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Contents

APRIL 1964

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Papers in any discipline of speleology are considered for publication in the BULLETIN. The upper limit for length is about 10,000 words or approximately 40 pages of manuscript, typed double-spaced. At least one copy but preferably two copies of the manuscript (typed, double-spaced) should be submitted to the Editor, Jerry D. Vineyard, Missouri Geological Survey, Box 250, Rolla, Missouri 65104. Photographs and line drawings, if required, should be submitted with the manuscript. In general, prints and line drawings will be photo-reduced to the size necessary for use in the BULLETIN.

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DISCUSSION of papers published in the BULLETIN is invited. Discussions should be 2000 words or less in length with not more than 3 illustrations. Discussions of papers in this issue should be forwarded to the editor by July 15, 1964.

NATIONAL SPELEOLOGICAL SOCIETY

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Cavern Development in the Greenbrier Series, West Virginia

By THOMAS E. WOLFE

ABSTRACT—The spatial distribution of major cavern passages within a local area is a key to determining their origin. Four hypotheses concerning the causes of accordance, or development of nearly horizontal cavern passages within a zone or plane through the limestone, are considered and evaluated as to their control of cavern formation in southeastern West Virginia. These four are: structural control, erosion level control, water table control, and lithologic control. The conclusions drawn with the aid of cross sections indicate that a major erosion level, described as the Harrisburg Peneplain, appears to have been a key factor in the local development of major horizontal cavern passages. Their accordance may have been produced as a result of water table stabilization over a long period during the planation of the erosion level. It is further suggested that this development took place well below the water table.

ACKNOWLEDGEMENTS

This paper is based on a thesis submitted in 1962 to the Graduate Faculty in the Division of the Social Sciences, University of Pittsburgh, in partial fulfillment for the degree of Master of Arts.

The writer acknowledges his indebtedness to many members of the Pittsburgh Chapter of the National Speleological Society who aided in field procedures, and in the mechanics of thesis preparation. Specific mention is given to Miss Hermine Zotter for stream tracing procedures. To Dr. H. V. B. Kline, Jr., Chairman of the Department of Geography, and Dr. N. K. Flint of the Department of Geology, under whose joint supervision this study was undertaken, I acknowledge my sincere gratitude. To Victor Schmidt, Allen McCrady, Mrs. Beverly Frederick, Frank Mielcarek and Miss Hermine Zotter, I wish to express thanks for aid in preparing the manuscript.

In addition to the members of the above organizations I thank the people of West Virginia in the area of study, without whose generous cooperation the field work would have been impossible. The assistance of Mr. G. Dallas McKeever will always be remembered. Finally I thank my patient wife, Jacqueline, for her proof reading, typing and photographic assistance.

INTRODUCTION

The spatial distribution of relatively horizontal cavern passages in caves in the Greenbrier limestone of southeastern West Virginia has an important bearing on the origin of caves. A degree of accordance of cave passages in the area of investigation has been suggested by Davies (1958) who relates their location to the headwaters of major drainage basins.

The principal aspect in this study of the problem of spatial distribution of such passages is to determine the degree of accordance, if any, associated with passage locations. The possible controls of location are to be evaluated in connection with the problem of their distribution in space.

Many competent observers differ in their opinions as to the origin of limestone caverns, and there is probably some truth in each opinion (Thornbury, 1954). The development of horizontal passages is important in explaining the origin of limestone caverns, since the horizontal nature of cave passages is one of their most common characteristics (White, 1959).

Theories of cave origin suggest that major horizontal passages exhibit levels or zones at which development appears to be most frequent. The suggested causes of such accordance are: (a) the relation of former erosional levels to the passage levels (Sweeting, 1950); (b) the relation of the position of the water table to the levels (Gardner, 1935; Swinnerton, 1932; Bretz, 1953; Woodward, 1960); (c) the relation of lithologic controls to the levels (Gardner, 1935); and (d) the relation of structural controls to the levels (Sanders, 1959).

This study is based on a review of published data, topographic and geologic maps, with field studies of the Greenbrier limestone series and related caves. It was necessary to map in the field the 11 members of the Greenbrier limestone with respect to thickness, areal distribution, and relations to surface and subsurface drainage, local topography, erosion levels, caves and cave levels.

In mapping the members of the Greenbrier series, absolute elevations based on sea level were determined with a Paulin altimeter calibrated in units of two feet. Referencing of the instrument to bench marks and other known elevation points was done frequently to assure accuracy to approximately the nearest 10 feet. Numerous samples were taken for comparison of lithologies across the study area.

Mapping surface and subsurface drainage on the Greenbrier series was necessary for evaluating water table control of cave levels. Additional information concerning the relation of drainage and water table to lithology, stratigraphy, rock structure and erosion levels was gained from the drainage data collected.

The field investigation included tracing courses of underground streams and correcting the courses of surface streams inaccurately shown on topographic maps.

Subterranean stream courses were traced by exploration where possible. Most frequently, however, fluorescein dye was used for relating resurgence points to cave streams or swallow holes where surface streams went underground. Activated charcoal was placed at probable resurgences and tested later for adsorption of the dye (Dunn, 1957).

Based on descriptions by Davies (1958) and additional information in the National Speleological Society's Speleodigest, 1956-1959, there are 81 caves in the area of study; 30 of these, falling along or near three lines of geologic cross sections, were chosen for examination. The cross sections were placed so as to traverse all 11 members of the Greenbrier Series approximately perpendicular to the strike of the outcropping rock (Figs. 7, 8, and 9).

In this study a cave is defined as an

integrated system of passages, developed by solutional processes, that extends beyond the penetration of daylight. This may include vertical shafts or ponors, springs, swallow holes, and resurgences, where these features provide entrance into horizontal passages.

The term horizontal passage in this study includes passages averaging less than five feet high and more than 200 feet long; passages more than five feet high and more than 100 feet long; and passages more than 10 feet high and more than 25 feet long. Some passages less than 200 feet long are included if termination is by fill or rock breakdown. Small solution pockets of questionable relation are excluded.

In recording elevation data, the ceiling of the cave passage was used consistently as a place of measurement. Although ceiling elevations change with the addition of dripstone and the falling away of large rock sections, they are probably less subject to variation than the lower portions of cave passages. Frequent flooding and the accumulation of rock, clay, and other debris on cave floors are factors that inhibit measurement at the actual floor level. A Paulin surveying aneroid was used for cave mapping in a manner similar to that described in the surface mapping of the areal geology. The direction and slope of passage was measured with a Brunton compass, as were strike and dip of beds within the caves.

This karst area of southeastern West Virginia is in the late youth stage. The area, along the strike of the outcropping Greenbrier limestone on the slope of the Allegheny Front (Marlinton and Lobelia quadrangles, West Virginia, Figure 2), has been chosen for the study of cavern levels because:

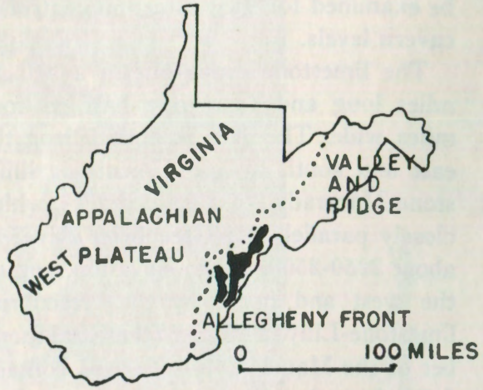

Figure 1

Location of study area, southern Pocohontas County, West Virginia.

(a) The broad exposure of limestone is easily defined geographically for an investigation of cavern levels,

(b) There is an abundance of soluble rock, thick enough to permit cavern development and the possible accordance of horizontal passages at several elevations,

(c) There are sufficient caverns to make such an investigation conclusive,

(d) Erosion levels are present which truncate the limestone so as to affect possible control of cavern development at corresponding elevations.

(e) The present position of the water table, below the elevation of many cavern passages, aids in evaluating evidence of past water table positions associated with peneplanation which are above the elevations of existing cavern passages.

(f) Interbedded shales are present in the limestone which are relatively impervious and insoluble so that their effect on lithologic control of cavern passages can be evaluated.

(g) Dip of the rock structures is gentle and joint patterns in the limestone can be examined for their effect on control of cavern levels.

The limestone crops out in a belt 15 miles long and from one half to four miles wide. The area is bounded on the east and south by the Greenbrier limestone-Maccrady shale contact which closely parallels the Greenbrier River at about 2250-2500 feet in elevation, and on the west and north by the Greenbrier limestone-Lillydale shale (the basal member of the Mauch Chunk Series) contact, following the contour of the eastern slopes of the Yew Mountains at 2750-3000 feet elevation. The actual area of study lies between a line drawn perpendicular to the general strike of the outcrop, west of Marlinton on the northeast and another line along the Pocahontas-Greenbrier County boundary on the southwest. These were drawn to limit the area at places where the outcrop narrowed to less than one-half mile in width. Also included in the area of study is a small, isolated exposure of Greenbrier limestone on the west side of Droop Mountain. This area exhibits certain lithologic and hydrologic qualities not found in the greater portion of the study area and its inclusion is of major significance in this report.

The followng districts are used for convenience in discussion (see Fig. 2).

Swago Creek—The region north of Stamping Creek.

Little Levels—The region south of Stamping Creek and east of Droop Mountain.

Lobelia-Jacox—The limestone area west of Droop Mountain southward to the county line.

All of the study area lies along the general strike of the Allegheny Front and elevations ange from 2,500 to 3,000 which are only about one third to one half of the total erosional scarp representd in the Front. Three miles from the upper limits of the limestone area, northwest of Stamping Creek, elevations rise to over 4600 feet at Black Mountain on the Allegheny Plateau. To the south and east, elevations drop to under 2000 feet along the course of the Greenbrier River, which marks the base of the Front as well as the local base level for drainage. Throughout the area, the strike of the rocks, the course of the Greenbrier River, and the northeast-southwest direction of the Allegheny Front have similar alignments because all are controlled by a homoclinal structure extending for more than 50 miles along the base of Back Allegheny Mountain. This homocline is located on the west flank of the larger Browns Mountain Anticline whose axis lies to the east of the Allegheny Front.

Surface drainage from Swago Creek, Stamping Creek, Hills Creek, Locust Creek and the Greenbrier River reflects the southeast slope of the topography. The dip of the underlying strata, however, is exactly opposite, to the northwest at about 4°. This results in gentle, cuesta-like limestone scarps facing the Greenbrier River, the higher elevations of erosional levels being near to the river with a gentle slope away to the northwest. Even the highest mountain levels have similar relationships. The uplands are at approximately 4000 to 4200 feet in elevation with summits near the Front in the southeast at more than 4600 feet.

There are no great contrasts in elevation within the area of study. Local relief varies no more than 150 feet on the broad limestone surfaces. The maxmium relief is in the Little Levels district on the surface that may represent the Harrisburg

Figure 2
Topographic map of Little Levels and vicinity (U. S. Geological Survey, Marlinton and Lobelia Quadrangles, West Virginia).

Peneplain. Elsewhere, along the flanks of the Allegheny Front, where the limestone area narrows to less than a mile in width, stronger local relief is found which encompasses the total thickness of the limestone.

Geology

Areal Geology—The Greenbrier Series comprising the middle portion of the Mississippian System in West Virginia, is made up almost entirely of marine limestone (McCue, et al, 1939). It lies directly beneath the Mauch Chunk Series and south of Randolph County. It is immediately above the Maccrady Series. Northward it rests upon the Pocono Series.

Within West Virginia, the outcrop of the Greenbrier is nearly continuous from the Virginia line at Mercer County, where it is over 1000 feet thick, northward to the Pennsylvania line at Monongalia County where it thins to approximately 100 feet. In the area of study in southern Pocahontas County the limestone is 605 feet thick in the south, decreasing to 407 feet in the north (Price, 1929).

Stratigraphy—The West Virginia Geological Survey recognizes 11 individual members of the Greenbrier Series in Southeastern West Virginia (McCue et al, 1939). Although the rapid thinning to the north causes many of these members to narrow and to disappear, all have been recognized in the area of study.

Alderson Limestone - This is the youngest member of the Greenbrier Series. It is a dark gray calcareous limestone, high in silica and weathers to a dirty yellow color. Portions are highly crystalline and fossiliferous. A plant fossil zone, occurring in chalky beds slightly above the middle of the member, has been recognized in the area of study and elsewhere (Reger, 1926). The Alderson limestone is easily located in the field because of its position directly beneath the Lillydale shale, the basal member of the Mauch Chunk Series. In the area of study it is 55 feet thick in the south thinning to 42 feet in the north.

Greenville Shale—The Greenville shale resembles a siliceous limestone far more than shale. Its composition ranges widely within the area of study, being more like that of a shale in the south, especially along U.S. Route 219 on Droop Mountain, and W. Va. State Highway 39 above Mill Point. It is brown to dark red; marine fossils are abundant. Thickness of the Greenville varies from 30 to 35 feet.

Union Limestone—This is the purest limestone in the Greenbrier series (Fig. 3). It is gray, weathers white, and is frequently oolitic and crystalline. A shaly layer is near the top of the formation. It is easily distinguished from the overlying Greenville shale, however, because of the latter's darker color and sandy nature. In the Little Levels section there is a zone at the top of the Union limestone which has a crystalline character and is known in the stone industry as "marble." The "marble" zone is as much as 30 feet thick grading into the lighter Union limestone at the base. This "marble" has only been observed in a small outcrop extending a few miles on either side of Stamping Creek. The Union limestone is the most widespread of the members of the Greenbrier Series and ranges from 113 feet thick in the north to 130 feet at Droop Mountain in the south.

