BULLETIN

OF THE

NATIONAL SPELEOLOGICAL SOCIETY

VOLUME TWENTY-TWO PART ONE

ORIGIN OF LIMESTONE CAVES
A SYMPOSIUM WITH DISCUSSION

GEORGE W. MOORE, Editor

J HARLEN BRETZ	WILLIAM R. HALLIDAY
RANE L. CURL	ARTHUR L. LANGE
WILLIAM E. DAVIES	JOHN V. THRAILKILL
GEORGE H. DEIKE, III	WILLIAM B. WHITE

JANUARY 1960

BULLETIN

of

THE NATIONAL SPELEOLOGICAL SOCIETY

VOLUME 22, PART 1 **JANUARY, 1960**

ORIGIN OF LIMESTONE CAVES

Published twice a year; Editor: William E. Davies, 125 W. Greenway Blvd., Falls Church, Va.; Associate Editor: Nancy G. Rogers, 2026 Key Blvd., Apt. 640, Arlington, Va.; Assistant Editors: William R. Halliday, 1117 36th N., Seattle, Washington; Thomas C. Barr, Jr., Department of Biology, Tennessee Polytechnic Institute, Cookeville, Tennessee.

Inquiries relating to the publishing of manuscripts in the BULLETIN should be addressed to the editor or assistant editor.

Office Address:
THE NATIONAL SPELEOLOGICAL SOCIETY
203 VIRGINIA HILLS AVE.
ALEXANDRIA, VIRGINIA

Subscription rate in effect January 1, 1960: $4.00.

The National Speleological Society is a non-profit organization devoted to the study of caves, karst, and allied phenomena. It was founded in 1940 and is chartered under the law of the District of Columbia. The Society is associated with the American Association for the Advancement of Science.

The Society serves as a central agency for the collection, preservation, and publication of information relating to speleology. It also seeks the preservation of the fauna, minerals, and natural beauty of caverns through proper conservation practices.

The Affairs of the Society are controlled by an elected Board of Governors. The Board appoints National Officers. Technical affairs of the Society are administered by a Research Committee of specialists in the fields that relate to speleology.

Publications of the Society include the **Bulletin** published twice a year, the **News** appearing monthly, and the **Occasional Papers**. All members receive the **Bulletin** and **News**.

A Library on speleological subjects is maintained by the Society. Material is available to Society members at a nominal charge to defray the cost of handling and to others through inter-library loan.

Introduction to the Origin of Limestone Caves*

by GEORGE W. MOORE

Abstract—This symposium presents evidence bearing on cave origin derived principally from the shape and spatial relations of caves. The observations suggest that most limestone caves were formed in a zone of saturation directly below a nearly horizontal local or regional piezometric surface. Acids resulting from chemical and biochemical processes operating in this zone during oxidation of sulfide minerals and organic matter present in the limestone are thought to have made the zone especially favorable for cave development.

Limestone caves, for all their interest as wonders of nature, would seem on first consideration to have an origin that is simple and obvious. It is surprising, therefore, to learn on what little evidence the ideas usually accepted today were based. Now, however, considerable new information is available because nearly a thousand caves in the United States have been mapped during the last two decades. A symposium to evaluate this information was held on December 28, 1959, at the Chicago meeting of the American Association for the Advancement of Science. It was sponsored jointly by the Geological Society of America and the National Speleological Society. The individual papers presented at the symposium and the discussion which followed them are published in this Bulletin.

Emphasis of the symposium was on the shape and spatial relations of cave passages and the bearing of these factors on the origin and development of caves. Within this framework, the separate investigations given below range broadly. Bretz has studied caves in Bermuda that were probably formed in a warm climate, and his results may be contrasted with those from Thrailkill's investigation of a cave at an altitude of 10,000 feet in the Rocky Mountains that may have developed under cold conditions. Caves in areas of folded limestone have received special study because they may be used to evaluate the factor of varying solubility in different limestone beds and separate it from other controls of cave pattern. Davies has considered the stages of cavern development in folded limestone of the central Appalachian region, and White has interpreted the evidence bearing on the genesis of cave passages in Pennsylvania. The different concepts of cave origin as illustrated by examples from the Pacific Coast region have been analyzed by Halliday. Curl has treated the relative statistical importance of random and non-random elements of cave origin, and Lange has considered the cave patterns to be expected when certain initial structures are subjected to simple solution. These contributions, together with the accompanying discussion, are representative of current thinking on these subjects in the United States today.

Agreement is not complete among the participants of the symposium on all aspects of the problem of the origin of limestone caves, but, in my opinion, the tenor of the meeting can be summarized as follows:

The network pattern of many cave passages strongly suggests that most caves formed in a zone of saturation rather than in an overlying zone where water moving downward from the surface would carve dendritic channels. This conclusion is modified by the fact that most caves have a horizontal pattern and are therefore not formed at random depth in the zone of saturation. A local or regional piezometric surface appears to provide this horizontal control, and most caves have evidently been formed directly below such a surface.

The cause of this greater rate of solution directly below a piezometric surface is not certain. No doubt a greater volume of water moving in this zone is part of the

---

*Approved for publication by the Director, U. S. Geological Survey answer, both because flow along the piezometric surface follows the shortest route between the points of inflow and discharge, and also because joints are more likely to be open closer to the surface of the ground.

But greater water flow directly below the piezometric surface does not appear to be the complete answer as cave passages commonly terminate abruptly downward. The zone directly below the piezometric surface therefore may have chemical attributes that make it especially favorable for cave formation. This is the zone in which conditions are sufficiently oxidizing so that there may be oxidation of sulfide minerals present in the rock, such as pyrite, with the formation of sulfuric acid. At the same time, oxidation of organic material in the limestone in this zone could take place through the agency of micro-organisms. Carbonic acid from this process combined with the acids derived from the sulfide minerals could operate together to make the layer at the top of the zone of saturation acidic and hence cause it to be the zone in which most limestone caves originate.

U. S. Geological Survey
Menlo Park, California

Origin of Caves in Folded Limestone*

by **WILLIAM E. DAVIES**

Abstract——Investigation of caves in folded limestone of the Appalachian region reveals five distinct features bearing on the origin of solution caves: (1) cavern passages develop across the dip or parallel to the strike of the limestone and generally have uniform gentle slope independent of the rock structure; (2) many caves have passages on multiple levels, and, within a region, the separation of levels is uniform: (3) intervals between passage levels correspond closely to intervals between gravel benches on the flanks of major surface valleys in the cavern region; (4) major caves are along large valleys, and only small caves and solution pockets occur in upland areas away from major valleys; and (5) cavern passages decrease in size and become more numerous in the part of the cave away from major surface valleys.

