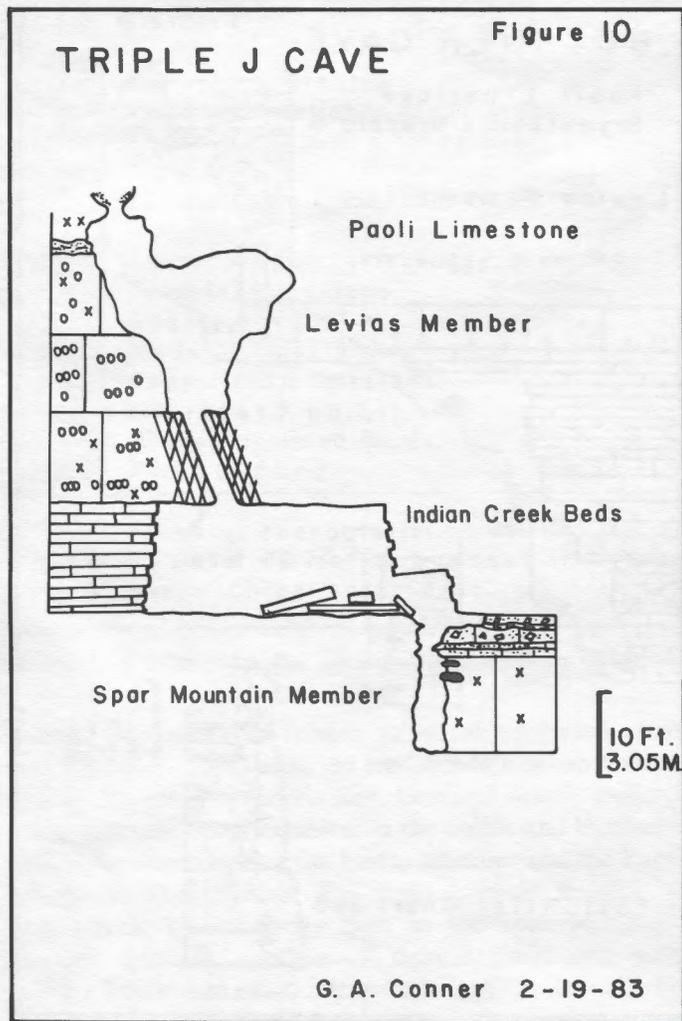
Figure 10. **Stratigraphic section for Triple J Cave. See Figure 5 for key.**

Spar Mountain Member leading to an offset lower pit 9 m away where 6 meters of strata are exposed down to a lower stream canyon in the top of the Fredonia Member. At the top of the entrance pit a finely crystalline micritic limestone is exposed. Below the lip of the pit 0.75 m of calcareous sandstone is exposed consisting of brown weathered very fine-grained quartz. The stratigraphic names of these two units is discussed in the summary of correlations. The Paoli Limestone measures 7.1 m thick. The lower sandy bed, the Popcorn Bed of Swann, is obscured by flowstone, but measures 9.1 cm thick resting on the Bryantsville Breccia Bed. The entire Levias Member measures 9 m thick with the Indian Creek Beds comprising 2.9 m. The Spar Mountain Member measures 10.4 m including a thin silty bed near the floor of the lower pit. Below, one foot of finely crystalline limestone is exposed in the floor of the stream canyon marking the upper unit of the Fredonia Member. Shaft may be entered safely in dry weather with modern rope ascending equipment.

Grotto Cave section (Fig. 8) was measured in the entrance chamber about 180 m southwest from Shaft. A steep slope

descends to a small dome and adjacent chamber where the section was continued. The surface reference elevation was 244 m mean tide measured with Paulin Altimeter. From there 6 m of Paoli Limestone was measured downward to a 3 cm grey silty lamination marking the Popcorn Bed. No Bryantsville Breccia was observed. The silty unit rest directly on a micritic bioclastic bed of upper Levias Member. The Levias measures 9.5 m including 2.8 m of Indian Creek Beds exposed at the boulder which must be climbed over in descent near the bottom of the chamber. The exposed section of Spar Mountain measures 8.6 m from the base of the Indian Creek Beds to the top of the Fredonia 22 m away in the adjacent chamber. The top and base of the Spar Mountain Member are marked by thin resistant sandy lentiles in relief. These sandy lentils are exposed in the adjacent chamber, but were not observed in the entrance chamber. Instead in the lower part of the entrance chamber there is 1.9 m of argillaceous limestone exposed, with no sand, immediately below the Indian Creek Beds. Again as at Salamander Cave, these argillaceous beds are included in the Spar Mountain Member in an effort to establish the base of the Indian Creek Beds in contact with the Spar Mountain Member. The sandy lentils in the adjacent chamber include three modes of detrital quartz.

Buckner Cave section (Fig. 9) lying 1.8 km to the south is an extended vertical profile starting at the entrance, elevation 247 m mean tide, continuing downward through the crawlway and Signature Room then through the stream canyon to the base of the waterfall. There is 0.9 m of Paoli Limestone exposed in the ravine above the entrance. The Popcorn Bed measures 15 cm of silty shale and the micritic laminar crusts of the Bryantsville Breccia Bed form the ceiling. The Levias Member measures 11.3 m including 3.7 m of Indian Creek Beds. Near the Signature Room the base of the Indian Creek Beds is well exposed near the ceiling where 2.4 m of slightly sandy crystalline limestone underlies them marking the contact with the Spar Mountain Member. The entire Spar Mountain Member measures 4.9 m with detrital chert in the sands. The Fredonia Member measures a total exposed thickness of 11.4 m traced through the stream canyon, with a very steep floor gradient, and ending in a waterfall. The Lost River Chert Bed is exposed as a resistant ledge below the lip of the waterfall.

The Triple J Cave section (Fig. 10) lies 900 m south of the Buckner Cave entrance and is estimated to lie at an elevation of 245 m mean tide. One meter of Paoli limestone is exposed inside the entrance in the sinkhole. On a ledge 36.6 cm of sandstone is exposed which is identified as the Popcorn Bed, the best development of the Popcorn in the Garrison Chapel area. Alternatively, this sandstone may be considered to be the upper sandstone exposed in Shaft Cave and consequently the identification of the Paoli Limestone at Triple J would be affected. At Triple J the Bryantsville Breccia Bed is not recognized. Considering the observation that the Popcorn Bed is much more thickly developed several kilometers

southeast of Triple J Cave and the exceptionally thick oolitic section in the upper Levias Member at Triple J where the Bryantsville is absent, it is preferable to refer the sandstone of question to the Popcorn horizon. The Levias Member is unusually thick measuring 12.0 meters attributable to a thick upper oolitic section; perhaps near the center of a convex oolite body. The Indian Creek Beds below measure 3.6 meters and rest directly on a sandy breccia bed marking the top of the Spar Mountain Member. Chert sand is also present in the breccia; however, the section is different from that at the Signature Room in Buckner Cave. In Triple J Cave the Spar Mountain measures 4.7 m to the floor at the entrance. Below the sandy breccia section lies 3.2 meters of micritic lime with sparse chert nodules. Farther downstream the lower Spar Mountain Member was recognized beyond Aqua Avenue at survey stations C5 and C11 through to the Cherty Channel. There a 0.5 m thick green sparry gastropod and brachiopod limestone capped by a 15.2 cm silty clay bed is recognized as the lower boundary of the Spar Mountain Member overlying a micritic limestone with concentrations of chert nodules representing the upper Fredonia. This same silty clay bed and gastropod limestone association is observed 6.4 km to the southeast in the Mountain Room and Blue Pool Canyon in Reeves Cave. Total thickness of the Spar Mountain Member in Triple J was not determined.

SUMMARY OF CORRELATIONS

Correlation of the reference cavern sections in the Garrison Chapel karst area to the units of Indiana out-crops is established by recognition of the Indian Creek Beds in the lower Levias Member which are recognized twenty miles away at the Cataracts on Mill Creek where Malott (1946) subdivided the Ste. Genevieve Formation in Indiana. Additionally, Malott (1952, p. 57) described the lithographic beds now named Indian Creek Beds where they appear in the "old tunnel section" 4.8 km east of the Garrison Chapel area.

The entire stratigraphic interval of the Spar Mountain Member was measured downward from the base of the Indian Creek Beds in Shaft, Grotto, and Buckner revealing an average thickness of 7.3 m, with a maximum of 10.4 m in Shaft and a minimum of 4.9 m in Buckner.

The upper portion of the Levias Member, the oolitic and bioclastic beds, overlying the Indian Creek Beds was measured in all five sections averaging 6.7 m except for a thickness of 8.3 m in Triple J entrance which is interpreted as the center of a convex oolite bar.

The upper sandstone near the top of Shaft Cave entrance is 7 m above a shaley bed interpreted as the Popcorn Bed of Swann. The intervening oolitic limestone is lower Paoli and the sandstone is agreeably equivalent to either the Basin Aux Vases Sandstone or the higher Renault Sandstone. The micritic limestone above is upper Paoli and confirmed by a thick massive sandstone higher on the slope; the Mooretown of Indiana outcrops or the Bethel of Basin usage. Two kilometers to the west on the Leininger farm 6.8 m of Bethel Sandstone was logged between the Beaver Bend and Paoli Limestone in Indiana Geological Survey Drillhole No. 155. Bethel Sandstone in the area is consistently more than 3.6 meters thick in known exposures.

Correlation of the individual beds within the Ste. Genevieve Formation and the Paoli Limestone in the Garrison Chapel area and karst valley is relatively straightforward with exception to the thin clastic beds within the Paoli Limestone which may be locally discontinuous within the area of an individual cave system.

REFERENCES

Beede, J. W. (1911)—The cycle of subterranean drainage as illustrated in the Bloomington, Indiana Quadrangle: Indiana Acad. Sci. Proc., v. 20, P. 81–111.

Conner, G. A. (1986)—Type section for Indian Creek Beds in the Ste. Genevieve Formation of South-Central Indiana: Indiana Acad. Sci. Proc., v. 95.

Gray H., Jenkins, and Weidman (1960)—Geology of the Huron area, south-central Indiana: Ind. Geol. Surv. Bull. 20, 78 p.

Malott, C. A. (1919)—The American Bottoms Region of Eastern Greene County, Indiana: Ind. Univ. Studies No. 40: 45 p.

Malott, C. A. (1922)—The physiography of Indiana, in Handbook of Indiana geology, Indiana Dept. Cons. Pub. 21, pt. 2, p. 59–256.

Malott, C. A. (1946)—The geology of Cataract Falls, Owen County, Indiana: Jour. Geology, v. 54, p. 322–326.

Malott, C. A. (1952)—Stratigraphy of the Ste. Genevieve and Chester formations of southern Indiana: Ann Arbor, Mich., Edwards Letter Shop, 105 p.

Marshall, R. B. (1910)—Bloomington, Indiana Quadrangle. U.S. Geological Survey 15 minute series.

National Speleological Society (1973)—Convention Guidebook: Bloomington, Indiana, Bloomington Indiana Grotto.

Perry, T. G., and Smith, N. M. (1958)—The Meramec-Chester and intra-Chester boundaries and associated strata in Indiana: Indiana Geol. Surv. Bull. 12, 110 p.

Powell, R. L. (1960)—Caves of Indiana: Indiana Geol. Surv. Circ. 8, 127 p.

Shaver, R. H. and others (1970)—The Indiana compendium of rock-unit stratigraphy: Indiana Geol. Surv. Bull. 43, p. 143.

Swann, D. H. (1963)—Classification of Genevievian and Chesterian (late Mississippian) rocks of Illinois: Illinois Geol. Surv. Rept. Inv. 216, 91 p.

Wayne, W. J. (1949)—A karst valley in western Monroe County, Indiana: Indiana Acad. Sci. Proc., v. 58, p. 258–263.

STRUCTURAL AND STRATIGRAPHIC INFLUENCES ON THE DEVELOPMENT OF SOLUTION CONDUITS IN THE UPPER ELK RIVER VALLEY, WEST VIRGINIA

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The upper Elk River Valley is located in northern Pocahontas and southern Randolph Counties, West Virginia. For over 8 km (5 miles), this valley is floored with Mississippian Greenbrier Group limestones dipping gently to the west. Upon reaching the Union Limestone near the top of the Greenbrier Group, the Elk sinks and then rises at two sets of occluded riverbank springs, also at the top of the Union Limestone and 8 km (5 miles) to the north. Over 29 km (18 miles) of surveyed cave passages, seen in and adjacent to the upper Elk River Valley, contain streams flowing for up to 12.9 linear kilometers (8 linear miles) and 244 vertical meters (800 feet) between sink and rise. Half of these passages are developed along joints which follow a NE-SW trending fracture trace carrying drainage from an adjacent river basin to the upper Elk River. Where the fracture trace crosses the Elk River, the river sinks, drops 38 vertical meters (125 feet) through both the upper Greenbrier Group limestones and the shaley Taggard Formation below (normally a major aquitard). The remaining passages are seen in several caves which parallel the Elk River Valley to the north of the fracture trace. These caves, extending over a 3.2 km (2 mile) linear distance along and beneath the Elk's Valley, underdrain it and consist of solutionally enlarged beds found at several distinct stratigraphic horizons. The underground Elk, seen in two of these caves, flows beneath the Taggard Shales until the elevation of the shales passes beneath that of the lower set of springs. This paper discusses the relationships between these two patterns of caves, outlines a sequence of cave development for this area, and discusses the nature of the underground flow paths of the Elk River and its tributaries.

Introduction and Background

The Elk River rises in northern Pocahontas and southern Randolph Counties in eastern West Virginia (Fig. 1), flows to the west, and drains into the Kanawha River at Charleston, West Virginia. Speculation about the existence of caves beneath the bed of the upper Elk River has occurred since the late 19th century. In 1898, Hu Maxwell, a West Virginia historian wrote:

"Theory and all known facts lead to the conclusion that a cave of enormous dimensions exists in Randolph County under or near the course of the Elk River between the Pocahontas County line and the mouth of Valley Fork six miles below. But no one has ever yet found an entrance into the cave, and its existence cannot be positively affirmed. The facts which are explained on the theory of a vast cave are these: Elk River, except in time of freshet, flows into a crevice at the foot of a mountain, or when very low, disappears among the boulders of its channel . . . and six miles below, the water rushes to the surface. Its underground
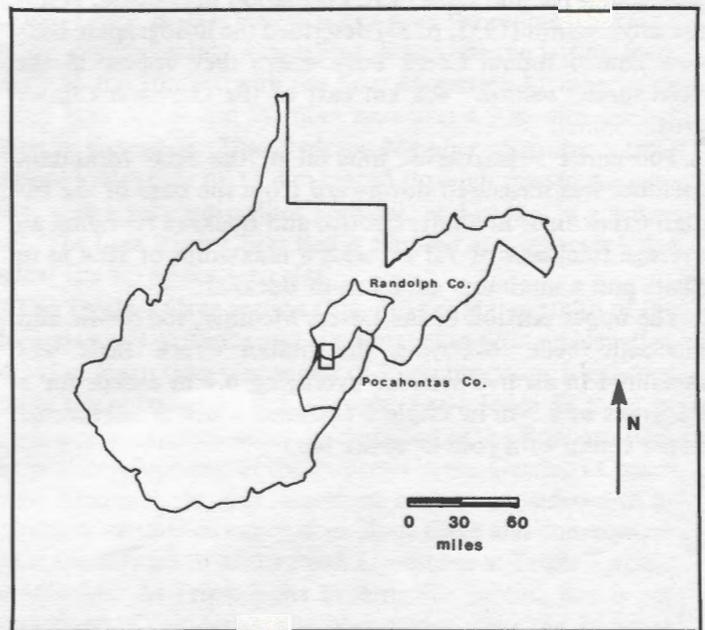

Figure 1. Map of West Virginia showing study area location.

course is through limestone and it must flow through galleries of large size. In 1896, near the point where the water sinks, a portion of the river bottom dropped down, leaving an opening about 15 feet square into which the whole river plunged and disappeared. No bottom was visible, and no one attempted to enter or examine. The next flood filled the opening with boulders.'' (Maxwell, 1898).

In spite of years of speculation and searching, no caves were known to exist beneath the bed of the Elk River. Indeed, only two sizeable caves approached the valley: the downstream end of the 12.9 km (8 mi) long Simmons Mingo/My Cave complex and Falling Springs Cave, developed beneath Falling Springs Run, an infeeder to the Elk River. Since 1981, over 9.7 km (6 mi) of passage have been explored and surveyed in three newly-discovered caves which parallel the surface bed of the Elk and which are developed up to 40 vertical meters (130 ft) beneath it. Also, the length and depth of Falling Springs Cave have been extended and, in one of the newly-discovered caves, a segment of the underground Elk River has (finally) been found flowing in accessible passage for a distance of about 800 m (0.5 mi).

In this paper, we discuss stratigraphic and structural influences on both the development and orientation of the Elk River valley caves, postulate a sequence of cave development for this area, and discuss the nature of the underground flow path taken by the underground Elk under both low and high flow conditions.

METHODS USED

As part of the work carried out in preparing this paper, over 8 km (5 mi) of surface surveys have been carried out to determine relative positions of cave entrances, the bed of the Elk River, springs, the top of the Union Limestone and other karst features with respect to the locations of several U.S. Coast and Geodetic Survey benchmarks in the Elk River valley. These surveys, carried out with handheld and tripod-mounted Brunton and Suunto compasses and clinometers, and fiberglass tapes, were repeated as necessary to obtain consistent results. Elevations were also obtained with an altimeter (accuracy ± 2 feet) calibrated at one of the benchmarks. Changes in atmospheric pressure, obtained with a recording barograph at the benchmark, were taken into account in adjusting the altimeter readings. The mean deviation between elevation differences obtained via surveys and altimeter readings was 4.0 feet. Surveys conducted in the caves were with handheld Suunto compasses and clinometers and fiberglass tapes. Survey loops were closed using the Survey Manipulation, Analysis and Plotting System (SMAPS) software package developed for cave surveys. The mean closure error for survey loops in the caves was 0.8 percent.

Limestone thicknesses were measured both on the surface and in caves as part of the surveys. Where contacts at the top and bottom of major members of the Greenbrier Group

were crossed in the caves, thicknesses were computed taking strike and dip into account. Numerous strike and dip readings were taken throughout the study area. Estimates of regional strike and dip were also obtained by taking the surveyed coordinates of widely-spaced points at the top of the Union Limestone, and, using least squares technique, fitting a plane to these points. The strike of the fitted plane differed from the mean of the observed strike readings by 3 degrees while the dip of this plane differed from the mean of the observed dip readings by 0.25 degrees.

Stream tracing was carried out using sodium fluorescein dye and activated charcoal detectors. Adsorbed dye was elutriated from the charcoal using a 10 percent solution of KOH in ethanol. Testing for the presence of dye was carried out using a Turner model 111 fluorimeter.

PHYSIOGRAPHIC AND GEOLOGICAL SETTING

The Elk River rises on clastic rocks in the Allegheny Plateaus Province in eastern West Virginia. Relief in the area is 500–700 m (1700–2300 ft) with ridgetops reaching elevations of 1280–1380 m (4200–4500 ft) and consisting of rocks of the (Upper Mississippian) Mauch Chunk and (Lower Pennsylvanian) Pottsville Formations. In the study area, the Elk River ranges from 760–690 m (2500–2260 ft) in elevation, flows north-northwest through a narrow, steep-sided valley and has a gradient of 7.6 meters per kilometer (40 feet per mile), both on the Greenbrier Group carbonates and on the clastics above and below.

The oldest rocks exposed in the area are those of the (Middle Mississippian) Greenbrier Group, a sequence of limestones containing thin interbedded layers of shales and sandstones. Locally, the Greenbrier Group varies in thickness from 92–104 m (300–340 ft) although only the upper 25–30 m (80–100 ft) of the Greenbrier are exposed in and immediately adjacent to the bed of the Elk River and its tributaries. A general view of the dry bed of the Elk River is shown in Figure 2. In the study area, the measured dip varies

Figure 2. **Dry bed of the Elk River. Exposed bedrock is Union Limestone. Photo by Bill Storage.**

between 1.0 and 1.5 degrees and the strike varies between due north and N15E. A map of that part of the Elk River valley that is discussed in this paper is given in Figure 3. The shaded area represents exposures of the Union Limestone, the highest major cave-forming unit in the Greenbrier Group. The letters refer to those major karst features in this area that are discussed in the text of this paper.
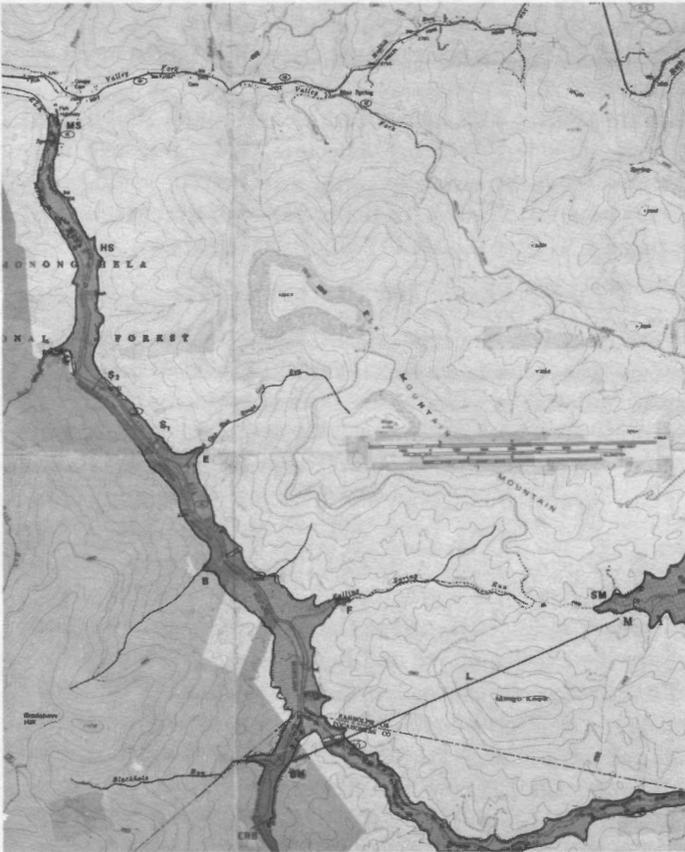
Figure 3. Limestone exposures and other major features in the Elk River area.

Faulting in the valley consists of low angle thrusts striking north-south and having minimal displacement. These faults modestly influence the directional orientation of the caves but have a greater influence on passage morphology. Where faults are encountered, passage walls/ceilings generally follow the fault plane. A substantial fracture zone/lineament trending N58E crosses the Elk River valley at the location where much of the Elk sinks. This feature (Fig. 3, L) as will be noted below, plays a major role in influencing the location of the underground Elk in the Greenbrier Group limestones.

STRATIGRAPHY

In the Elk River valley, the stratigraphic sequence of limestones and interbedded clastics in the Greenbrier Group influences the placement of cave passages in the limestones. In descending stratigraphic order, these members are described below. Descriptions and thicknesses are based on

Reger (1931), Wells (1950), and the authors' measurements in the area. A column is given in Figure 4.
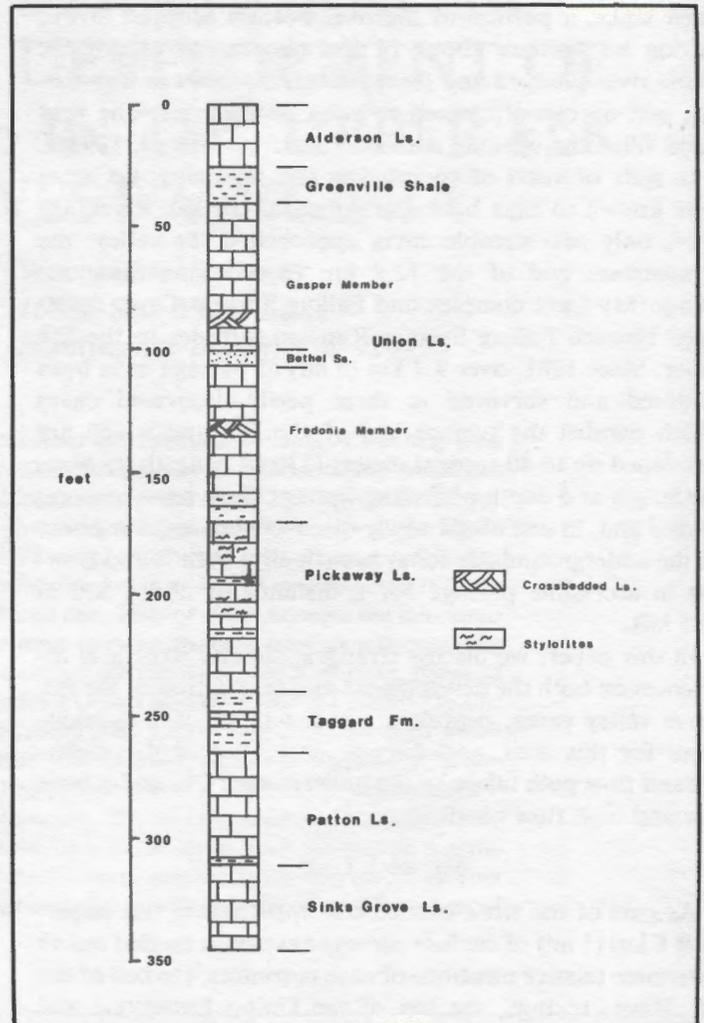
Figure 4. Stratigraphic column of the Greenbrier Group in the study area.