Pickaway Limestone — Directly be-

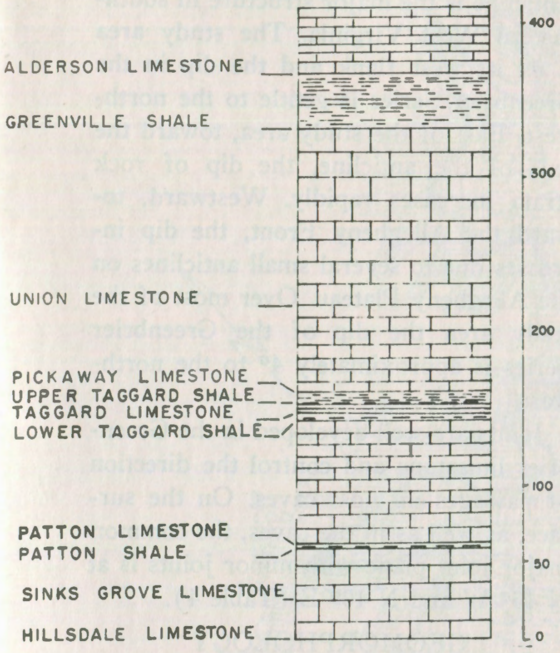

Figure 3

Generalized stratigraphic section of the Greenbrier Series in Pocohontas County, West Virginia (after Lucke, 1939).

neath the Union limestone is another fairly pure member of the Series. It is the most readily recognizable of the limestone members of the Series because of the presence of partings or "sheets" caused by thin shale bands along the bedding planes. (The contact, however, with the overlying Union limestone was not observed within the area of this study). A shaly layer said to be near the Pickaway-Union contact (Price, 1929) in the study area was used as an approximate boundary between the two members. The Pickaway thins from about 100 feet in the south to 57 feet in the north.

***Taggard Formation* — The Taggard formation is composed of three recognizable members: the Upper Taggard shale, Taggard limestone, and Lower Taggard shale. This formation is a good marker in the field because it consistently appears as two red shales separated by a thin, five foot band of light colored limestone. Neighboring limestone members of the Series are then easily recognized through their stratigraphic positiion above or below the shale beds. Usually the shales are each no more than 10 feet thick, the entire formation being less than 30 feet thick throughout most of the area. Geomorphologically, the Taggard plays an important role in control of surface and subsurface drainage because of its relative impermeability and insolubility.**

Patton Limestone—The Patton limestone in Pocahontas County is the purest limestone within the area of study. The Patton limestone is most easily identified in a weathered condition. It weathers to a light gray, smooth surface interrupted by rough areas caused by protrusion of many small fossil fragments.

Patton Shale—Thin and lenticular, the Patton shale is an important stratigraphic marker located just beneath the Patton limestone and above the Sinks Grove member. It is high in insoluble materials and acts as a barrier to percolating vadose water. Its maximum thickness of 12 feet is along the Stamping Creek road. It thins rapidly northward.

Sinks Grove and Hillsdale Limestones —Because of the lack of a recognizable contact or line of separation, these basal limestones of the Greenbrier Series are frequently grouped together. They are not alike, however, and each has distinctive characteristics. The Sinks Grove is a dark, hard, and thick-bedded limestone that weathers gray. In the south it is about 50 feet thinning to 30 feet northward. The Hillsdale, lighter in color with an abundance of chert nodules and colonial corals *(Lithostrotion)*, is easily distinguished from other members in the field. It represents the bottom of the Greenbrier Series thinning from 29 to 15 feet northward and lying on the thick, red Maccrady shale throughout the area of study.

The foregoing descriptions are of significance, for lithology acts as a control in establishing accordance of many features. Springs, resurgences, and the water-filled portions of intermittent streams whose greater courses are usually underground are often developed on the impermeable and less soluble shale members of the Greenbrier Series. Due to the slight dip of these shales to the northwest, one might expect to find accordant levels at which these springs, resurgences and water-filled stream beds are developed and maintained by a lithologic control, i.e., the shale beds.

Shale members, such as the Greenville, the Upper and Lower Taggard, and the Patton, were located in the field simply by tracing dry stream beds across the Greenbrier Series; under normal run-off conditions the only surface water or seepage was found on the beds of shale. Wet weather springs along road cuts appeared at similar stratigraphic localities. These factors, as well as visual identification of the shales, facilitated the location and mapping of all the Greenbrier members. Thinning of the limestone members northward results in a greater proportion of shale in the northern part of the study area. This is reflected in a greater abundance of springs and resurgences. The distribution of caverns in the study area, however, is not affected by this.

Structure — The Browns Mountain Anticline is the major structure in southeastern West Virginia. The study area is on its west flank and the dip in the Greenbrier Series is gentle to the northwest. East of the study area, toward the axis of the anticline, the dip of rock strata increases rapidly. Westward, toward the Allegheny Front, the dip increases due to several small anticlines on the Allegheny Plateau. Over most of the study area the dip of the Greenbrier Series is approximately 4° to the northwest.

Joints are well developed in the Greenbrier limestone and control the direction of passages in most caves. On the surface, as well as in the caves, the common major joint plane with minor joints is at N 45° W and N 40° E (Table 4).

GEOMORPHOLOGY

Surface Drainage — On limestone the drainage is interrupted and lacks a distinct pattern; elsewhere the drainage is surface run-off with dendritic pattern. South and east of the Greenbrier River the drainage has a trellis pattern where erosion of open folds has occurred, as in the valley along the axis of the Browns Mountain Anticline. Such a transitiion from dendritic to trellis pattern is to be expected along the Allegheny Front and might have been established in the area of study were it not for the abundance of limestone which causes the interrupted drainage pattern.

Under normal run-off conditions[1] there are no streams that maintain surface courses across all members of the Greenbrier limestone. However, in times of heavy rain Stamping Creek flows across

1 At Marlinton the average annual precipitation is 47 inches. July is the wettest month with 5.31 inches. November is the driest month with 2.93 inches. Annually there is considerable variaton from less than 40 inches to more than 63 inches.

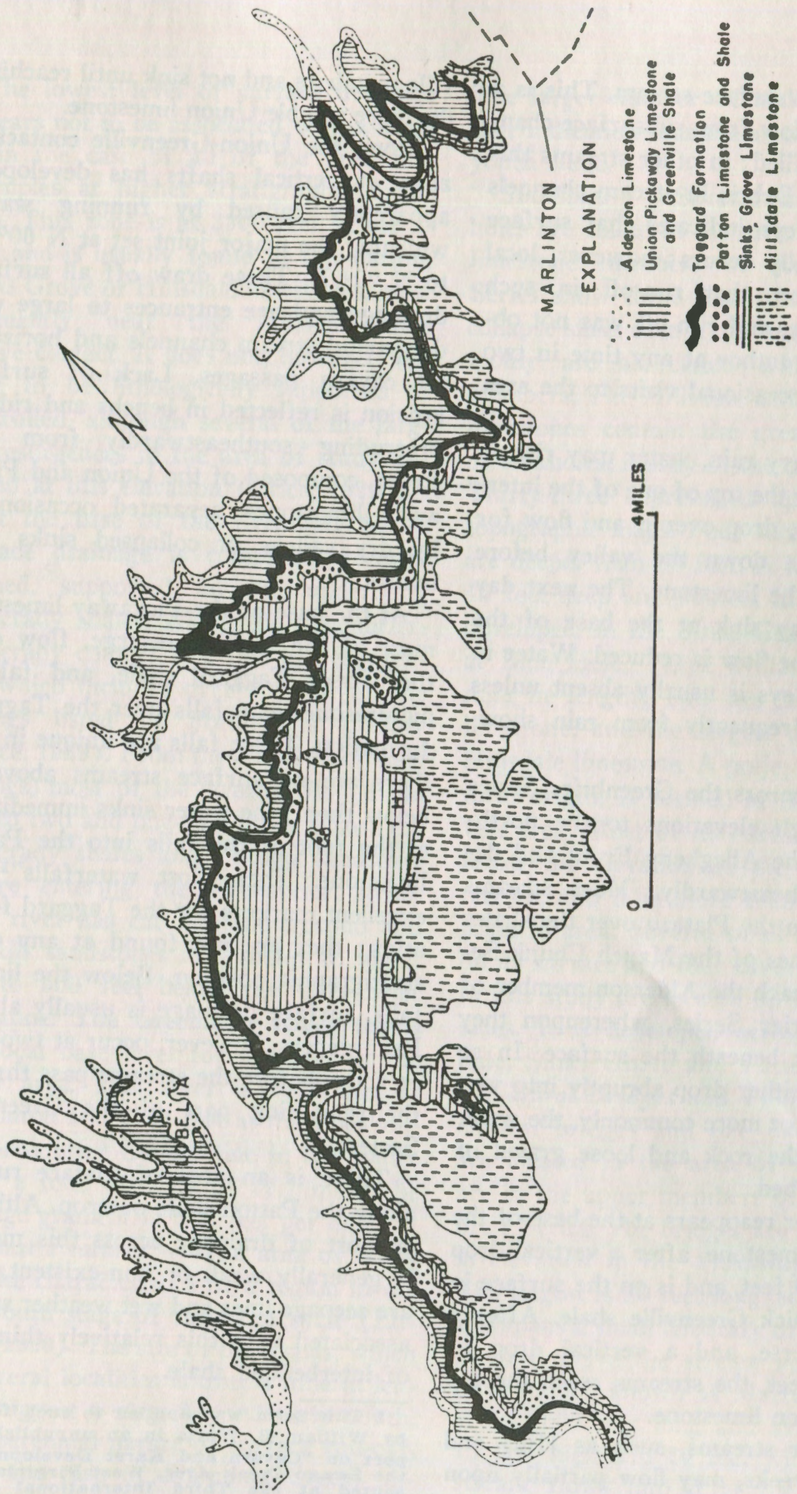

Figure 4
Distribution of limestone, southern Pocohontas County, West Virginia.

the Series as a surface stream. This is a result of overflow from subsurface channels that are filled; in other streams this rarely occurs. Debris in stream channels along dry valleys indicates that surface flow occasionally occurs; however, local residents report that run-off in such streams is rare, and run-off was not observed by the author at any time in two years during occasional visits to the area in all seasons.

After a heavy rain, water may rise in a dry valley at the top of one of the interbedded shales, drop over it and flow for nearly a mile down the valley before sinking into the limestone. The next day the water may sink at the base of the shale when the flow is reduced. Water in such dry valleys is usually absent unless replenished frequently from rain showers.

Drainage across the Greenbrier Series starts at high elevations to the northwest along the Allegheny Front and descends southeastwardly. Most streams descend from the Plateau over the shales and sandstones of the Mauch Chunk Series. They reach the Alderson member of the Greenbrier Series, whereupon they usually sink beneath the surface. In so doing they either drop abruptly into vertical shafts, or more commonly, the water seeps into the rock and loose gravel of the stream bed.

The water reappears at the base of the Alderson limestone, after a vertical drop of about 40 feet, and is on the surface in areas of thick Greenville shale. After a short traverse, and a vertical drop of about 30 feet, the streams reach the top of the Union limestone.

Larger streams, such as Hills and Bruffey Creeks, may flow partially upon the surface over the Alderson and Greenville members and not sink until reaching the more soluble Union limestone.

Along the Union-Greenville contact a zone of vertical shafts has developed, apparently caused by running water widening the major joint set at N 60° E to N 70° E. These draw off all surface drainage and are entrances to large underground stream channels and horizontal cavern passages. Lack of surface erosion is reflected in benchs and ridges protruding southeastwardly from the Front, composed of the Union and Pickaway limestones, separated occasionally by dry valleys or collapsed sinks and uvalas.

At the base of the Pickaway limestone most of the streams resurge, flow over the Upper Taggard shale, and fall as picturesque waterfalls over the Taggard formation. These falls are unique in that there are no surface streams above or below them; the water sinks immediately at the foot of the falls into the Patton limestone. These 'lost waterfalls"[1] are excellent markers for the Taggard formation; they are not found at any other stratigraphic position. Below the line of falls, surface drainage is usually absent. Resurgences, however, occur at two lower zones before the streams pass through the remaining part of the Greenbrier Series.

There is an area of surface run-off along the Patton shale outcrop. Although support of drainage across this member is generally weak or non-existent, there are seepage lines and wet weather springs associated with this relatively thin band of interbedded shale.

1 This term was applied to such features by William B. White in an unpublished report on "Cavern and Karst Development in the Swago Creek Area, West Virginia," presented at the Third International Speleological Congress (Vienna, Sept., 1961).

The lowest level of surface drainage appears not to be associated with a shale as in the case of all of the preceding examples at higher stratigraphic localities. This zone is at 2300 feet in elevation and is usually found in the Patton, Sinks Grove or Hillsdale limestones, most frequently near the Hillsdale-Sinks Grove contact. It does not, however, appear to be lithologically supported or controlled, although several of the largest resurgences in the area of study are found at this elevation (Price, 1929).

At the base of the Grenbrier Series surface drainage is completely re-established, supported on the underlying Maccrady shales. Along the Greenbrier-Maccrady contact is a line of resurgences which includes over 60% of all the springs listed in Pocahontas County (Price, 1929). From these and other such springs, most of the streams flow from one to two and one-half miles across the Maccrady shales and Pocono sandstone before entering the Greenbrier River. This river has cut into the Pocono and Catskill sandstones and shales to about 250 to 500 feet below the Greenbrier limestone. The Greenbrier River forms the local base level for drainage in the study area. This river is 2115 feet at Marlinton and 1953 feet at the Pocahontas-Greenbrier County line in the south. Over a total distance of 22.7 miles the average gradient is 7.62 feet per mile.

Karst Features — The area of study has the characteristics of a region in the late youth stage of the karst cycle (Lobeck, 1939). The size of the uvalas, which in several localities is over a mile in length, suggest a stage beyond early youth. The perennial nature of surface run-off, as in the case of Stamping Creek, implies that maturity has not been reached. The larger number of sinkholes is further indication that the area is in the late youth stage.

Sinkholes — Several hundred sinkholes are found in the area of study. All limestone members of the Greenbrier Series show these features. Dolines and collapse sinks occur; the latter more commonly are associated with the upper members. The Hillsdale and Sinks Grove limestones contain the greatest number of sinkholes, mostly of the doline variety. Thirty-three depressions appear on the topographic maps. Four such depressions are deeper than 50 feet. A karst window 45 feet deep and 60 feet in diameter, is developed, on the Sinks Grove limestone at Blue Hole. Three uvalas are over a mile in length; two are in the Union limestone, and the largest one is in the Hillsdale limestone. A polje, not of structural origin, is formed in the Little Levels area. Most of its surface is 90 feet below the elevation of the surrounding terrain, and it is more than two square miles in area. Several small streams sink on its surface and four caverns examined in this study are located on its floor and sides. It is developed across the Hillsdale, Sinks Grove and Patton members.