The stages of cavern development in folded limestone beds probably are: (1) random solution at depth in a zone of satuation to produce nonintegrated solution tubes and pockets; (2) integration of tubes into mature caverns at the top of the zone of saturation during a period when the water table was uniform in altitude, and flow was constant for a long period of time (direction of flow was toward major valleys); (3) deposition of clastic fill under alternating conditions of saturation and aeration; and (4) relative uplift of the cave above the zone of saturation with modification of passages by deposition of speleothems, erosion to fill material, and collapse.

During the last 20 years a large amount of data on caves has been collected by scientists and amateurs. The data are such that they permit a reexamination of ideas concerning the origin of limestone caves. Theories proposed previously (Davis, 1930, Bretz, 1942; Swinnerton, 1932) were based on the examination of relatively few caves, most of which were in non-folded rock. With the broadening of speleological studies these limitations have been removed.

Study of caves in folded rocks gives more conclusive evidence about their origin than can be found in undisturbed limestones. The roles of bedding, water table, and surface geomorphologic features in relation to solution are distinct in folded rock for the chance of coincidental placement of these features can be eliminated. The chance that a soluble bed of limestone will coincide with the elevation of an erosional feature, such as a river terrace, or the chance coincidence of the piezometric surface with the slope of bedding, is ruled out for all but very small areas because of the many changes in attitude of beds characteristic of folded rock.

Since 1948 data on caves in folded rock have increased greatly. Systematic studies of caves on a state-wide basis have been accomplished for most of the Appalachian Mountains. In the West, caves in California, Utah, and Colorado have been or are now being studied. During this period many caves in undisturbed limestones have also been described. The data from these investigations make it possible to understand more clearly the problems involved in the development of solution caves. The ideas presented in this paper are based on personal observation of 500 caves in the Appalachian Mountains from Pennsylvania through Tennessee (Davies, 1950, 1959) as well as published descriptions of caves in other areas (Stone, 1953). The general aspects presented in this paper were published in an abridged form in 1957 (Davies, 1957). In the present discussion a cave is defined as mature, integrated solution openings. Isolated primitive tubes and pockets

---

* Publication authorized by Director, U. S. Geological Survey

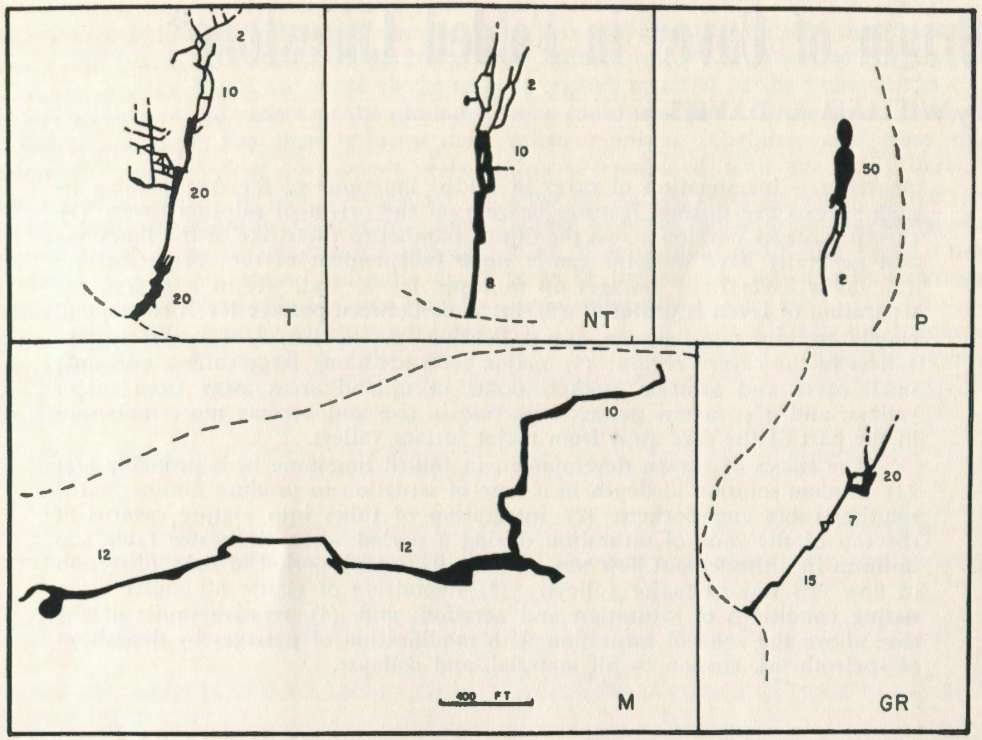

Figure 1

Plans of caves in West Virginia. (T) Trout, (NT) New Trout, (P) Propst, (M) Mystic, (GR) Grimes. Top three caves are in folded limestone; bottom two are along front of Allegheny Plateau. Dashed lines indicate flank of valley or plateau front. Numbers indicate passage heights.

are excluded from the term "cave."

Previous theories of cave origin have emphasized interpretations based on minor cavern features. These features have shown conclusively that solution development takes place beneath the piezometric surface in a zone now referred to as phreatic. Such evidence, however, gave little indication of the depth relative to the water table at which the solution took place. Hence the development of solution caves was assumed to take place at random depths in the phreatic zone. Examination of the gross features of caverns —the plan, elevation, and cross section of passages—provides data that indicate solution development is not random but is closely controlled by the gradient of the piezometric surface.

THE EVIDENCE

Plans of most caves in folded rock reflect local rock structures. The passages are joint controlled; faults exert very little influence and a passage rarely follows a fault for any great distance. Where caves are developed on the flanks of anticlines or synclines they are simple in plan, consisting of a major passage and a few subordinate parallel passages. At the crests of anticlines where dips are low the cave is a maze consisting of a series of passages developed in two intersecting systems. Less commonly this plan also occurs where the cave is developed along the axis of a syncline.

Closer examination of plans of caves in folded rock shows that the passages of a cave branch and are more numerous as the distance from adjacent surface valleys increases. Trout Cave, south of Franklin, Pendleton County, West Virginia, illustrates this (fig. 1). At the entrance, on the flank of the valley of the South Branch, the cave is one large passage with no known parallel side passages. In the interior of the cave the passage gradually reduces in size and 600 feet from the entrance successive side passages branch from the main passage. Such a development approximates that of surface drainage in a dendritic or trellis pattern except that patterns in the cave are more angular and interconnected.