ALDERSON LIMESTONE

The youngest member of the Greenbrier Group, dark grey, shaley, weathering yellow and about 8 m (25 ft) thick. It outcrops 25–30 m (80–100 ft) above the Elk River bed and is not a major cave former.

GREENVILLE SHALE

A dark red, thin-bedded, sandy shale, 4–6 m (15–20 ft) thick. A major aquiclude, it separates the Alderson from the main carbonate sequence below.

UNION LIMESTONE

One of the major cave formers in the study area; 40–43 m (130–140 ft) thick and in three parts. The upper limestone (Gasper Member) is 21–24 m (70–80 ft) thick, is light grey, sandy in places, oolitic, and occasionally crossbedded. Below it is a 1–2 m (3–5 ft) thick sandstone/sandy limestone

(Bethel Sandstone Member) which serves as a minor perching bed. The lower limestone (Fredonia Member) is lithologically similar to the Gasper Member.

PICKAWAY LIMESTONE

Another major cave former, the Pickaway is hard, stylolitic, weathers yellow to tan and varies in thickness from 17–21 m (55–70 ft) in the area. This limestone does not outcrop on the surface in the Elk River valley. The Pickaway contains two unnamed shaley beds, each about 300 cm (one ft) thick. These beds are found 7 and 14 m (22 and 45 ft), respectively, below the top of the Pickaway and are significant in that they control the locations of passage floors and ceilings in several of the caves. The Pickaway also contains several other beds of unnamed shales and siltstones, these generally only a few centimeters thick but acting as local aquitards in the caves.

TAGGARD FORMATION

This formation consists of an upper red shale, 1.5–3 m (5–10 ft) thick, a limestone weathering almost white 1.5 m (5 ft) thick, and a lower red shale, also 1.5–3 m (5–10 ft) thick. While not exposed in the Elk River valley, the Taggard is seen in several of the Elk River valley caves and serves as both a capping and a perching bed.

PATTON LIMESTONE

Dark grey, partly oolitic, sandy, with stylolites in its upper part and, in places, crossbedded. Not exposed on the surface but seen in the lowest levels of the Elk River valley caves and in Simmons-Mingo Cave. Thickness varies from 12–15 m (40–50 ft).

SINKS GROVE LIMESTONE

The lowest member of the Greenbrier Group in the study area, the Sinks Grove is dark, weathers yellow, is impure and slightly oolitic. Exposed only at the lowest levels in Simmons-Mingo Cave, it is not seen in any of the Elk River valley caves. Thickness is 8–11 m (25–35 ft).

LOCAL KARST HYDROLOGY

For a distance of almost 10 km (6 mi), the valley of the Elk River is floored with Mississippian limestones of the Greenbrier Group. Where it crosses into the upper Union Limestone, the Elk River sinks in its bed (Fig. 3, ERB and BH) and for much of the year the entire flow of the Elk is underground. The Elk rises 8.8 km (5.5 mi) to the north at a series of alluviated springs at river level where the top of the Union Limestone passes beneath the streambed (Fig. 3, MS). Under higher flow conditions, some of the Elk also rises at another set of springs (Fig. 3, HS), 1.6 km (1 mi) upstream of the main springs and 12 m (40 ft) above them. Draining an area of 238 km² (92 mi²) and having a measured discharge varying between 0.3 and 7 m³/sec (11 and 250 cubic feet per second) at the springs, depending on flow con-

ditions, the upper Elk River may be the largest sinking stream in West Virginia.

A detailed picture of karst hydrology in the entire Elk River basin was given in an earlier paper (Medville, 1977) and is briefly summarized below. The carbonate sequence in the upper Elk River valley is a free-flow aquifer with capping and perching beds as described by White (1969). This aquifer is anisotropic with subsurface flow concentrated in enlarged bedding-plane partings and joints. The direction of sub-surface flow is controlled by regional structure with the hydraulic gradient following the regional dip to the northwest. In very general terms, streams in the area sink in the upper 9 m (30 ft) of the Union Limestone, drop through the Union and lower limestones, and then rise stratigraphically back to the top of the Union where this horizon passes beneath the bed of the Elk River at the downstream (northern) end of the study area. A more detailed examination of the nature of the subsurface flow of the Elk River between its sink point and its rising is one of the subjects of this paper.

THE SINKING OF THE ELK RIVER

At the town of Slaty Fork, West Virginia, two streams; Old Field Fork and Big Springs Fork, join, the combined flow designated as "Elk River." At this locality, the Elk is flowing on the Greenville Shale and higher clastics and continues to do so for 4 km (2.5 mi) as it flows north. The river then reaches the upper Union Limestone and becomes a losing stream. Within 800 m (a half mile) of reaching the Union and near the mouth of Blackhole Run, an infeeder from the west, the Elk crosses what has been previously described as a lineament or fracture zone (Medville, 1977) trending N58E. At this point the north-flowing Elk turns and follows the lineament to the northeast for a few hundred meters before resuming its northerly course.

Where the river crosses the lineament (Fig. 3, BH), a substantial amount of its remaining water flows into open bedding plane partings and joints along its east bank at an elevation of 760 m (2490 ft). The largest of these openings, Black Hole Cave, is only a few meters long and is almost entirely choked with logs and other surface debris. The quantity of water sinking here varies with flow conditions and with the changing ability of Black Hole Cave to accept water. This small cave may be the "crevice" noted by Maxwell (1898) although other ephemeral swallets downstream of Blackhole Run have been seen. In drought, all of the Elk River will sink in its bed 400 meters upstream of Black Hole Cave (Fig. 3, ERB), while in flood, the cave's entrance is submerged beneath several meters of water and the inflow to this cave, while substantial, will be unnoticeable.

The water sinking at Black Hole Cave flows to the northeast for 180 m (600 ft) along the lineament and is seen again at the downstream end of the Simmons Mingo/My Cave System (described below) where it appears as a 6 m (20 ft) waterfall emerging from the top of the Upper Taggard

Shale. The water then enters a sump (The Crayfish Pool, elev. 721 m (2366 ft) in the upper Patton Limestone and is 38 m (124 ft) lower in elevation than the Elk River bed at Black Hole Cave. The waterfall, Taggard Formation, and Crayfish Pool below it are shown in Figure 5. Dye placed at the Black Hole entrance appears at this waterfall within 15 minutes.

Figure 5. Waterfall breaching Taggard Formation at downstream end of Simmons Mingo/My Cave System. Photo by Bill Storage.

Based on observations of brecciated zones in passage ceilings and occasional slickensides, the lineament along which the Simmons Mingo/My Cave System is developed is hypothesized to be a right lateral. strike-slip fault (Mylroie, personal communication, 1986). The lineament/fault is significant in that it permits solution to occur at a substantial vertical distance beneath the bed of the Elk River and indeed, permits the Elk to flow beneath the Taggard Shales and into the upper Patton Limestone. The hydrogeological problem encountered involves the subsequent flow regime and passage morphology of the underground Elk River between the Crayfish Pool in My Cave and its rising at the springs 8.7 km (5.4 mi) to the northwest. With a spring elevation of 689 m (2260 ft), the vertical separation between the two points is only about 30 m (100 ft).

With respect to the flow path taken by the underground Elk River, four possibilities exist:

(a) The underground Elk River, flowing at a uniform gradient of about 4 m/km (20 ft/mi), gradually climbs stratigraphically, passing back through the Taggard Shales from below within 1600 m (1 mile) of the Crayfish Pool. All passage to the north of this point would be found in the Union and Pickaway Limestones.

(b) The underground Elk remains below the Taggard Shales, paralleling the surface gradient of the river bed; about 8 m/km (40 ft/mi). At a point where the plane of the Taggard Shales passes beneath the elevation of the Elk River springs (about 4 km [2.5 mi] upstream of the springs), the underground Elk crosses the Taggard and then flows with a negligible gradient toward the springs.

(c) An intermediate pattern exists in which the underground Elk passes through the Taggard Shales several times; i.e., a "bumpy path" hypothesis.

(d) The underground Elk River flows beneath the Taggard Shales to an elevation lower than that of the springs and then rises up as a phreatic lift in the vicinity of the springs.

Since the Elk River is the major base level stream for almost a 260 km² (100 mi²) area and since its subsurface gradient may define the top of the saturated zone, the nature of this gradient is of some interest. A case could be made for each of the four hypotheses given above. An associated exploration problem is to find, if possible, the underground Elk River in one or more places between the downstream end of My Cave and the springs. This problem is compounded by the facts that the underground Elk flows at depth beneath its bed and thus may be inaccessible, and that it may flow in recently developed, low gradient conduits, which, if not entirely water filled, could be prone to flooding.

In the remainder of this paper, we discuss the nature of the caves which have been found in the Elk River valley, stratigraphic and structural influences on the locations of these caves in the Greenbrier Group limestones, the relation-
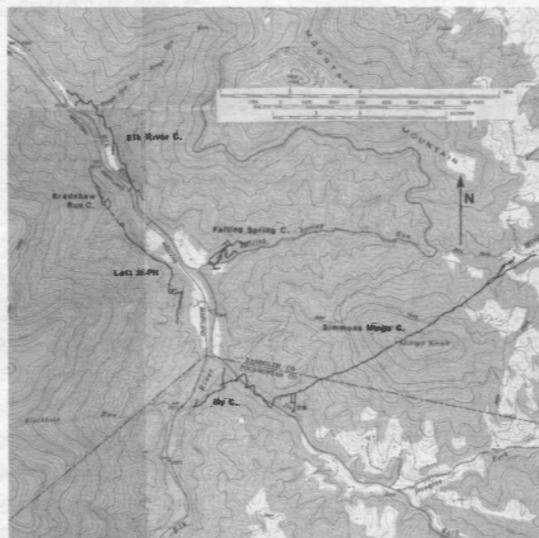
Figure 6. Major caves in the study area.
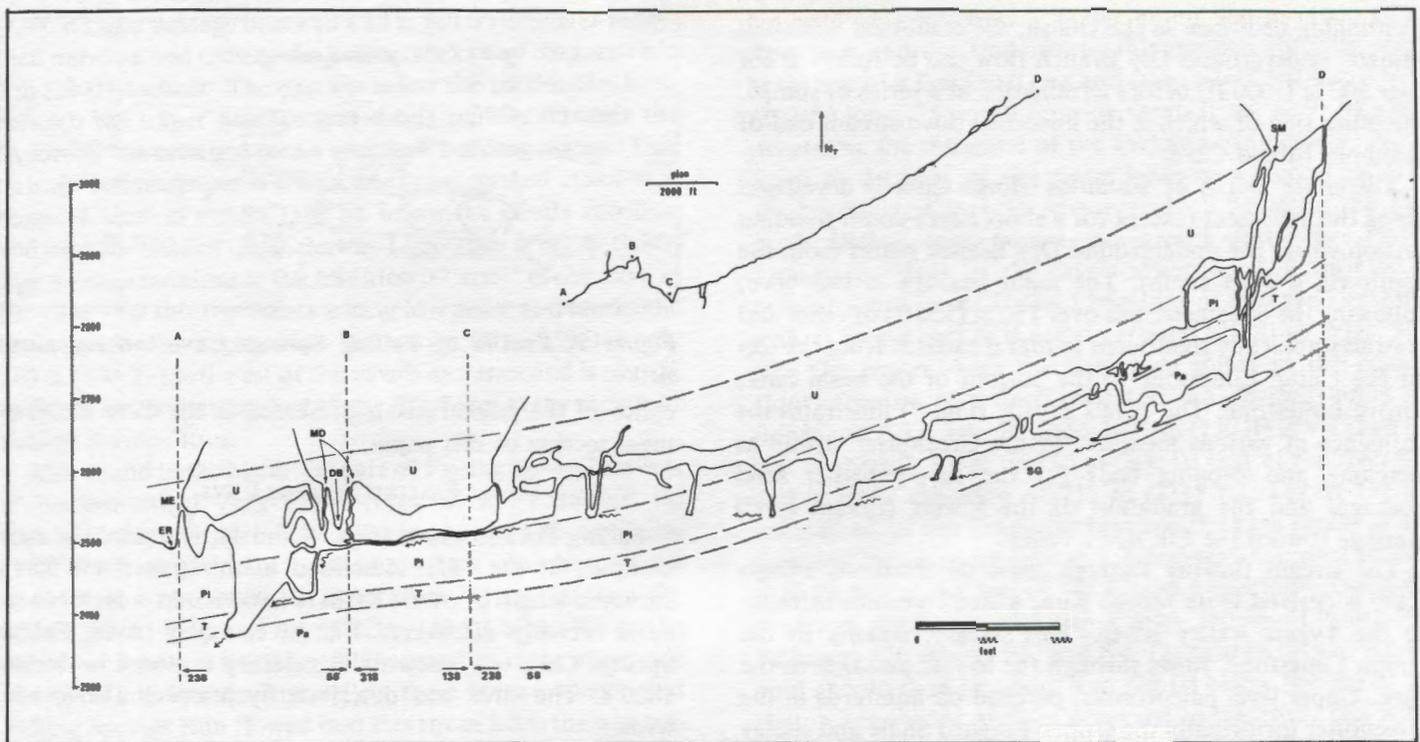
Figure 7. Extended profile of Simmons Mingo/My Cave.

ships between these caves, and the observed subsurface flow of the Elk River where it is seen in these caves.

CAVES IN THE ELK RIVER VALLEY

To date, over 29 km (18 mi) of passage have been surveyed in five major caves in and adjacent to the Elk River valley (Fig. 6). These caves are significant in that they contain current and paleo-flow routes for the underground Elk River. In this section, the basic patterns of these caves are discussed with emphasis placed on stratigraphic and structural controls on passage orientation, placement of passages in the Greenbrier Group limestones, and passage morphology.

SIMMONS MINGO/MY CAVE

The Simmons Mingo/My Cave System (Fig. 7) is the longest and deepest of the Elk River area caves, extending along the lineament for 4300 m (14,000 ft) and having about 210 m (700 ft) of relief. At least 13 km (8 mi) of passage have been surveyed in this cave by members of the Potomac Speleological Club since the mid-1960s. Systematic exploration associated with the surveying has resulted in the connection of Simmons Mingo and My Caves by divers in February, 1978 and in the discovery of new entrances to the cave. A comprehensive account of the history of exploration of this system is given by Swicegood (1982).

Although only the downstream (My Cave) end of this system approaches the Elk River valley, the entire Simmons Mingo/My Cave System is hydrologically significant in that it intercepts the underground Dry Branch (Fig. 6, DB), the

largest infeeder to the Elk River in the study area, draining 32.4 km² (12.5 mi²); and that it diverts water from the Tygart River drainage, 6.4 km (4 mi) to the east of the Elk River.

The Elk River entrance to My Cave (Fig. 7, ME) is 6 m (20 ft) below the top of the Union Limestone and over 15 m (50 ft) higher than the bed of the Elk River. This entrance opens to the top of a 12 m (40 ft) paleo-trunk, the floor of which descends to the elevation of the Elk River bed. Solution scallops along the walls of this passage indicate that the Elk once flowed into this entrance and then to the northeast, following the joint set along which this part of the cave is developed (W. White, pers. comm.).

This large entrance passage and an extension at its ceiling level can be followed for several hundred meters to the northeast to the top of a 12 m (40 ft) wide canyon with its floor over 24 m (80 ft) below. A stream at the base of this canyon, having a base flow of 0.1 cms (3 cfs), flows from the northeast and represents the Simmons Mingo drainage, the underground Dry Branch, and local infeeders to My Cave. As noted above, this canyon breaches the Taggard Formation and terminates downstream at a sump where the water from Black Hole Cave also enters.

The canyon, up to 30 m (100 ft) high, can be followed upstream for about 300 m (1000 ft) to junctions with active local infeeders and fossil drainage routes from beneath the surface Dry Branch. In this area, the cave stream drops rapidly for almost 30 m (100 vertical ft), from the lower Union Limestone to the bottom of the Pickaway Limestone.

Continuing upstream in the Union, the combined Simmons Mingo/ underground Dry Branch flow can be followed for over 300 m (1000 ft) before terminating at a series of sumps, the other side of which is the historical downstream end of Simmons Mingo Cave.

The entire length of Simmons Mingo Cave is developed along the lineament (except for a short north-south trending section where the underground Dry Branch enters from the south via a deep sump). The main passage in this cave, following the lineament, has over 150 m (500 ft) of relief and is stratigraphically significant in that it extends from the top of the Union Limestone to the bottom of the basal Sinks Grove Limestone. The cave's profile (Fig. 7) illustrates the influence of various members of the Greenbrier Group as perching and capping beds for the cave's higher level passages and the gradation of the lowest (stream level) passage toward the Elk River valley.

The stream flowing through most of Simmons Mingo Cave is derived from Mingo Run, a small western infeeder to the Tygart Valley River. This stream, sinking in the Union Limestone, flows through the lowest passages in the cave. Upper level paleotrunks, perched on aquitards in the Greenbrier (principally the Upper Taggard Shale and shaley beds in the Pickaway Limestone), can be followed for about 1200 m (4000 ft) to the southwest of the cave's entrance above Mingo Run. These passages as well as the one containing the cave's stream then climb stratigraphically into the Union Limestone near the cave's historical downstream end at the Simmons Mingo/My Cave sump beneath the Dry Branch valley. While the cave stream in this vicinity flows through comparatively small and submerged passages, a much larger, low-gradient, paleotrunk parallels this stream, 20-27 m (70 to 90 ft) above it. This passage also climbs stratigraphically, crosses the aquitards from below, and grades toward the upper Union Limestone where it is exposed in the lower Dry Branch Valley. A more detailed discussion of stratigraphic controls on the development of the Simmons Mingo/My Cave System and of the signifi-
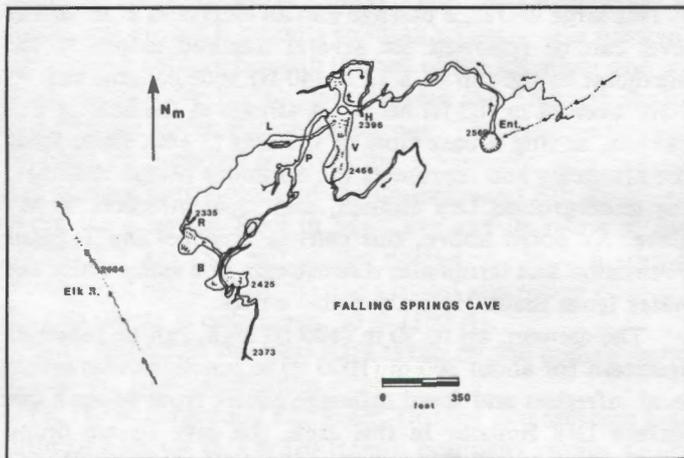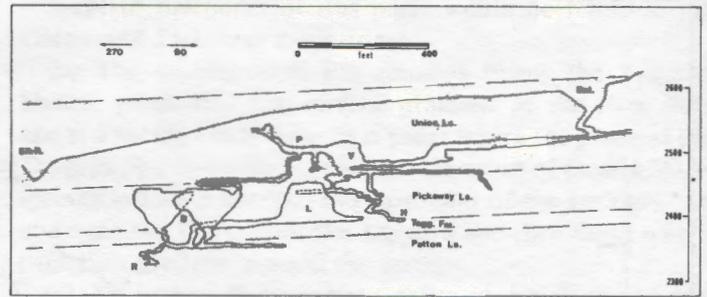
Figure 9. **Profile of Falling Springs Cave looking along strike.**

cance of the paleotrunk is presented in the Cave Development section of this paper.

FALLING SPRINGS CAVE

Falling Springs Cave (Figs. 8 and 9), is one of the most complex of the caves described in this paper and has a surveyed length of over 4200 m (14,000 ft). In contrast to the more recently discovered Elk River valley caves, Falling Springs Cave was known and partially explored in the late 1800's. The cave was described by Maxwell (1898) who wrote:

"This interesting series of pits, galleries and rooms is a combination of a cave and sink-hole. Falling Spring Run heads against Mingo Knob and Elk Mountain and after flowing one and a half miles and receiving numerous tributaries which makes it a stream of considerable size, it approaches within a quarter mile of Elk River where it plunges into a yawning gulf 200 feet in circumference and 40 feet deep, and the water is seen no more. It enters a gallery from the bottom of the pit and is supposed to reach the subterranean channel of Elk River, but exploration has not yet established this as a fact."

More recent exploration was carried out in the mid-1960's by Schmidt (1965), who partially mapped the cave and by the Potomac Speleological Club in the early 1970's. While Maxwell speculated that Falling Springs Cave could lead to the hypothetical underground Elk River, Schmidt's map gave little indication of its depth, lateral extent or complexity. In order to determine these and to understand the relationship, if any, between this cave and the other caves in the Elk River valley, a resurvey was undertaken by the authors and others in 1981. Because of the complexity of the cave, Falling Springs is still not completely explored or surveyed.

Falling Springs Run is an eastern infeeder to the Elk River, draining about 6.5 km² (2.5 mi²) on the west side of Mingo Knob. This stream reaches the top of the Union Limestone 550 m (1800 ft) east of the Elk and flows into a 30 m (100 ft) diameter, 10 m (30 ft) deep, vertical-walled sink. The top of the sink is about 5 m (15 ft) below the top of the Union Limestone. The cave's entrance at the base of the sink is 6 m (20 ft) wide and 1 m (4 ft) high and leads to a passage 5-6 m (15 to 20 ft) wide and high. This passage extends to the north for a short distance but then turns to the

Figure 8. **Plan view of Falling Springs Cave.**

southwest; the main orientation of the cave. After 400 m (1300 ft), this passage opens to a 12 m (40 ft) diameter room, then narrows and crosses the Union/Pickaway contact via a 7 m (22 ft) deep pit. The passage below the pit doubles back beneath the upper passage and drops rapidly through the Pickaway via enlarged joints and then bedding planes. This passage terminates in a gravel and mud-choked crawl at a point 56 vertical meters (185 ft) below the cave's entrance and near the base of the Pickaway Limestone (Figs. 8, 9: H). The passage terminus is the traditional "end" of the cave in the sense that this represents a local low point and marks the end of the earlier exploration. This point (elev. 2396) is only 183 m (600 ft) northwest of the cave's entrance and is also 21 m (70 ft) lower than the bed of the Elk River at the mouth of Falling Springs Run.

Also found in the historical part of Falling Springs Cave is a chamber called Vic's Room (Figs. 8, 9: V) reached via crawls on the left side of the entrance passage about 330 m (1100 ft) from the cave's entrance. This chamber, in the lower Union Limestone, is 23 to 30 m (75 to 100 ft) wide, 60 m (200 ft) long and up to 12 m (40 ft) high. While the room terminates at a bedding plane crawl near the north side of the Falling Springs Run valley, there is no evidence that Falling Springs Run flowed into this room from the surface.