Natural Bridges and Tunnels — Two natural bridges and one natural tunnel are located in the area of study. They are in the upper members of the Greenbreir Series. The bridges are at 2750 feet in elevation in the Pickaway limestone. The largest is 30 feet long, six feet wide, and spans a small tributary of Dry Creek, 10 feet above the stream bed. The natural tunnel, known as Martens Cave, is about 1000 feet long and averages over 15 feet high and 20 feet wide. A small stream flows into it at the south end from a blind valley. It is at 2580 feet in elevation in the Alderson limestone.

Lapies (Karren) — These features are rare but are developed on a small scale in several localities. Most lapies are not more than six feet high. They are generally found in the Patton and Pickaway limestones on slight slopes along dry valleys.

Subterranean Drainage — In the previous description of surface drainage there is much that would suggest the existence of large networks or systems of underground run-off. Several of these systems were entered and examined in the investigation of horizontal cavern passages. Others were tested and proved connected through the use of fluorescein dye. These connections are, in some cases, greater than three miles in length. (Fig. 5).

Blind Valleys — The Alderson limestone appears to contain the greatest number of blind valleys. Streams sinking near the top of the Greenbrier Series. are responsible for these features. Downstream from these sinks, erosion from running water ceases. Thus, blind valleys occur frequently at higher elevations. They are not, however, completely restricted to the upper member of the Greenbrier Series.

Caves — More than 80 caves are in the area of study. 30 were investigated in detail. Caves are found in all the members of the Greenbrier Series. In association with the horizontal cave passages, many vertical shafts were also studied. They occur within caves as well as at the entrances. They are common at the top of the Union limestone just below the Greenville shale contact at approximately 2750 feet elevation. Many such ponors are plugged with debris and, therefore, remain unexplored. Some appear to be abandoned swallow holes in dry stream beds, while others farther upstream draw off surface drainage from the Greenville shale. Six of the caves in the study were entered via rises or resurgences of underground streams. The longest such cavern is more than three miles in length and contains at least five major horizontal passage levels. The most common type of cave entrance, not a ponor or resurgence, is an opening at approximately the same elevation as one of the horizontal passages within. A second common type is a swallow hole or sink hole generally at the head of a blind valley which may give access to cavern levels. Five such entrances were utilized in the study of horizontal passages.

Erosion Levels — Several erosion levels and river terraces are developed on and around the exposure of Greenbrier limestone (Fig. 6). There is, however, only one erosion level on the limestone; this is at 2250 to 2550 feet. Another is just above the Alderson member at 2,900 to 3,100 feet. There are no river terraces developed across the study area because all terraces are below the position of the limestone which is approximately 200 feet above the river.

The level at 2250 to 2550 feet has been identified by Price (1929) as the Harrisburg Peneplain. It slopes to the south along the Greenbrier River and is about 400 feet above the river level. North of Marlinton the level is more than 2500 feet in elevation; at Jerico Flat it is approximately 2450 feet; farther south at Key Flats it is 2400 feet; still farther south near Mill Point it is 2350 feet. Its greatest development locally is at Little Levels, near Hillsboro. In the north it has leveled the Pocono sandstone; at Key Flats it crosses the Maccrady shale; and

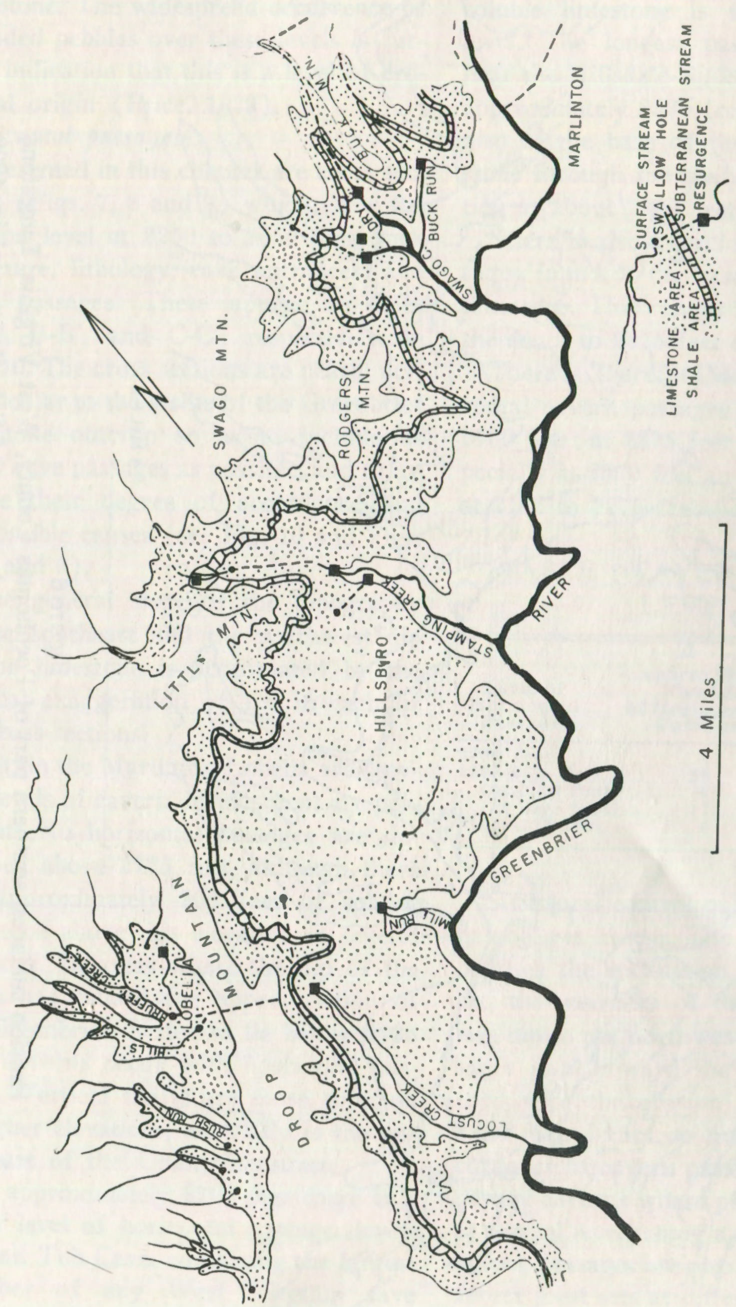

Figure 5
Drainage features, southern Pocohontas County, West Virginia.

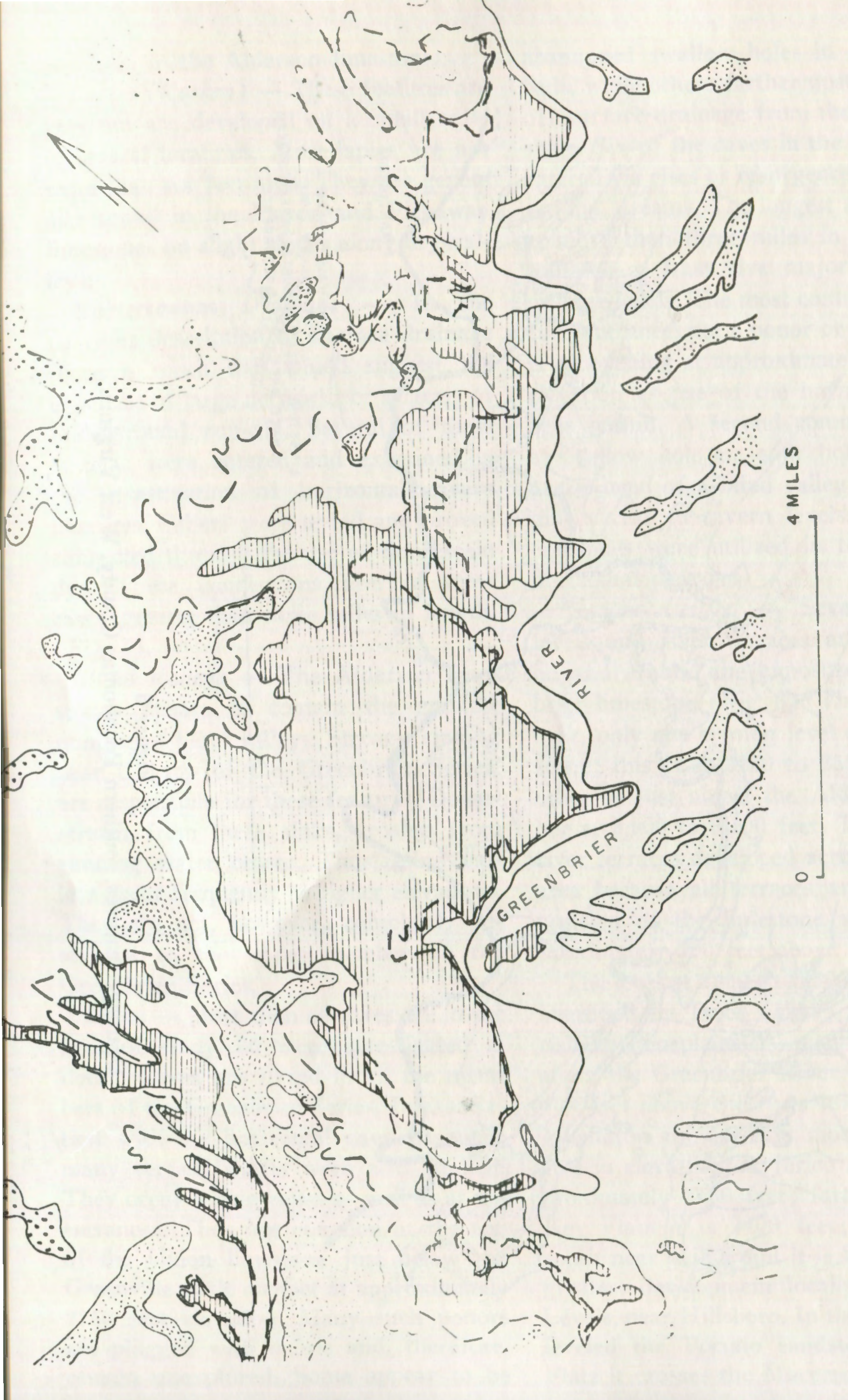

Figure 6
Erosion surfaces, southern part of Pocohontas County, West Virginia. Limestone areas bounded by dashed lines. Coarse dots show area of Schooley peneplain, 4000 to 4600 feet; fine dots show Allegheny-Harrisburg peneplain, 2250 to 2550 feet.

at Hillsboro it is across the Greenbrier limestone. The widespread occurrence of rounded pebbles over these levels is further indication that this is a level of erosional origin (Price, 1929).

Horizontal passages

Presented in this chapter are cross sections (Figs. 7, 8 and 9) which show the erosion level at 2250 to 2550 feet, rock structure, lithology, cave entrances, and cave passages. These appear as lines A-A', B-B', and C-C', respectively on Fig. 10. The cross sections are nearly perpendicular to the strike of the Greenbrier limestone outcrop so as to include as many cave passages as possible, and to indicate their degree of accordance and its possible causes (see Fig. 10 and Figs. 7, 8, and 9).

The general slope of the topography to the southeast and the northwest dip of the limestone is accentuated by the vertical exaggeration of 1:6 in each of the cross sections.

Within the Marlinton-Lobelia area several levels of cavern development are persistent. No horizontal passages are developed above 2725 feet, although there are approximately 200 feet of soluble limestone above this elevation in several localities. In areas where the dip of the strata has caused the upper portion of the Greenbrier Series to lie below 2725 feet, caverns occur with horizontal passages. Vertical shafts are more common at higher elevations, especially in the upper part of the Union limestone.

At approximately 2700 feet there is a minor level of horizontal passage development. Tub Cave, containing the largest chamber of any West Virginia cave (Davies, 1958), is at this level.

Between 2275 and 2575 feet there is an extensive zone of horizontal passages, although most of the purer and more soluble limestone is found above this level. The longest passages are found near the Hillsdale-Sinks Grove contact at approximately 2300 feet in elevation and also at the base of the Pickaway limestone through the shaly Taggard formation at about 2500 feet in elevation.

There is also a level of horizontal passages found at the base of the Hillsdale limestone. This ranges from 2112 feet in the south to 2275 feet in the north.

There is, therefore, accordance of horizontal cavern passages at approximately 2700 feet; at 2275 feet to 2575 feet (especially at 2500 feet and 2300 feet); and at 2112 to 2275 feet (Table 1).

TABLE 1 CAVERN PASSAGE LEVELS

Level of Horizontal Passages	Approximate Number of Horizontal Passages	Approximate Total Length of Explored Passages in Area of Study
2700 feet	4	½ mile
2275-2575 feet	23	12 miles
(at 2500 feet)	(8)	(3 miles)
(at 2300 feet)	(7)	(6 miles)
2100-2275 feet	6	½ mile

Structural control of accordant cavern passages is absent. The dip of the strata opposes the inclination of the passages, i.e., the members of the Greenbrier Series dip to the northwest at 4° while passages slant toward the southeast in accord with the erosion level at 2250 to 2550 feet. Joints do not control the accordance of cavern passages. This can be seen in caverns where passages are found at several levels along a single joint; elsewhere, passages are also found along different joint sets at different levels.