Size of cave passages varies according to the distance from the adjacent surface valleys. In the part of the cave nearest the valley the passages are large but away from the valley they are progressively narrower and lower in height. Trout Cave also serves as an example of this (fig. 1). Near the entrance it is 20 to 50 feet wide; 350 feet from the entrance it is 10 to 15 feet wide; and at 750 feet, where the cave divides into numerous passages, individual passages are 5 to 15 feet wide. The passages progressively decrease in size and at 1,150 feet from the entrance the passages are a complex of crawlways a few feet wide and high. Similar changes in size of passages are common in many Appalachian caves and are well displayed in Propst and New Trout Caves in West Virginia (fig. 1). The gradual headward reduction in size of passages is also apparent in caves in unfolded limestones such as Cornwell, Snedegars, and Organ-Hedricks Caves in West Virginia.

Similar indications of gradual reduction in the size of solution openings away from major valleys have been obtained from observations of wells in the Mammoth Cave area of Kentucky. Only a few wells drilled in areas close to the valleys are successful in encountering water-filled channels. Those that tap such channels have large yields. The number of wells encountering water-filled channels increases away from the valleys but the yield per well decreases (Richmond Brown, U. S. Geological Survey, personal communication).

Another clue in the origin of caves is in the general slope of passageways. Although rock fall and cave fill often mask the true floor of a cave they are seldom of such magnitude that they conceal the overall slope of the passage system. With few exceptions this slope is in the direction of the major surface valleys in the vicinity of the cave. The slopes are mostly gentle; in some caves they are almost imperceptible; in others they range up to 5 or 6 percent; in only a few caves is 6 percent exceeded. In evaluating the slope it should be borne in mind that the slope referred to is that for a system of passages at a given level. In multiple-level caves the slope of passages at all levels is towards major valleys at about equal rates. In Trout Cave, West Virginia, a cave which opens onto the flank of the South Branch of the Potomac River, the point closest to the river (the entrance) has an elevation of 1,975 feet. The cave consists of a number of crawlways 1,400 feet from the entrance and the elevation is 2,000 feet, giving an overall slope of 1.7 percent down towards the valley. Rexrode Cave, Pendleton County, West Virginia, consisting of a single high passage developed in vertical bedded limestone, is 2,040 feet in elevation at the base of the debris slope at the entrance. The cave trends northeast towards the South Branch of the Potomac River and 250 feet from the entrance the floor is at elevation 2,015 feet. This slope of 6 percent continues for several hundred feet to a point where the cave is blocked by rock fall.

In nonfolded limestones the general slope of passages is also towards the major valleys. Organ-Hedricks and the related Greenbrier Cavern system, which has over 16 miles of passages, has a general overall slope towards Second Creek in Greenbrier County, West Virginia. Mammoth Cave, Kentucky, is in three levels each of which slopes at the rate of 2 percent towards Green River. Culverson Creek Cave in Greenbrier County, West Virginia, is a large cavern 6 miles west of the Greenbrier River. The cave trends east towards the river for over 11,000 feet and in this distance the main passage drops about 100 feet. The passage is at right angles to the strike and in part it is counter to the dip for the cave crosses a syncline with low angles of dip.

Many caves in folded limestone show very little relationship between the bedding of rock and the development of passages. This condition is difficult or impossible to explain by the theory of random solution development of caves. Most cave passages are along joints; a few follow faults. Where the dip of beds is between 15° and about 80° the passages show little influence of bedding as far as plan and profile are concerned. Where the dip is less than 15° some caves have passages that are developed along the dip; where the dip of beds is greater than 80° the major development of passages almost always follows the bedding planes.

Most caves in folded rock are developed in a single level. In such caves the passages are relatively uniform in elevation with a gentle slope towards the major surface valleys. The passages maintain their uniform level where they cross the strike or, if they are developed parallel to the strike, they have a uniform level with no trend down dip. Hamilton Cave, West Virginia, a labyrinth, is developed across the axis of an anticline with moderate dips (fig. 2). At the axis of the anticline the passages are 5 to 8 feet high but on the flanks the passages are reduced until they are a foot or less in height. Throughout the cave the floor is bedrock at a constant elevation. In 37 other caves in folded rock in West Virginia the passages are along the strike and are at a uniform level with only a gentle slope towards the major surface valley.

Distinct multiple-level passages* occur in 4 of 277 caves in folded rocks in West Virginia. With no significant exceptions these passages maintain uniform slope and vertical spacing in the caves. In checking the elevations of the passages against surface features there is a close tie between the vertical spacing of river terraces and the vertical spacing of cavern passages within a region (table I).

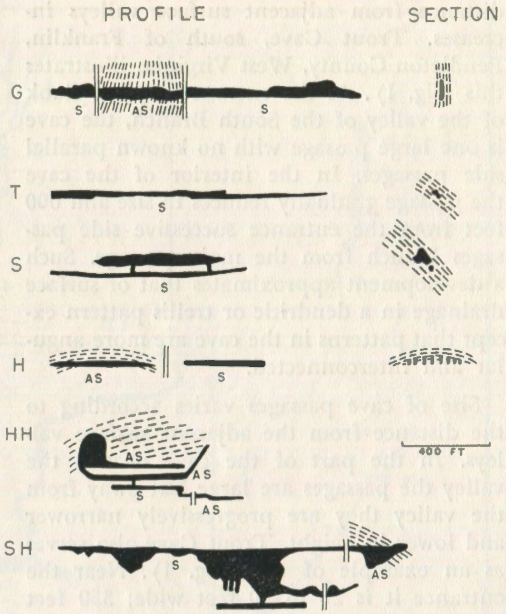

Figure 2
Profiles and sections of caves in folded rock. (G) Grand Caverns, Virginia, (T) Trout, (S) Sinnit, (H) Hamilton, (HH) Hellhole, (SH) Schoolhouse, West Virginia. Portion of cave closest to surface valley is on the left. S indicates passages along strike; AS indicates passages across strike. Dashed lines indicated bedding of rock.

Conditions reflecting slightly different cavern development are along the South Branch, 4 miles south of Franklin, West Virginia, where three caves are in Trout Rock. Each of these caves consists of only one level but each is developed at a different elevation and the intervals between the caves correspond closely to the intervals between river terraces in the region. Similar separation of single-level cavern passages are common along Thorn Creek, a tributary to the South Branch south of Franklin (table II).