The apparent floor of Vic's Room consists of clastic fill and large breakdown blocks. Two unobvious routes through the breakdown lead downward to fragments of two separate flowing streams, each of which is about 12 m (40 ft) below this apparent floor. Both of these streams breach the Union/Pickaway contact, can be followed downstream for a few meters, and then are lost in breakdown and mud chokes in the upper Pickaway. Neither of these streams is related to the cave's entrance stream although one can be followed upstream for several hundred meters toward the cave's entrance area. These streams, flowing at depths of about 43 m (140 ft) below the entrance, indicate the existence of deeper drainage within the cave. During flood conditions, constrictions in the lower part of the cave's entrance passage result in substantial backflooding into Vic's Room with subsequent deposition of organic material in the room's floor. This water then migrates downward through the breakdown and fill in the floor to the hypothetical lower levels.

More significant than Vic's Room is a substantial paleo-trunk (Figs. 8, 9: P) offset from the room and 6-10 m (20-30 ft) above its local floor. This passage also trends to the southwest and ends in breakdown along the hillside about 230 m (750 ft) downstream from the cave's entrance and just below the elevation of the valley floor. This higher level passage ultimately joins the cave's entrance passage just above the Union/Pickaway contact and, based on solution scallop orientation and graded fills in its floor, appears to represent a former flow path used by Falling Springs Run when it sank farther down-valley than it does at present.

In October 1981, an unobvious route in the floor of the paleo-passage above Vic's Room was found leading to a

low, muddy, southwest-trending passage formed at the Union/Pickaway contact. After about 300 m (1000 ft) of tight, wet and drafting crawls, this passage abruptly opens at the top of a 6 m (20 ft) pit and steep mudslope into a 60 m (200 ft) long, 15 m (50 ft) wide room (Figs. 8, 9: B) which penetrates the thickness of the Pickaway Limestone. A low crawl at the base of this room leads to a second room of similar size and then to passages which penetrate the Taggard Shales and extend downward into the Patton Limestone. Here, at the cave's lowest level, 75 m (250 ft) below the top of the Union Limestone at the cave's entrance sink, is found part of the underground Elk River (Figs. 8, 9: R). This water, seen through open joints in the passage floor, consists of a deep pool with no obvious outlet but flowing to the north. The pool is 40 m (130 ft) lower than the bed of the Elk River, is 150 m (500 ft) east of the river bed and is at an elevation of 712 m (2335 ft). Taking the dip component of the limestone between the cave entrance and the pool into account (about 1.2 degrees), the pool is 70 m (230 ft) below the top of the Union Limestone. Using the observed thicknesses of the Union (40 m—130 ft), the Pickaway (20 m—65 ft), and the Taggard (6 m—20 ft), the pool should then be about 6 m (20 ft) below the top of the Patton Limestone and, as observed in the cave, this is the case. As with the Crayfish Pool seen 1.6 km (1 mi) to the south in My Cave, the Taggard Shales act as a capping bed, rather than the more usual perching bed, for the
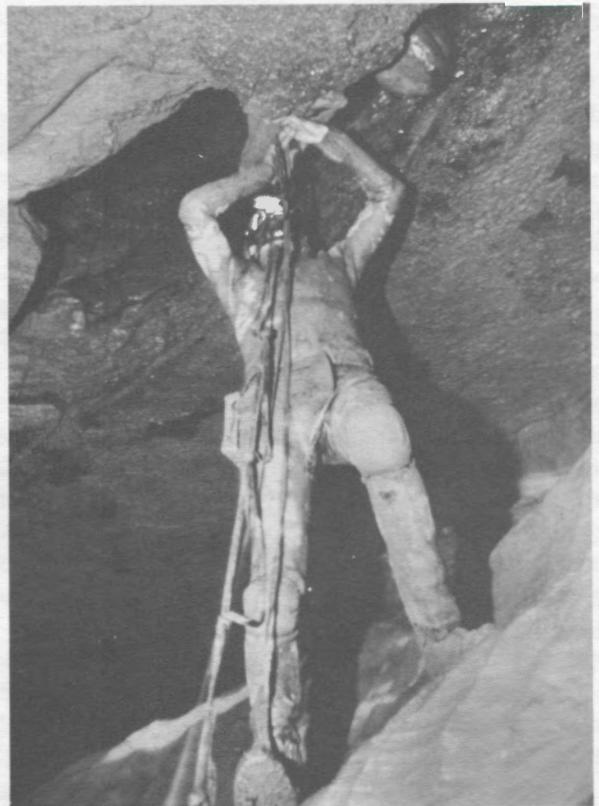
Figure 10. Contact between lower Taggard Shale (ceiling) and Patton Limestone in Falling Springs Cave. Photo by Ron Simmons.

underground Elk. While the exploration leading to the pool represents the culmination of the search begun in the late 1800's by Maxwell and continued by others, it is, in a sense, anti-climactic in that having reached the underground Elk River, there is, in this cave, no way to follow it.

Above the pool is one other passage of interest. Here, a 12 m (40 ft) climb leads back up through the Taggard Shales and into the base of the Pickaway Limestone. This is illustrated in Figure 10. The ceiling is the bottom of the lower Taggard Shale and the person is standing on the Patton Limestone. A low passage at the top of this climb extends 180 m (600 ft) to the east-northeast, following the dip of the limestone back up-valley and toward the historic part of the cave. This passage then opens to yet another substantial chamber, 75 m (250 ft) long, 12 m (40 ft) wide and 15-24 m (50-80 ft) high (Figs. 8, 9: L). Large piles of leaves found in the floor of this room are evidence of inflowing water at times when access to this part of the cave is not possible. While the survey indicates that this room is only 75 m (250 ft) to the west of Vic's Room and that the high points in its ceiling approach the elevation of the floor of Vic's Room, there is no evidence of a traversible connection between the two.

The known extent of Falling Springs Cave lies almost entirely beneath the valley of Falling Springs Run with the major passages following joints which trend N55-70E. Although some passages do trend north-south, the cave is not developed for any significant distance in this direction and, in this sense, Falling Springs Cave is more similar to the Simmons Mingo/My Cave complex than it is to the other Elk River valley caves to the north.

Internal drainage in Falling Springs Cave is complex and circuitous. The cave's entrance stream sinks into mud and/or joints in the floor of its passage at various places, depending on flow conditions. The cave's internal streams, as noted above, sink within a few meters of the points at which they enter negotiable passages. With the exception of the cave's entrance passage and one of its internal streams, every major passage in the cave has been abandoned by permanently flowing water. Rather than having a more commonly found dendritic pattern with infeeder streams flowing toward a master conduit, Falling Springs Cave consists of several stacked layers of passages generally found at specific stratigraphic horizons. The crossing of these horizons via pits and climbs occurs at widely spaced and unobvious locations in the cave, making the cave's exploration a somewhat haphazard and unpredictable process.

Exploration has also been impeded by evidence that the cave floods from below. That is, pool level, representing the underground Elk River, rises for substantial vertical distances (in excess of 20 m [70 ft]) in response to precipitation in the Elk's recharge area. The farthest points in the cave take over three hours to reach and lie beyond low passages that flood if the pool rises only a few meters. Since the rapidity of response of the underground Elk to storm events occurring up to 32 km (20 mi) away is not known, exploration and survey of the lower parts of the cave have been inhibited.

ELK RIVER CAVE

The Elk River Cave (Fig. 11) was found during a search of infeeders to the Elk River during 1981. As with Falling Springs Cave the entrance is in a high-gradient eastern infeeder to the Elk River; Rough Gap Run. This stream drains about 3.6 km² (1.4 mi²) above its sink point at the cave entrance. The entrance is a narrow joint in the streambed and is about 20 m (60 ft) below the top of the Union Limestone.

In September and October of 1981, about 2750 m (9000 ft) of passage were mapped with the survey ending at a point where the underground Elk River is first seen in the cave.
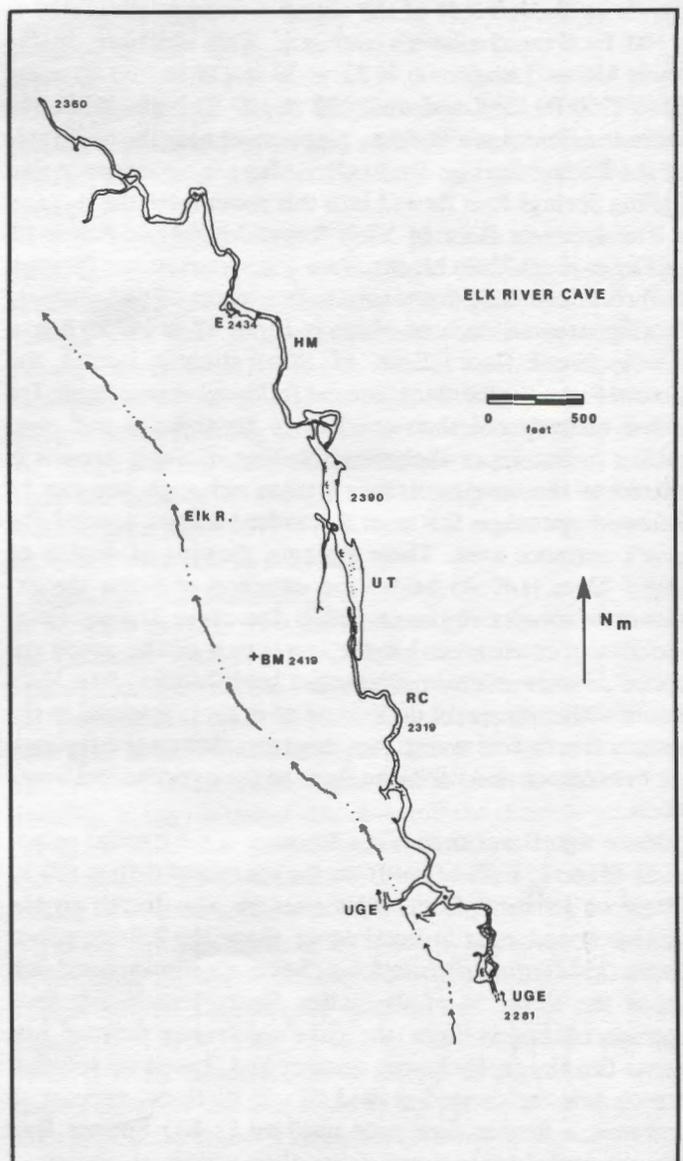

Figure 11. **Plan view of the Elk River Cave.**

This exploration was described in an earlier article (Storage, 1981).

In March, 1982, severe flooding completely plugged the entrance to this cave with silt and rocks. The cave was reopened in September of 1982 after several excavation attempts were made. At that time we discovered that major infilling had occurred in the cave's entrance area including gravel and mud fills up to 4.5 m (15 ft) in depth. In addition, a total collapse of part of the entrance room had taken place where several breakdown blocks, the largest measuring 3 x 3 x 4.5 m, had fallen from the ceiling.

The surveyed length of this cave is over 4200 m (14,000 ft). An additional 610 m (2000 ft) of river-level passage has been explored upstream (south) to a sump. Access to this unsurveyed river passage is through an area characterized by very low air space in drought. It has not been possible to enter this part of the cave since the autumn of 1983.

For descriptive purposes, the Elk River Cave passages can be grouped into four reasonably distinct levels corresponding to various stratigraphic horizons in the upper Greenbrier Group as shown in Figure 12A. A similar profile for caves on the west side of the Elk River is shown in Figure 12B and will be discussed in the next section of this paper. In both profiles, the view is perpendicular to the major axis of the caves; facing toward N53E. The cave entrances have the proper apparent lateral separation (about 1070 m (3500 ft)) when viewed in this direction. Finally, the general locations of major contacts, taking dip into account, is also shown.
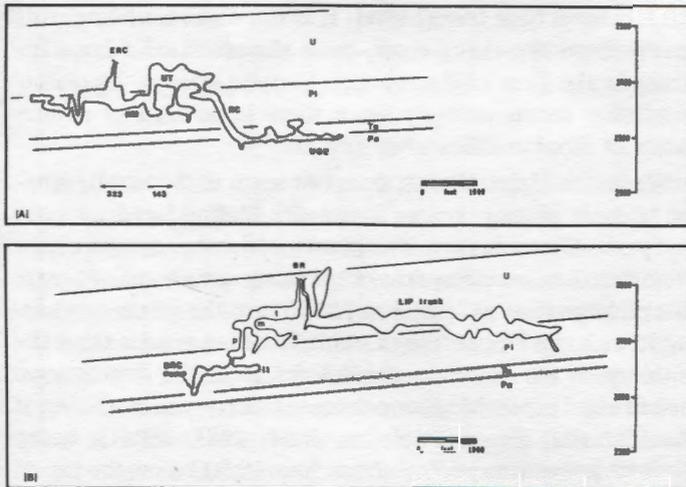

Figure 12. **Profiles of caves paralleling the Elk River valley.**

The first major level encountered in the Elk River Cave (but not the highest level) is developed 18-24 m (60-80 ft) below the entrance and consists of abandoned trunk fragments in the Pickaway Limestone. A series of pits and joints beneath the cave's entrance drops through the Union/Pickaway contact to this level; developed on the uppermost of two shale beds in the Pickaway. Here, a major trunk remnant, the Happy Maggot passage (Figs. 11, 12A: HM), is encountered. This passage trends south for 240 m (800 ft), terminating in a mud choke. A continuation of this passage

trending north from the entrance, as well as the upper portions of Reverse Canyon, described below, are also formed at this level. These passages are generally rectangular or elliptical in cross section and are frequently filled with silt or mud to a depth of several meters. In much of the Happy Maggot passage, it appears that the Union/Pickaway contact and the upper shale bed in the Pickaway Limestone act as capping and perching beds, respectively, for the large volume of water occasionally flowing in this passage.

The second major level encountered (the cave's highest level) is directly above the Union/Pickaway contact at a depth of about 12 m (40 ft) below the cave's entrance. This level includes the Upper Trunk and the remainder of the passages found to the north of the entrance. This latter section is similar to the Happy Maggot passage in cross section and ends in breakdown beneath a shallow sink in the field above.

The Upper Trunk (Figs. 11, 12A: UT) is about 610 m (2000 ft) long and is terminated by breakdown at both ends at points where it approaches surface valleys. While the floor of this passage is only 12 m (40 ft) lower than the cave's entrance, it is also about 180 m (600 ft) east and updip of the entrance and as a result, is just above the Union/Pickaway contact. This passage is reached by ascending a series of joints at the south end of the Happy Maggot passage. These joints open to the north end of the Upper Trunk. At the other (south) end of the Upper Trunk, a 4.5 m (15 ft) deep pit at the Union/Pickaway contact allows access to Reverse Canyon and the lower portion of the cave. While several other shafts, up to 15 m (50 ft) deep, are found along the length of the Upper Trunk, these are of more recent vadose origin and are choked at their bottoms.

The Upper Trunk in the Elk River Cave is a major paleo-flow route for the underground Elk River. This passage is one of the largest in the Elk River Valley, averaging 4.5 m (15 ft) high and 12 m (40 ft) wide with sections up to 24 m (80 ft) wide. The elevation of the floor of this passage (2390-2400 feet) is about the same as that of the bed of the Elk River, 240 m (800 ft) to the west. Scallops indicate that the paleo-flow direction at this level was to the north, paralleling the current flow direction of the Elk River. Several small infeeders enter this passage at locations corresponding to sinking surface streams. These infeeders flow for a few meters in the Upper Trunk before exiting through small openings in the passage floor.

Reverse Canyon (Figs. 11, 12A: RC) begins beneath the south end of the Upper Trunk, descends through the Pickaway Limestone, and ends 300 m (1000 ft) to the south where it joins the Elk River Passage. Reverse Canyon is rectangular in cross section, is 4.5-9 m (15-30 ft) wide and 3-8 m (10-25 ft) high, and contains a small stream (under .1 cfs) which flows to the south for several hundred meters. This is the only stream seen in any of the Elk River valley caves that flows in this direction. Several pits, found in the first few hundred meters of Reverse Canyon, drop through the

lower Pickaway Limestone to the third significant level, on top of the Upper Taggard Shale. Although major passage development does not take place at this stratigraphic horizon, it is significant in that it terminates pits and narrow joints originating in the Upper Trunk. Only short passage segments are found here and, as with the passages beneath Reverse Canyon, these resemble inverted "T" 's in cross section, 1.5-3 m (5-10 ft) wide, 15-30 cm (6-12 in) high at the base, and 1.5-6 m (5-20 ft) high in the center. In both this and the other Elk River valley caves, the Pickaway/upper Taggard contact serves as an aquitard for drips and seeps within the cave, although for larger volumes of water, e.g., the underground Elk River, it is breached from above and below.

At its south end, Reverse Canyon is perched on the Taggard Shales for a short distance and then crosses the Taggard before joining the Elk River Passage (Figs. 11, 12A: UGE). This fourth (and lowest) level of cave development is 43-46 m (140-150 ft) below the cave's entrance and is 3-9 m (10-30 ft) below the top of the Patton Limestone. The nature of the Elk River Passage differs from that of the rest of the cave. This passage is generally smaller and more irregular in cross section, averaging 3 m (10 ft) in width and height, and containing large amounts of breakdown derived from the less competent Taggard Shales above.

Formed in the upper Patton Limestone, the passage containing the underground Elk River (Fig. 13) represents base

Figure 13. Underground Elk River in the Elk River Cave. Photo by Dave Black.

level for the Elk River valley caves. To the north (downstream), this passage can be followed for about 30 m (100 ft) to an end in breakdown. This point is 5200 linear meters (17000 ft) from the main Elk River springs (Fig. 3: MS) and is only 3-6 m (10-20 ft) higher in elevation than these springs. While the likelihood of additional traversible passage in this direction and at this elevation is considered to be small, given the low hydraulic gradient, such passage may exist, especially if the underground Elk climbs back into the Union and Pickaway Limestones along the gradient to the springs.

In the upstream direction, the Elk River Passage can be followed for at least 900 m (3000 ft) through several regions of low airspace, before terminating at a sump. All of the river-level passage is in the Patton Limestone with short side passages and occasional high ceilings extending upward through the Taggard Shales. At river level, the passage is almost choked at several points by breakdown.

With the exception of the Upper Trunk, every major passage in the Elk River Cave floods to the ceiling. It is apparent that in times of high flow, the underground Elk fills its passage, overflows into Reverse Canyon and then flows north (evident from the orientation of small sand dunes [scallops] in the passage floor) to a series of unenterable pits and drains. During such occurrences, the water level rises at least 12 m (40 ft) into the normally southward flowing stream in Reverse Canyon. We have also seen evidence of severe flooding in upper Reverse Canyon, 24 vertical meters (80 ft) above base (river) level. It is not known whether this results from the rising river, or is the result of a large increase in the flow of the Reverse Canyon stream. The latter possibility seems unlikely since there is no sign of disturbance of floor cobbles after floods.

While the Upper Trunk does not seem to flood, the Happy Maggot passage below it appears to flood at least once per year. Green leaves, live plants and other recent debris are often seen in ceiling cracks. At its upstream end, water in this passage rises at least 3 m (10 ft) into the joints connecting it with the Upper Trunk. This flooding results from the inability of the sediment choked drains at the downstream end of the Happy Maggot passage to carry water sinking at the entrance. For example, in June, 1981, after a heavy shower, water was pooled about 3 m (10 ft) below the top of the 12 m (40 ft) pit leading into the Happy Maggot passage near the cave's entrance. At this point this passage is about 6 m (20 ft) high. The entire section of cave north of the entrance, which normally has no active stream, floods under similar circumstances.

Because of the frequency of very local storms, the aerial extent (over 230 km²-90 mi²) of the drainage basin, and the high infeeder stream gradients, it is not unusual for some tributaries of the Elk River to flood while others are completely dry. Thus the lower cave may be inaccessible when the entrance is dry and vice versa.
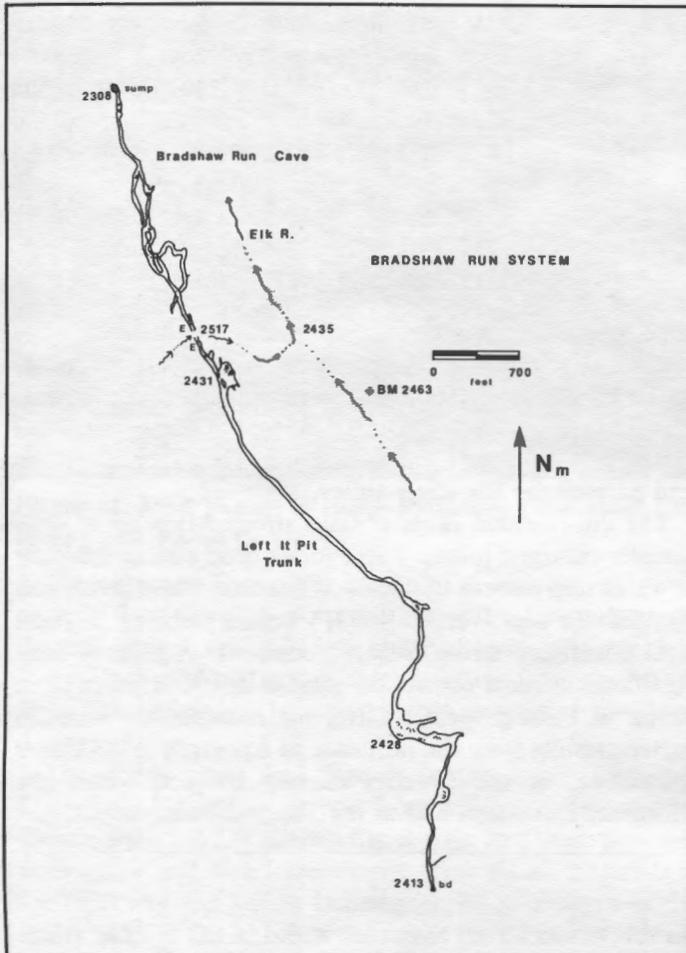
Figure 14. Plan view of the Bradshaw Run system.

BRADSHAW RUN CAVE

Bradshaw Run Cave (Figs. 12B and 14) was discovered and surveyed in 1982. The cave's entrance is in the bed of a high gradient (76 m/km—400 ft/mi) western infeeder to the Elk River draining about 2.6 km² (one square mile). The entrance, at an elevation of 767 m (2516 ft), is about 4.5 m (15 ft) below the top of the Union Limestone. Because of channeling in a 24 m (80 ft) wide alluvial fan, the entrance accepts about three-fourths of the surface stream regardless of flow conditions. At the entrance the stream falls 4.5 m (15 ft) through sandstone boulders and flows horizontally for 12 m (40 ft) before intersecting a large canyon passage near its ceiling. A 11 m (35 ft) waterfall is formed by the entrance stream dropping down the west wall of this north-south trending canyon formed in the Union Limestone. As with the caves described above, the entrance stream is lost almost immediately in breakdown and mud. To the south, the large canyon passage can be followed only 15 m (50 ft) to a massive breakdown choke beneath the valley containing the entrance. To the north, this passage can be followed as a dry trunk, 8-12 m (25-40 ft) wide and 3-9 m (10-30 ft) high, occasionally interrupted by breakdown (Fig. 12B: t). The passage gradient, wall scallops and sediment and cobble

orientation indicate northward flow in this and all other passages in the cave. After 300 m (1000 ft), the trunk ends abruptly at the top of a mud slope with 12 m (40 ft) of relief (Fig. 12B: m). The presence of organic debris and fresh mud indicates that this cave floods to a level midway down this slope. This point is at an elevation of 739 m (2425 ft) and corresponds to the elevation of the surface bed of the Elk River, 240 m (800 ft) to the northeast.

At the base of the mud slope and in the lower Union Limestone, an abandoned stream passage is encountered (Fig. 12B: a). This passage parallels the upper canyon and is about 300 m (1000 ft) long. At its southern (upstream) end, it approaches the valley and terminates in breakdown. Several small streams, emerging from cross-joints, flow perpendicular to this passage and exit through mud chokes.