Lithologic control of cavern passages is almost completely absent. A few small passages formed above impermeable

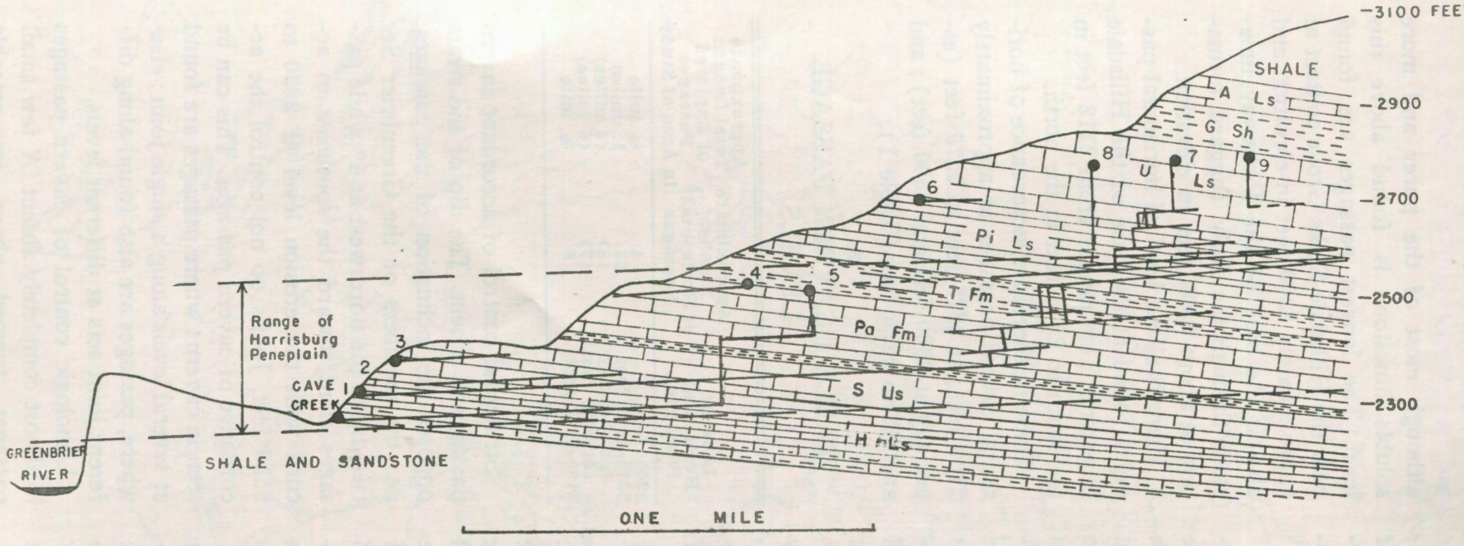

Figure 7

Profile along line A-A'. Heavy dots are cave entrances; heavy horizontal lines are cave passages, dashed where inferred through dye tests; heavy vertical lines are vertical shafts. Vertical exaggeration x6.

A Ls	Alderson limestone
G Sh	Greenville shale
U Ls	Union limestone
Pi Ls	Pickaway limestone
T Fm	Taggard formation
Pa Fm	Patton formation
S Ls	Sinks Grove limestone
H Ls	Hillsdale limestone

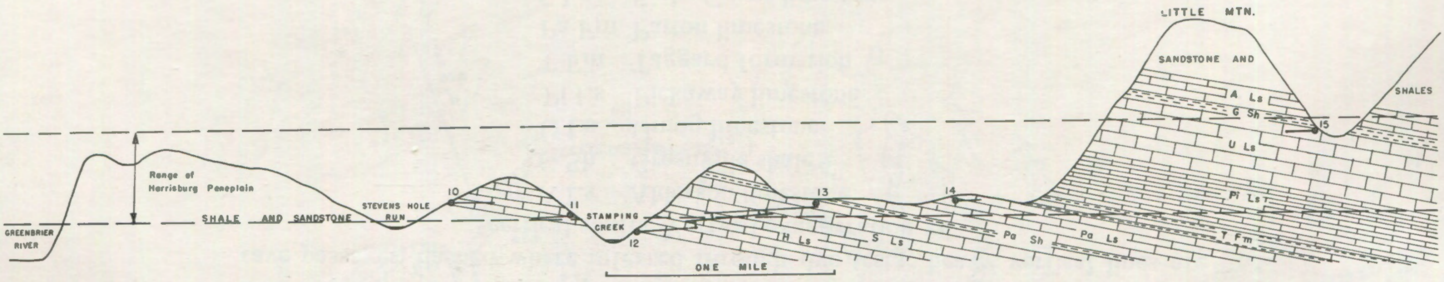

Figure 8

Profile along line B-B'. Heavy dots are cave entrances; heavy horizontal lines are cave passages, dashed where inferred through dye tests; heavy vertical lines are vertical shafts. Vertical exaggeration x6.

A Ls	Alderson limestone
G Sh	Greenville shale
U Ls	Union limestone
Pi Ls	Pickaway limestone
T Fm	Taggard formation
Pa Ls	Patton limestone
Pa Sh	Patton shale
S Ls	Sinks Grove limestone
H Ls	Hillsdale limestone

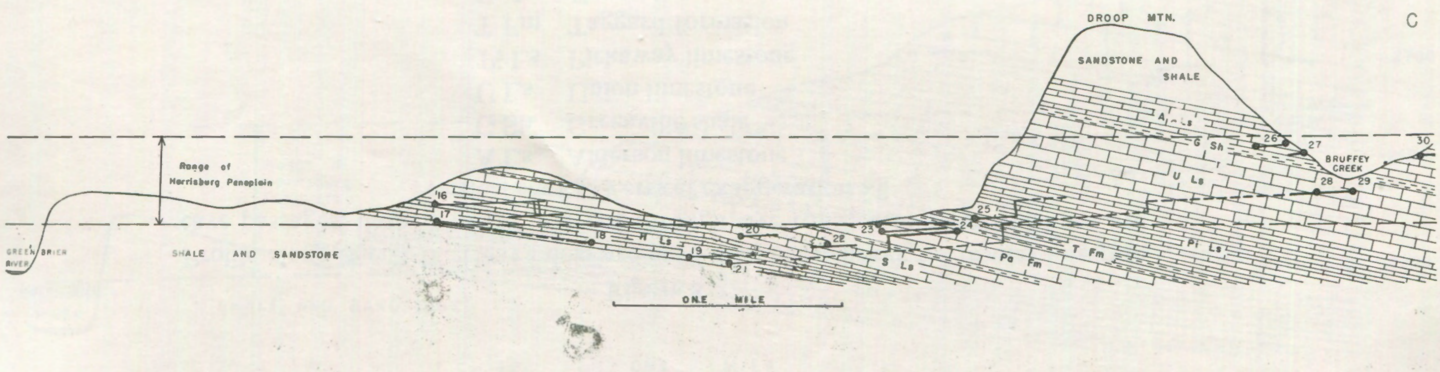

Figure 9
Profile along line C-C'. Heavy dots are cave entrances; heavy horizontal lines are cave passages, dashed where inferred through dye tests; heavy vertical lines are vertical shafts. Vertical exaggeration x6.

A Ls	Alderson limestone
G Sh	Greenville shale
U Ls	Union limestone
Pi Ls	Pickaway limestone
T Fm	Taggard formation
Pa Fm	Patton limestone
S Ls	Sinks Grove limestone
H Ls	Hillsdale limestone

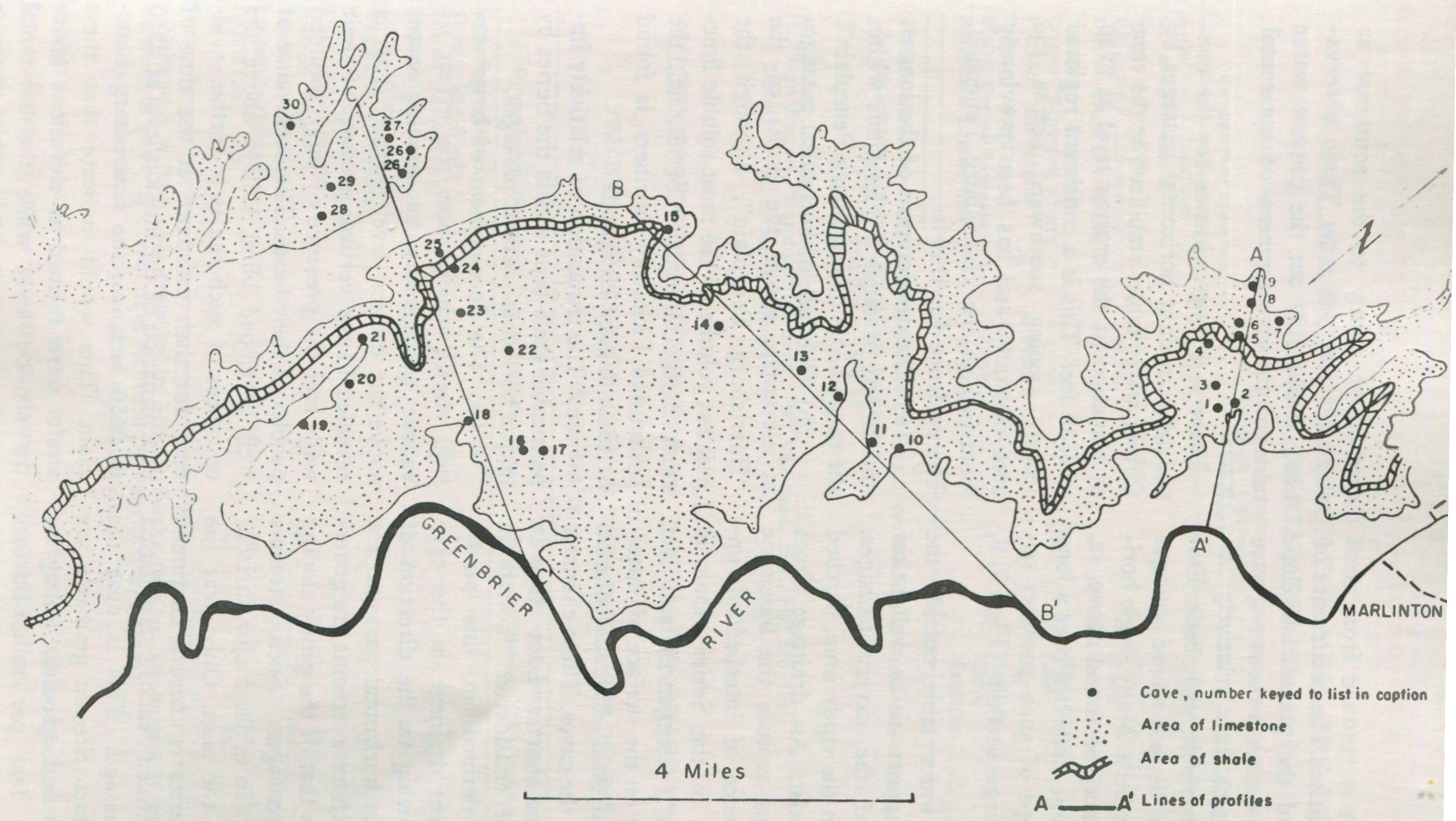

Figure 10
Location of caves, southern Pocohontas County, West Virginia. Profile lines keyed to figures 7, 8 and 9.

shale beds may have resulted from present vadose circulation. The occurrence of these is rare, and the greatest development of passages occurs without response to lithologic control from relatively impermeable and insoluble shale beds. Evidence for this can be seen where passages cut through shale beds. Many single horizontal passages may be found above, in, and below the same shale bed over a long distance, the slope of such passages oply shown on all cross sections (Figs. 7, 8, and 9).

The present water table outside the limestone area appears to be well below the elevation of the cavern passages. However, within the study area, perched water tables exist. As drainage from higher elevations crosses the limestone areas, the presence of interbedded, impervious shales in the Series result in "lost waterfalls", resurgences, and wet weather springs on the surface of waterfalls, rapids and small, sinuous solution channels within the caves. These channels are generally too short and too steep in gradient to be considered "horizontal passages" as defined in this study. Although present drainage in the cave passages is flowing in the direction of the slope of the horizontal passages the gradients of such cave streams are generally many times that of the gently sloping "horizontal" passages. Such streams frequently drop from one major horizontal passage to the next. Only near the base of the Series is there a continued correlation between vadose circulation and cavern passages. This is near the Maccrady contact. Stream gradients are much steeper underground, falling as much as 500 feet per mile. Surface gradients average about 200-400 feet per mile. The passages in the caves, however, slope gently to the southeast at about 50 feet per mile. These observations would rule out the present water table in the development of horizontal levels.

There is strong evidence for the control of accordant horizontal passages by former water tables stabilized at the time of planation of the erosion level at 2250 to 2550 feet. This is a consistent regional feature sloping southward across the area of study and has been previously identified as the Harrisburg Peneplain. The evidence for this is:

(a) The development of the longest and largest passages at elevations within the range of the "Harrisburg Peneplain".

(b) The lack of horizontal passages at elevations above the limits of the "Harrisburg Peneplain", although the greatest volume of the most soluble limestone in the Greenbrier Series, i.e., the Union and Pickaway members, is found at these higher elevations.

(c) The truncation of relatively impermeable shale beds within the Series by major horizontal cavern passages.

(d) The development of large vertical shafts which show the effect of vadose enlargement by running water above the erosion level surface. This is revealed in the vertical grooves of their walls and the presence of large rounded pebbles at their bases. The occurrence of well developed blind valleys above the entrances of such shafts is further evidence for their existence at the time of peneplanation of the erosion level at 2250 to 2550 feet, i.e., the Harrisburg Peneplain. This would indicate that these shafts were formed at elevations above the erosion level while the horizontal passages were developing in connection with stabilized water tables at lower

TABLE 2

RELATIVE SOLUBILITY OF THE MEMBERS OF THE GREENBRIER SERIES

Greenbrier Member	Calcium Carbonate Content	Solubility a
Alderson Limestone	90.88%	Medium
Greenville Shale	Not available	Low
Union Limestone	86.76%, 86.27%b	High
Pickaway Limestone	89.3%	High
Upper Taggard Shale		Low
Taggard Limestone	79%c	Medium
Lower Taggard Shale		Low
Patton Limestone	94.19%	High
Patton Shale	Not availalbe	Medium
Sinks Grove Limestone	82.9%	High
Hillsdale Limestone	70.64%	Medium

Data based on Price, "Pocahontas County," W. Va. Geol. Sur. unless otherwise noted.
a. Based an a total of soluble parts:
100-75% soluble — High
75-50% soluble —Medium
50-25% soluble — Low
b. From Reger, "Randolph County," W. Va. Geol. Sur., pp. 700-704.
c. Total for all three members

TABLE 3

THICKNESS OF THE MEMBERS OF THE GREENBRIER LIMESTONE

(Recorded in Feet)

THICKNESS OF THE MEMBERS OF THE GREENBRIER LIMESTONE

(Recorded in Feet)

Greenbrier Member	Northern Part of Study Area		Southern Part of Study Area	Approximate Thickness
Alderson Limestone	A	B	C	D
Greenville Shale	42	55	55	40
Union Limestone	35	20	30	20
Pickaway Limestone	113	125	130	150
Upper Taggard Shale	57	87	100	75
Taggard Limestone		23		10
Lower Taggard Shale	18	8	25	5
Patton Limestone		.8		10
Patton Shale	80	42	190	100
Sinks Grove Limestone	3	0	5	5
Hillsdale Limestone	29	10	50	50
TOTALS	410	407	15	50
			600	515

Column A is from data recorded by John B. Lucke (McCue, Lucke and Woodward, 1939).
Columns B and C are from data recorded by Paul H. Price (1929).
Column D is from measurements by the author.

elevations within the erosion level zone. The evidence of waterfall retreat along the floors of the blind valleys falling into these shafts might further suggest the existence of such shafts during the time of peneplanation.