Cross sections of cave passages have been given very little study with regard to genesis. An approach to the development of cave passages is possible by applying the physics involved in the stress pattern around an opening in limestone. Solution is most rapid along lines of weakness in rock such as joints, major fractures, and faults, and cave development follows these features. Close examination of passages indicates that the cross section of the passage is determined by additional secondary fracturing in the rock around the opening being developed by solution. The fractures open routes for movement of water and are reflected in solution enlargement of primitive passages. The gross pattern of the fractures, reflected in the cross section of the passage, are therefore indicative of stress conditions developed in the limestone around the cavern opening as solution progresses. Since solution is a relatively slow process and no disruptive stresses are induced in the rock to produce the opening, the shape of the passage that evolves should be such that the stress distribution around the opening was close to the ideal during the time the opening was developed.

If a cave were dissolved from limestone at great depth, with a cover of more than 500 feet, stress conditions developed around an opening would be such that a passage would tend to attain a form reflecting fracture patterns that were compatible to equilibrium at the depth of solution. This stability would result from a tangential stress uniform on all points of the boundary of the opening. This opening would be an ellipse (fig. 3) with axis a:b = (m − 1) :1 where m (the reciprocal of Poisson's ratio)

TABLE I

CAVERN AND TERRACE LEVELS

Schoolhouse	*Hellhole*	*Terraces*
Height Above Base Level (feet)		Height Above River (feet)
382 (Level at ceiling of cave)	397 (Upper part, north passage)	—
257 (Sand and Dome Rooms)	250 (Floor, entrance room and east passage)	250
217 (Base of pits and wells)	227 (Middle part, north passage)	220
	167 (Passage to Little Hellhole)	175
122 (Grind Canyon)	115 (Passage at base of Little Hellhole, slopes to base level)	130
		40

Base—Judy Spring, elevation 1,763 feet.

Base, North Fork, 1 mile south Tanyard School, 1,700 feet and Mouth of Seneca, 1,530 feet.

TABLE II

RELATION OF CAVE AND TERRACE LEVELS

Cave	*Elevation Above River*	*River Terrace Elevation **
Hoffman School	240 feet	260 feet
Hamilton	230	—
Minor Rexrode	230	—
Trout	180	200
Sinnit—upper	135	140
New Trout	75	70
Flute	70	—
Sinnit—lower	40	40

* Franklin, West Virginia, and mouth of Thorn Creek

---

* Determination of levels is based on profiles of solution ceilings and bedrock floors. Where alteration of the ceilings had occurred the relic forms of former arches and similar features were used as a guide.

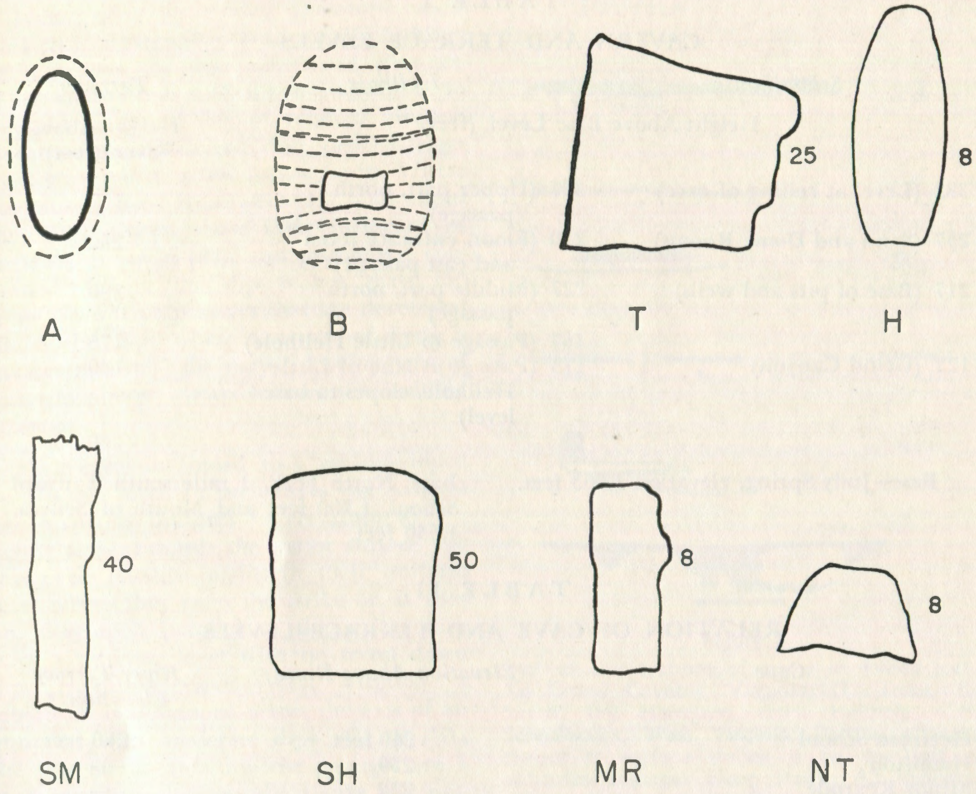

Figure 3
Cross section of cavern passages. (A) Passage in equilibrium with stress at depth of 500 feet or more; dashed line is limit of stress zone, (B) Stress zone around opening at shallow depth, (T) Cross section of passage in Trout Cave, (H) Hamilton Cave, (SM) Smokehole Caverns, a cave developed in rocks with vertical dip, (SH) Schoolhouse Cave, (MR) Minor Rexrode, (NT) New Trout, West Virginia. Numbers indicate height of passage.

is about 4.54 or an a:b axis ratio of 3.54:1 (Schoemaker, 1949).

If a cave passage were dissolved at depths of less than 500 feet, a different condition of stress would develop around the primitive openings. The strength of the limestone is great enough that fracturing from compressive force at this depth is less significant than the fracturing from the sag of rock beds over the opening. At shallow depth the limestone beds over an opening act either as fixed or cantilever beams (fig. 4). As such they tend to sag into the opening, creating a zone of tension that extends as a semiellipse or parabola above the opening. Adjacent to this zone of tension is a zone of compression extending to the walls of the opening. On the floor the beds are arched slightly by the transfer of compressive forces surrounding the opening. This zone of compressive arching reflects the shape of the tension zone above but is of less magnitude. The fracturing in the zones of tension and compression would have a cross section in the shape of two intersecting parabolas. The size of the parabolic stress ring would be proportional to the width of the opening. Within the stress zone fractures and bedding plane openings afford routes along which solution occurs. If random solution under shallow cover but completely below the water table occurred, cave passages dissolved along the fracture lines should be elliptical or parabolic in section.