Fifteen feet (4.5 m) down the mud slope, a 2 m (8 ft) diameter passage continues to the north. This passage is perched on a sandy bed in the lower third of the Union Limestone. This bed may correspond to the Bethel Sandstone, found further to the north in West Virginia, where it is a prominent marker bed in the Union. After several hundred meters, a 15 m (50 ft) pit (Fig. 12B: p) drops through the lower Union Limestone, leads to a short section of low passage on the Union/Pickaway contact, and then intersects a still deeper, large trunk fragment (Fig. 12B: lt). The unnamed upper shale layer in the Pickaway Limestone forms the floor of this passage for about 300 m (1000 ft). After crossing this shale bed, the passage then drops steeply through the remainder of the Pickaway and terminates at a deep pool, perched on the upper Taggard Shale.

This pool, 63 m (208 ft) below the cave's entrance and at an elevation of 703 m (2308 ft), is 8 m (27 ft) higher than the downstream end of the underground Elk River passage, seen in the Elk River cave, 300 m (1000 ft) to the northeast. Stratigraphically, the pool is 12 m (40 ft) higher than the underground Elk, taking the slight westward dip of the limestone into account. During the only visit to this part of the cave, water depth in the surface bed of the Elk River was at least 2 m (6 ft). Thus, it is possible that the observed pool level was higher than at times of low flow. No current was present in this pool when observed. Given this fact and the pool's stratigraphic horizon, we conclude that this pool does not represent base level elevation for the underground Elk River.

LEFT IT PIT

The southern termination of Bradshaw Run Cave beneath the valley where the entrance is located and strong airflow from breakdown beneath this valley led to speculation concerning the existence of a continuation of this cave to the south. By projecting the dominant joint trend of Bradshaw Run Cave across the valley and as a result of extensive digging, the entrance to Left It Pit was opened. This entrance is a narrow joint dropping 6 m (20 ft) into a small streamway. After 45 m (150 ft), this passage terminates at the top of a 12

As the aerial extent of the limestone exposure in the Elk River valley increased, the river intersected both the Simmons Mingo lineament at the top of the Union Limestone, about 800 m (a half mile) upstream of Dry Branch, and exposed limestone farther down valley. Over a period of time, a majority of the river, enlarging joints along the lineament (e.g., the passage inside the Elk River entrance to My Cave), sank and continues to sink in these joints, developing the lowest portion of the Simmons Mingo/My Cave System. As a result of the rapid dropping of local base level to a significant (over 30 m—100 ft) depth below the elevation of the Elk's riverbed, the Simmons Mingo stream was able to abandon its former passage and resurgence site and to join the underground Dry Branch.

The caves paralleling the Elk River valley and seen farther downstream contain a substantial amount of passage in the vicinity of the current elevation of the Elk River. These passages, at elevations of 722-738 m (2370-2420 ft) (Fig. 15), are higher than the pool at the downstream end of the Simmons Mingo/My Cave System (elev. 721 m—2366 ft), and, stratigraphically, are over 27 m (90 ft) above it. While the underground Elk River occasionally rises into some of these passages from below and uses them as overflow routes (this is discussed in the next Section), we believe that these long, valley-aligned paleo-passages were developed prior to the Elk's capture at the lineament. At such time, the Elk, flowing in the upper Union Limestone for several kilometers, would have been able to sink in its bed and to flow beneath the hillsides paralleling its valley, underdraining the riverbed before rising in springs farther down valley. Ample evidence exists for this having been the case. Several segments of large diameter, paleo-passages are seen in the valley, both in the caves described in this paper (e.g., the Upper Trunk in the Elk River Cave) and in several smaller caves as well. One of these; Conrad Cliff Cave, contains a 210 m (700 ft) long segment of dry passage, 6-9 m (20-30 ft) wide and high, ending in mudchokes and rockfall where hillsides curve around and intersect it. This and other similar passages parallel the Elk, are either at the elevation of, or up to 6 vertical meters (20 ft) higher than the riverbed and contain solution scallops indicating former flow to the north.

The nearly complete absence of speleothems in the Elk River valley caves makes a comprehensive program of radiometric dating difficult to achieve. It is possible, however, to develop a general chronological sequence of passage formation on a cave-by-cave basis. Using the available evidence, we conclude that: (a) the Simmons Mingo cave stream, flowing in the highest passages in that cave, originally rose near the top of the Union Limestone in the Elk River/Dry Branch area, at a time when limestone was first exposed in the Elk River valley, (b) the upper levels of the major valley caves, found at and above the current riverbed elevation, were formed relatively rapidly, slightly thereafter, as more limestone was exposed, and (c) upon capture of the Elk River at the lineament, a relatively rapid drop in local base level took place in all of the caves with both the underground Elk River and other sinking streams passing through the Taggard Shales.
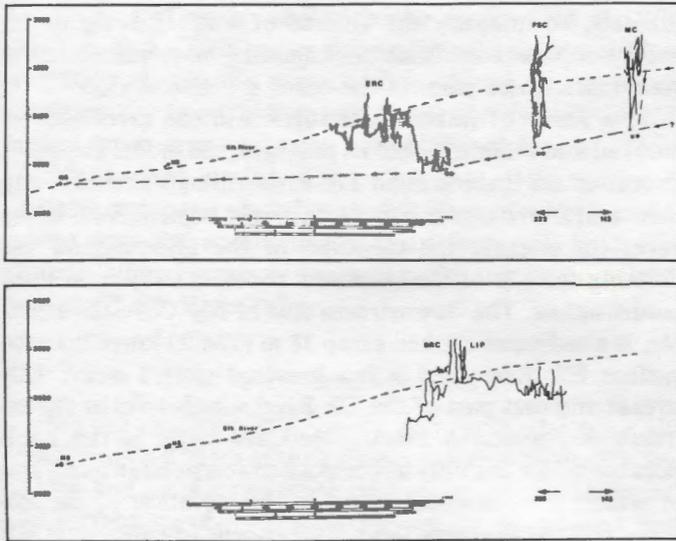
Hydrological Relationships

We have noted that the Elk River sinks in its bed in the upper Union Limestone and rises at a series of springs 10 km (6 mi) to the north where the top of the Union passes beneath the river bed. Earlier in this paper four hypotheses were presented concerning the nature of the flow path of the underground Elk between these points: (a) The path has a uniform gradient of about 4 m/km (20 ft/mi) to the springs, (b) the path remains beneath the Taggard Shales until the elevation of the lower springs is reached (gradient of 8-10 m/km [40-50 ft/mi]) and then flows horizontally to the springs, (c) the path is "bumpy"; passing through the shales from above and below several times before reaching the springs, and (d) the path remains beneath the Taggard Shales for a significant distance below the elevation of the lower springs and then rises as a phreatic lift to the springs.

Although over 16 km (10 mi) of surveyed cave passage exists beneath and immediately adjacent to the Elk River valley, the Elk River itself is observed flowing in one cave for about 900 m (3000 ft) and is possibly seen in two other caves as deep pools at the lowest levels of these caves (the Crayfish Pool in My Cave where some of the Elk River enters from above and the pools in the lowest part of Falling Springs Cave). Thus, only scattered observational data exist for drawing conclusions. These data are summarized in Table 1 and illustrated in Figure 18. Using this information, we may summarize the characteristics of the underground flow path of the Elk River as follows:

(a) Depth beneath riverbed. For a 2.6 km (1.6 mi)

Table 1. Elevations of Caves, Riverbed and Springs in the Elk River Valley

Feature	Pool Elevation	Riverbed Elevation Closest to Pool	Vertical Separation	Comments
My Cave	721 m (2366 ft)	759 m (2490 ft)	38 m (124 ft)	Pool is in upper Patton Ls.
Falling Springs Cave	712 m (2335 ft)	751 m (2464 ft)	39 m (129 ft)	Pool is in upper Patton Ls.
Elk River Cave	695 m (2281 ft)	738 m (2420 ft)	43 m (139 ft)	Underground Elk River flows in upper Patton Ls.
Bradshaw Run Cave	703 m (2308 ft)	735 m (2410 ft)	31 m (102 ft)	Pool perched on Upper Taggard Shale
Upper Elk River Springs	—	698 m (2290 ft)	—	Occluded springs at river level; 15 m (50 ft) below top of Union Ls.
Lower Elk River Springs	—	689 m (2260 ft)	—	Occluded springs at river level; top of Union Ls.

Figure 18. **Vertical relationships between Elk River valley caves, Elk River bed, and springs.**

distance, from where it is first seen entering My Cave at the Crayfish Pool, to the downstream end of the river passage in the Elk River Cave, the subsurface Elk is 38-43 m (125-140 ft) lower than the surface bed and has a gradient that slightly exceeds that of the riverbed: 10 m/km (53 ft per mile) vs. 8 m/km (44 ft per mile).

(b) Stratigraphic Location. The Elk River, sinking at and above Black Hole, drops through the Union and Pickaway Limestones, the Taggard Formation below, and then into the upper Patton Limestone. Where it is seen in the lowest levels of Falling Spring Cave and for its entire length in the Elk River Cave, the pool/river level remains in the upper 6 m (20 ft) of the Patton but climbs stratigraphically to the north. Only at the downstream terminus of the Elk River Cave does the river approach the Patton/lower Taggard contact. Thus, we conclude that the lower Taggard Shales do not function as a capping bed upstream of this point.

(c) Relationship to springs. The elevation of the down-stream terminus of the underground Elk River passage is 692 m (2270 ft). This is only a few meters higher than the elevation of the main Elk River springs 5 km (3.1 mi) to the north (Fig. 3: MS). Thus, while the subsurface Elk River has about the same gradient as the riverbed upstream of this point, its downstream gradient is negligible. It is not merely coincidental that it is at the downstream end of the traversible portion of the underground Elk River where the elevation of the west-dipping plane of the lower Taggard Shales approaches that of the Elk River springs and it is only at this point where the shales begin to act as a capping bed. To the north of this point, the Elk breaches the shales from below and climbs through the Pickaway and Union Limestones to the springs. It is possible that the shales will force the river to flow at elevations lower than that of the springs (hypothesis (d) above), and that the Elk will then rise under artesian conditions at the springs. We have no evidence,

however, that this is the case. The Taggard Shales are easily breached in several places in the Elk River Valley caves and are probably only locally important as an aquitard. Rather, these are gravity, occluded bluff springs as described by Mylroie (1977). The rising of the Elk takes place over a 180 m (600 ft) distance at three such springs, no more than 3 vertical meters (10 feet) apart. Under low flow conditions, the upper two springs are dry and only the lowest in elevation discharges water (0.3 cms—10.5 cfs measured). Under seasonally high flow conditions, all three springs discharge (over 7 cms—250 cfs measured). Under conditions of very high flow, an additional set of four springs, 1.6 km (1 mi) upriver and 12 m (40 ft) higher in elevation, also discharge. These high springs (Fig. 3: HS) are active only after extreme precipitation events (e.g., following over 13 cm (5 in) of rainfall in 48 hours during the period Nov. 3-5, 1985, when much of eastern West Virginia experienced severe flooding) and may be evidence for backflooding in the lowest levels of the caves. The Elk River, sinking farther upstream, has been traced to both sets of springs under such conditions.

In general terms, the hydrological relations which exist beneath the upper Elk River valley appear to be straight-forward. When examined in greater detail, however, these are complex with fairly subtle interactions taking place between the conduits, the various sink points of the Elk and its tributaries, and discharge points. It is apparent that two major conduits exist beneath the Elk river valley; the Bradshaw Run complex paralleling the valley on the west for almost 3 km (2 mi) and the Elk River cave beneath the east side of the valley. The Bradshaw Run system appears to represent an older, now abandoned flow path developed entirely in the Union and Pickaway Limestones. The Elk River Cave in contrast, while primarily consisting of abandoned passages at well-defined stratigraphic horizons, also contains a conduit in the upper Patton Limestone which carries the underground Elk River. We do not rule out the possibility that another active conduit exists in inaccessible lower levels of the Bradshaw Run System. The volume of water observed in the Elk River Cave under fairly average conditions (0.4-0.6 cms; 15-20 cfs) is, however, about the same as that seen at the lower Elk River Springs, and we conclude that a separate, parallel base level conduit does not exist.

We have noted that the northern, downstream terminus of the Bradshaw Run conduit is in the lower Pickaway Limestone at an elevation of 703 m (2308 ft). The trend of this cave, if projected to the north-northwest for another 850 m (2800 ft), will pass 21 vertical meters (70 ft) beneath the bed of the Elk River (Fig. 3: S1). At this location, a substantial volume of water (over 1.4 cms—50 cusecs in high flow) sinks in boulders in the riverbed over a 90 m (300 ft) section. If further projected to the north-northwest for another 1500 m (5000 ft), this path will again intersect the riverbed, this time at river level (elevation 698 m—2290 ft). It is at this point where the upper set of Elk River springs are located (Fig. 3: HS).

Given this circumstantial evidence, we can speculate that at some time in the past, this flow path, formed entirely above the Taggard Shales and terminating at the upper springs, was independent of the conduit seen in the Elk River Cave and containing the underground Elk River. The latter conduit, apparently more recent, is stratigraphically lower and terminates at the lower set of springs.

While at some time in the past, two separate conduits may have existed, the current situation is more complex. Evidence exists for the integration of the two conduits upstream of the upper set of springs and indeed, for hydrological connections between the valley caves. All stream traces conducted while both sets of springs are active result in dye emerging at all springs. This holds for dye placed in the bed of the sinking Elk River (Fig. 3: S1 and S2), as well as the entrances to Bradshaw Run Cave (Fig. 3: B) and the Elk River Cave (Fig. 3: E). We conclude that at these, and by inference, other sinkpoints in the valley, water drops vertically to the currently used Elk River conduit and resurges at the lower springs with overflow rising at the upper springs. Even if a continuation of the Bradshaw Run flowpath does continue to the north-northwest as hypothesized above, we believe that any flow through this is pirated by the conduit containing the underground Elk and consequently, when the upper springs are dry, all such water flows to the lower springs.

Connections between the two conduits are also used by the underground Elk when its conduit is full. At such times, backflooding will occur with the overflow rising at the upper springs and filling the lower passages in the valley caves. In effect, these connecting conduits are subsurface estavelles with water both descending and ascending in them, depending on the flow regime.

Even though it is not physically possible to traverse these connecting conduits, all of the observational evidence in the Elk River valley caves supports this conclusion. For example, backflooding occurs at several widely-spaced locations in the western Bradshaw Run system. At the extreme upstream end of Left It Pit, a passage descends 9 vertical meters (30 ft) beneath the elevation of the cave's major conduit, becoming too narrow to follow near the base of the Pickaway Limestone. While normally a downstream route for a small volume of water entering an adjacent dome, a substantial volume of water sometimes rises in this passage from below. The orientation of cobbles and sand scallops in the passage floor, the orientation of wall scallops in the limestone and the complete absence of sediment in this part of the cave all indicate that the passage serves as a phreatic lift and that the cave's major conduit is now used only as an overflow route. At the opposite (north) end of the Bradshaw Run System, a similar situation occurs. Again, while the passage leading to the terminal sump at this end of the cave normally carries a small stream flowing down toward the sump, under some conditions the pool level rises substantially, backflooding this passage. It is not possible, unfortunately, to quantify the volume of water flowing in the lower conduits when such backflooding takes place since at such times, these parts of the caves are inaccessible.

As a result of internal obstruction in the caves such as rockfall and sediment-choked passages, the model presented above: of the underground Elk River filling its conduit and then uniformly rising into successively higher levels in the caves (in essence, the elevation of the underground Elk defining the top of the saturated zone), is subject to some modification. The downstream end of My Cave for example, is a sediment-choked sump 38 m (124 ft) lower than the surface Elk River bed a few hundred meters away. This stream and that part of the Elk River which sinks at the entrance of the nearby Black Hole Cave merge at this pool. Because of the inability of the pool to accept large quantities of water, it occasionally rises to the elevation of the Elk River bed. At the same time, it is possible to enter other Elk River valley caves and to descend in open passages to elevations that are well below the riverbed.

A related situation exists with respect to the sinking of the Elk at Black Hole Cave. Due to obstructions in the narrow cave entrance and armoring of the riverbed by sediments and clastic rocks, the rate of inflow of water into this cave is limited. Consequently, some of the river will often flow beyond its sink point at Black Hole Cave and the riverbed farther downstream will be bank full. Under such conditions open air passages, immediately adjacent to the riverbed and extending for considerable vertical distances beneath it, are enterable. This occurs until the cave's internal obstructions prevent discharge from taking place as rapidly as the inflowing water and local backflooding takes place in the caves. As a result, the Elk River karst can modify seasonal flood behavior as the conduits beneath the valley accept water and buffer the impacts of flood pulses.

We should note, however, that for a variety of reasons, the aquifer has a limited ability to do this. First, flowthrough time in the conduits is quite rapid. Dye placed at the Black Hole Cave sinkpoint is detected at the lower Elk River springs, 8.9 km (5.5 mi) downstream, within 24 hours. Also, the springs, while alluviated, are still capable of discharging considerable quantities of water. Under fairly high flow conditions for example, discharge of over 7 cms (250 cfs) has been gauged at two of the three lower springs. Finally, because of the limited ability of the swallets in the riverbed to accept water, the majority of the flow in the river under flood conditions remains on the surface. At the time when the 7 cms (250 cfs) discharge at the springs was recorded for example, the Elk was in full flood and it was not possible to measure discharge in the river (estimated discharge at that time was over 28 cms (1000 cfs) based on the 18 m (60 ft) width of the river, average water depth in excess of 2 m (6 ft) and velocity of 1-2 m/sec (3-5 ft/sec).

Under such circumstances, any contribution by the aquifer to modifying flood behavior is overwhelmed by the combination of large surface flow above it and rapid flow

through it. This is similar to the findings of E. White (White, E. L., 1975) who, in a statistical analysis of 62 carbonate basins in the Appalachians, found no relationship between the karst and runoff properties (specifically, between basin area and mean annual flood) for the 12 most highly karsted basins. She notes that "dampening (of runoff) does take place but the presence of carbonate rock alone does not automatically mean there will be damped floods." This is entirely consistent with our observations in the upper Elk River valley.

Acknowledgements

REFERENCES

Maxwell, Hu (1898)- History of Randolph County, pp. 281–285, Morgantown.

Medville, D. (1977)- Karst Hydrology in the Upper Elk River Basin, West Virginia, *NSS Bulletin,* **39**:18–26.

Medville, D. and E. Werner (1977)- Karst Hydrology and Water Chemistry in a Mixed Sedimentary Terrain, IN Tolson, J. and F. L. Doyle, (eds.)- Karst Hydrogeology, pp. 443–457.

Mylroie, J. (1977)- Speleogenesis and Karst Geomorphology of the Helderberg Plateau, Schoharie County, NY, *New York Cave Survey Bulletin* **2,** 336 pp.

Reger, D. B. (1931)- Randolph County: West Virginia Geological Survey, 989 pp.

Schmidt, V. et. al. (1965)- The Elk River/Dry Branch Region of West Virginia, *Netherworld News,* **14:**2.

Storage, W. K. (1981)- Elk River Cave, *NSS News,* **19:**253–254.

Swicegood, R. (1982)- Simmons-Mingo and the Elk River System, IN: Anderson, R. and L. Baker (eds.)- *Capital Area Cavers Bulletin* No. 1, 137 pp.

Wells, D. (1950)- Lower Middle Mississippian of South-Eastern West Virginia, *American Association of Petroleum Geologists Bulletin* **34:**892–922.

White, E. L. (1975)- Role of Carbonate Rocks in Modifying Extreme Flow Behavior, Pennsylvania State University, Dept. of Civil Engineering, 164 pp.

White, W. B. and E. L. White (1983)- Patterns of Cave Development and Speleogenesis in West Virginia IN: Medville, D., G. Dasher and E. Werner, (eds.)- *1983 NSS Convention Guidebook,* 146 pp.

BACTERIAL DEPOSITION OF IRON AND MANGANESE OXIDES IN NORTH AMERICAN CAVES

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Deposits of hydrated iron and manganese oxides are common as stalactites, wall crusts, and as thick layers in sediment in caves at Dubuque, Iowa, and are known to occur elsewhere. Some of the deposits are composed of abundant, microscopic, curved, rod-like structures produced by the iron and manganese precipitating sheath bacteria Leptothrix *and* Crenothrix. *Bacteriological enrichment techniques cultured the iron precipitating bacteria* Leptothrix *sp. and* Gallionella *sp. in abundance from active iron oxide stalactites, mud, and water from caves near Dubuque. The metal oxide deposits are concluded to be at least partly the result of organic (bacterial) rather than inorganic precipitation reactions. Observations from many caves in the eastern United States with concentrations of iron-precipitating bacteria at seeps' but without associated animals, suggest that these bacteria do not form an important base of a food chain for cave-inhabiting invertebrates.*

INTRODUCTION

The occurrence of hydrated iron and manganese oxides as sedimentary deposits in caves has been widely noted (Hill, 1976, 1982; White, 1976). The minerals tend to occur mostly as crusts and coatings. It is usually assumed that they are transported into caves as suspended particulate or colloidal matter, and thus do not qualify as chemical sediments, although some of these are formed *in situ* by the chemical oxidation of iron sulfide.

Stalactites and stalagmites of these minerals are also known, but are rare (Hill, 1976; Hicks, 1950; White and Ellisher, 1958). Hydrated iron oxides ($Fe_2O_3 \cdot nH_2O$; limonite and/or goethite) are found as stalactites and "flowstone" deposits, and some cave sediments may have thick limonite layers. Manganese oxide minerals usually occur as thin coatings on pebbles and on stream beds, but extensive deposits of over a meter in thickness can occur, such as in Jewel Cave, South Dakota (Conn and Conn, 1977; Hill, 1982). While many manganese oxide minerals exist, those sampled from caves in the eastern United States have usually been todorokite (White, 1976), although psilomelane and birnessite are also mentioned (Potter and Rossman, 1979). These are usually thought to be chemical precipitates which stain speleothems, but do not form speleothems themselves (White, 1976).

IMPORTANCE OF BACTERIA

It is now well established that microorganisms are very important geochemical agents in the dissolution and precipitation of minerals (for example, see: Berthelin and Dommergues, 1977; Ehrlich, 1976, 1981; Ghiorse and Chapnick, 1983; Muir, 1978; and Schweisfurth et al., 1978).

It is also well recognized (at least in theory, but seldomly supported by detailed observations) that the ultimate source of the metal deposits in caves is from iron and manganese minerals, usually sulfides and carbonates, weathering and oxidizing in the overlying strata, and that bacteria are often critical in both their dissolution and precipitation reactions (Broughton, 1971, 1972; Cubbon, 1976; Dyson and James, 1981; Harder, 1919). It has been proposed that bacteria utilize the organic part of complex manganese-containing molecules carried in solution by groundwater (such as humic acids) thus freeing the manganese ions and causing them to be deposited on rock surfaces, and Moore (1981) gives circumstantial evidence for this process. The sheathed heterotrophic bacteria *Clonothrix fusca* and *Leptothrix ochracea*, *L. pseudo-ochracea* and *L. discophora* are among those known to precipitate iron and manganese, usually from $FeCO_3$ and $MnCO_3$ in solution, in domestic water supply systems (Ehrlich, 1981; Trudinger, 1976, and references; Wolfe, 1960). The presence of mineral-impregnated sheaths, stalks, and filaments is characteristic for such bacteria. Biological Fe and Mn oxidation is most rapid at pH 6.0 to 7.5 which is what would be expected in a cave environment. There is also evidence that some bacteria selectively and differentially precipitate manganese rather than iron when both are present, and they can do so from water with less than 0.01 ppm of Fe and undetectable Mn in the original water (Trudinger, 1976).

Another class, the stalked bacteria, grows at near-neutral pH and can precipitate both Fe and Mn, and includes

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species of *Hyphomicrobium, Metallogenium*, and chemo-lithotrophic *Gallionella* (Ehrlich, 1976; 1981; Pringsheim, 1949a; 1949b; Thimann, 1955). The metals are deposited as an unstable residuum, from the oxidation of a ferric salt, from which an electron is removed for the organism's metabolic processes. The usual end product is a ferric hydroxide which autooxidizes to a hydrated ferric oxide. The living cells of such bacteria may be abundant but are individually visible only upon staining and with very high magnification.

Thiobacillus ferrooxidans (or *Ferrobacillus ferrooxidans*) and related sulfide oxidizing bacteria are commonly known as iron precipitating agents but they require (or generate) highly acidic conditions (Pohl and White, 1965) which would not normally be maintained in caves. However, where massive sulfides are present in limestone, the acidic conditions may be locally met (Jagnow, 1978; Moorehouse, 1968) and may be contributory to cave dissolution.