Although vadose circulation shows signs of active enlargement of existing

TABLE 4 — TREND OF JOINTS

Greenbrier Series Member	*Joint Sets Major*	*Minor*
Hillsdale Limestone and Sinks Grove Limestone	N 60° E	N 45° W N 40° E
Patton Limestone	N 70° E	N 40° E N 45° W
Union Limestone	N 70° E	N 40° W
Pickaway Limestone	N 65° E	N 40° W
Alderson Limestone	N 65° E	N 05° W

TABLE 5
RIVER TERRACES AND EROSION LEVELS

	Location (elevations in feet)			
RIVER TERRACES	**Seebert**	**Mill Point**	**Buckeye**	**Marlinton**
Third	2165	2240	2240	None
Second	2135	None	None	2215
Flood Plain	2050	2050-2055	2100	2123
Stream Level	2040	2045	2090	2115

EROSION LEVELS	**Elevation (in feet)**	**General Slope**
Schooley Peneplain	4000-4600	4 degrees NW (locally)
Weverton Peneplain	2900-3100	4 NW
Harrisburg Peneplain	2250-2550	Approx. 7 ft./mi. south

cavern passages, it does not appear to have been capable of remaining perched over shale beds long enough to have caused accordance of cavern passages in such a wide area. The size of passages both in volume and length, although not of major concern in this study, and the location of passages without response to varying lithologies, are also evidence of erosion level control.

The cavern level at 2700 feet may correlate with the erosion level at 2900-3100 feet. Although it is somewhat below this level, it more logically can be associated with this perod of peneplanation and water table stabilization than with the erosion level at 2250-2550 feet or with structural, lithologic, or present water table controls. This level is found within the Union and Pickaway limestone, principally at Tub Cave. The cave is the uncollapsed portion of a large solutional cavity, the other part of which has formed a large collapse sink nearly a quarter of a mile in diameter and more than 150 feet deep. Such a volume of solution within the Union and Pickaway limestones is unusual. The correlation with this level and the erosion level at 2900-3100 feet seems the most plausible explanation for its development.

The level at 2100 to 2270 feet is found at the Maccrady shale contact at the base of the Greenbrier Series. It is, however, interesting to note the marked slope of this level to the south and southeast, even

where he shale contact is found at the cave entrance. The contact dips to the northwest with the strata, but cave passages at this level do not. This level might be included with the level at 2275 to 2550 feet associated with the principal erosion surface in the area of study. Such Cavern levels may have several horizontal passages at varying elevations. Their entrances, however, may well be located above the Maccrady shale contact or above one of the interbedded impervious shales of the Greenbrier Series. These entrances, as well as waterfalls within the caves, appear to have been formed by vadose water circulating on the shales; the accordance of horizontal passages, however, appears to have resulted during planation of erosion levels across the area of investigation.

Cavern passages investigated in this

CONCLUSIONS

study are accordant at several elevations. It is concluded that rock structure is of little importance in the development of accordance of the passages. Lithologic control of accordant passages also appears to have been insignificant as is the present vadose circulation and associated perched water tables.

It is further concluded that the major control of spatial distribution and accordance of cave passages reflects water table stabilization during the planation of the erosion level at approximately 2250 to 2550 feet across the area of study. Possible association of an upper area of passage development at 2700 feet with the former erosion level at 2900 to 3100 feet is also inferred.

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PROCEEDINGS OF THE NATIONAL SPELEOLOGICAL SOCIETY

ABSTRACTS OF PAPERS SUBMITTED FOR THE MEETING IN CUSTER, JUNE 1962

BIOLOGY SESSION

INSECTS AND SPIDERS OF CAVES OF COLORADO AND SOUTH DAKOTA

Robert W. Ayre
East Northport, N. Y.

A semi-popular account of recent field work by members of the NSS and the Colorado Chapter of the NSS. Stress was on the spider fauna of Fly Cave Colorado.

BAT BANDING IN VIRGINIA AND WEST VIRGINIA

Lyle G. Conrad
Biological Survey of Virginia Caves

Virginia and West Virginia contain numerous caves, but the area has had only preliminary investigations made in respect to the study of bats. Bats often found in the Virginia caves include the Little Brown Bat, *Myotis lucifugus;* Big Brown Bat, *Eptesicus fuscus;* Pipistrelle, *Pipistrellus subflavus;* Indiana Cave Bat, *Myotis sodalis;* and the Bigeared Bat, *Plecotus townsendii virginianus.*

Others appear from time to time. Relatively rare cave species include the Leib's Bat, *Myotis subulatus leibii;* Gray Bat, *Myotis grisescens;* and Say's Bat, *Myotis keeni septentrionalis.* A report has been made of a tree bat, the Silver-haired Bat, *Lasionycteris noctivagans,* as having been seen in a Virginia cave. Two other tree bats, the Red Bat, *Lasiurus borealis* and the Hoary Bat, *Lasiurus cinereus,* would be worth looking for.

The author started to band bats in the Virginias in 1960. So far, a meager dent has been made in the banding of bats and the determination of their life histories. It is hoped, that with the use of mist nets and other apparatus, more knowledge will be gained soon.

PROGRESS OF THE BIOLOGICAL SURVEY OF VIRGINIA CAVES

John R. Holsinger
Biological Survey of Virginia Caves

This paper briefly covers the activities of the Biological Survey of Virginia Caves (B.S.V.C.) during the year, June 1961-June 1962. The B.S.V.C. was organized by the author in April 1961 and was made a research project of the National Speleological Society in the summer of 1961. The Survey is now operating on a small grant from the Society's research fund.

The B.S.V.C. has been instrumental in obtaining many new and significant range extensions for almost all the known types of cavernicolous organisms in Virginia. Several range extensions have been obtained for cavernicoles in West Virginia, but as yet this state has not received concentrated field work by the Survey. In addition, more than five new troglobitic species have been uncovered and eight contributions to scientific journals have been published, or are in press.

The primary purpose of the B.S.V.C. is to systematically collect, organize, and analyze bio-speleological data and to facilitate studies on systematics, geographic distribution, and evolutionary patterns of cavernicoles.

Three persons are now active in the Survey, including John R. Holsinger (Director), John E. Cooper, and Lyle G. Conrad.

NOCTURNAL MIGRATION OF *HADENOECUS SUBTERRANEUS*

Brother G. Nicholas, F.S.C.
Department of Biology, University of Notre Dame

A study was made on the population fluctuations of the cave cricket, *Hadenoecus subterraneus,* in Cathedral Cave (37° 12' 50"N.; 86° 03' 11"W.), Mammoth Cave National Park, Edmonson County, Kentucky. Daily observations, averaging three hours each, were made from 26 November, 1960, to 28 February, 1962. Twelve quadrats were established at 10 foot intervals throughout the cave. Three of these are in the entrance zone, three in the twilight zone, and six in the dark zone. All observations of activities of *H. subterraneus* were made in these quadrats.

Over 3,000 crickets were marked with pigmented shellac. A coding system was developed so that time and place of marking, and place of recapture could be determined. Supplemental observations were made on cave crickets in twelve nearby caves. Data were obtained on mortality, mating behavior, migration, homing tendencies, predation and food habits, although only nocturnal migration is considered in this paper.

All observations made in Cathedral Cave have been codified on 3,400 I.B.M. cards. A program was written for use in an I.B.M. 1620 computer that enabled determination of total population; mean densities, standard deviation and standard error of each species (including *H. subterraneus*) per quadrat and per zone; weekly, biweekly and monthly means of all environmental parameters; and correlation of these parameters with population fluctuation of all species.

H. subterraneus comprises approximately 75% of the total population of Cathedral Cave considered on an annual basis. It is troglophilic, periodically leaving the cave to feed. Its droppings constitute an important nutritive source for troglobitic (obligative cavernicoles) species within the cave. Minor fluctuations of the *H. subterraneus* population occur in each zone of the cave with an overall decrease of about 10% during the summer compared to the rest of the year.

A daily nocturnal migration occurs with one-third of the total population of *H. subterraneus* from all quadrats leaving the cave after twilight and returning before dawn. This movement is for feeding purposes. It does not occur when the temperature is below -5° C and/or the relative humidity is less than 85%. 97%of all marked individuals recaptured during the day were found in their home quadrats. Similar migrations have been noted in surrounding caves within the Mammoth Cave National Park and in caves of the Edwards Plateau in Texas, although no marking has been done on individuals in these latter caves.

The other species of cave cricket present, *Ceuthophilus stygius,* constitutes less than 2% of the total population and displays no migratory movements.

GEOLOGY SESSION

A METHOD OF PREPARING CAVE INDICES AND SOME PRELIMINARY RESULTS ON LOCATION AND SIZE DISTRIBUTION FOR CAVES IN THE UNITED STATES

Richard R. Anderson
Red Bank, New Jersey

Information on more than 10,000 caves in the United States, plus many foreign caves, is now in the NSS Cave Files. A method of indexing much of this information is described. The cave name and location is given in full. Other data, as cave type, size, entrances, and special equipment needed, is coded to conserve space, and the key to this code is described. Provision is also made for extending the indexing system to include biological, geological, and other special data, and to provide for such problems as caves with multiple names, or with multiple entrances.

As of April 1, 1962, the information for over 4,600 caves, representing 39 of the states, has been indexed. A sample index is shown.

With the method described, the data can be processed by regular accounting machines, and several examples of the possible results are shown. One is a map of the U.S. showing the distribution of caves within the country. A second example is a table showing the length distribution by states, with a rough breakdown by types.

Some conclusions are drawn as to the usefulness of this type of index, and the effects of making the indices available to cavers (and possibly to others) In particular, conservation is stressed, and a special provision is made so that in certain cases the exact location can be deleted before the index is printed.

ON THE DEFINITION OF A CAVE

Rane L. Curl
University College, London

A cave is a space rather than an object and consequently its definition involves the specification of its boundaries. This can be done in various ways for different purposes, but all definitions must involve a minimum dimension, if only to separate "cave" from such contiguous spaces as intercrystalline pores. It is proposed therefore to specify a defining dimension or *module* for a cave and for its entrances. The problem of associating a suitable shape with the module is discussed.

Caves defined by a module of human size and shape are termed Proper Caves as they are customarily given proper names when assessible. Proper entrances may be defined similarily although proper caves may or may not have proper (and natural) entrances.

Because this concept provides a uniform basis upon which other cave properties may be studied it is useful in applications. In addition it suggests a possibility of reasonably clearly separating caves into groups according to their module range.

CAVERN FORMATION IN THE BLACK HILLS OF SOUTH DAKOTA, WITH SPECIAL REFERENCE TO JEWEL CAVE

Dwight D. Deal
University of New Mexico

Black Hills caves have a more complex speleogenisis than any other caves known to the author. They are formed in the upper part of the Mississippian Pahasapa Limestone which has undergone at least three periods of solution.

During late Mississippian and early Pennsylvanian time a karst surface was formed on the Pahasapa. The Permo-Pennsylvania Minnelusa Formation was deposited unconformably on this surface.

After lithification of the Minnelusa and prior to the formation of the present caves, extensive solution, fracturing, and calcite deposition occurred. The formation of caves, deposits of manganese oxides, veins of coarsely crystalline brown calcite and a breccia of angular limestone, dolomite, and chert fragments cemented by brown calcite occurred.

The present caves were formed by phreatic solution and are controlled by Laramide jointing and the stratigraphy of the Pahasapa Limestone, which becomes more dolomitic toward its base. Occasional differential solution took place and the brown calcite veins projected to form boxwork cores. Partial draining of some caves occurred and climatic changes affected the carbonate balance so that carbonate deposition took place in the water-filled passages. This deposition varied from a thin calcite crust accompanied by the calcitic cementation of cave clay in Wind Cave to foot-long calcite crystals in Sitting Bull Crystal Cave.

In Jewel Cave another solutional period differently redissolved the larger calcite crystals in the upper part of the cave and silica, dissolved from the chert in the limestone, was deposited as siliceous cement in the clay on the passage floors.

Subsequent draining of the caves has allowed the development of more usual types of cavern formations.

CAVE OCCURRENCES IN THE PRYOR MOUNTAINS, MONTANA

Jerold K. Elliott

Caves occurring in the Pryor Mountains of south-central Montana exhibit definite relationship to occurrences of small patch feels occurring in the "A" or "Cave" member (Chesterian) of the Mississippian limestone. The writer feels that the nature of the permeability development, especially in relation to fracture systems and biothermal development, plays an important part in the location and extent of cave systems. This study of the Pryor Mountains exhibits this relationship.

Initial cave excavation occurred at post-Madison, pre-Amsden time. These cavities were filled by the Amsden shales and re-excavated in the late Pliocene-Pleistocene time. Tyuyamunite occurs in cave fills as secondary mineralization.

Four known caves in the Pryors are true glacieres. Descriptions, some maps, and photographs of many of the caves are included.

APPLICATIONS OF EXPERIMENTAL GEOLOGY TO PROBLEMS IN CAVERN DEVELOPMENT

Ralph O. Ewers
Cincinnati Museum

Prevailing theories of cavern development have been based largely on the analysis of data collected in field observations of caves in which an uncertain and probably highly complex series of events and conditions have played important roles. An analysis of a single genetic factor is nearly impossible in a natural cavern due to the super-position of the factor on pre-existing features or the subsequent addition of still more factors.

Therefore, experimental geological techniques involving a limited number of controlled variables may serve to clarify our recognition of specific factors in speleogenesis.