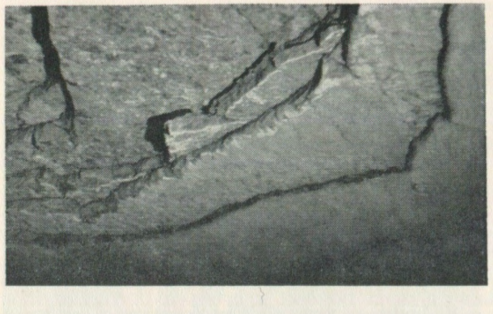

Figure 4
Rock beams spanning the ceiling of Poorfarm Cave, West Virginia.

Figure 5
Trout Cave, West Virginia, showing the trapeziform shape of passage.

From the viewpoint of rock behavior under pressure cavern passages should be elliptical or parabolic in section regardless of the depth at which they formed providing they were completely below the water table during the time of solution development. Of the 120 caves in folded limestones in West Virginia only one, Hamilton Cave, has cross sections of passages that are elliptical. All others are subrectangular, triangular, or trapeziform in cross section (figs. 3, 4, 5) suggesting that other factors override simple stress control in determining the shape of passages.

The influence of bedding on the shape of passages varies with the dip of beds. In dips of 20° or less the ceiling and rock floors reflect bedding planes (figs. 5, 6). Beds with dips from 20° to nearly vertical generally have little influence on the shape of passages; where wide rooms occur the ceiling commonly reflects bedding but in passages 15 feet or less in width the ceiling is low to moderately arched. Where the limestone is vertical or nearly vertical the passages are narrow and high with flat, irregular ceilings (fig. 7).

The influence of bedding on the longitudinal profile of caves in folded rocks is generally small. Most caves in folded limestone are developed along strike joints. Such caves have passages that are nearly horizontal and seldom migrate or extend up or down dip. In other caves, passages extend across the dip. In some caves the cross-dip passages are in the form of mazes (Hamilton Cave, West Virginia) while in others (Grand Caverns, Virginia) they are secondary transverse passages connecting primary strike passages (fig. 3). Descriptive data on over 400 caves in the folded Appalachians (Davies 1950, 1958; Stone 1953; unpublished data Virginia Cave Survey) show only four major caves that have passages following the dip. In Breathing Cave, Virginia, the passages follow or are offset along the dip; in Kooken, Seawra and Hipple Caves, Pennsylvania, the passages are elongated down dip.

In the northern part of West Virginia there is evidence that certain beds of limestone are favorable to cavern development. The most prominent zone of solution is along the junction of the Coeymans and New Scotland Limestones (Lower Devonian). In West Virginia 18 large caves, each over 1,000 feet long, and 14 moderate to small ones are in this zone. Another distinct solution zone is in the Lenoir-Mosheim Limestones (Ordovician) where there are 20 large caves and 4 small caves in West Virginia. Even in these soluble zones cavern development is concentrated at specific elevations. These elevations, as cited previously, coincide with river terrace intervals. Between these elevations no mature caves occur although primitive tubes and pockets are common.

Figure 6
Schoolhouse Cave, West Virginia, showing flat arch ceiling along a bedding plane.

Figure 7
Smokehole Caverns, West Virginia, a cave developed in vertically bedded limestone.

The extent of limestone at or near the surface bears no direct relation to the size or number of caves. In plotting the geographic distribution and size of caves two features are apparent—(1) large caves are confined mainly to the upper parts of drainage systems, and (2) the number of caves in headwater areas is greater than that in the lower portion of drainage basins. In the Potomac Basin there are about 500 caves. Of these 429 are in the headwater areas; the remainder are along the lower parts of major rivers, mainly the Shenandoah. Of the 33 large caves, over 1,000 feet long, all are in the upper third of the drainage basin; none are in the lower two-thirds (fig. 8).

Additional evidence for development of caves in folded limestone can be obtained from the non-folded limestones adjacent to the folded areas. The non-folded limestones of Mississippian age cropping out along the Alleghany Front and in the deep valleys along the eastern part of the Alleghany Plateau contain about 100 caves in Pennsylvania, Maryland, and West Virginia. These caves are characterized by main passages that extend primarily parallel to the plateau front or valley wall onto which they open. Major passages that extend into the plateau are generally less than 300 feet long and terminate by sloping upwards to the top of the soluble zone. In the plateau area random horizontal development of cave passages occurs only where the overlying rock has been eroded and the limestone forms a broad pediment. Such cavernous areas are around Hillsboro, Lewisburg, and Union in the southeastern part of West Virginia.

In connection with the Alleghany Plateau it should be cited that numerous deep oil wells that have penetrated the otherwise cavernous Mississippian and Devonian limestones have not encountered any significant cavern openings where the cover over the limestone is more than 100 feet thick and the site of the well is away from major valleys.

Earth fills that are deposited within passages of caves are part of progressive solution development. Fills laid down under phreatic conditions have been described as unctuous red clay free of clastic materials (Bretz, 1942). Detailed examination of fills in 150 caves from Pennsylvania to Tennessee and west to Kentucky and Indiana showed no clay deposit in a cave-fill sequence that was not preceded by clastic sediment. The examination of fills in Appalachian caves did reveal that all fills follow roughly the same sequence—silt at the base giving way to sand, gravel, silt in ascending order. At the top, and generally packed to the ceiling of passages, is red silty clay or clay (figs. 9, 10, 11, 12).