More data on the bacteria, their classification, and characteristics are given in Bergey's Manual (8th Edition, Buchanan and Gibbons, 1974), and the important review of Ghiorse (1984).

DUBUQUE CAVE DEPOSITS

Extensive sulfide mineralization occurs in limestone and dolomite of the upper Mississippi Valley of Iowa, Wisconsin, and Illinois, some of which can be studied in caves and mines near Galena, Illinois, and Dubuque, Iowa. Various oxidation products of these sulfide minerals are known (Bradbury, 1959; Brown and Whitlow, 1960; Heyl *et al.*, 1959). Iron and manganese oxide deposits occur in caves and mines (e.g. in Weber, Muenster, Kemling, and other Dubuque caves), as crusts, flowstone, and stalactites (Figs. 1-4). The deposits are either exposed or covered by later layers of calcium carbonate. There are also extensive layers (up to 50 cm thick) in sediment exposed in man-made trenches in cave floors. X-ray diffraction determinations of the minerals show them to be the iron mineral goethite ($HFeO_2$) and the manganese minerals birnessite ($(Na, Ca)Mn_6O_{13} \cdot 3H_2O$) and todorokite ($(Mn, Mg, Ca, Ba, Na, K)_2Mn_5O_{12} \cdot 3H_2O$).

Quantitative x-ray fluorescence analysis of a birnessite stalactite from Weber Cave gave the following results: Mn, $45 \pm 2\%$; Zn, $4 \pm 2\%$; Ca, $4 \pm 2\%$; Fe, $2 \pm 1\%$; Ni, $0.5 \pm 0.2\%$; Co, $0.5 \pm 0.2\%$; Pb, $0.2 \pm 0.1\%$, Ba, $0.2 \pm 0.1\%$. Similar analysis of a todorokite-goethite wall "flowstone" deposit yielded: Mn, $10 \pm 2\%$; Ca, $20 \pm 5\%$; Fe, $5 \pm 1\%$; Ba, $2 \pm 1\%$; Zn, $2 \pm 1\%$, Ni, $0.5 \pm 0.2\%$; Co, $0.3 \pm 0.1\%$; Pb, $0.2 \pm 0.1\%$.

Examination with an optical microscope and scanning electron microscope showed that all sampled iron (but not manganese) deposits are composed mostly of slender, curved, rods. These are identical in size and morphology to those illustrated (Buchanan and Gibbons, 1974) for the iron-precipitating sheath bacterium *Leptothrix ochracea* which is
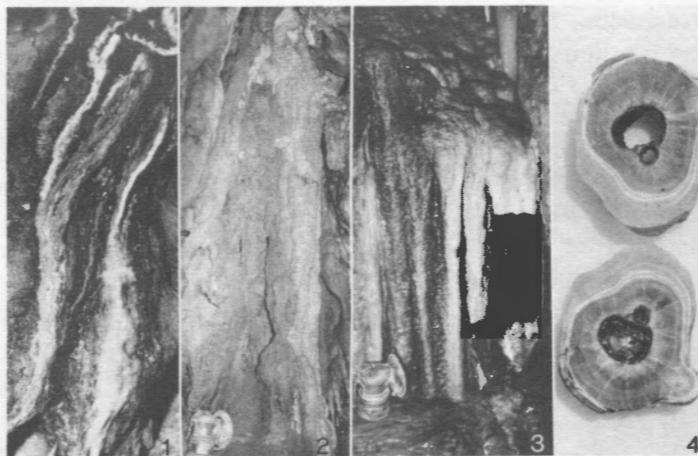
Figure 1. Area of active deposition of iron and manganese hydroxides and calcite on wall in Weber Cave, Iowa. Area in photo is about 0.3 m high (pencil at photo bottom suggests scale). Live *Leptothrix* sp. sheath bacteria were recovered from the iron hydroxides.

Figure 2. Massive goethite "flowstone" deposit adjacent to calcite flowstone in Weber Cave, about 1.2 m high, 0.2 m wide, and 0.15 m thick, composed predominantly of rods of size and shape characteristic for *Leptothrix* sp. sheath bacteria.

Figure 3. Manganese hydroxide core of flowstone and stalactite, exposed where calcite cover has been broken off. Dark surface coating of flowstone is assumed to be manganese hydroxide as well.

Figure 4. Calcite stalactite with soft birnessite manganese hydroxide core (removed), which was at least 15 cm long and 5 cm wide at the base.

common to seeps, chalybeate springs, swamps, etc., and is responsible for the production of "bog iron" ores (Harder, 1919). It has been often speculated (from compelling but largely circumstantial evidence, and to my knowledge, not been definitively proven) that cave deposits of metal oxides are at least partially the result of biological (bacterial) rather than inorganic precipitation reactions. The purpose of this report is to give the results of an attempt to support this hypothesis.

BACTERIAL CULTURING

Samples were taken of iron and manganese oxide deposits from several caves in the vicinity of Dubuque; notably Weber, Muenster, Kemling and Crystal Lake and Level Crevice caves. These consist of "old" and presumably inactive deposits exposed under sediment layers, and "new" and presumably active, moist, exposed, wall crusts, as well as cave water and pool-bottom mud samples. Several media and procedures exist for the detection, enrichment, and isolation of iron-precipitating bacteria (Harder, 1919;

Pringsheim, 1949a). I used Winogradsky's ferric hydroxide hay infusion enrichment medium and Molisch's and Pringsheim's agar media for isolation. The media were made with sterile (autoclaved) cave water. Twenty 125 ml Enlenmeyer flasks containing 75 ml of medium, were each inoculated with one gram of aseptically collected cave samples, and then incubated. Another 20 identical cultures were autoclaved after inoculation as controls for detecting non-biological iron precipitation. Although the cave habitats are 10°C, incubation was at 18°C to increase the speed of the growth process.

The following results were obtained from the samples collected in the caves near Dubuque. In the culture media the presence of iron-precipitating bacteria is indicated by the formation of a reddish surface film. The presence of iron-precipitating bacteria in this film must then be confirmed by preparing stained slides and examining cell morphology with an oil immersion microscope. No iron-precipitating bacteria were found to be alive in the old, dry, and inactive stalactitic or flow deposits or in the buried layers in soils. None were found in drip water from unstained wall and ceiling rock or stalactites. The iron-precipitating bacteria were found in the flasks inoculated from muds in cave pools near seasonal inflow sites, in sumps with an "iron scum," and in the moist Fe and Mn wall crusts and small stalactites. There was no iron precipitation in any control flask. Chemoautotrophic *Gallionella*, with its characteristically twisted ribbons, occurred only in samples from the Level Crevice sumps (Fig. 7). Sheathed and mucilaginous filaments, containing linearly arranged cell bodies about 1 μm in width, characteristics for both heterotrophic *Leptothrix* and *Crenothrix*, were recovered from both sump and wall-ceiling deposits (Figs. 5-6, 8). *Crenothrix* and *Gallionella* have been previously reported from Dubuque cave waters (Moorehouse, 1968). *Crenothrix* reproduces by non-motile conidia. In my cultures I detected only the flagellated reproductive cells characteristic of *Leptothrix*. The bacteria will not grow on isolation media, and the specific characteristics could not be determined (see Buchanan and Gibbons, 1974).

MINERALOGICAL SIGNIFICANCE

The recovery of iron-precipitating bacteria from the deposits suggests that the deposits may, at least in part, result from organic (biological) rather than inorganic precipitation reactions. The source of the metals is undoubtedly from the oxidation or solution of sulfide or carbonate minerals higher in the overlying rock. Dissolved iron and manganese sulfate, carbonate or organic complexes could be produced slowly, and would be locally abundant enough to support the bacteria and result in the wall, ceiling, and floor deposits of iron and manganese hydroxides. The deposits of mixed metal content may have been precipitated by *Leptothrix pseudo-ochracea* or *L. discophora* which are known to deposit manganese as well as iron. *Leptothrix ochracea* seemingly precipitates only iron. Alternatively, the
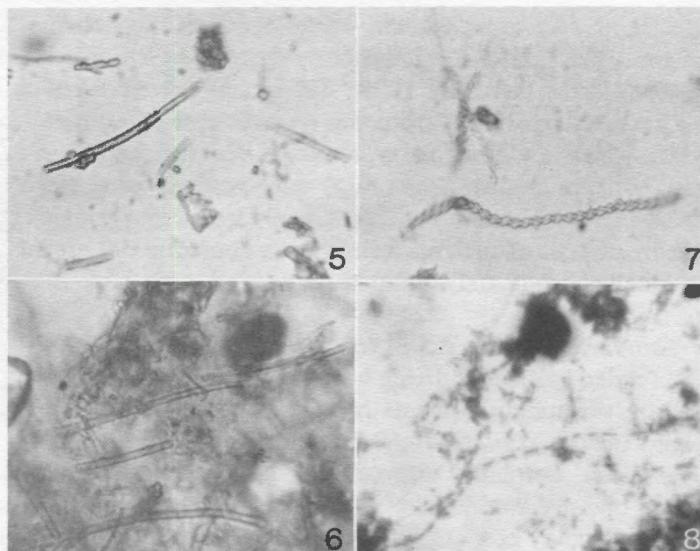
Figures 5-8. All photomicrographs at about 1500x magnification, taken with oil immersion objective.

Figure 5. Elongate smooth rods of iron hydroxide, about 4 μm wide, deposited by *Leptothrix* sp. sheath bacteria; from the inactive massive iron oxide deposit in Figure 2. The rods are indistinguishable in shape and size from those precipitated in chalybeate springs and as "bog iron."

Figure 6. Iron impregnated sheaths of active *Leptothrix* sp. bacteria from sump in Level Crevice Cave, Dubuque, Iowa.

Figure 7. Characteristic curved ribbon of iron hydroxide precipitated by *Gallionella ferruginea* stalked bacteria, cultured from Level Crevice Cave.

Figure 8. Linearly arranged cell bodies of *Leptothrix* sp. bacteria inside invisible sheath, cultured from active wall deposit of iron hydroxides. The iron in the sheath has been dissolved by mild HCl flushing, and the cell bodies stained by crystal violet. The cells are about 1 μm in width.

exclusively manganese oxide deposits may be precipitated by still other bacteria, since many species are known to deposit manganese (Ehrlich, 1981; Ghiorse, 1984). From my cultures I could not arrive at an identification of what might be depositing the manganese oxides.

Few caves occur in limestone and dolomite which are as heavily mineralized as those around Dubuque, so that cave waters with similarly abundant iron and manganese salts in solution would not be expected to be common. This study should indicate that until each case of these oxides in caves has been individually examined, it cannot be assumed beforehand whether or not the deposit is biogenic in origin. Detecting the microscopic rod-forms of impregnated bacterial sheaths in iron deposits is sufficient as a sign for at least a partial biological origin from *Leptothrix* or *Crenothrix* bacteria.

However, the presence of impregnated sheaths should not be uncritically accepted as evidence that the entire deposit has been bacterially deposited for several reasons. Iron itself autooxidizes rapidly under aerobic conditions at neutral pH. In addition to deposition of the metals by active microbial metabolism, the metals may be adsorbed to acidic extracellular organic polymers produced by the microbes, and there may be non-specific metal deposition on dead cells and in the empty sheaths after the cells have left. Further study to determine the quantitative importance of the bacteria under conditions of known pH, metal, and organic content of the cave waters are appropriate.

Biological Significance

Several studies or reviews have examined the questions of the taxonomic makeup, distribution, and food chain significance of bacteria in caves (e.g., Barr and Kuehne, 1971; Dickson, 1975, 1979; Dickson and Kirk, 1976; Howarth, 1983; Pasquali et al., 1978). Most of these studies have found the bacteria to be heterotrophic (and thus secondary producers), dependent upon the input of organic matter from outside of the cave. Some indirect evidence for the chemoautotrophic (primary producers) basis for aquatic and terrestrial food chains in caves has been provided by the findings of Caumartin (1963), Gounot (1967), and Christiansen (1970). These implicate *Perabacterium spelei* and other bacteria as the first links in a chemoautotrophic food chain in caves. Some deep sea food chains are known to be based on chemoautotrophic bacteria (Felbeck, 1981; Spiess et al., 1980).

Since the Dubuque caves have only a limited groundwater and terrestrial fauna, there is little possibility in that region for a food chain linkage based upon iron oxide-depositing heterotrophic bacteria. However, the iron-precipitating sheath bacteria also occur in the southeastern United States in areas where there is a significant diversity of aquatic cave life, especially isopod and amphipod crustaceans. In some such areas I have observed the bacteria to form extensive iron precipitates (all with *Leptothrix ochracea* morphology) at the wet edges of flood-debris banks where slow oxidation and leaching of the sediment provide iron in solution. In particular these have been in Cave Spring, Salt River, and Driftwood caves, Alabama; Lost Cove and Blowing caves, Tennessee; and Saratoga and Fogelpole caves, Illinois; but also in other caves as well.

However, I have never observed macroscopic life forms such as collembolans or crustaceans in association with these deposits. Probably the biologically-useless iron precipitates far exceed in volume any potentially useful bacterial substance, which may amount at most to only 4% organic content in the precipitate (Thimann, 1951). In addition, where the iron is deposited, there may also be toxic levels of other elements. Thus, these bacteria apparently do not appreciably contribute to the base of the food chain in cave ecosystems.

REFERENCES

Barr, T. C. Jr., and R. A. Kuehne. 1971. Ecological studies in the Mammoth Cave system of Kentucky. II. The Ecosystem. *Ann. Spéléol.*, 26: 47–96.

Berthelin, J. and Y. Dommergues. 1976. The role of heterotrophic microorganisms in the deposition of iron and carbon in soil profiles. pp. 609–631. In: Nriagu, J. O. (ed.). Environmental geochemistry. vol. 2: Metal transfer and ecological mass balance. Ann Arbor Science, Ann Arbor, Michigan, pp. 427–797.

Bradbury, J. C. 1959. Crevice lead-zinc deposits of northwestern Illinois. Illinois State Geol. Surv. Rept. Invest. 210. 49 pp.

Broughton, P. L. 1971. Origin and distribution of mineral species in limestone caves. *Earth Sci. J.*, 5:36–43.

Broughton, P. L. 1972. Secondary mineralization in the cavern environment. *Studies in Speleol.*, 2:191–207.

Brown, E. E. and J. W. Whittlow. 1960. Geology of the Dubuque South Quadrangle, Iowa-Illinois. U.S. Geol. Surv. Bull., 1123-A. 93 pp.

Buchanan, R. E. and N. E. Gibbons, (eds.). 1974. Bergey's manual of determinative bacteriology. 8th ed. Williams and Wilkins, Baltimore. 1268 pp.

Caumartin, Victor. 1963. Review of the microbiology of underground environments. *Natl. Speleol. Soc. Bull.*, 25:1–14.

Christiansen, K. 1970. Survival of collembola on clay substrates with and without food added. *Ann. Spéléol.*, 25:849–852.

Conn, H. and J. Conn. 1977. The Jewel Cave Adventure. Zephyrus Press, Teaneck, N.J. 238 pp.

Cubbon, B. D. 1976. Cave Flora, pp. 423–452. In: Ford, T. D. and Cullingford, C. H. D. (eds.). The Science of Speleology, Academic Press, New York. 593 pp.

Dickson, G. W. 1975. A preliminary study of heterotrophic microorganisms as factors in substrate selection of troglobitic invertebrates. *Natl. Speleol. Soc. Bull.*, 37:89–93.

Dickson, G. W. 1979. The importance of cave mud sediments in food preference, growth and mortality of the troglobitic amphipod crustacean *Crangonyx antennatus* Packard (Cragonyctidae). *Crustaceana*, 36:129–140.

Dickson, G. W. and P. W. Kirk, Jr. 1976. Distribution of heterotrophic microorganisms in relation to detritivores in Virginia caves. (With supplemental bibliography on cave mycology and microbiology). pp. 205–226. In: Parker, B. C. and Roane, M. K. (eds.). The distributional history of the biota of the southern Appalachians. Part IV. Algae and fungi. University Press of Virginia, Charlottesville, Va.

Dyson, H. J. and J. M. James. 1981. The incidence of iron bacteria in an Australian cave. In: Beck, B. F. (ed.). Proc. 8th Int. Congress Speleology (Bowling Green, Kentucky): 79–81.

Ehrlich, H. L. 1976. Manganese as an energy source for bacteria. pp. 633–644. In: Nriagu, J. O. (ed.). Environmental geochemistry, vol. 2: Metals transfer and ecological mass balance. Ann Arbor Science, Ann Arbor, Michigan. pp. 427–797.

Ehrlich, H. L. 1981. Geomicrobiology. Marcel Dekker, New York, New York. 393 pp.

Felbeck, H. 1981. Chemoautotrophic potential of the hydrothermal vent tube worm, *Riftia pachyptila* Jones (Vestimentifera). *Science* 213: 336–338.

Ghiorse, W. C. 1984. Biology or iron- and manganese-depositing bacteria. *Ann. Rev. Microbiol.* 38:515–550.

Ghiorse, W. C. and S. D. Chapnick. 1983. Metal-depositing bacteria and the distribution of manganese and iron in swamp waters. In: Hallberg, R. (ed.). Environmental biogeochemistry. Proc. 5th Int. Symp. Env. Biogeochemistry (ISEB). *Ecol. Bull. (Stockholm)* 35:367–376.

Gounot, A. M. 1967. La microflore des limons argileux souterrains: son activité productrice dan la biocenose cavernicole. *Ann. Spéléol.,* 22:23–146.

Harder, E. 1919. Iron depositing bacteria and their geologic relation. U.S. Geol. Surv. Prof. Pap. 113, 89 pp.

Heyl, A. V., Jr., A. F. Agnew, E. J. Lyons, and C. H. Behre, Jr. 1959. The geology of the Upper Mississippi Valley Zinc-lead district. U.S. Geol. Surv. Prof. Pap., 309. 310 pp.

Hicks, F. L. 1950. Formation and mineralogy of stalactites and stalagmites. *Natl. Speleol. Soc. Bull.,* 12:63–72.

Hill, C. A. 1976. Cave Minerals. Natl. Speleol. Soc., Huntsville, Ala. 137 pp.

Hill, C. A. 1982. Origin of black deposits in caves. *Natl. Speleol. Soc. Bull.,* 44:15–19.

Howarth, F. G. 1983. Ecology of cave arthropods. *Ann. Rev. Entomol.,* 28:365–389.

Jagnow, D. H. 1978. Geology and speleogenesis of Ogle cave. *Natl. Speleol. Soc. Bull.,* 40:7–18.

Moore, G. W. 1981. Manganese deposition in limestone caves. In: Beck, B. F. (ed.). Proc. 8th Int. Congress Speleology (Bowling Green, Kentucky): 642–644.

Moorehouse, D. F. 1968. Cave development via the sulfuric acid reaction. *Natl. Speleol. Soc. Bull.,* 30:1–10.

Muir, M. D. 1978. Microenvironments of some modern and fossil iron- and manganese-oxidizing bacteria. pp. 937–944. In: Krumbein, W. E. (ed.). Environmental biogeochemistry and geomicrobiology, vol. 3: Methods, Metals and Assessment. Ann Arbor Science, Ann Arbor, Michigan. pp. 717–1040.

Pasqualini, A., B. Fumanit and L. Visona. 1978. Microflore et activité de groupements fonctionnels dans les sédiments de trois grottes de l'Italia centrale. *Int. J. Speleol.,* 10:73–105.

Pohl, E. R. and W. B. White. 1965. Sulfate minerals: their origin in the central Kentucky karst. *Amer. Mineral.,* 50:1461–1465.

Potter, R. M. and G. R. Rossman. 1979. Mineralogy of manganese dendrites and coatings. *Amer. Mineral.,* 64:1219–1226.

Pringsheim, E. G. 1949a. Iron bacteria. *Biol. Rev.,* 24:200–245.

Pringsheim, E. G. 1949b. The filamentous bacteria *Sphaerotilus, Leptothrix, Cladothrix,* and their relation to iron and manganese. *Philos. Trans., B.* 233: 453–483.

Schweisfurth, R., D. Eleftheriadis, H. Gundlach, M. Jacobs and W. Jung. 1978. Microbiology of the precipitation of manganese. pp. 923–928. In: Krumbein, W. E. (ed.). Environmental biogeochemistry and geomicrobiology, vol. 3: Methods, Metals and Assessment. Ann Arbor Science, Ann Arbor, Michigan. pp. 717–1040.

Spiess, F. N., K. C. Macdonald and T. Atwater. 1980. East Pacific rise: hot springs and geophysical experiments. *Science,* 207:1421–1433.

Thimann, K. V. 1955. Life of bacteria. McMillan Co., New York. 750 pp.

Trudinger, P. A. 1976. Microbiological processes in relation to ore genesis. pp. 135–190. In: Wolf, K. H. (ed.). Handbook of strata-bound and stratiform ore deposits. vol. 2.

White, W. B. and A. M. Ellisher. 1958. The occurrence of unusual minerals in Pennsylvania caves. Netherworld News, 6:77–80. (Reprinted in 1958 Speleo Digest).

White, W. B. 1976. Cave minerals and speleothems. pp. 267–327. In: Ford, T. D. and Cullingford, C. H. D. (eds.). The science of speleology. Academic Press, New York. 593 pp.

Wolfe, R. S. 1960. Microbial concentration of iron and manganese in water with low concentrations of these elements. *J. Amer. Water Works Assoc.,* 52:1335–1337.

BOOK REVIEWS

Cave Life, Evolution and Ecology. David C. Culver. Harvard University Press, Cambridge, Mass., London, 1982. 189 pp. $23.00 (available from NSS Bookstore and others).

Biospeleologists will be interested to learn that David Culver has published an important book which synthesizes many theoretical, laboratory, and field data on cave life. The book is primarily for those interested in theory of evolutionary ecology, and secondarily for cave biologists. This is not a picture book for the popular science market and most cavers would find the concepts and mathematics presented rather formidable. However, cavers and advanced biology students who are interested in the natural history of caves would do well to check the book out of the college library and digest as much of it as possible.

Culver covers most of non-taxonomic cave biology in eight chapters. Topics include adaptation, life history tactics, regressive evolution, allozyme variation, species interactions and community structure, zoogeography, and future directions. Cavers may find chapters one through four rewarding. Culver introduces more linear/matrix algebra and differential equations as he goes along, so chapters five and six on allozymes and species interactions become harder to follow. The final chapters on zoogeograpy and future directions get back into a prose vein and should be fairly intelligible to college-level readers.

Culver's main goal seems to be to bring biospeleology into the mainstream of theoretical biology. He gives many good examples of how cave populations should be of interest to theoretical biologists who want to test fundamental assumptions and hypotheses about population genetics, ecology, and evolution. Because cave ecosystems are much simpler than those above ground, it should be easier to understand and quantify actual ecological phenomena there. The author also thinks that cave communities are closer to ecological equilibrium than are many epigean communities, therefore making caves more suitable for hypothesis testing.

Culver introduces ideas from the recent literature that may help cave biologists rethink their assumptions. For instance, mutualism in general may be a more important species interaction than previously thought, so perhaps cave biologists should be on the lookout for evidence of it.

The burning question of what drives regressive evolution is covered in some detail. Culver is fair-minded in his discussion of the selection hypothesis (energy economy and/or pleiotrophy) versus the neutral mutation hypothesis. He strives to show that both are plausible, although he admits to a bias on the side of neutral mutations. I would have extended his arguments to show that not only are both models plausible, but both may actually be operative in the same population at different times. Selection does not have to be constant, so we can postulate a population accumulating neutral loss mutations until a food crunch comes along, at which time marginal energy economies take on selective value (or alternatively, some pleiotropic side effects become less tolerable).

Culver may have confused the topic of selection by saying that we should, but do not, see greater selection for regressive features at higher trophic levels because of greater food scarcity there (p. 74). This is used as evidence against selection. It seems to me that food scarcity is also determined by density, whatever the trophic level, so perhaps we shouldn't expect a clear-cut effect at higher trophic levels.