The author has attempted to evaluate experimentally the effects of phreatic solution on a wide variety of joint and bedding plane configurations under graded and artesian conditions, emphasizing the early formative period, and comparing these effects to observable cavern features. These experiments indicate that phreatic solution takes place in all joint and bedding plane systems which is maximum at or nearest the upper surface of the phreatic zone, decreasing roughly exponentially with depth and favoring a shallowest-possible phreatic origin for most caverns.

OBSERVATIONS OF HIGH ALTITUDE CAVES IN GUATEMALA

Russell H. Gurnee
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Guatemala, largest of the Central American Republics, has three distinct regions: the lowlands (Pacific and Peten), the midlands, and the highlands. These regions, brought about by volcanic activity and block faulting, have made the east-west chain of mountains the highest in Central America.

Cretaceous limestone, laid down on the present midlands, has been fractured, twisted and thrust up to elevations in excess of 12,000 feet by faulting action and earth movement.

The Cuchumatanes Highlands are a limestone horst thrust up to 13,000 feet, and cover an area of about 1,200 square miles. Erosion of this plateau has taken place underground and many of the springs and rivers 5,000 feet below have their source in the plains of the Cuchumatantanes.

Exploration by the NSS in November 1961, resulted in the recording and photographing of six caves above the 8,300-foot level and one cave at 11,400 feet. Samples of limestone, fossils and karst development were noted at 12,100 feet.

An Indian sacred ritual cave was mapped, an underground stream surveyed and many pits and chasms explored.

SUBMERGED KARSTIC FEATURES IN THE FLORIDIAN PLATEAU

Louis A. Hippenmeier

Many flooded caves in Florida contain evidence that they have been dry at some time in the past. In addition, sinkholes have been detected in the Straits of Florida and in the Gulf of Mexico at a depth of as much as 1,500 feet below sea level. It is believed that many of these sinkholes and caves developed under vadose or shallow phreatic conditions and inundated by eustatic changes in sea level during the Cenozoic coupled with a gradual downwarping of portions of the Floridian Plateau as a result of isostatic compensation for the Ocala Uplift and regional downwarping of the earth's crust as a result of the developing geosyncline in the Gulf of Mexico.

SPELEOLOGICAL POTENTIAL OF THE BOB MARSHALL WILDERNESS AND ADJACENT AREAS

Howard McDonald

The Bob Marshall Wilderness Area and adjacent Federal lands comprise one of the largest still-unexplored and unstudied areas within the continental United

States. This area, astride the Northern Rocky Mountains, contains several million acres of uninhabited, unmapped, and largely unknown mountainous country.

The geology of the area is complex, as it is presently known. Deposits of Madison limestone of Mississippian age, contorted and displaced by the famous Lewis Overthrust, could conceivably contain caves of tremendous depth and size. Limestone thicknesses of several thousand feet are known to exist.

While legend and tales told by those who have traversed this immense area cannot, at present, be relayed as fact, this paper will attempt to correlate the campfire tales of hunters, rangers, and others who have visited the area with known geologic facts in an attempt to show the speleological possibilities of the region in question.

Known caves and cave areas will be discussed along with verified geology, taken from various sources. The wild tales of geologic wonder will be analyzed for their fragments of truth and possible bearing on the region's speleology. Research to date will be reviewed. Chief among conclusions to be drawn will be the theory that this area may be, in fact, the greatest cave area of the West, clinging to its many secrets for decades to come, until more reliable methods of reconnaisance are developed to aid the geologist and explorer.

FURTHER WORK ON THE TOLLY PROJECT

William J. Stephenson
Bethesda, Maryland

At the 1960 Convention, a report was given on preliminary work which had been done at Tolly Cave, Va., in an effort to obtain a reasonable figure for the minimum time required to form a cave. Tolly Cave being a simple, one channel cave which was probably formed by free surface stream solution, it was thought possible to compute the present volume of the cave, measure the rate of stream flow and the amount of solids added to the stream while passing through the cave and from these factors, compute the minimum time required to form the cave.

The first readings gave a time of about five million years. Further work has shown that solution conditions are not constant as previously presumed but tend to vary greatly. Additional observations would give figures requiring a length of time which would appear to be inconsistent with other known geological data. It is quite possible that at some time during the life of the cave, conditions must have existed which would have promoted cave formation much faster than the present rate. Another interesting fact is the discovery that under some conditions the stream is depositing material in the cave rather than removing it.

SOME CONSIDERATIONS ON THE USE OF NATURAL CAVES AS FALLOUT SHELTERS

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Huntsville, Alabama

Two sciences are combined, atomic physics and speleology, to give an idea of the value of natural caves as human protection against radioactive fallout due to atomic fission or fusion explosions that might be caused by enemy action. This paper ignores blast protection and concentrates on the dust or rain that settles to the ground downwind of the actual explosion and that covers many times the area of the blast damage.

There are many characteristics of natural caves that tend to make many unsuitable as fallout shelters. Such factors as directly inflowing water may actually accumulate radioactive debris in the cave. Many of these speleologically well known facts are listed and a figure arrived at to show that only 2 per cent of the caves in Madison County, Alabama, would be likely fallout shelter.

SOME LIMITATIONS ON SPELEO-GENETIC SPECULATION IMPOSED BY THE HYDRAULICS OF GROUNDWATER FLOW IN LIMESTONE

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Department of Mathematics
The Pennsylvania State University

This paper analyzes some aspects of ground water flow in limestone in terms of known principles of fluid mechanics. It is shown that limestone and sandstone acquifers are no longer described by the same equations at approximately Reynolds Number equals 4, long before the onset of turbulence. Turbulence sets in at Reynolds Number near 2000. Both limitations are passed in limestone channels before the channel reaches the dimensions of a cave. Most caves must have been opened by water in turbulent flow.

Weyl has shown that the controlling factor in limestone solution is the rate of diffusion of ions through the laminar streamlines. His formulae are applied to show that the efficiency of solution is good while the fractures are very small (less than .01 cm.) but that the efficiency falls off very rapidly as the fracture grows. For fractures of gentle slope (1°) the flow will become turbulent when the fracture width reaches 0.5cm. In turbulent flow there is efficient mixing in the center of the stream and the rate controlling factor becomes the rate of diffusion of ions across the laminar boundary layer. The efficiency of solution undergoes a sort of hydraulic jump at the critical passage width for the laminar-turbulent flow transition and increases by seven orders of magnitude.

Kay's principle of the self-acceleration of an optimum flow path through the limestone is rephrased in terms of the hydraulic jump of the solution efficiency.

In a set of possible paths, the first to achieve turbulent flow will enlarge orders of magnitude faster than the others, thus explaining why there are fewer passages than fractures in the bedrock.

Cavern development will take place along those flow lines that permit the highest velocities. It is suggested that speleogenetic theories might better be couched in terms of the flow velocities and hydraulic gradients which directly control the rate of solution rather than karst water tables which control cavern development only indirectly.

THE CHEMICAL EVOLUTION OF SOME CAVE WATERS

Heinrich D. Holland
Princeton University

The evolution of cave waters can be divided into three stages: a stage of carbonation in the soil zone, a stage of solution of calcite and|or dolomite, and a stage of equilibration with cave air. Of all the physical chemical data necessary for the interpretation of the major features of the chemistry of cave waters only the solubility product of dolomite is still uncertain.

Water samples from Indian Echo Cave, Pennsylvania, Carpenter Cave, Pennsylvania, and Luray Caverns, Virginia, were analyzed, and their composition was used to interpret their chemical evolution. The results show that in these caves $CaCO_3$ precipitation takes place essentially only due to CO_2 loss from cave water to the cave atmosphere, that during $CaCO_3$ precipitation activity product $a_{Ca^{+2}} \times a_{CO_3}$ -- can exceed the solubility product of calcite by as much as a factor of seven, that the solubility product of dolomite at 12°C is near 10^{-17} and that dolomite is not precipitated even when the activity product $a_{Ca^{+2}} \times a_{Mg^{+2}} \times a^2_{CO_3}$ -- exceeds that number by a factor of 200.

A COMPARISON BETWEEN LABORATORY MODELS AND NATURALLY OCCURRING DOMEPITS

Max W. Reams
University of Kansas

The term domepit and others referring to vertical cavities in soluble rocks are unsatisfactory. Foiba(e), from the Italian Carso, is suggested to replace these. It is defined as a natural, somewhat cylindrical cavity with nearly vertical walls, formed by solution of relatively soluble rock. In laboratory experiments limestone blocks were subjected to hydrochloric acid and shown to produce cavities resembling foibe. The important prerequisites for foibe development, at least in central Kentucky, are:

1. A soluble rock, preferably well jointed.
2. A mechanism to deliver large quantities of water per unit area for a prolonged period; normally, this mechanism is an insoluble layer.

3. An insoluble layer or water table to produce a floor.

The effect of water pouring into foibe during rainfalls and dripping water during dryer periods produces vertical walls. The flat or concave floors are formed by an insoluble layer impeding the enlargement or by the intersection of a water table. Ceiling channels may play a considerable role in the development of central Kentucky foibe. The sulfate found in waters in foibe of central Kentucky may be derived from the limestones and not the overlying shale as previously thought.

PROCESSES OF CAVERN BREAKDOWN

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Cave Research Foundation
and
William B. White
The Pennsylvania State University

Breakdown occurrences have been studied extensively in the large cavern systems of the Mammoth Cave Area and in caves elsewhere in folded limestones.

Rosettes of straight breakdown block edges show strong preferred orientation suggesting that fracturing occurs along pre-existing zones of weakness. Wide-span ceilings have a measurable sag.

Some processes activating cavern breakdown are: 1. loss of buoyant support by draining of galleries; 2. undercutting of banks by floodwater stoping at the base level (sometimes resulting in tension dome collapse); 3 removal of support by free surface streams flushing out fill; 4. crystal wedging and attack by sulfate mineralization; 5. frost wedging (important in alpine caves and near entrances of temperate caves); 6. accidental overlap of several cavern galleries; 7. undercutting and removal of material by vertical shafts and shaft drains; and 8. weakening of ceiling beds through attack by acid surface water (particularly where passages cut across steeply dipping beds).

One or more of the mechanisms of cavern breakdown are operative during all stages of development. Thus, breakdown takes place continuously and plays an important role both in the initial enlargement of the cavern system and in its final degradation.

ABSTRACTS OF PAPERS PRESENTED AT THE MEETING AT MOUNTAIN LAKE, JUNE 1963

BIOLOGY SESSION

STUDIES ON THE ECOLOGY OF THE MAMMOTH CAVE COMMUNITY

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The Mammoth Cave fauna includes nearly 150 species of animals, more than half of which are uncommon or accidental. Approximately 40 species are of primary ecological significance in the biological community of the cave system, interacting with soil and water bacteria and fungi. This community is composed of a heterogenous assemblage of spatially and temporally variable subunits localized in ecologically favorable situations. In the drier, upper levels of the cave, cavernicoles are found, with few exceptions, in domepit areas or near terminal breakdowns, in microhabitats of high relative humidity, high bacterial count, and reduced air flow. A few abundant and wide-ranging species inhabit damp and extensive levels immediately above the lowest or stream level of the system. The primary sources of food are: 1) organic debris transported into the cave by water, 2) guano of troglozenes, especially cave crickets (*Hadenoecus subterraneus*), 3) autochthonous production by chemosynthetic iron bacteria, and 4) artificial introductions by man. Seasonal fluctuations in temperature, relative humidity, and flow of air currents are pronounced in the upper levels of the cave, and seasonal flooding in stream passages is pronounced. At Moonlight Dome, in the Frozen Niagara section, the rate of evaporation, as determined by a 5-cm white sphere Livingston atmometer, was 200 times higher in winter than in summer.

A REVIEW OF AUSTSRALIAN BIOSPELEOLOGY

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A historical outline of biospleological study in Australia reveals that little interest has been taken in this until very recent years, and, indeed, many workers have stressed that Australia has no troglobitic fauna. This is however quite false. A review of the forms recorded is given, with some notes on the speciation and probable origin of some of the more interesting forms. The organization of bat research through the Commonwealth Scientific and Industrial Research Organization is described, and brief reference made to work currently in progress.

BIOLOGY OF SOME CUBAN CAVE FAUNA

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Observations on the fauna of several caves in the Guanayaro Valley, Las Villas Province, Cuba were made between 1954 and 1960. The biology of two reptiles, the Cuban boa, *Epicrates angulifer*, and the lizard, *Anolis lucius*, was especially emphasized.

Epicrates is a predator upon the bat, *Phyllonycteris poeyi*. Data accumulated over a six-year period demonstrate that the snakes feed and are active only during the early evening hours when the bats are leaving the cave. Feeding takes place at a narrow opening deep within the cave through which the bats must fly. As many as nine snakes have been found in this area during a single evening. The ability to capture flying bats in a completely dark environment is probably due to the presence of heat sensitive labial pits on the jaws. The clock mechanism which enables the snakes to know when to assemble at the feeding station has not yet been explained.

An attempt was made to estimate the boa population in the cave by a simple mark and recapture technique. Unfortunately, a number of snakes were removed from the cave during the four years of the mark and recapture study (1956 to 1960) so that no accurate population estimate can be made. Some data, however, on the stability of the population and movements of individual specimens within the cave resulted from this work. A total of 40 snakes were marked, from which 110 recaptures were recorded. One snake, marked in 1956, was seen each year until 1960. These results, plus the apparent fact that reproduction does not take place in the cave (young have never been taken inside the cave), suggest that the snakes do not spend their entire lives in the cave but that they may remain either in or near it for a number of years. Nothing is known of movements in and out of the cave. Large adults have rarely been found on the surface in the vicinity of the cave but none of these were a part of the cave-marked population.

Anolis lucius is a medium-sized Anoline lizard in and about the entrances of small caves throughout the Guanayaro region. Its egg-laying habits are unlike those of any other Anoline lizard. The eggs are attached to the ceilings of caves in communal nest sites. On the basis of shell counts from the cave floors these nests, plus other peculiarities of *Anolis lucius* set this species apart from its generic relatives. It is cavernicolous, it seems incapable of metachromic changes, it has a distinctly audible voice, and the eyelids are unique in having "window panes" (modified transparent palpebrals), permitting the eye to function when closed, possibly an adaptation to survival in the dry, often dusty cave environment.