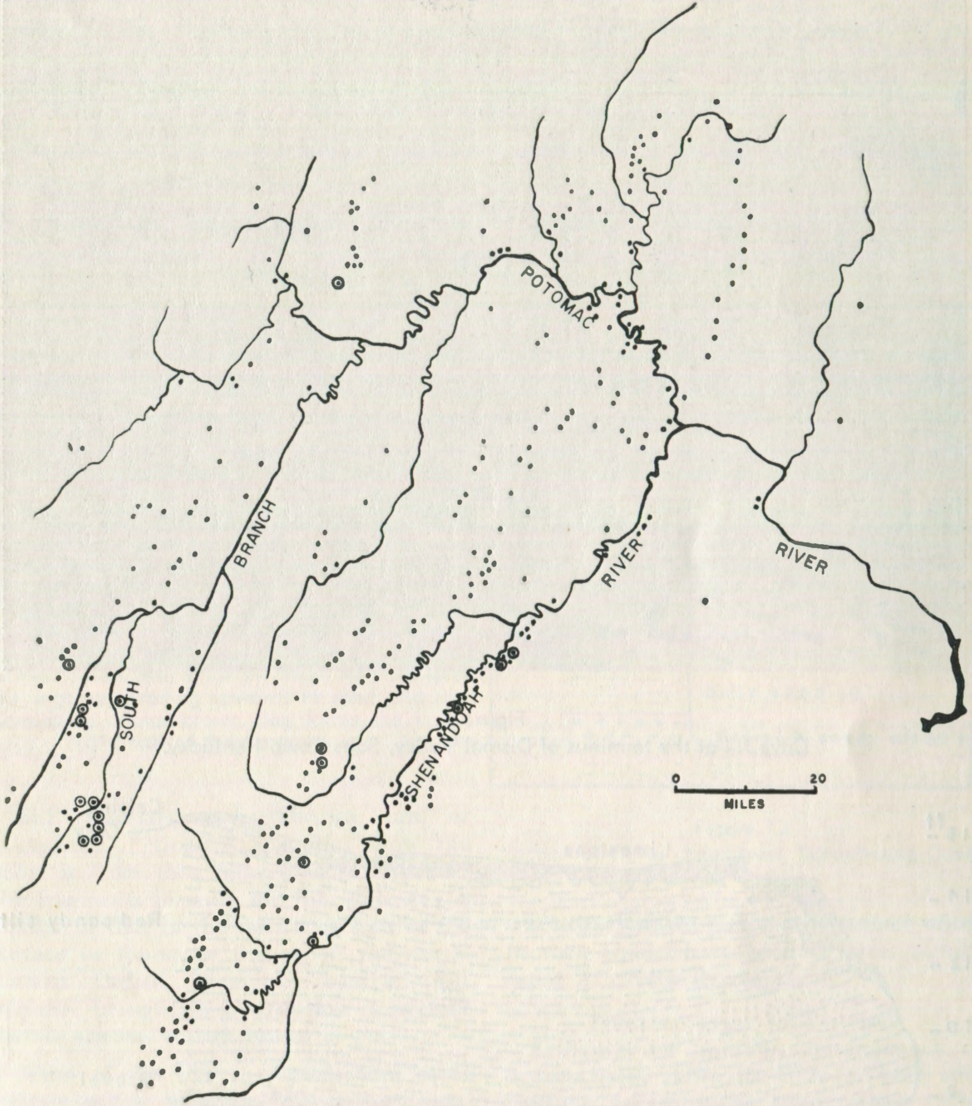

Figure 8
Distribution of caves in the Potomac River Basin. Each dot represents a cave; circled dots are caves with lengths greater than 1,000 feet.

Figure 9
Cave fill at the terminus of Dismal Valley, Salts Cave, Kentucky.

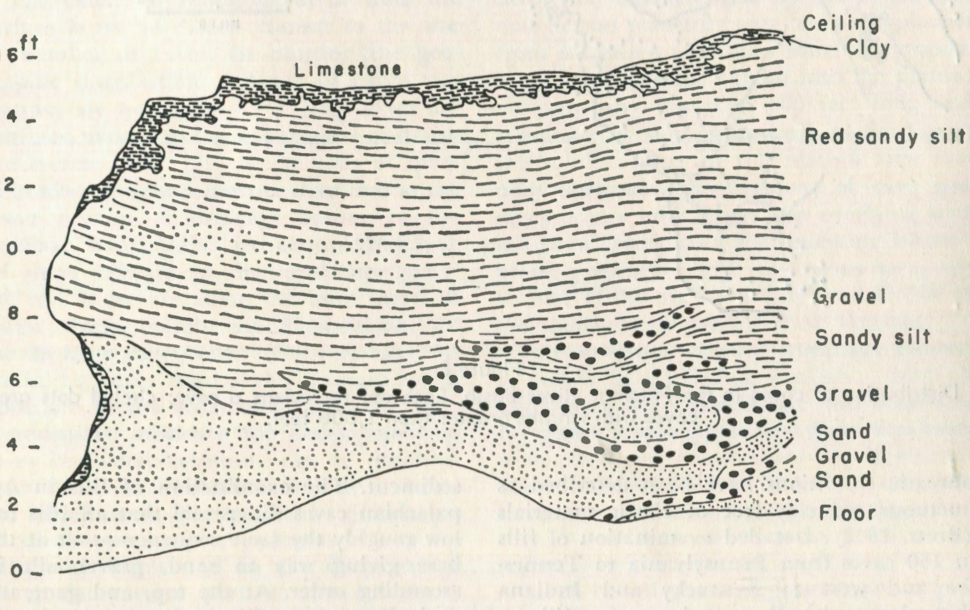

Figure 10
Section of fill at terminus of Dismal Valley, Salts Cave, Kentucky.

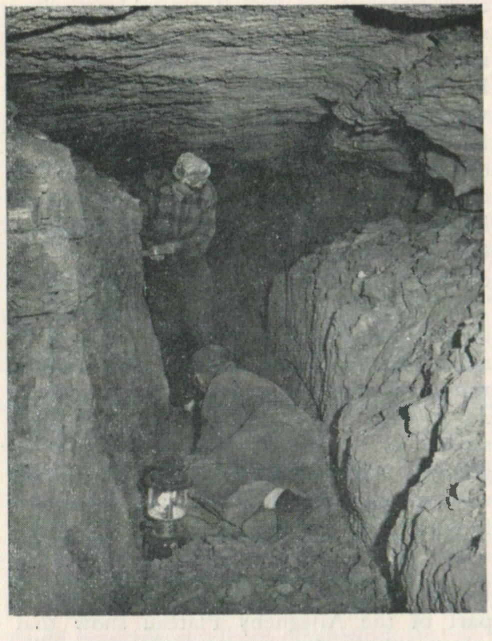

Figure 11
Schoolhouse Cave, West Virginia. At path level fill is gravel grading upwards to sand and silt. Laminated orange-brown clay forms the upper half of the exposure.

Fill materials are red-brown, tan, or orange-red. Petrographic studies show the color is from thin films of clay that coat the fragments forming the fill. This clay is similar to that in the terra rosa soils at the surface in limestone regions in the southeastern United States. In contrast, fill material brought in by invasion of present surface streams is dark brown to gray.

Many of the fills in Appalachian caves contain sulfate minerals, primarily gypsum. The sulfate varies from microscopic minerals scattered in small amounts throughout the fill to coarse gypsum crystals. The latter occur in beds where the gypsum constitutes over 50 percent of the fill. Studies in Mammoth Cave (Davies and Chao, 1959) indicate that the sulfate was probably carried into the cave by the same waters that brought in the fill. The sulfate thus introduced appears to have been developed under arid conditions on the surface. Such aridity possibly may have been reflected in a relatively stable piezometric surface which in turn would have been of great significance in cavern development.