I was a bit disappointed that there was not a more extensive discussion of how the interaction of certain effects could all lead to regression of eyes and pigment. For instance, founder effect may severely limit and define the collection of pre-existing regressive alleles available in a "new" cave population. Whether by genetic drift (early) or selection (later on), this collection could then increase in average gene frequency and lead to relatively rapid loss of, say, the eye, especially in a polygenic system where losing one or several links in the chain of developmental genes is enough to sort of botch the eye's growth. Waiting for new mutations to happen may not be necessary. The preceding scenario, incidentally, may help explain the genetic differences observed by Wilkens in different populations of cave *Astyanax,* even though their eyes were similarly reduced. Even if drift decreases some of the loss alleles instead of increasing them, the eventual result will be reduction as long as several loss alleles increase enough to make their probability of joint occurrence high (see p. 69). As to why pigmentation also decreases, I would quibble on the selection side by saying that there may be energy economy in not having to maintain a metabolic pathway just for laying down pigment, but at any rate the issue is confused by lack of dietary pigments in caves as well as lack of light to cause interactive changes in the integument. We should commend Culver for *not* making up his mind on regressive evolution, behavior not often exhibited by previous authors.

In a similar way, Culver presents evidence that cave community structure may follow different paths, depending on physical constraints of the environment and the particulars of whatever species are interacting with each other. In other words, in caves, as in the outside world, there are many more and wondrous modes of life than we imagine. Caves are not always the unchanging prisons of weird beasties that we think. For example, Culver discusses crustacean invasions and species replacements that have been observed in West Virginia caves.

I was a bit surprised by some of the production goofs that Harvard University Press, or the author and reviewers, allowed to get by. The illustration of the head of one blind fish (in Fig. 2–9) is upside down, making a strange beast look even stranger. One graph (Fig. 4–3) is hard to read and could have been improved by outlining each of the populations represented and a distribution map (Fig. 7–3) requires a magnifying glass to read. One can only hope that there are no similar mistakes in the many mathematical expressions presented. I was pleased by Culver's writing style, which is often in the first person and is laced with some humor and humility. In the book's last paragraph the author underlines the need for careful collecting by admitting to personally decimating several populations of cave isopods. Such candor is rare and refreshing.

The summaries at the end of each chapter contain many valuable research ideas and should be read by graduate students and experienced cave biologists alike. More syntheses like this book are sorely needed.

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The Florida Sinkhole Research Institute, College of Engineering, University of Central Florida in Orlando sponsored a conference where 63 papers were presented and published. The papers were subdivided into six subject categories:

I. The geologic framework and mechanisms of sinkhole development; 18 papers

II. Site studies and evaluation of sinkhole susceptibility; 16 papers

III. Sinkhole-like features (subsidence pits); 7 papers

IV. Environmental/societal impact of sinkholes; 8 papers

V. Case histories: remedial engineering of sinkholes; 6 papers

VI. Engineering in sinkhole-prone area; 8 papers

off is usually retarded because no channels are formed. Solutionally-formed sinkholes, unlike the suffosional (soil-piping) or subsidence sinkholes, are not affected by depth to water table. Their formation is a function of bedrock type, land slope, and composition of surficial materials. In some areas they are concentrated along fold and fault structures and close to the valley margins. The frequency of solutionally-formed sinkholes decreases exponentially with depth for sinkholes from Florida, the Appalachians, Puerto Rico, and the Dominican Republic.

Subsidence and soil-piping sinkholes, the principal land use hazards in urbanized areas, were the subjects of most papers in this proceedings. The suffosional sinkholes can occur on all carbonate rock types including the manganese-rich dolomites in the subtidal zone in South Africa. In some areas the mechanisms of suffosional sinkhole formation are a result of groundwater withdrawal when the aggressive surface-derived water leads to rapid solution of the limestone. In other areas aquifer dewatering and arch collapse are enhanced by runoff modification and by accelerated transport of the underlying soils due to point source input from pavement and roof runoff. There are also sinkhole features related to the volume loss and subsidence due to mineralogic changes in the non-carbonate clastic sediments. During January 1977 withdrawals of large quantities of water from a Florida aquifer resulted in a 60-foot drop in the surface and the formation of 22 new sinkholes.

High resolution seismic-reflection profiles, Landsat, and Seasat satellite images have been used for detection of possible soil-piping sinkholes. Remote sensing and geophysical methods of gravity, seismic refraction, horizontal and vertical electrical soundings, electrical resistivity, and magnetometer surveys are used to predict sinkhole collapse-prone areas. Test drilling was used to detect sinkholes in New Jersey. Land use planning maps have been developed using slope, soil permeability, and width/depth information in discriminate and Fourier series analyses for prediction of all types of sinkholes.

Some of the related hazards associated with sinkholes include the transport of toxic fumes through the underground conduits which rise into homes; and spills or leaks of hazardous chemicals in holding lagoons or on a sinkhole plain. The legal aspects of sinkhole collapse were discussed. Remedial action, such as constructing beams to span sinkholes under homes, filling sinkholes and point source input areas with gravel of decreasing size, and pumping to carry water away from a sinkhole were proposed. One needs to be cautious—treatment of one karst problem can lead directly to the cause of another karst problem. For instance, treating sinkhole flooding problems can lead to induced collapse problems.

The Second Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst will be held February 9–11, 1987, in Orlando, Florida. Dr. Yuan Daoxian, director of the Institute of Karst Geology in Guilin, China, will be the banquet speaker.

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Limestone Geomorphology. Stephen Trudgill. London: Longman, 1985, 196 pp. $19.95.

Since his student days at Bristol University, Stephen Trudgill has been one of Britain's most productive karst geomorphologists and he has produced in *Limestone Geomorphology* a book which, although intended primarily for geography and geology students, will interest any caver who is interested in the broader field of karst. Some sections may be heavy going for those with no understanding of geology or chemistry, but overall the style is lively, the writing clear and the illustrations wide-ranging. Moreover, the text is scientifically correct, yet concise, well-referenced and, at under $20, reasonably priced.

The general approach of the book is along the contemporary lines of detailed process studies and their use in explaining the development of the surface and underground karst landscape. Studies of current erosion and deposition have brought karst geomorphology a long way since the 1960's but explaining the production of specific features is still a problem, even in the case of such fundamental forms as sinkholes (Williams, 1985). In part, this limited success is a function of scale differences and an insufficient number of careful, long-term studies. More so it is because many of the most accessible and striking karst features are essentially relict—the products of climates and processes long since past. Fortunately caves act as fine indicators of past environments and, as Trudgill clearly indicates, detailed studies of cave deposits are bringing us ever closer to a full understanding of cave and karst development at least over the last several hundred thousand years. In this respect cave studies are at an exciting threshold since we can now start to unravel the chronology of cave and karst development.

The eleven chapter format of the book is straightforward—a progression through rock types, processes, forms and applications. Following a brief introduction, chapter two deals with the classification and description of carbonate rocks and presents an outline of solution chemistry. Chapter three examines the spatial and temporal variations in processes and chapter four considers the microforms or karren which can be most easily related to these present processes. Larger, more complex features are at the heart of the text. Chapter five is on caves and chapter six shows how karst features are an integral part of surface and underground hydrologic networks. Landform description, especially morphometry, is the focus of chapter seven and the complex issue of process-form relationships is covered in chapter eight. Coastal karst processes and forms occupy chapters nine and ten, and chapter eleven concludes with some valuable examples of the importance and application of karst studies.

Inevitably, there is some unevenness in the text. The process sections are excellent and provide a contemporary review of research in the last decade. In particular, they show the importance of the soil-bedrock interface where the distribution and behaviour of percolating water has a profound effect both on the development of surface features and on subsurface cave formation. By contrast, individual landforms are accorded less attention and for fuller coverage, readers should consult either Marjorie Sweeting's classic *Karst Landforms* or Joe Jennings' updated *Karst Geomorphology*. Cavers may be disappointed that the cave section is not larger, but this is not a text on speleology. Nonetheless, caves are an integral part of karst and their importance is clearly shown.

For students of karst, this book is a must. For scientifically-inclined cavers who want to know what is going on above, around and below their caves, it is highly recommended.

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REFERENCES

Jennings, J. N. (1985). *Karst Geomorphology,* 2nd edition, Oxford, Basil Blackwell, 293 p.

Sweeting, M. M. (1972). *Karst Landforms,* London, Macmillan, 362 p.

Williams, P. W. (1985). Subcutaneous hydrology and the development of doline and cockpit karst. *Zeitschrift für Geomorphologie,* N.F., 29 (4), 463–482.

ANTHROPOLOGY SESSION

A COMPARISON OF MURRAH CAVE WITH OTHER VAL VERDE COUNTY CAVE SITES

April MacDowell

Val Verde County cave and rockshelter sites have long been recognized as important, partly because of the excellent preservation of perishable materials especially from the long Archaic tradition in the area. Murrah Cave was one of the first sites excavated in the area (1937) and the material is located at The Museum, Texas Tech University, Lubbock. Though archaeological techniques of that time were not as well developed as today, information from more recently excavated sites (such as Hinds Cave, less than three miles away) was used to enhance interpretation of Murrah Cave artifacts. Also, Murrah Cave material was useful in overall regional studies of the area through time.

The Archaic hunting and gathering way of life in this area has been long viewed as stable and uniform until the arrival of the Europeans. However, recent work, especially at Hinds Cave, has shown several changes through time in resource exploitation and woven artifact styles. In particular, there seems to be several changes including a population increase about 2500-1000 BC. This is the time period when Murrah Cave was most intensively occupied. Also, a number of changes occurred about 1000-500 BC when Montell, Marshall, and Castroville points began to appear. Some authors have postulated a movement of Plains peoples into the area. There also seems to be a decrease in use of some cave sites, including Murrah Cave, at this time. Preliminary studies indicate a possible increase in utilization of open sites. Perhaps this is related to the influx of Plains peoples.

SEMINOLE SINK: EXCAVATION OF A VERTICAL SHAFT TOMB, VAL VERDE, TEXAS

Ron Ralph, Leland C. Bement, and Solveig A. Turpin

The skeletal remains of at least 22 individuals were exhumed from beneath the vertical shaft opening to a subterranean solution cavity, 41VV260, in Seminole Canyon State Historical Park in Val Verde County, Texas. The Texas Archaeological Survey, the University of Texas at Austin, carried out a multi-disciplinary study in 1984 and 1985 which was sponsored by the Texas Parks and Wildlife Department and authorized by Texas Antiquities Permit No. 414. The broken and dispersed fragments of 21 skeletons were compacted into one stratum beneath a conical talus formed of rocks and trapped sediments. The one temporally diagnostic artifact, an Early Corner notched dart point, and radiocarbon dates place this burial episode during the Early Archaic Period over 7,000 years ago. On the crest of the cone lay the buried fragments of an adult male, cremated and dropped down the shaft about 400 years ago.

Paleontological studies, speleogenesis, and cave sedimentology generally support the established paleoclimate model with the additional suggestion of an erosional episode between 10,000 and 5,000 years ago that resulted in the exposure of the modern entrance. Bioarchaeological analyses demonstrate that the Early Archaic population was well adapted to their environment. Childhood stress, anemia, and minor trauma are detectable, but the major pathologies are high caries rates and early tooth loss with concomitant transference of stress attributable to a high carbohydrate diet based largely on fibrous desert succulents. The burials in Seminole Sink, when placed in the context of Archaic lifeways, suggest the extant model of free-ranging nomadism should be revised in favor of a limited territorial range centering on the diverse resources of the canyon system.

USES OF CAVES BY EARLY MAN

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Man has used caves in one way or another for essentially all of his existence. Earliest uses involved such primary needs as shelter from the elements or protection from hostile animals or other bands of proto-humans. As man's adaptations and complexity increased and changed, so did his use of caves. They became a permanent or seasonal home in several areas of the world and a shrine or ceremonial chamber in others. Some caves in France contain the best examples of prehistoric rock art in the world. Man's use of caves continues in the present. Caves in Mexico and the Middle East are still being used as permanent living quarters or as religious shrines.

BIOLOGY SESSION

GENETIC DIVERGENCE OF ALLOPATRIC CAVE CARABIDS

William J. Badaracca, Department of Biological Sciences, University of Cincinnati, Cincinnati, OH 45221

The formation of the Ohio River, approximately 1.2 million years ago, effectively isolated a northern population of an obligate cave carabid beetle in the genus *Pseudanopthalmus* from the southern population, resulting in divergence and the formation of two geminate species, *P. tenuis* in Indiana and *P. barberi* in Kentucky. In addition, the northernmost populations in Indiana show a more recent divergence from *P. tenuis* to form a sibling species, *P. stricticollis*.

Electrophoretic data from 10 enzymatic loci have been examined from four populations of *P. barberi*, from six populations of *P. tenuis*, and from three populations of *P. stricticollis*. The average genetic similarity (I) between the species on either side of the river is 0.67. These data indicate that the Ohio River has been an effective barrier to gene flow between these cave regions. The genetic similarities among conspecific populations and between *P. tenuis* and *P. stricticollis* are, with one exception, greater than 0.90%. These data indicate populations on the same side of the Ohio River have not diverged in the absence of a barrier and the recent origin of *P. stricticollis* from *P. tenuis* is consistent with their isozyme similarity. These data are complemented by levels of genetic variability and similarity reported between populations of four sub-species of another Kentucky cave carabid, *Neaphaenops tellkampfi*. Thus, the findings on *P. barberi*, *P. tenuis*, and *P. stricticollis* are consistent with their present-day distributions and presumed evolutionary histories. Further, the presence of the same rare alleles in all species at several loci is consistent with the hypothesis that the species were formed when the Ohio River divided the range of a widespread ancestral form.

MICRO WHIP-SCORPIONS IN SOUTHWESTERN CAVES

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Micro whip-scorpions (palpigrades) are tiny, blind, slender arachnids 2mm in length. They are depigmented and have a long, multi-segmented tail that is easily broken. Their only structures for capturing prey are chelate chelicerae. These arachnids are found in all warmer regions of the world and have been collected in Texas, California, and Oregon.

Nine European and Cuban species have been described from caves. Until recently, the American mainland species were only known from sub-surface (epigean) habitats. The first cavernicole was found in Malheur Cave, a lava tube in eastern Oregon. More recently, micro whip-scorpions have been found in Chrome Cave and Grapevine Gulch Cave in the Mother Lode district of the Sierra Nevada, California. These specimens were found in soil deposits under rocks or organic material.

The epigean populations of the far west are extremely difficult to locate because they tend to remain in the deepest soil horizons and must be extracted with the aid of a specially designed funnel. Western caves present the biologist the best access to these unusual arachnids. Within the distributional gap between California and Texas there are likely to be several caves in which these creatures have taken refuge from the drying soil conditions. The equipped collector need only watch for a microarachnid that resembles darting pieces of fine white thread. To avoid breaking the tail, the specimen should be captured on a fine brush or straw moistened with alcohol.

EYE MORPHOMETRICS OF CAVE AND SPRING POPULATIONS OF *GAMMARUS MINUS* (AMPHIPODA: GAMMARIDAE)

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Number of lenses, total eye area, and head length were measured for samples of four spring and four cave populations of the amphipod *Gammarus minus* from four karst drainages in southern West Virginia. Data were analyzed by using the allometric equation $y=ax^b$. For spring populations, eye area showed positive allometry for all populations (b=1.55), while lens numbers showed a variety of patterns, ranging from negative allometry to positive allometry. Compared to spring populations from the same basin, cave populations showed reduced eye area and lens number. This held for both small and large individuals. There were no consistent differences in allometric coefficients (b) between cave and spring populations. Cave populations also differed among themselves, both in eye area and lens number. In one population (Organ Cave), the number of lenses shows a statistically significant decrease with increasing size of the animal. In some populations, the distribution of numbers of lenses was unimodal in shape, while in others it was bimodal.

EVOLUTIONARY PATTERNS IN CARABID BEETLES

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Species arise as a result of reproductive isolation, which fosters genetic dissimilarity in populations. Measurements of dissimilarity (genetic distance) between populations have proven useful in understanding evolutionary processes.

Many species of trephine beetles in eastern North America are presumed to be descendants of edaphic ancestors, which were widespread during cool, wet climates associated with glacial maxima. With the onset of warm, dry interglacial periods, continuous populations were fragmented to mountains, sinkholes, cold springs, and caves that mimicked the glacial climate.

In the evolutionary transition from a fully epigean beetle to one fully cave limited, it appears logical to postulate an intermediate form. This intermediate would be taxomonically and morphologically related to the epigean form, yet be pre-adapted (living within caves, cold springs, sinkholes, and deep gorges, has a close taxonomic and morphological affinity with montane species (*T. schwarzi* and *T. hydropicus*), and appears to be the intermediate between epigean and cave beetle forms.

Genetic patterns in populations of *T. cumberlandus* were compared with those of montane endemic species of *Trechus*, and with cave obligate trephine species in hetrozygosity between species, and for comparison of geographic differentiation using Roger's coefficient of genetic similarity(s).

EYE PIGMENTS OF CAVE CRUSTACEANS AND THEIR RELEVANCE TO THEORIES OF REGRESSIVE EVOLUTION

Thomas C. Kane, University of Cincinnati, and David C., Culver, Northwestern University

Most genetic studies of structural reduction in cave organisms are of two kinds: (1) purely morphological, utilizing the techniques of quantitative genetics, or (2) purely genetic, utilizing the techniques of gel electrophoresis. The first approach does not elucidate the underlying genetics beyond statements about the number of genes involved and the fraction of the variation that is genetic. The second approach elucidates genetic structure, but the genes identified rarely have anything to do with the morphological structures being studied. Three eye pigment systems in crustaceans hold considerable promise as a third approach that has elements of both phenotype and genotype. The biosynthetic pathways of photoactive rhodopsin, light absorbing ommochromes, and light reflecting pteridines are known, and either the pigments themselves or the enzymes involved can be assayed. Of special interest is rhodopsin since its maintenance is energetically much more expensive than the other two. If energy economy is important in regressive evolution, rhodopsin should disappear first. Preliminary results for cave and spring populations of the amphipod *Gammarus minus* are presented.

GEOGRAPHIC VARIATION AND POPULATION STRUCTURE IN CAVE CARABID BEETLES

Thomas C. Kane, Department of Biological Sciences, University of Cincinnati, Cincinnati, OH 45221

An understanding of patterns of geographic variation is important in interpreting evolutionary relationships between closely similar taxa and in inferring levels of gene flow between geographic populations. For troglobitic species, dispersal and gene flow are restricted to subterranean routes. Thus, the interconnectivity of caves and the presence of geological barriers become important factors in determining the geographical distribution and the degree of gene flow among populations of troglobitic species.

In the eastern United States, approximately 200 species of trechine carabid beetles are presumed relics of surface dwelling ancestral forms that were widespread during cooler, wetter climates associated with glacial maxima. Presently, many of these trephine species are relatively abundant and show interesting patterns of distribution within the karst regions to which they are restricted. As predators, many of these species also play important ecological roles in the various terrestrial and riparian cave communities.

Population structure and geographic variation have been examined in four genera of troglobitic trechines (*Ameroduvialis*, *Darlingtonea*, *Neaphaenops*, *Pseudanophthalmus*) in the Cumberland Plateau (MP-II) and the Pennyroyal Plateau (MP-I) using the technique of gel electrophoresis. Population structure in these species is determined in large part by the presence of partial and/or complete barriers to gene flow, such as non-cavernous strata and large rivers. A general consequence of troglobite evolution appears to be a significant reduction in gene flow over the geographic range of the species. Finally, in several taxa examined, electrophoretic data indicate that substantial geographic variation and genetic divergence have occurred subsequent to the initial cave isolation of the ancestral stock.

THE GYPSUM CAVE FAUNA OF THE SOUTHWESTERN UNITED STATES

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Extensive deposits of cavernous gypsum occur in many parts of northern Mexico; western, northwestern, and southwestern Texas; and eastern New Mexico. The best studied of these regions is Culbertson County, Texas, but some collections have been made in several parts of Mexico, New Mexico, and the northwestern part of Texas. In Mexico only one possible troglobite, *Nesticus nahaunus* Gertsch, is known. Three possible troglobites (a linyphiid spider, a cambalid millipolid, and a trichonisic isopod) are known from northwestern Texas. In Culbertson County, Texas, and adjacent Eddy County, New Mexico, three aquatic troglobites (two amphipods and an **asellid** isopod) and at least four terrestrial troglobites (a nesticid spider, camalid and fuhrmannodesmid millipeds, and a campodeid dipluran) are known. The distribution and zoogeographic relationships of the fauna of these regions is discussed.

NATURAL HISTORY OF BIG-EARED BATS IN VIRGINIA

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A maternity colony of Virginia big-eared bats has been studied every weekend for three years starting in early March and terminating in late October of each year. The purpose of the study was to determine when the females first arrive at the cave in the spring, when they give birth, when the young become volant, and when the final exodus occurs in the fall. Night vision and video recording equipment were used to study the nightly activity patterns of the bats at the cave. Preliminary analysis of the data indicate that bats start arriving at the cave in mid-March and are gone by the end of October. Patterns of nightly departure and return to the cave vary over these eight months. During March, the bats frequently do not leave the cave. In April and May, the bats return from their foraging bouts many hours before sunrise. During June, the bats emerge from the cave in the early evening and do not return until shortly before dawn. In July, the activity pattern becomes bimodal. This bimodal pattern is probably related to either lactation or early volancy of the young rather than just the availability of insects. During August, the bimodal pattern disappears. In September and October, the bats start returning to the cave early and the patterns are similar to those of April and May. The bats gradually depart for the season beginning in early September.

DEMOGRAPHICS OF MORTALITY IN A FREE-TAILED BAT (*TADARIDA BRASILIENSIS*) MATERNITY COLONY

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Skeletal samples taken periodically through the summer from the floor of a large free-tailed bat maternity colony were sorted into age classes. Overall mortality (normalized for sample effort) was highest during the parturition period. The youngest age classes (I & II) made up 68% of the mortality of the first sample. The second sample yielded 49% in classes I and II. The proportion of younger age classes in the sample decreased through the summer as young matured. The total mortality rate also declined through the summer. Mortality for adults and young is highest during and immediately following parturition. Extrapolation to total mortality was precluded by sample design. This technique may prove useful in monitoring deviation from normal rates of mortality in very large bat colonies. Rates of guano deposition were determined incidental to this study.

COMPUTER APPLICATIONS SESSION

CAVE MAPPING SYSTEM, VERSION IV.4

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The Cave Mapping System (CMS) is an integrated package of cave survey data routines developed for the Apple IIe (with an extended 80 column card) or the Apple IIc. It is written in Apple Pascal, Version II.1 so it requires 128k of memory space.

CMS allows a user to build files of cave survey data containing, for each record, the name of the present and previous station; the distance, azimuth, and elevation from the previous to the present station; the X, Y, and Z coordinates of the present station; and finally the left wall, right wall, floor, and ceiling distances from the present station.

Various routines allow the user to enter, modify, display, print, or make maps from the data. In data entry, users may use feet and inches, decimal feet, or meters; directions may be in azimuth or bearing form; backsight data may be included; and instrument and light height may be recorded and accounted for. Comments may be imbedded anywhere between data records.

Data modification options allow conversion between feet and meters, loop closure, data entry error correction, or declination corrections. All files may be displayed on the screen or printed.

The user may display or print stick maps based upon the files. Plan views and profile views can be made. Plan views can be oriented in any direction, drawn to any scale, and centered about any point. Profiles can be along any axis, drawn to any scale, and centered on any point. The user may include scale grids or station names on the maps if he wishes. He may also display or print rose charts showing distributions of shot directions.

THE NSS MEMBERSHIP COMPUTER SYSTEM

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When the cost of the existing service bureau began to intrude on the NSS budget, the Executive Committee decided that the Society should acquire their own computer. Existing functions were thoroughly documented and a "wish list" of new features was drawn up. No existing software package was able to come close to meeting the requirements so custom software was necessary. Three different programming languages were considered with Microsoft COBOL being the ultimate choice. The final system consist of over 30 programs and is completely menu driven and designed to be "user friendly".

Selection of hardware occupied more time than selection of the software because of various personal preferences. A

selection committee came up with almost one alternative for every member on the committee. The IBM PC-XT was eventually chosen because of the wealth of available hardware and software options.