Other fauna observed in the Guanayara caves include the Cuban racer, *Alsophis angulifer* (also a bat predator, capturing its prey in the roosting areas during the day); the pigmy boas, *Tropidophis semicinctus*, and *T. melanurus;* the geckos, *Sphaerodactylus* sp. and *Tarentola americana;* the frogs, *Eleutherodactylus* sp. and *Hyla septentrionalis;* the land crab, *Gecarcinus ruricoli;* the roach, *Periplaneta americana;* the click beetle, *Pyrophorus noctilucus;* and, rarely, the Cuban hutia, *Capromys sp.* and the common rat, *Rattus norvegicus*

ASPECTS OF AQUATIC ECOLOGY IN MAMMOTH CAVE

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Several biological and physico-chemical factors, including plankton counts, dissolved oxygen, total alkalinity, pH and temperature were studied on a monthly basis in Echo River, Styx River and Crystal Lake in Mammoth Cave between November, 1961 and November, 1962. Stable conditions generally prevail during summer and fall but the influx of water during winter and spring rains causes sudden changes only somewhat less marked than those occurring in surface streams or ponds. Thus, environmental cues are available to aquatic cave animals. Maximal annual variations are as follows: oxygen, 7.2-12.6 ppm; alkalinity, 86-190 ppm; temperature, 8.6-14.6 C; and, pH, 7.3-8.1. Free-swimming zooplankters occur seasonally in the cave stream but are essentially absent in Crystal Lake. All bottom samples can be expected to contain protozoa, rotifers, tardigrades and microcrustacea. Food relationships among the organisms are not known at present.

PRELIMINARY REPORT ON THE PLEISTOCENE FAUNA OF ROBINSON CAVE, OVERTON COUNTY, TENNESSEE

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Over 21 working days underground in Robinson Cave, Overton County, has produced the largest and most varied fauna yet recovered from the Late Pleistocene of Tennessee. Three locations in the cave netted 10 species of carnivores, 15 species of insectivores, two types of deer, 17 rodents, two species of edentates, and one probiscidian in addition to numerous birds, snakes, salamanders, lizards, turtles, millipedes and snails. Four extinct animals, the Jefferson ground sloth, *Megalonyx jeffersoni,* the dire wolf, mastodon and the giant *Eptesicus grandis,* indicate an age at least of Late Pleistocene and one specimen, *Dasypus bellus,* seems to indicate the close of the Sangamon. Three climates are inferred from the present habitats of the surviving animals. First, a climate somewhat warmer than present day Tennessee, as indicated by the armadillo; second, a climate similar to that existing now in Canada and northern United States characterized by the arctic shrew, northern bog lemming, caribou, jumping mice, porcupine, pine martin, and certain other mice; and a third, dryer, northern plains climate with the thirteen-lined ground squirrel as evidence. Flourine content studies made on representative samples of bone support the theory that the armadillo material has been in place longest and lead to the interesting speculation that deposition began at the end of the Sangamon and extended into the height of the Wisconsin. It is postulated that the material funneled into the underground cavities, where it was found by means of drains in the bottom of trap pits which once extended to the surface. Subsequent collapse, cementation and decoration by flowstone has obscured the point of entry. Several techniques novel to cave paleontology were used in excavating and recovering the material in addition to painstaking lab analysis which is continuing at the time of writing.

LIFE HISTORY AND THE CONTROL OF POPULATION SIZE IN AMBLYOPSID FISHES

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Among amblyopsid fish adaptation to the low food supply in caves, as indicated by low growth and metabolic rates and close control of population size, is best exemplified by *Amblyopsis*, the genus most specialized for cave life. Compared to the epigeic and troglobitic *Chologaster* and the troglobitic *Typhlichthys* both species of *Amblyopsis* show lower population density, lower population growth rate, and less population fluctuation. The lower rate of population growth of *Amblyopsis* is only partially explained by older age at first reproduction and lower fecundity. In addition, *Amblyopsis* reproduces when its population density is low and even then only a small proportion of the potentially breeding population is involved. This, in addition to greater longevity, means that the population structure of *Amblyopsis* is more skewed toward old age classes than that of *Chologaster* or *Typhlichthys*. Correlated with change in age distribution is the lesser extent of size fluctuation of *Amblyopsis* populations. This suggests, in addition to density dependent reproduction, density dependent cannibalism as a means of population size control, especially since *Amblyopsis* shows life history changes which are adaptive in reducing mortality of young. This reduction of mortality of young is a consequence of parental care, larger eggs and thus longer development. Longer development results in free swimming fry which are larger when they leave the female gill cavity and so are better able to resist being carried away by floods, to escape predation, and to forage over wide areas.

GEOLOGY SESSION

ATTAPULGITE FROM CARLSBAD CAVERNS, NEW MEXICO

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The clay mineral Attapulgite occurs in well-cemented cave fill in the Lower Cave, Carlsbad Caverns. The clay deposit is in a maze of small solution pockets and tubes. Two varieties are present, a gray clay, mainly montmorillonite, and a pink clay composed of approximately equal parts of attapulgite and montmorillonite. Both varieties are in the same area and grade one to another. Quartz is present, up to 15%, in each type of clay. The pink clay is strongly cemented by 32% calcite forming a bond that prevents dispersion. The gray clay disperses readily.

SCINTILLITES: A VAREITY OF QUARTZ SPELEOTHEMS

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Sparkling red to red-brown speleothems composed entirely of quartz occur in Jewel Cave, Jewel Cave National Monument, on the west flank of the Black Hills, South Dakota. They have a compound origin and are associated with quartz deposition in the cave fills. The speleothems are composed of two parts: a core and an outer coating.

The cores are solutional remnants of red to red-brown microcrystalline chert which occurs as beds and nodules in the Mississippian Pahasapa Limestone. Some extend over 40 mm. from the cave wall and have rounded cross sections up to 8 mm. across. The solution of the chert was a late event in the formation of Jewel Cave and occurred just before the final removal of fluids from the passages.

Most of the silica was deposited in the cave fills a few tens of feet below the chert beds. Some silica was deposited on the chert remnants and formed a 0.5 - 1.0 mm. layer of transparent euhedral quartz crystals on the cores of the silica speleothems. Individual crystals in the outer layer range up to 0.5 mm. in size.

A MODEL FOR CAVERN DEVELOPMENT UNDER ARTESIAN GROUNDWATER FLOW, WITH SPECIAL REFERENCE TO THE BLACK HILLS

Alan D. Howard
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Three classes of groundwater flow within limestone are responsible for the development of caverns: *subsurface stream, integrated water table,* and *artesian.* Subsurface streams are comparable in method of flow and properties to surface streams. Integrated water table flow occurs as lateral flow at the top of a nearly planar water table. Artesian flow of groundwater is through enclosed solutional cavities in the completely saturated zone where there is no free water surface. In the Black Hills of South Dakota structural situations have promoted the development of artesian groundwater circulation through limestone, and all three of the above classes of groundwater flow are involved in the groundwater movement through the limestone. Caverns formed through the action of the last two categories of flow within limestone are similar, but criteria are given to distinguish between the two classes of origin on the basis of cavern morphology. These criteria are applied to Wind Cave in South Dakota, but mapping and structural correlation has not progressed far enough to afford a conclusive choice between the two possible modes of origin.

CARBONATE CHARACTERISTICS AND ITS RELATIONSHIP TO CAVERN DEVELOPMENT

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The carbonates are best classified by their textural characteristics. The dolomites are considered to be mainly of secondary origin. The limestones may be classified as basinal, biohermal (biostroms, bioherms, reefs), clastics, (calcirudites, calcarenites, calcilutites), oolites and piolites, and the non-carbonate constituents (evaporites, sand grains, etc.). Diagenetic changes occur within these "facies," creating favorable areas for cavern development. Deformation and the resulting fracture patterns are also affected by the relative strength of the various facies. Therefore, conventional theories of cavern development may benefit from the study.

ABRUPT CHANGE IN CAVE HISTORY WHEN VENTILATION BEGINS

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Water in the soil derives a large amount of carbon dioxide from the decay of humus, and it is this carbon dioxide that gives the water its well-known capacity to dissolve limestone. The soil carbon dioxide is rich in radiocarbon, whereas the limestone contains almost none. But as stalactities have a far larger radiocarbon content than they would if all the soil carbon dioxide reacted with the limestone, it is evident that the water moves downward toward the cave too fast to utilize more than a small part of its dissolving capacity.

When the soil water enters an unventilated cave, it is greatly undersaturated with respect to calcite, and it therefore continues to dissolve calcite. The dissolving process does not become fully effective, however, until the downward movement of the soil water is arrested by the water table, where the water can at last remain in contact with the limestone long enough to take full advantage of its dissolving capacity. When, on the other hand, the soil water enters a *ventilated* cave, the result is very different. As the undersaturated water dripping from the ceiling then encounters air that contains little carbon dioxide, it immediately begins to lose the carbon dioxide it holds in solution, and hence its ability to dissolve calcite. It consequently becomes supersaturated, so that it can form stalactites.

The presence or absence of ventilation thus makes a vital difference in the chemical behavior of cave water. The moment at which downward surface erosion first makes a hole that lets outside air into a cave is therefore one of the principal turning points in the history of that cave. It marks the transition form a period in which solution is dominant to one in which deposition is dominant.

SOME PRELIMINARY RESULTS OF A STUDY OF CARLSBAD CAVERNS

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Department of Geology
Princeton University

In a study of Carlsbad Caverns, New Mexico, now in progress, most of the effort is being directed toward two aspects of the geology. The first of these is an attempt to explain the origin of the cave. Carlsbad exhibits well-developed levels and flat bedrock floors, both of which are unrelated to bedding. Some of the hydrologic-geochemical models being investigated are multiple-source — single-outlet flow; single-source — single-outlet flow; and single-source — reversing flow (i.e., backflooding of water from the Pecos River).

Also being studied is the distribution and migration of calcium and magnesium in the vadose zone. Hydromagnesite and dolomite, as well as aragonite and calcite, are widely distributed in the cave. The relationship between hydromagnesite and "cave coral" is receiving considerable attention.

SEDIMENTATION IN CAVES — A REVIEW

William B. White
Pennsylvania State University and Cave Research Foundation

This paper summarizes present knowledge of sediments in limestone caves. A possible classification of cavern sediments is as follows:

- I. Clastic fills
  - A. Autochonous fills
    - 1. Breakdown
    - 2. Weathering detritus
    - 3. Organic debris
  - B. Allochonous fills.
    - 1. Clay fills.
    - 2. Sand fills.
    - 3. Gravel and cobble fills.
- II. Chemical sediments.
  - A. Carbonates
    - 1. Calcite travertines
    - 2. Calcite-aragonite travertines
  - B. Evaporites
    - 1. Gypsum
    - 2. Epsomite
    - 3. Mirabolite
  - C. Manganese and Iron hydrate deposits
  - D. Phosphates
  - E. Ice

The above are the end-member types; mixed sediments also occur. Examples of each type and its significance are presented. Our present knowlede of many sediment types is very limited and should be extended. From cavern stratigraphy and facies change information on age, paleoclimate, and paleohydrology may potentially be obtained.

CHEMISTRY OF KARST GROUNDWATER IN BRUSH VALLEY, CENTRAL PENNSYLVANIA

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Brush Valley is an anticlinal valley floored with Ordovician limestones in Centre County, Pennsylvania. Streams rising on clastic rocks on the bounding mountain flanks for the most part sink in ponors at the limestone contact. This water reappears at three big springs along the south side of the valley. The springs, Penns Cave, Spring Bank, and Elk Creek Rise, have flows on the order of 20, 10, and 30 second-feet. Field measurements on five ponors, the three springs, and a sampling point in Elk Creek one mile downstream from its rising were conducted at two-week intervals from October 1961 to October 1962. Temperature, flow rate, and pH were measured in the field. Samples collected were titrated by the Schwartzenbach method for total hardness, Ca^{++}, and Mg^{++} ion concentration.

Over the one year interval the following results were obtained: The chemistry of the sinking streams is almost constant with a total hardness of about 20 ppm. and a pH of 6.8 to 7.1 in spite of flow variations from .05 to 3 second-feet. There is no systematic seasonal variation in either hardness or pH of the springs. pH tends to remain within the range of 6.9 to 7.5. Hardness varies from 50 to 180 ppm. but is related to the flow rate rather than the season. It is concluded that the residence time of the ground water in Brush Valley is too short for the water to equilibrate with the limestone and hence the springs are always undersaturated. This is confirmed by the measurements on Elk Creek. After a mile of aeration pH rose to 8.0 to 9.0 by loss of excess of CO_2 to the atmosphere. Travertine is not being deposited.

ABSTRACTS OF PAPERS PRESENTED AT THE CLEVELAND MEETING, DECEMBER 27, 1963

BIOLOGY SESSION

THE FAUNA OF MAMMOTH CAVE: A STUDY IN COMMUNITY COMPOSITION AND EVOLUTION

Thomas C. Barr, Jr.
University of Kentucky

More than 150 species of animals have been reported or described from Mammoth Cave, Kentucky, in the last 131 years. Thirty-five of these are obligatory cavernicoles, or troglobites, including flatworms, gastropods, spiders, pseudoscorpions, opilionids, mites, isopods, amphipods, atyid shrimps, crayfishes, copepods, ostracods, collembolans, diplurans, beetles of three families (Carabidae, Catopidae, Pselaphidae), psocids, diplopods, and amblyopsid fishes. In a typical terrestrial biociation which commonly develops near entrances, the primary food input is guano of the trogloxene cave cricket *Hadenoecus subterraneus* (Scudder). Guanobic cavernicoles (snails, diplopods, collembolans, diplurans, catopids) are preyed upon by carabid and pselaphid beetles, spiders, pseudoscorpions, and mites. Terrestrial community activity is seasonal because (a) *Hadenoecus,* a nocturnal feeder at the surface, emerges from the cave less frequently during the winter, and (b) rate of evaporation may be 200 times greater during winter than summer, resulting in disappearance or reduction in number of stenohygrobic troglobites. Mammoth Cave lies along a major north-south (Pennyroyal) dispersal corridor for cavernicoles, and at the western terminus of a northwest-southeast (Cumberland saddle) corridor. The regional cave community has apparently evolved through colonization from diverse sources at different times since the late Pliocene.