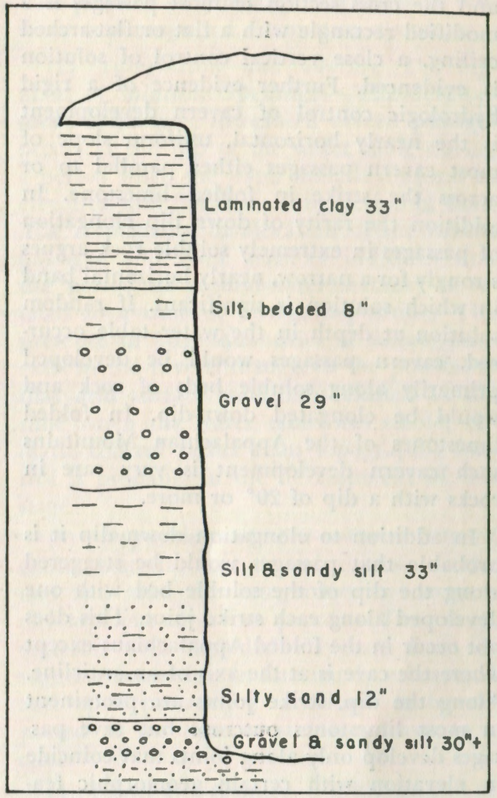

Figure 12
Section of fill in upper level, Schoolhouse Cave, West Virginia.

INTERPRETATION OF EVIDENCE

Evidence for solution development of caverns below the water table has been conclusively presented by Bretz (1942). The evidence gained from a study of caves in folded rock permits a more detailed interpretation of time and space relationships during the stage of solution excavation.

The shapes of cavern passages contradict the concept of random solution below a peneplain. If solution openings were formed in a zone deep beneath the water table the cross section of passages should generally be elliptical or parabolic reflecting stress conditions about the opening as the passage developed. Since this is not the case, and the cross section of most passages is a modified rectangle with a flat or flat-arched ceiling, a close vertical control of solution is evidenced. Further evidence of a rigid hydrologic control of cavern development is the nearly horizontal, uniform slope of most cavern passages either parallel to or across the strike in folded limestone. In addition the rarity of down dip elongation of passages in extremely soluble rock argues strongly for a narrow, nearly horizontal band in which solution is significant. If random solution at depth in the water table occurred, cavern passages would be developed primarily along soluble beds of rock and would be elongated down-dip. In folded limestones of the Appalachian Mountains such cavern development is very rare in rocks with a dip of 20° or more.

In addition to elongation down dip it is probable that passages would be staggered along the dip of the soluble bed with one developed along each strike joint. This does not occur in the folded Appalachians except where the cave is at the axis of an anticline. Along the dip, strike joints are prominent in most limestones outcrops but cave passages develop only along joints that coincide in elevation with certain geomorphic features, primarily river terraces.

Development of multilevel caves with each level horizontal indicates that in progressive solution development there is a repetition of rigid hydrologic control. If no control existed solution would occur at random throughout the whole extent of the limestone forming one vast chamber or numerous small passages along all major joints and fractures. This is not the condition observed in the field where most limestones contain only small, nonintegrated solution tubes between cavern levels.

Progressive branching of cavern passages, their reduction in size away from major valleys, and their gentle slopes towards major surface valleys, indicate an integration of solution networks. It is probable that this integration is a result of increased flow and channelling in a narrow zone in the water table close to the surface valley. The channelling reflects the selected enlargement of portions of integrated passages and in many respects it resembles a river system except that it is completely submerged and follows a closely controlled hydraulic gradient. This idea is in accord with the conclusions derived by Kaye (1957) from laboratory experiments on the effect of movement of solvents on limestone. The enlargement of passages reflects an increasing flow through the developing passages. Grooves, rounded rock shelves, and ceiling channels are indicative of this movement. The most rapid flow in ground water is at or just below the piezometric surface. In accord with Kaye's observations, solution would be most rapid in this zone of flow. At greater depths below the piezometric surface, where there is little movement of ground water, solution activity is greatly reduced and probably is limited to the formation of small pockets and tubes.

Features of caves along the Allegheny Front and along major valleys in the eastern part of the Allegheny Plateau show that solution is confined to a zone along the edge of the limestone outcrop. The termination of passages a short distance back from the plateau front and their slope upwards to the top of the limestone result from the intersection of an active zone of movement in the ground water and the limestone formation. The apparent absence of large solution openings in limestone beneath the Allegheny Plateau suggests that integrated solution development is absent deep in the ground water.

The increase in the number of caves in the upper parts of river basins and the occurrence of most large caves in the headwater areas (fig. 8) indicate that stability in these areas favors cavern development. In the lower portion of river basins geomorphic fluctuations, reflected in fluctuations of the piezometric surface, would be greater than in the headwaters. Such fluctuations would reduce the length of time of stable ground-water conditions and the chance of integrating primitive openings into mature caves would be far less than in upstream areas.

Earth fills in caves give additional evidence of shallow deposition. The clastic materials progressing from fine through coarse and back to fine grained material, capped by clay, is a sequence that indicates deposition from moving water. In examining the steps of cavern development it is obvious that fills succeed solution development and precede deposition of speleothems. Kaye (1957) has postulated from his experiments on solvent flow in limestone solution that the enlargement of passages would ultimately result in developing passages so large that the supply of water could not fill them. The development of cave fill fits this postulation well for it appears that the fill is progressively developed at the time when the cave is in transition from solution below the piezometric gradient to conditions of aeration above the gradient. The fill reduces the size of passages and permits the extension or temporary return of phreatic conditions. The extension of the fill to the ceiling occurs under ponded conditions since passages would be almost completely blocked. Under such conditions only clay could be transported for deposition.

CONCLUSIONS

In examining and interpreting the evidence three points stand out: (1) Cavern passages in plan, profile, and section show that solution development occurs at a time when a zone of maximum solvent flow in the water table is nearly horizontal, (2) the absence of parabolic shape in cavern passages (reflecting solution along fractures from stress around the developing opening and development completely below the piezometric surface) indicates the passages were integrated and maturely enlarged by solution in a narrow zone near the top of the ground water, (3) the slope of passages shows a gentle gradient of the piezometric surface towards major surface valleys. With these features in mind it is postulated that cavern development is a progressive, noncyclical process involving four distinct stages:

(1) *Random Solution at Depth*—In the initial stages of solution primitive tubes, pockets, and similar solution features are developed at depth in the ground water. In a dense tight limestone initial solution may be dominantly intermolecular; later solution is mainly along joints and fractures. The product of this stage is a series of random, nonintegrated, immature openings.