Design requirements, language considerations, hardware configuration, and operating experiences are discussed. A copy of the system, including the complete database as of March will be available for demonstration.

CONSERVATION MANAGEMENT AND SESSION

THE BIGHORN RESEARCH PROJECT

Bob Brown, P.O. Box 2, Elbe, Washington 98330

There are three areas of the project that should be of interest of cavers attending this session. They are as follows:

1. As part of the project, we are required to develop management recommendations for Bighorn Cave. A committee has been established for this purpose and this committee has developed and submitted interim recommendations to the National Park Service.

2. The organization has developed a new inventory system for this project which is designed to provide thorough coverage of a cave while allowing for a moderate level of detail. This computerized system should be of interest to anybody involved with cave inventory work.

3. The Bighorn Project is a large-scale, multi-faceted NSS project. It is being coordinated by the Northwest Cave Research Institute, which is an NSS Conservation Task Force. This project is a new approach to organizing meaningful work projects at major federally-owned caves. The NCRI plans to conduct additional future projects. The system used to fund, organize, and man this type of project will be explained.

CAVE MANAGEMENT IN THE BUREAU OF LAND MANAGEMENT
(CARLSBAD RESOURCE AREA)

Jim Goodbar, Bureau of Land Management, Carlsbad Resource Area Headquarters, P.O. Box 1778, Carlsbad, NM 88220

Over the past few years, the BLM has taken great steps in its recognition of caves as an important resource and has signed into effect a national cave management policy. This paper deals with that policy and how it is being implemented.

The basic goals of BLM cave resource management are to (1) identify and protect cave resources on public lands; (2) integrate the above into multiple use planning efforts; (3) provide for uses such as scientific studies and research, educational activities, recreation, and guano extraction; and (4) increase the awareness of land-use managers and the public of management requirements for unique cave resources.

The Carlsbad Resource Area manages over 50 known caves. The basic philosophy of our management is to manage cave resources at the lowest level necessary to protect them. Two basic types of cave management are practiced: intensively managed caves (gated, permitted caves with high resource values) and extensively managed caves (ungated, unpermitted, with low resource values).

The BLM has entered into a number of memoranda of understanding and cooperative management agreements with other Federal agencies as well as many caving organizations. The details of these will be discussed as will the recently completed draft resource management plan for the Carlsbad area.

CAVE MANAGEMENT:
THE BUREAU OF LAND MANAGEMENT APPROACH

Buzz Hummell, Bureau of Land Management, Roswell, New Mexico

This paper deals with the Bureau of Land Management's philosophy and methods of managing cave resources on public lands in New Mexico.

Our approach is basically conservation/preservation oriented, with the objective of managing cave resources in coordination with other natural resource programs as part of comprehensive land use plans.

MANAGING YOUR VOLUNTEERS:
AN IMPORTANT ASPECT OF CAVE MANAGEMENT

Janet C. Queisser, Rt. 3, Box 105, Salem, VA 24153

There is always too much to be done and never enough people to do it. Even funded projects have to rely on volunteer efforts to carry out their objectives. How do you stimulate interest in a project? How do you get volunteers and keep them working? How do you make meetings interesting, but useful? How do you get a committee to work? Approaches to these questions and other issues are discussed.

INTERPRETING WILD CAVES

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Managers of wild caves can benefit from making available some form of interpretation of the resource for the caving public. Benefits include providing wanted information, spreading a conservation message, and improving public relations. Although visitors to developed and wild caves differ greatly, interpretation becomes an effective management tool when aimed at the type of visitor most commonly using the resource. An experimental tour of Fort Stanton Cave is described as an example of wild cave interpretation.

CAVE MANAGEMENT OF TEXAS STATE PARKS

Mike Walsh and Ron Ralph

In 1985 we learned that the Texas Parks and Wildlife had acquired two of our favorite training caves, the Devil's Sinkhole and Gorman Falls Cave. Upon investigation, we were surprised to learn that the Texas Parks and Wildlife now controlled 125 to 175 caves. Our offer to assist in the development of a cave management policy was answered with a request to join their newly formed Cave Task Force. We are now actively involved in the development of cave management policy.

In 1986 we signed a memorandum of understanding with the Texas Parks and Wildlife. This was largely patterned after the one between the NSS and the Bureau of Land Management. One of the first things we had to do was to construct the procedure and forms to get cavers into the caves. The second phase is to inventory all 125 to 175 caves. Survey, photo-documentation, biological collection, etc., are all being worked on at this time. As we get into the field, we are finding more and more caves. The number may go over 200!

We will be working on Texas Parks and Wildlife cave management philosophy objectives, recreation use policy, and other related topics. In addition, we are working on the master plans of several new parks. The Texas Parks and Wildlife is committed to the protection of their caves.

THE INDIANA KARST CONSERVANCY:
STANDING BETWEEN THE CAVE AND THE VANDAL

William L. Wilson, President, Indiana Karst Conservancy, 2307 Evergreen Court, Terre Haute, IN 47802

Caves contain unique scientific and scenic values that should be preserved for future generations. Unrestricted access to some caves has resulted in extensive damage to cave resources and pollution of the cave environment. Much of the damage is difficult or impossible to repair. The Indiana Karst Conservancy is a nonprofit corporation that was formed in December, 1985, by concerned cavers for two purposes: (1) to maintain access to caves for responsible individuals, and (2) to protect caves from degradation caused by unconscientious visitors. In order to reduce the negative effects of excessive traffic, the conservancy has restricted access to four caves by leasing the cave passages from private landowners and constructing fences or gates at the cave entrances. Members of the NSS can obtain the combination to locks on the cave gates by writing a designated cave manager, known as a "patron". Combinations are changed periodically, and gates are inspected and repaired as necessary. Nonaffiliated, casual cavers who apply for access are referred to the local grottos where they may learn conservation ethics from NSS members prior to entering the cave. Considerable attention is paid to demonstrating to the landowner that the organized caving community is managing the cave in a responsible manner, thus protecting the owner and maintaining access for responsible individuals. The successful operation of the Indiana Karst Conservancy may serve as a model for cavers in other areas who wish to acquire, manage, and protect the caves they value.

GEOLOGY SESSION

GEOLOGIC CONTROLS ON SURFACE AND SUBSURFACE
STREAM DIVERSION IN A KARST AQUIFER IN
WARREN COUNTY, KENTUCKY

Anthony S. Able and Nicholas C. Crawford, Center for Cave and Karst Studies, Western Kentucky University, Bowling Green, KY

Studies of the Brush Creek–Clear Fork Creek area ten miles southwest of Bowling Green, Kentucky, indicate that the majority of the cave streams are flowing in a direction concordant with the regional dip of the rock units. In the few cases where flow directions do not parallel the regional dip, local dip appears to be influencing the groundwater movement. Dip control has also been identified as a major factor influencing cave stream diversion. In two cases cave streams have moved out of their original basins of flow and crossed a drainage divide to flow to another basin. Geologic structure is the dominant controlling factor in the movement of groundwater in the area.

THE KARST/PALEOKARST RELATIONSHIP TO
COLLAPSE BRECCIA PIPE FORMATION

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The southern Colorado Plateau province of Arizona and Utah is the focal point of exploration for mineral deposits hosted by collapse breccia pipes. The Grand Canyon region reveals pipe structures whose formation relates directly to a buried karst developed during the Mississippian-Pennsylvanian unconformity, 300 million years ago. The top of the Mississippian-age Redwall Limestone exhibits sinkholes, caverns, and collapse features resulting from solution.

Breccia pipes are vertical, cylindrical rock columns formed by collapse of overlying stratigraphic units into Redwall caverns. The "throat" of downward displaced brecciated fragments is surrounded by the "collapse cone" of inward-dipping strata caused by dissolution of near-surface Permian carbonates and evaporites. Pipe throats develop to several hundreds of feet in diameter and can exceed 3,000 feet in vertical extent. Collapse cones may show deformation up to one-half mile away from the centralized throat. Porosity in the pipe creates a favorable environment for deposition of copper, arsenic, lead, zinc, uranium, gold, and silver.

Breccia pipes are remarkable for their great penetration upwards through noncarbonate rocks. They are formed by a slumping and upward stoping process that is inevitable above deeply buried caverns that grew so broad their roofs could no longer bear the weight of the overlying section.

Northwest and northeast trending reactivated faults in the Precambrian basement may have increased local fracture density, controlling alignment of cavern systems and facilitating the upward stoping into overlying aquifers. Grand Canyon Caverns, Stanton's Cave, and Cave of the Domes are three examples of joint-controlled Redwall caves developed along the northwest or northeast directions. Domepit development, indicative of gravitating water's effect on cavern ceilings, is a characteristic feature of the caves.

In outcrop exposures, the Redwall develops giant amphitheaters spanned by circular arches, demonstrating pressure arch fracturing and the tendency to collapse along joint surface enlarged by descending waters.

Exploration for collapse cones and indications of a breccia pipe at depth is complicated by the presence of locally abundant karst on the Permian Kaibab Limestone. Features of Permian paleokarst, recent karst and gypsum dissolution affect the near surface strata, though they do not dominate the landscape.

TRACING THE FLOW OF CONTAMINANTS IN KARST AQUIFERS

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The source and generalized flow route of contaminants flowing directly into karst aquifers at stream sinks or sinkhole drains can be traced by first contouring the water table surface from levels obtained from wells, followed by qualitative dye traces using fluorescent dyes and activated charcoal or cotton dye detectors. Several case studies where the author has traced the flow of contaminants from sinkholes or injection wells to springs will indicate the technique.

The majority of contaminant traces performed by the author have involved more complicated dye traces where contaminant was traced through the soil and then through the carbonate aquifer to a spring or springs. As dye percolates through the soil, much of it is absorbed by the clays, and the remainder is greatly diluted as it trickles slowly into a subsurface stream. This situation usually necessitates automatic water samplers for collection and a flurometer or spectrofluorometer for dye analysis.

Case studies will illustrate the use of fluorescent dyes to trace the flow of contaminants from leaking underground gasoline tanks, leaking underground tanks containing toxic chemicals, and septic tank drain fields. In each case a garden hose was left running from four to 48 hours to flush the dye through the soil into the aquifer below.

Perhaps the most difficult traces of all are those which involve slowly leaking surface impoundments. Substantial quantities of dye must be dumped into large lagoons to create initial concentrations of even one ppm. On one occasion the author used two dyes simultaneously to trace two leaking hog waste lagoons to the same spring. Other studies deal with traces of lagoons containing toxic waste.

CLAY VERMICULATIONS IN IOWA, PENNSYLVANIA, AND WEST VIRGINIA

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Clay vermiculations are splotchy or ramifying aggregations of fine clastic materials. Although they typically occur on cave ceilings, they may be present on surfaces at any inclination, even on the floor. Their substrate may be dolomite, limestone, chert, fossils, or travertine--any rock surface that is smooth and dense. They are about an inch long, 1/10th inch wide, and 1/100th inch thick; adjacent vermiculations or branches are separated by about half an inch of bare rock.

The vermiculations reported to date all occur in caves of humid-temperate areas, but temperature, *per se*, does not seem to be a controlling factor, so long as it remains above freezing. It does not appear necessary for the substrate to remain moist (as from condensation) most of the time, but flowing or dripping water appears to prevent the formation of vermiculations. The presence or absence of light is not a factor in their occurrence.

Clay vermiculations seem to evolve from films of clay or other fine-grained materials in the presence of moisture and a substance or substances which cause the film to break up and the pieces of it to contract. The process may be related to flocculation or to the development of soil aggregates.

CARLSBAD CAVERN AND OTHER CAVES IN THE GUADALUPE MOUNTAINS, NEW MEXICO: A SULFURIC ACID SPELEOGENESIS RELATED TO THE OIL AND GAS FIELDS OF THE DELAWARE BASIN

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Sulfur isotope data and pH dependence of the clay mineral endellite support the hypothesis that the large cave passages in the Guadalupe Mountains, New Mexico, were dissolved primarily by sulfuric acid rather than by carbonic acid. Massive gypsum deposits and native sulfur in the caves have S^{34} values as low as -25.6 and -20, respectively. These values correspond to S^{34} values of H_2S gas and sulfur in the Gypsum Plain which are known to have been generated by oil and gas related reactions.

In this paper it is proposed that the progressive eastward migration of the halite margin in the Gypsum Plain could have been a major factor controlling cave development in the Guadalupe Mountains. Where halite beds are still intact, they have acted as impermeable barriers, preventing hydrogen sulfide from rising to the surface in the basin. Instead, the gas rose into the Capitan reef and dissolved out caves by a sulfuric acid reaction.

Recent dating results suggest that the Big Room level of Carlsbad Caverns is about 850,000 years old, and that the Bat Cave level is about 1.3 million years old. Other caves higher in the Guadalupe Mountains may be as old as three million years.

STRUCTURAL SEGMENTS AND SEGMENT ANALYSIS

Roy A. Jameson

Segment analysis is a procedure for identifying and surveying early flow paths on fractures (structural segments) and interpreting conduit integration and enlargement to form caves. In West Virginia, segment analysis is useful in dendritic caves with complex hydrologic histories where closely spaced initial, subsequent, divisionary, competitive, or floodwater flow paths must be distinguished. There, the detailed pattern of structural segments often influences conduit growth and route reorganizations.

Factors conducive to segment analysis include prominent fractures, lithologically uniform bedrock of low dip, and minimal collapse or other sedimentation. Conduit growth should not have been so extensive or so directed as to have destroyed the transmissive fractures, removed them from view, or created new fractures mistakable for the transmissive ones.

The locations and types of structural segments are inferred by criteria that vary with the geological setting and type of conduit growth. For example, in paragenetic tubes, early flows were on fractures near tube bases where solution pockets or anastomoses often indicate high initial permeabilities. In entrenched canyons, early flows were above the highest undercuts or other features of entrenchment, at ceilings or nearby at the bases of half tubes preserved from earlier tubes or fissures. Structural segments are guided by individual fractures. Therefore, remnants of early conduits or appropriate parts of the modern passages must be concordant to the candidate fractures or fracture zones.

Midline diagrams showing the elevations and geometry of the structural segments are prepared using leveling and horizontal surveys. Conduits are divided into sections of segments at junctions. Morphologic observations of junctions and other evidence are used to infer sequences of integration of flow paths. Conduit evolution is then interpreted and modeled using the midline diagrams, modern passage features, lithologic and sedimentologic data, and knowledge of the processes affecting conduit growth.

SEGMENT ANALYSIS IN THE NORTH CANYON OF SNEDEGAR CAVE, WEST VIRGINIA

Roy A. Jameson

Detailed mapping and analysis of structural segments in the Union Limestone (Mississippi and Greenbrier Group) in the North Canyon and associated passages of Snedegar Cave, indicate Stage I phreatic growth as ungraded tubes. Flow was guided mostly by bed partings (37%), systematic joints (29%), or bed-joint intercepts (20%). Thrust faults and their intercepts with joints guided 11% of the 1,382 feet of inferred tubes. The Stage I tubes lay on two levels separated by joint conduits. At the end of Stage I, flow paths formed a complex network with several closed loops.

Stage II began with the earliest onset of vadose conditions. Low discharge streams incised the apices of the ungraded tubes forming narrow trenches. Lower parts of the ungraded conduits grew under closed-conduit flow in pressure loops. Where Stage I flow paths branched in a downstream direction the higher downstream path was abandoned because stream depth was insufficient for flow to continue past high points. This process reorganized the flow system into three active conduits and three abandoned tubes. The active conduits became canyons (the North Canyon, the Headwall Passage, and the Saltpetre Maze Passage) as the streams cut down, removing pressure loops and grading the floors of the narrow trenches. The joint conduits between the two levels enlarged as shafts.

Stage III began with the introduction of clastic sediments. The sediments promoted undercutting, leading to the development of wide undercut surfaces. Wide trenches formed beneath these surfaces. A partial grading of the floor between the two levels was effected in the North Canyon by headward incision and lowering of the lip of the shaft combined with a flow-path diversion. Collapse produced wedge-shaped breakdown where undercutting was extensive below bedrock bounded by faults, joints, and the narrow trenches.

THE GEOLOGY OF CROCKETT'S CAVE, A NEW MEXICO GYPSUM CAVE

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Crockett's Cave is a gypsum cave located 13 km west of Carrizozo, New Mexico, on the west side of the Carrizozo Malpais. The cave has formed by solution of a 10-m thick bed of massive gypsum within the upper gypsiferous member of the Permian San Andres Limestone. It is located on the southeast flank of the Carrizozo Anticline. Within the cave, the bedding has an average strike of N60E, dipping about 33 degrees SE. With 1,158 m of surveyed passage, the original solutional cave can be viewed only on the updip edges of the cave. Throughout the majority of the cave the original gypsum ceilings have collapsed and the ceilings are presently being supported by the more competent beds of overlying limestone.

Crockett's Cave contains perhaps the best display of boxwork of any cave in New Mexico. The 30 m geologic section measured inside the cave demonstrates several of the factors controlling speleogenesis and passage morphology. It would have been impossible to measure the equivalent geologic section of the surface due to the poor resistance to weathering. The cave also contains numerous gypsum stalactites in the Big Room, an impressive room more than 100 m long and 30 m wide. The Big Room was originally reported to be formed in a tight anticlinal fold. However, detailed geologic mapping and cross-sections have revealed that the apparent anticline in the upper portion of the Big Room has resulted from large-scale, intact flexing and collapse of the overlying limestone into extensive solution cavities in the underlying gypsum. the scalloped gypsum walls and the location of extensive calcite raft deposits both indicated the cave was modified by a vadose stream flowing to the southwest.

The gated cave entrances are on Bureau of Land Management land and a permit for entry must be obtained from the Bureau of Land Management. Due to the dusty nature of portions of the cave, the presence of bat guano, and reports of histoplasmosis in the cave, the Bureau of Land Management recommends wearing dust masks while in the cave.

WESTERN OKLAHOMA GYPSUM CAVES

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There are three primary areas of gypsum cave development in the Permian-age gypsum of western Oklahoma. In northwest Oklahoma, the outcrop of the Blaine Formation in the Cimarron Gypsum Hills stretches from Harper County southeast to Canadian County. The Blaine Formation consists of four gypsum members separated by tongues of Flowerpot Shale. In ascending order, these are the Medicine Lodge, Nescatunga, Shimer, and Haskew Gypsum members. Alabaster Caverns, with 2,300 feet of tourist trail, is the only commercial gypsum cave in the country.

The second major area of cave development occurs in the Cloud Chief Formation of the Weatherford Gypsum Hills in Custer and Washita Counties. The Corn Caves, near Corn, Oklahoma, consist of numerous highly dissected gypsum caves. The caves in this area are noticeably lacking in gypsum speleothems but contain large colonies of *Myotis velifer*.

The third major area of gypsum caves in in the southwest corner of Oklahoma. This extensive area of nearly flay-lying gypsum is called the Mangum Gypsum Hills. It consists of approximately 50 feet of gypsum, with thin stringers of dolomite and red shales. These gypsum members are equivalent to the Blane Formation in northwestern Oklahoma. Jester Cave is the most extensive gypsum cave in this area. With 50 entrances and more than six miles of surveyed passage to date, Jester Cave is currently the longest gypsum cave in the free world.

CHANNEL SEDIMENT SIZE AND SLOPE OF SUBSURFACE STREAMS

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Cobble-size sediments from active stream channels in Organ Cave, West Virginia, were correlated with channel variables including width, channel slope, and passage slope. The drainage area was used as a surrogate for discharge as a flow variable. Seven separate stream reaches were studied. The channel slopes ranged from 0.6% to 4.2%; passage slope closely paralleled the geologic dip and ranged from 1.7% to 16%. Mean sediment size ranged from 23 to 82 mm. A linear regression equation using mean sediment size (d) as the criterion variable and channel slope (s) and area (A) as predictor variables explained 80% of the variation:

$$d(mm) = 1007s(\%) + 17.2A(km^2) - 2.77$$

The average passage gradient was generally steeper than the channel gradient at the sampling sites, and the passage gradient also showed a high correlation with sediment size. The power equation obtained by Hack (1975) in a study of small surface river valleys in Virginia consistently predicted smaller grain sizes of greater slopes than were measured for this study. The

Shield's threshold of motion criteria, however, suggest that even larger size bed material could be moved. The channel sediment size in subsurface streams appears to be in dynamic equilibrium with prevailing geologic and hydrologic variables.

KARSTIC REGIONS AND SPELEOGENETIC DIVERSITY OF NEW ENGLAND

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The New England region (Connecticut, Rhode Island, Massachusetts, Vermont, New Hampshire, and Maine) has a high number of documented caves (estimated to total over 800). Although most are small, with lengths or depths less than 100 m, the caves exhibit a remarkable diversity in morphology, geologic setting, and genetic history. Taken as a whole, they represent a microcosm of speleogenetic processes observable from many large, well defined and studied karstic regions in the United States.

New England speleogenetic regions are groupable into three districts based on physiographic setting, bedrock lithology, and cavern development: (1) the Appalachian foldbelt; (2) isolated exposures of carbonate terrane; and (3) scattered areas of pseudokarstic phenomena.

The Appalachian foldbelt encompasses the Taconic and Berkshire Mountains in westernmost Connecticut and Massachusetts and the Green Mountains in Vermont. A narrow, yet continuous, band of carbonate rock, generally low-grade marble of Cambrian and Early Ordovician age, extends through the westernmost part of New England from southwestern Connecticut north to the Canadian border of Vermont. Cavern development within the marble belt is confined to exposures of calcitic or dolomitic Lower Ordovician deposits on the flanks of mountains or along valley floors. Caves are generally aligned along bedrock strike or along well-defined fracture sets. Most caves have formed where surface water flowing across insoluble metamorphic terrane immediately sinks into adjacent carbonate units.

Isolated exposures of marble and limestone occur throughout the New England states. In the few areas where caves have formed through dissolution, fortuitous geologic circumstances have prevailed.

The majority of caves of New England are nonsolutional in origin. Pseudokarstic phenomena include complex passage networks within extensive talus deposits, spacious cliff caves enlarged through frost wedging, rift or "purgatory" caves resulting from subsidence, block glide, or spalling, and sea caves. At least two Connecticut caves in Triassic basalt may, in part, be related to lava-tube development.

SEA LEVEL CONTROL OF CAVE DEVELOPMENT IN THE BAHAMAS

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The development of caves in the Bahamas is intimately connected with the position of sea level at the times of cave formation. Recent work by cave divers in the Bahamas has shown that the halocline, the boundary between the Ghyben-Herzberg freshwater lens of an island and the underlying ocean water, is a site of enhanced solutional aggressiveness. This has also been shown by the work of others from Yucatan, Mexico, and from Bermuda. The enhanced aggressiveness of the halocline region is supported by direct observation, chemical measurements, and theoretical calculations. Cave passages have been observed to follow the halocline from near sea level on the island platform margins to significant depths as the freshwater lens curves beneath the island interior.

While the halocline is clearly important in Bahamian cave development, other evidence demonstrates that caves will form high in the Ghyben-Herzberg freshwater lens, above the halocline. Throughout the Bahamas, large cave passages, now air filled, exist at least 7 m above current sea level. Many of the caves are known to be developed in rocks younger than 150,000 years of age, a time when sea level is not known to have been more than 6 m above present. These large caves mush have formed when a past, higher sea level pushed the freshwater lens into the +7 m range. Most of these caves are located in the interior of the islands, and Ghyben-Herzberg freshwater lens morphology would argue that the halocline was many meters below the horizon of conduit development. The close association of the conduits with what must have been an area very near the top of the freshwater lens implicates the vadose/phreatic contact as another zone of enhanced solutional aggressiveness. Cave passages in the Bahamas, especially ones currently submerged, are perhaps polygenetic. Not only can they form at the top and bottom of a freshwater lens, but the numerous Pleistocene sea level fluctuations may have repeatedly placed a given cave passage in both settings.