OBSERVATIONS ON THE ECOLOGY AND BEHAVIOR OF THE CAVE CRICKET, *HADENOECUS SUBTERRANEUS* (SCUDDER)

Orlando Park and David Reichle
Northwestern University

The population of the cave cricket, *Hadenoecus subterraneus,* was investigated in two portions of the Mammoth Cave system, namely Moonlight Dome and Whites Cave. Included were studies of aggregation, periodism, diet, and position in the Mammoth Cave community. Direct observation and gut contents demonstrated that this species is a nocturnal predator, feeding on both intercave and intra-cave animals. Activity was investigated under constant experimental conditions of darkness, temperature, and relative humidity similar to that of the cave environment. A twenty-four hour periodism exists, with a nocturnal peak of activity about midnight, and an inactive period during the day, which corresponds with their observed movements and diet in nature. It is noteworthy that in these experiments only a portion of the population exhibits peak activity on any given night. This suggests that the whole cave population does not migrate nightly, but that over a given period most of the crickets emerge from the cave.

MNOLOGICAL STUDIES IN MAMMOTH CAVE

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Some biological and physico-chemical factors, includinig plankton counts, dissolved oxygen, total alkalinity, pH and temperature were studied on a monthly basis in Echo River, Styx River and Crystal Lake in Mammoth Cave between November, 1961, and November, 1962. Stable conditions generally prevail during summer and fall but influxes of water during winter and spring rains cause sudden changes. Environmental cues are thus available to aquatic cave animals. Maximal annual variations are as follows: oxygen, 7.2-12.6 ppm; alkalinity, 86-190 ppm; temperature, 8.6°-14.6°C; and, pH, 7.3-8.1. A few zooplankters occur seasonally in the cave streams but are absent in Crystal Lake. All bottom samples may contain protozoans, rotifers, tardigrades and microcrustaceans. Food chains are only partly known at present.

THE IMPORTANCE OF BASE LEVEL FLUCTUATIONS IN THE BIOLOGY OF CAVE ORGANISMS

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Data from the literature and new data from Indiana, Kentucky, Missouri, Pennsylvania, and Tennessee show that annual fluctuations of regional base level in caves are widespread geographically and have continued through geologic time. These annual base level fluctuations in water level depend either on differential runoff into major streams which backflood into caves or on differential runoff into sinkholes, fissures, and shafts of caves. Percolating groundwater has little effect on the fluctuations considered here.

The rates of change in the cave environment and the regularity of these changes are more important than the magnitudes of change in explaining biological or geological phenomena of a seasonal nature. In aquatic environments, as water level falls from late spring through early winter, there are slow changes in food supply, water temperature, and water chemistry which are associated with slowing of growth rate and maturation of gonads in aquatic troglobites. With first spring floods there are fast changes in food supply, water temperature, and water chemistry which are associated with the onset of reproduction. This situation is contrasted with that in the more stable terrestrial environment where seasonal reproduction of troglobites is less marked. In terrestrial environments there is seasonal import of food by trogloxenes, or air currents and modification of microclimate by changes in evaporation rate and temperature, plus slight changes in $pO_2|pCO_2$ ratio and water vapor content in the air.

The changes in the cave environment which are biologically important are also geologically important. As many investigators now believe, seasonal changes in base level are particularly important in the cavern process of solution.

REPRODUCTIVE AND MOLT PERIODS IN A CAVE CRAYFISH

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The population of the cave crayfish *Orconectes pellucidus* in Shiloh Cave, Indiana, was studied over a period of three years. The per cent of breeding males in the population and spermatogenic activity in the testes was highest during late fall and lowest during summer months. The percentage of females with large, yolky oocytes in the ovary reached a peak during March and April and receded to an annual low during late summer months, presumably as eggs were laid. A few females carrying eggs on the abdominal appendages were found during summer months. Eggs must have been laid as early as April, since very small young were found during the first part of May.

Major annual periods of molting were found to occur (1) during the fall months, predominantly September and October; and (2) during late winter and spring, predominantly February and March. A fall molt period among males is concurrent with the increase of breeding males, while a spring molt period is the time when many males changed to the non-breeding form. Apparently many adult females molted during the fall period and some during the spring period. Females which participated in egg laying apparently molted after the young had hatched, and due to the extent of the egg laying period, molting was less synchronized among females than among males.

ALGAE IN CAVES AND A STUDY OF THEIR ECOLOGY

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Research on cave algae is still in its infancy. Scattered reports on the occurrence of aglae in different caves have appeared since the beginning of this century, but a systematic study began only in the nineteen-fifties. A group of Hungarian botanists undertook algological investigations of most of the larger caves in Hungary, and, as a result of their work, the algal flora of the caves of that country is comparatively well known. Studies in other countries followed and by now algal collections have been or are being made in many of the major cave systems of the world.

The discovery of chlorophyll-containing, pigmented plants living in permanent darkness of caves poses some problems concerning their ecology: (1) Do the algae live in the caves in an actively vegetative form or do they occur in resting stages? (2) If they carry on an active life, what kind of energy are they utilizing for assimilation? (3) How do the algae get into the caves at all? (4) Do they have any role in the food chain of other cave organisms?

Investigations of the algal flora of caves produce some interesting results as far as the floral elements are concerned. Arctic, Antarctic, halophil, and thermal species have been reported. The importance of the occurrence of such forms is discussed, and a comparison is made between algal florae of some caves in the U. S. A., Israel, and Hungary.

PRELIMINARY STUDIES ON THE GEOGRAPHIC DISTRIBUTION OF TROGLOBITIC INVERTEBRATES IN THE CENTRAL APPALACHIANS

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During recent field work in the central Appalachians more than 200 caves were biologically explored. As a result of this investigation new insights were gained relative to zoogeography and evolutionary patterns of obligatory cavernicoles. Some troglobites, such as anophthalmid beetles, pseudotremid millipedes, and chthoniid pseudoscorpions, are endemic to one or several caves located in a small geographical area. Kenkiid planarians, gammarid amphiods, asellid isopods, conotylid millipedes, and certain entomobryid collembolans contain troglobitic species which are moderately endemic, i. e., range in caves over a comparatively restricted geographical area or are restricted to caves situated in one or several adjoining drainage basins. Still other groups, such as linyphiid and nesticid spiders and certain other entomobryids, are respresented by troglobitic species which extend their ranges over a wide geographical area and in some instances over several states.

Four factors are postulated to account for varying degrees of speciation and endemism among troglobites: (1) geological events that have either modified or enlarged karst areas and caves in particular regions; (2) distribution of epigean ancestors; (3) length of time and degree of isolation of certain species to caves; and (4) variations in the rate of genetic changes in different species and populations of cavernicoles. Migration and gene exchange through subterranean water channels developed under drainage divides is offered as an explanation for the present distribution of certain species of aquatic cavernicoles.

FALL SWARMING AT BATS AT DIXON CAVE, KENTUCKY

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On 17 days between July 30 and October 11, 1963, over 12,000 bats were caught and tagged at Dixon Cave, Ky. About half were taken in the cave in daytime; the rest were captured in a mist net outside at night. *Myotis sodalis, M. lucifugus, M. grisescens,* and *Pipistrellus subflavus* were found in the cave. In addition to these species *Myotis subulatus, M. keenii, Eptesicus, fuscus, Lasiurus borealis* and *Nycticeius humeralis* were taken in the net. Traffic

peaked during the last week of August and had fallen sharply by mid September.

Recoveries of *M. lucifugus* and *M. sodalis* show that some of these bats travel quickly back north to their summer range after convening at Dixon Cave. A *M. sodalis* banded on September 1 was recaptured in a barn in St. Josephs County, Michigan, over 300 miles from Dixon Cave, on September 10, 1963.

BAT HIBERNATION IN THE MAMMOTH CAVE REGION OF KENTUCKY

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Studies of the bat populations in the caves in the vicinity of Mammoth Cave have been carried on since 1957. About 50 caves were surveyed during all seasons of the year to obtain information on the seasonal abundance and habits of various species. This region of central Kentucky is an important area for the hibernation of *Mytois sodalis, Myotis grisescens,* and *Myotis lucifugus.* Banding of these species has revealed something of the summer range of populations which hibernate in this area.

Four other species have been found hibernating in the area, but in far less numbers than the above three species. Information has been obtained on the comparative selection of the habitat for hibernation of all these species. *Myotis sodalis* and *Myotis grisescens* form dense clusters in a narrow temperature zone. Some competition for hibernating space occurs in at least one cave system between these two species. *Myotis lucifugus* form semi-dense clusters in a wider zone of temperature, but where the humidity is close to saturation. Some correlation exists between the degree of aggregation and colony size. *Myotis sodalis* and *Myotis grisescens* are found in only a few caves, but have hibernating colonies up to about 100,000 individuals. *Myotis lucifugus* are found in more caves, but form smaller colonies, up to about 5,000. *Pipistrellus subflavus* are the most dispersed and have colonies up to about 500.

GEOLOGY SESSION

HYDROCHEMISTRY AND SEDIMENTATION IN MAMMOTH CAVE

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Water in Mammoth Cave comes from three sources: (1) direct infiltration from sinkholes in the Mammoth Cave Plateau; (2) underground flow from the Pennyroyal Plain; and (3) intermittent inflow from the Green River. The flow of water through the lower portions of the cave is very complex and at times rapid. Each of these three sources of water has a different chemical character and a different potential to dissolve limestone. These differences in solution potential have resulted in differences of chemical erosion in various parts of the cave system. The complex set of variables which controls the flow of water in and out of the cave causes considerable shifting of the sediment deposits found in the cave.

OUT OF PHASE SEASONAL TEMPERATURE FLUCTUATIONS IN CATHEDRAL CAVE, KENTUCKY

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Caves deeper than 15 meters from the nearest outside surface have an annual temperature fluctuation that is smaller than 1°C. Such caves near the southern border of the conterminous United States have a nearly constant temperature of about 20°C, and those near the northern border, about 5°C. The temperature of these caves is approximately equal to the average annual surface temperature at their locations, and it is dependent on the altitude as well as on the latitude.

The temperature fluctuates measurably in caves shallower than 15 meters. Daily temperature measurements over a 16-month period at five stations in Cathedral Cave, Kentucky, show the nature of this fluctuation. An outside annual fluctuation of about 30°C is reduced to 4°C at a depth of 10 meters. At this depth the underground temperature maxima and minima lag their surface counterparts by about three months.

ORIGIN OF SULFATE MINERALS IN THE CENTRAL KENTUCKY CAVE AREA

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A suite of sulfate minerals, primarily gypsum with considerable mirabolite and minor amounts of other sulfates, occurs in quantity in the caves of south-central Kentucky. Sulfates are not, however, a major constituent of the clastic fills on the cave floors. The origin of these deposits has been variously ascribed to sulfide weathering, primary gypsum occurrences in the limestone, and inwash from an arid soil supposed to exist in central Kentucky in Pleistocene time.

Many fresh roadcuts made in connection with improvements in Mammoth Cave National Park and in the construction of the Nolin River reservoir permitted an examination of fresh exposures for source materials for the sulfate.

Pyrite occurs disseminated in the upper part of the Girkin limetone and through much of the Big Clifty sandstone. The Girkin limestone is separated from the Big Clifty by an unconformity which is occupied in places by a black shale containing considerable elemental sulfur in weathered section. At the top of the Big Clifty sandstone is a two-foot thick layer of black shale rich in plant debris and containing thin coal beds. This bed contains large quantities of layered nodular pyrite. Pyrite also occurs as small grains in the Haney limestone.

The occurence of the sulfate minerals in and on the walls rather than the fills, evidence of chemical attack on the limestone of the cave walls, and the existence of an abundant source of sulfides, suggest that the weathering and transport of overlying sulfides, primarily pyrite, is the primary source of the cavern sulfate minerals.

THE CENTRAL KENTUCKY KARST — A REVIEW

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The Central Kentucky Karst is a segment of the band of karsted Mississippian limestone that parallels the western flank of the Cincinnati Arch from southern Indiana to Tennessee. The area includes parts of Mammoth Cave National Park and the associated large cavern systems.

The Sinkhole Plain to the east is a low-relief dolina karst with many sinking streams along its eastern edge. The Mammoth Cave Plateau consists of flat-topped ridges with underlying large caverns and intermediate karst valleys with deeply incised valley sinks. The deep valley of the Green River separates the karst from a less extensive karst and the Pottsville Escarpment to the west. Recharge into the ground-water system is from the sinking creeks rainfall on the sinkhole plain, vertical shafts that ring the capping rock of the ridges, and backflooding from the Green River.

Mammoth Cave and the Flint Ridge Cave System are the principal caves of the area. The caves are composed of two principal components: horizontal passages, some now active, which carried horizontal flow at the base level; and vertical shafts which are the vertical routes for ground-water moving from the edge of the caprock to the base level. The caves contain a variety of features including many solutional features and a complex series of sediments including carbonates, sulfates, breakdown, and clastic fills.

PRELIMINARY RESULTS ON THE PALEOHYDROLOGY OF MAMMOTH CAVE AND THE FLINT RIDGE CAVE SYSTEM

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The large cavern systems of south-central Kentucky — Mammoth Cave, and the Flint Ridge Cave System — act now and have acted in the past as major conduits for ground water moving from the recharge area of the Sinkhole Plain east of the cavernous ridges to discharge points in the gorge of the Green River. Ground water moves in well defined conduits at or just below the regional base lelvel. Direction and approximate velocity of past flow is recorded by flute and scallop markings on the passage walls. These were mapped over large parts of the cavern system to obtain information on past flow conditions recorded in the higher and now abandoned levels of the caves.

Drainage in Mammoth Cave has been consistently to the west and that in the Flint Ridge System has been to the north. There appears to have been little lateral migration of the discharge points in the recorded sequence. The caves have not been systematically downcut; sudden piracies have changed levels quickly, leaving an abandoned upper level with its bedrock floor. Both high narrow canyons and elliptical tubes are common hydraulic elements. These blend into each other both laterally and vertically.

The present drainage at the base level is anomalous: the development of a drainage conduit has been interrupted both by Pleistocene filling of the Green River bed and by backflooding from the Brownsville Dam.