ORIGIN OF THE SOLUTION CAVITIES IN HELL'S CANYON, IDAHO

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Nearly 2,000 feet of massive-bedded, late Jurassic-aged Martin Bridge Limestone is exposed along the narrow confines of Hell's Canyon of the Snake River between Idaho and Oregon. The limestone has been severely faulted and folded to the point that confining shales, basalts, and sandstones have undergone low-grade chlorite metamorphism. Cavities formed in a shallow

syncline sometime after the canyon's filling with Columbian River basalts approximately 16 million years ago. At an early stage of down-cutting of Hell's Canyon, water sank into the newly exposed carbonates and moved parallel to the Snake River along primarily strike-oriented passages that formed near the trough of the syncline. Smaller dip and fracture controlled passages of steeper gradient connect the longer strike-oriented passages. A high-angle normal fault which cuts across the hinge line of the syncline apparently diverted the ground water movement with the suggested velocities expected under low-gradient water table conditions.

As the Snake River cut downward, Allison Creek did likewise separating most of the recharge zone from the caves. This is suggested by accordance of cave entrances across the narrow canyon walls. Continued downcutting created steep surface gradients and an associated reduction in recharge area, thus eliminating significant water movement through the caves today. Non-integrated pocket caves are scattered throughout the Martin Bridge Limestone as well, having formed in lithologically favorable areas with some occasional structure control.

SILICEOUS CRUSTS ON CAVE WALLS

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Siliceous crusts are fairly common features replacing the limestone in cave walls. Crusts in Mammoth Cave are white, composed of very finely crystalline quartz, and form on limestone bedrock only. The crust thickness is 0.3 to 1.5 cm. It forms primarily around shafts that intersect lateral passages. The crust is a moist paste near water sources and grades laterally to friable powder in dry areas. Evaporation is probably necessary to increase the concentration of the silica enough for precipitation to occur. The source of the silica appears to be sandstone of the Big Clifty Formation, fragments of which occur in the shafts and overlying sinkholes.

Similar siliceous crusts are also found in caves in the Black Hills, South Dakota. These crusts predate a thick layer of calcite spar that coats the cave walls. The thickness of the siliceous crust is rather uniform (about 8 mm), which suggests that it was not formed by point sources of recharge. The quartz is partly opal and partly finely crystalline. The insoluble residue in the South Dakota samples is distinctively sponge-like, in comparison to the granular insoluble residue from the Mammoth Cave crusts. In the Black Hills, the percent of insoluble material in the crust is four to eight times greater than in the bedrock. In Mammoth Cave, the crusts have an insoluble percentage only about three times greater than of the bedrock.

THE UTILIZATION OF GEOLOGIC STRUCTURE IN A KARST REGION FOR THE REMOVAL OF STORM WATER RUNOFF

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Bowling Green, Kentucky, in the south central portion of the Pennyroyal Plateau, is located entirely upon a sinkhole plain. The city is almost completely dependent upon the karst aquifer for removal of storm water runoff. Sinkholes are very efficient at collecting storm water runoff and directing it into the subsurface drainage system. Runoff therefore sinks naturally into the cave drainage system beneath the city at thousands of locations, usually flowing directly into the aquifer through sinkhole drains.

In order to reduce sinkhole flooding of homes, buildings, and streets (two lives were lost in 1978), the city and county have adopted a storm water management plan which includes: (1) restricting development within sinkhole floodplains; (2) storm water retention basins; and (3) drainage wells. Over 400 drainage wells have been drilled to date to direct runoff into solutionally enlarged joints, bedding planes, and caves. Many of the wells do not intersect good interconnected voids and therefore have low drainage capacities.

Research is in progress by the Center for Cave and Karst Studies to determine the best locations for drainage wells. It is hoped that the research will increase the efficiency of the wells and also reduce sinkhole collapse and groundwater contamination problems. The research involves the use of the following: (a) an improvised periscope and a down-hole camera for looking at voids in existing wells; (b) exploratory drilling; and (c) pressure testing using a double packer system to determine the drainage capacity of voids at different levels in the wells.

RECONNAISSANCE GEOLOGY OF MERCER CAVERNS, CALIFORNIA: A STRIKE-ORIENTED COLLAPSE CAVERN

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Mercer Caverns, at 649 m elevation, is located in the Mother Lode gold belt, western Sierra Nevada, and has formed along the strike of vertically dipping dolomitic calcite marble of the Permian (?) "Calaveras Group". 1,033 m of passage reaches a depth of 58 m and is essentially a single phreatic chamber. An overlying Mio-Pliocene erosion surface and an adjacent 9.2 million year old, basalt-filled pit infer initial Miocene solution. Groundwater drained by down-cutting San Domingo Creek perhaps 4 million years ago initiated massive collapse along vertical foliation and horizontal joint surfaces due to loss of bouyant support. Deposition of an ochreous clayey silt nearly filling the lower cave followed closely. An initial calcite depositional phase of flowstone, draperies, and stalagmites followed partial flushing

of the upper cave. Redeposition of terra rosa in the lower cave sealed drainage ways and locally ponded vadose waters. Reaching saturation, the waters overcoated the walls, breakdown, and existing speleothems with orange dogtooth spar 6 to 40 mm long. At this time a groundsloth blundered into the cave and was cemented into calcite flowstone. This episode also resulted in the bulk of the cave's decorations. Following this, large amounts of dark brown soil were washed into the upper portions of the cave. Currently, calcite speleothems are being deposited. Speleothems noted include stalactites, soda-straw stalactites, draperies, flowstone, stalagmites, gours, anthodites, crystals, crusts, blisters, shields, helectites, coralloids, pearls, rafts, and moonmilk of calcite, aragonite, hydromagnesite, and cristobalite ("opal") composition.

HYDROCHEMICAL PROCESSES IN A MARBLE CAVERN: CAVE CITY, CALAVERAS COUNTY, CALIFORNIA

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Most speleophiles and geologists are well aware that natural caves in carbonate rocks such as limestone and marble result from dissolution, or "corrosion", of the rock by slightly acidic groundwaters. However, the actual hydrochemical processes involved are in many cases quite complex and poorly understood.

A multi-faceted field study of groundwater chemistry was conducted during 1983-84 at Cave City Caverns, a well-known marble cave in the Mother Lode region of California. Complete inorganic chemical analyses were made of water samples collected from several locations in the cave as well as in streams nearby. In addition, selected mineral and rock samples were chemically analyzed and CO_2 gas measurements were made, both inside the cave and in the soil zone, for comparison with the hydrochemical data. Analyses of C isotope ratios in the marble rock samples and in selected water samples were used to help determine the ultimate sources of the carbonate in the cave waters.

Analysis of the Cave City data indicates that three processes commonly assumed responsible for corrosion in caves—sulfide oxidation, mixing corrosion, and the "temperature effect"—cannot explain entirely the aggressiveness of the cave waters. Instead, the primary cause of corrosion appears to be the mixing of carbonate aquifer waters with low-oxygen groundwaters flowing into the cave aquifer from other types of metamorphic rocks surrounding the marble unit.

PSEUDOKARST DEVELOPMENT IN LACUSTRINE DEPOSITS IN THE SHOSHONE AREA, CALIFORNIA

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Dissection of Pleistocene lacustrine sediments near Shoshone, California, has resulted in the development of pseudokarst including sinkholes, box canyons, and caves. The sediments, deposited in ancestral Lake Tecopa, consist primarily of well-bedded siltstones and clays with additional interbedded layers of volcanic ash and unconsolidated alluvial material. Pseudokarst development has followed the establishment of the drainage of the present-day central valley by the Amargosa River and is currently in progress.

Pseudokarst development encompasses a broad range of expression, from small surficial depressions caused by the piping of alluvial material below the desert hardpan to large multi-level caves eroded from less resistant beds in the more consolidated siltstone, clay, and ash layers. Some of these caves display pseudokarst equivalents of both speleothems and speleogens and correspond to surface sinks and deranged drainage patterns.

BASE LEVEL CONTROL OF CAVERNOUS FLOW PATHS: A NEGATIVE TEST OF THE GARDNER MODEL

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The Gardner model of groundwater flow in carbonate rocks is one of the few that recognizes the possible existence of anisotropic conditions in stratified limestone aquifers. According to the Gardner model, when a strike-oriented surface stream entrenches into gently dipping limestone, caverns develop on the updip side of the stream within certain beds that have high hydraulic conductivity. As each bed with high conductivity is breached, caverns develop. The resulting caverns are dip-oriented, simple gravity-flow systems with gradients that are initially bedrock controlled. Garrison Chapel Karst Valley, in southwestern Monroe County, Indiana, is an especially fine field case for testing the Gardner model. The geologic setting and geomorphic history of the area are consistent with Gardner's hypothetical situation. Prior to the entrenchment of the strike-oriented surface stream, Richland Creek, Garrison Chapel Valley was drained by cave passages that conveyed groundwater mostly south or southwest and discharged into tributaries of Indian Creek. The early conduits were oriented nearly parallel to strike and had gradients of 1.1 to 2.5 m/km. Entrenchment of Richland Creek occurred during the early Pleistocene in response to the glacial diversion of the Teays River into the ancestral Ohio River. At present, four separate cavernous conduit systems convey groundwater west from Garrison Chapel Valley to springs at the heads of tributaries to Richland Creek. The springs are at elevations of 40 to 50 m lower than the floor of the karst valley. The active flow paths drain in a downdip direction, have gradients averaging 11 to 24 m/km, and have downcut through 13 to 42 m of

limestone strata in the Blue River Group (Mississippian). Cave passages on different levels are close together in the upstream direction, rather than maintaining uniform stratigraphic separation as predicted by the Gardner model. Cavernous flow paths cross-cut strata, thus indicating that, on a regional basis, the Blue river Group functioned as a single, isotropic hydrostratigraphic unit with respect to hydraulic conductivity. Cavern positions were controlled by hydrologic gradients between upland recharge areas and a sequence of changing base levels along valley floors. The stratigraphic positions and longitudinal profiles of cavernous drainage levels in the Garrison Chapel area are inconsistent with the Gardner model and are better explained by the base level concept of Powell. The Gardner model may, in general, be applicable in some areas of low relief and gently-dipping limestone, but specific examples have not been identified.

MICROGRAVITY AS A TOOL FOR CAVE MAPPING

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During the past year the Center for Cave and Karst Studies in cooperation with the Green River Grotto of the National Speleological Society has been involved in an extensive program of cave prospecting, exploration, and surveying. The Lost River Cave System has been the major focus of this research. In addition to detailed mapping of the accessible portions of the cave, it is our goal to delineate those parts of the system which are either water-filled or blocked by other physical obstacles. Knowledge of local geology and hydrogeology, topographical analysis, and dye tracing has allowed the delineation of the hypothesized route of the trunk passage from the furthest accessible downstream portion of the cave to the Lost River Rise, the resurgence of the Lost River. Relatively simple microgravity procedures, used in conjunction with the above techniques and exploratory drilling, have proved useful in mapping the route of the cave. The actual field technique involves conducting gravity traverses perpendicular to the hypothesized location of the cave passage and proceeding in a "leap frog" fashion along observed anomalies. The reliability of this procedure was tested by making traverses over known cave locations and by drilling into selected anomalies.

LUMINESCENCE OF CAVE CALCITE DEPOSITS: A CURRENT APPRAISAL

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With few exceptions, calcite speleothems exhibit a green-white phosphorescence when excited with a bright white light such as a flash bulb or strobe and a blue-white phosphorescence when excited by ultraviolet. Luminescence spectra measured under ultraviolet and laser excitation reveals a complex band shape which is dependent on the excitation wave length and varies from specimen to specimen. Ultra violet excitation emphasizes bands near 405 and 450 nm while excitation with 488 and 514.5 nm lines of an argon ion laser produces luminescence in the green-yellow region. The luminescence of cave calcites is quite different from the luminescence (or lack of it) associated with vein calcites and calcites in ore deposits, most of which is a bright crimson due to Mn^{2+} in the $CaCO_3$ structure and which, except when co-activators such as Pb^{2+} are present, must be excited by electron beams or other energetic sources. Cave calcites also often exhibit crimson luminescence under electron beam excitation, but not from excitation by ultraviolet or visible light. It is hypothesized that the characteristic long decay-time luminescence of cave calcites is due to the humic substances that are also responsible for the tan-orange-brown colors seen in many speleothems. There is evidence that the bands seen in the blue are due to fulvic acid components and those seen in the green-yellow are due to the humic acid component.

A GEOCHEMICAL MODEL FOR THE DEVELOPMENT OF GYPSUM CAVES

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Gypsum caves occur as complex network mazes, such as the large gypsum caves in the Soviet Union, and as fragments of conduits. Both patterns are remarkably similar to the passage plans of limestone caves as are the cross-sections and the solutional sculpturing. Unlike limestone, gypsum dissolves by a simple dissolution reaction releasing Ca^{+2} and SO_4^{-2} into solution. The equilibrium saturation is about 2,000 ppm. The laboratory investigation of Liu and Nancollas shows that gypsum dissolution kinetics is mass-transport controlled and described by a first order rate equation. The rate of approach to saturation is more rapid than the dissolution of limestone implying that infiltration waters in gypsum are close to saturation. However, the exponential tail of the integrated rate curve allows slow dissolution at depth although the initiation phase of gypsum caves extends over longer times than the initiation phase in limestone. The higher solubility and faster dissolution rate shorten the enlargement phase in cavern development. Because of the mass transport control, the cavern enlargement process is more sensitive to the onset of turbulence than is the case in limestone aquifers.

SIERRA DE EL ABRA, MEXICO

Margaret Hart
Exploration in the Sierra de El Abra in San Luis Potosi and Tamaulipas has been an ongoing aspect of the Association for Mexican Cave Studies speleology since the 1960s. The region lies in the front ranges of the Sierra Madre Oriental between Ciudad Mante and Ciudad Valles. It is bounded on the west by Highway 85 (the Interamerican Highway) and on the east by the coastal plain at the base of the range. The combination of karst topography; thick, aggressive, and often nasty vegetation; and tropical climate produces a unique terrain which requires a variety of exploration techniques developed and used almost exclusively in this particular area. Major caving projects and the history of exploration in the region are discussed.

CREVASSE CAVES IN ANTARCTICA

David Honea
Various caves in a large glacial ice tongue that descends from the flanks of Mt. Erebus on Ross Island have been explored via access from McMurdo Research Station. Most of these caves are developed in crevasses which originate when the ice descends from about 2,800 m elevation to sea level. Access becomes possible when the floating ice tongue extends out into McMurdo Sound, where some of the ice caves extend below sea level. Ice stalactites and stalagmites, as well as crystalline ice formations, are present. Internal ambient temperatures can range from about -10 degrees to -40 degrees C. Although not extensive, the intriguing differences and similarities between these ice caves and conventional caves make for interesting exploration.

SUMIDERO DEL RIO SAN JOSE DE ATIMA, HONDURAS

Steve Knutson
The exploration of the cave carrying the flow of the Rio Atima in the Department of Santa Barbara, Honduras, was begun in February, 1981, with a penetration of only 500 m on ledges during high water. The effort was continued in April, 1985, with a further 350 m gained in three push trips. The resurgence, 1,700 m linear distance away and 170m lower, was entered for over 900 m, leaving a gap of 400 m. In March, 1986, an attempt will be made to complete this sporting through-trip.

PURIFICACION III: CUEVA DE LA LLORONA

Dale Pate
Cueva de la Llorona is a multiple-drop cave that was extended to a depth of 398 m during an expedition in October, 1985. It may prove to be a feeder into Sotano de Las Calenturas, a 6-km long system located several kilometers to the north.

ORIGINS OF AMCS CAVING

Terry Raines
This paper presents a review of the early days of caving in Mexico, from the deep caves of Tlamaya to the 410 m rappel into El Sotano. Cavers of the Association for Mexican Cave Studies pioneered the use of Jumars and other vertical techniques in deep cave systems but lacked wetsuits that make wet caving so routine today.

PURIFICACION II: CUEVA DEL TECOLOTE

Peter Sprouse
Cueva del Tecolote is situated southeast of Sistema Purificacion in the Sierra Madre of Tamaulipas, Mexico. In November, 1985, 20 cavers succeeded in mapping four km of new passage in the cave. Most of the new discoveries were large, horizontal boreholes at a depth of 200 m below the entrance. The total length of the system is currently 7,015 m.

SISTEMA PURIFICACION: CAMP CHALLENGER

Terri Treacy Sprouse
During the last two weeks of March, 1986, twelve cavers from the United States, Canada, and Mexico continued exploration of Sistema Purificacion in Tamaulipas, Mexico. A remote camp was set, 5 km in from the Cueva del Brinco entrance at a depth of 600 m. The main objectives during the five days of survey were to explore the many leads in this remote portion of the cave and to try to extend the system to the south. Over 5,700 m of new passage were added to the system (bringing the total length to over 60.8 km). Two new streams were discovered as well as two additional connections to the Infiernillo section of the cave. The cavers exited after seven days underground through the Infiernillo Entrance.

PALEONTOLOGY SESSION

QUATERNARY VERTEBRATE FOSSILS FROM
ORGAN CAVE, WEST VIRGINIA

Fred Grady, 1201 South Scott Street, Arlington, VA 22204
Since the late 1940s vertebrate remains have been collected in Organ Cave, Greenbrier County, West Virginia. Some 29 taxa of fossil vertebrates have been identified, not counting modern domestic species. Five taxa are extinct: *Dasypus bellus*, *Smilodon* sp., *Mylohyus nasutus*, *Equus complicatus*, and *Mammut americanum*. Four others, *Myotis griscescens*, *Ursus arctos*, *Rangifer tarandus*, and *Erithizon dorsatum*, no longer occur in West Virginia. Two taxa are the only records for West Virginia and another is only the second record for the state. The Organ Cave fauna includes species with northern, western, and presumed southern affinities.

THE CONTRIBUTION OF NEW MEXICAN CAVES TO
PLEISTOCENE PALEONTOLOGY

Arthur H. Harris, Lab for Environmental Biology, University of Texas at El Paso
Paleontologic cave sites and open (non-cave) sites differ basically in their sampling of faunas, showing different taxonomic, size class, and number biases. Open sites tend to preserve mammals best, and thus a comparison of mammalian fossils from the two classes of sites present open sites most competitively.
Comparison of mammals known from the latest Pleistocene New Mexican sites gives an excellent standard for the importance of cave sites within the state. Some 121 mammalian taxa are known from the mid and late Wisconsinan age—roughly 60,000 to 10,000 years ago. About 93% are represented in cave sites and 35% in open sites; 65% of the taxa have been recorded *only* from caves, compared to 7% unique to open sites.
Six extinct species of mammals have been described from New Mexican caves (as have three species of birds), and five of these are known *only* from cave sites.
Taxonomic and biogeographic importance aside, the many specimens of numerous taxa that commonly are associated in caves (only four of 14 open sites have five or more taxa represented while 18 or 28 cave sites meet that criterion; maximum number of taxa for open sites is 26, while the maximum cave site number is 51) allow an approximation of past environmental conditions unapproached by open site data.

SPELEAN HISTORY AND SOCIAL SCIENCE SESSION

EDWARD DRINKER COPE'S CONTRIBUTIONS TO SPELEOLOGY

Fred Grady, 1201 South Scott Street, Arlington, VA 22204
Edward Drinker Cope (1840-1897), while better known as a vertebrate zoologist and paleontologist, also made considerable contributions to speleology. From 1867 to 1871 Cope explored a number of caves in the eastern United States and described both modern and fossil faunas. After 1871 Cope concentrated of other studies but continued to write occasional papers on cave faunas, especially on fossil bones found in caves.

THE CAVE PAPERS OF EDWARD MCCRADY, HENRY T. KIRBY-SMITH, AND
HARVEY M. TEMPLETON

Larry E. Matthews, Hendersonville, TN
McCrady, Kirby-Smith, and Templeton did extensive cave exploration in the southern half of middle Tennessee during the late 1930s, the 1940s and early 1950s. During that time period they published several scientific papers on cave biology and vertebrate paleontology. Supposedly, they had discovered the McCrady Canyon-Waterfall Room area of Cumberland Caverns, Warren County, Tennessee, during this time period but documentation was lacking.
While researching the history of Cumberland Caverns, it was discovered that all three men had kept journals of their cave explorations. These journals document many important cave discoveries. Because of their historical and scientific value, these journals are being prepared for publication. The Kirby-Smith papers have already been published in the *Journal of Spelean History*

SURVEY AND CARTOGRAPHY SESSION

LASER PROFILES OF CAVE PASSAGES

Bob Buecher, 7050 East Katchina Court, Tucson, AZ 85715
Several methods are described for using a small, battery powered Helium-Neon laser to determine ceiling heights, cross-sections, and passage profiles in caves.

The methods discussed all involve using the laser to project a small, bright point of light that is used as a target; normal cave surveying instruments are used to determine the position of the target.
The four methods that have been used to assess the usefulness of the laser in cave surveying are: (1) Right triangle ceiling height determination; (2) Simultaneous triangulation with two instruments; (3) Intersecting the plane formed by rotating the laser about a fixed axis; and (4) Use of an optical rangefinder and a laser target.

A LOOK AT COMPASS AND CLINOMETER ERROR IN THE OTR SURVEY
COURSES.

John Ganter, 1016 Taylor Street, State College, PA 16801.
Data from survey courses held at the 1983 and 1984 West Virginia Old Timers Reunions were examined in an attempt to determine the types of errors present and their sources. Both readings for specific instruments and shots and transverse mis-closures were considered. Systematic error became visible when individual instruments were compared over populations of both shots and users. Random error is elusive, but its magnitude appears to decrease with user experience and increase with both inclination and length of the shot. Oddly enough, the relationship between a user's total deviations from the averages established by his fellows and his resulting traverse mis-closure appears to be weak. Larger samples and better course design will be required to explain these relationships more clearly.

PRODUCING COMMUNICATIVE CAVE MAPS

John Ganter, 1016 Taylor Street, State College, PA 16801.
Cave maps have the ability to efficiently convey spatial information such as the position and extent of passages, the condition of the cave at a specific time, and the relationship of the cave to surface features. Through design (the application of thought to solving a cartographic problem) and craft (the translation of design into reality through manual dexterity) the cartographer can create effective maps which convey his or her message. Symbolism; viewing conventions; ancillary information; typography; and multiple-scale, special purpose maps are discussed. Special problems such as visual hierarchy and figure-ground contrast are covered as well.

UNITED STATES EXPLORATION SESSION

HIGH TECH RIDGE WALKING: THE LOCATION AND EXPLORATION OF
ROBINSON CAVE, BOWLING GREEN, KENTUCKY

Christopher G. Groves and Nicholas C. Crawford, Center for Cave and Karst Studies, Western Kentucky University, Bowling Green, KY
In March of 1985, the U.S. Centers of Disease Control issued a health advisory for the Bowling Green, Kentucky, area in response to potentially toxic and explosive fumes rising into homes and schools from caves beneath the city. As a result of the advisory, the U.S. Environmental Protection Agency Emergency Response Team (Superfund) began an investigation into the problem and was authorized to spend up to $1,000,000 to locate the source of the fumes and rectify the problem. Nick Crawford was retained as the hydrology consultant for the project and graduate students from the Center for Cave and Karst Studies were hired to dig open, explore, and survey caves. A major goal of the investigation was to gain entry into a hypothesized, but as yet unexplored, river passage within the Lost River Cave Systems that was suspected to contain floating chemicals believed to be the cause of the fume problems. The cavers attempted unsuccessful entrance digs at nine locations, having at their disposal a backhoe, a trackhoe, jackhammers, and strange Japanese expanding putty.
In late April efforts were concentrated in the area of an entranceless cave that had been accidentally blasted open in 1964, briefly explored, and then resealed. Exploration began from the surface using a drill rig and microgravity equipment. Soon the drill intersected a seven-foot high void, and within a few days a 30-inch, 33-foot deep shaft was drilled into Robinson Cave. Over 7,500 feet of passage were explored and mapped, including two streams, a nice section of trunk passage, and a spectacular waterfall.
Unfortunately, the main stream sumped after a short distance, thus ending hopes for a downstream connection with Lost River Cave. Several organic solvents were detected within the cave at low concentrations, but in spite of this, aquatic cave life is thriving.

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.

Once the paper has been typeset and laid-out, the senior author will be sent one set of proofs for review. Any corrections other than printer errors will be done at the author's expense. A reprint order form will be sent with the proofs. At this time all authors will be requested to contribute page charges of $25 per page to help defray the cost of publication. The actual cost to the society is about $100 per page. Acceptance of manuscripts for publication is not contingent upon payment of page charges.

CONTENTS