(2) *Integration and Mature Development of Solution Openings*—The development of mature, integrated cavern passages occurs at the top of the water table during a period when the water table is uniform in elevation and flow for a long period of time. The coincidence of elevation of the cavern passages and river terraces indicates that the period of ground-water stability is related to a time of terrace deposition. The presence of large quantities of sulfate minerals in the cave fills suggests the possibility that arid surface conditions existed at the time when the water table was stable; climatic control rather than topographic control is probable in the development of this stage.

(3) *Deposition of Fill*—Cave fills of clastic materials are deposited towards the end and after the integration and mature development of cavern passages. The clastic material with included clay and fine silt suggests deposition in alternately submerged and open passages, a condition to be expected as the time of stability draws to a close.

(4) *Uplift and Erosion*—With the end of stable conditions the cavern passages are raised above the level of the water table and are air filled. In this stage the passages are modified by deposition of speleothems and erosion of fill material. The ultimate development in this stage leads to total destruction of the cavern by collapse and erosion.

The theory of cave origin proposed here is applicable to all types of solution caves in all types of rock structures. The need for special development area by area is not necessary. Two factors determine the form of the cave. The first is the gradient of the piezometric surface which can be from horizontal to vertical. The second is the attitude of the structure of the soluble rock. These two factors when properly integrated can account for all types of cavern development.

In closing it should be noted that the four-stage development proposed in this paper supports in part Swinnerton's (1932) idea that caverns are developed by lateral flow at the top of the water table.

ACKNOWLEDGMENTS

The author acknowledges with gratitude the help of all members of the National Speleological Society through whose efforts the bulk of data on caves has been collected. Henry Douglas, Director of the Virginia Cave Survey, a voluntary project of the National Speleological Society, furnished valuable data on Virginia caves. George W. Moore, U. S. Geological Survey and William White, Pennsylvania State University, furnished much constructive criticism through many helpful discussions.

REFERENCES CITED

Bretz, J H., 1942, Vadose and phreatic features of limestone caverns: Jour. Geology, v. 50, p. 675-811.

Davies, W. E., 1950, The caves of Maryland: Maryland Dept. Geol., Mines, and Water Resources Bull. 7, 70 p.

---- 1957, Erosion levels in the Potomac drainage system and their relation to cavern development: D. C. Speleograph, v. 12, p. 1-5; reprinted in Speleo Digest, no. 3, 1957, p. p. (2) 32-36.

---- 1958, Caverns of West Virginia: West Virginia Geol. Survey, v. 19A, 330 p.

---- and Chao, E.C.T., 1959, Report on sediments in Mammoth Cave, Kentucky: U. S. Geol. Surv. Admin. Rpt. to U. S. Nat. Park Serv., 117 p.

Davis, W. M., 1930, Origin of limestone caverns: Geol. Soc. America Bull., v. 41, p. 475-628.

Denkhaus, H. G., 1958, The application of the mathematical theory of elasticity to problems of stress in hard rock at great depth: Assoc. Mine Mgrs. South Africa, Symposium Paper no. 2, 19 p.

Kaye, C. A., 1957, The effect of solvent motion on limestone: Jour. Geology, v. 65, p. 35-46.

Schoemaker, R. P., 1949, A review of rock pressure problems: Am. Inst. Mining and Metall. Engineers Trans., v. 181, p. 334-351.

Stone, R. W., *Ed.*, 1953, Caves of Pennsylvania: Natl. Speleol. Soc. Bull., v. 15, 143 p.

Swinnerton, A. C., 1932, Origin of limestone caverns: Geol. Soc. America Bull., v. 43, p. 663-694.

U. S. GEOLOGICAL SURVEY,
WASHINGTON 25, D. C.

DISCUSSION

J HARLEN BRETZ, *Univ. of Chicago*: I note both in this paper and in your report with Ed Chao [Sediments in Mammoth Cave, U. S. Geol. Survey Adm. Rept. to U. S. Natl. Park Service, 1959] that the cave fills discussed are relatively coarse-grained. This is in contrast to what I found in Missouri where the fills are mainly unctuous red clay. How do you account for this difference?

AUTHOR: Our work in Mammoth Cave and in Appalachian caves indicates that the fills are formed at the end of the stage of solution below the water table. Two significant changes in the cavern condition probably occur at this time: (1) the major passages reach mature size and the supply of ground water available is no longer great enough to maintain a "phreatic" state; and (2) the passages are alternately filled with water and are drained. This condition is enhanced by some relative rise of local baselevel because of normal erosion. When these changes occur rapidly, the fill deposits would be clastic in nature. Where passage enlargement and uplift were not so great as to exceed the supply of water available to maintain "phreatic" conditions, the fills would be deposited from slowly moving water and would consist primarily of clay and silt. I would like to point out that in the Appalachian caves most clastic fill is topped by either clay or fine silt. This material is generally packed tightly to the ceiling and reflects deposition in pools in blocked passages. From this there is evidence that "pooling" is the key to the difference between coarse-grained and clay fills.

WILLIAM B. WHITE, *Pennsylvania State Univ.*: How thick is the zone of flow beneath the piezometric surface; how much below the water table are the passages when they are maturely excavated?

AUTHOR: I'll answer this in the reverse order from which it was asked. The top of the cavern passages must be very close to the top of the ground-water or piezometric surface. I'd say that the passages at most could only be a few feet below the piezometric surface, otherwise solution would extend upward into the fractures above the passage and enlarge it accordingly. The thickness of the zone of flow is probably slightly greater than the height of the passage. This height, of course, is from bedrock floor to bedrock ceiling in areas where collapse has not modified the passages.

Origin of Bermuda Caves

by J HARLEN BRETZ

ABSTRACT—Throughout Pleistocene time, the calcareous island group of Bermuda has repeatedly been partially inundated and emergent. The land areas have been continuously attacked and reduced by rain and ground water, but they have been recurrently renewed by deposition of marine limestone and, on surviving lands, of shore-borne and wind-transported carbonate sand, now eolianite. At present, the karst topography and the caves are largely below sea level, and their origin must date from times of continental glaciation. When the islands were larger because of lowered sea level, a lens of fresh ground water occupied the present position of the caves. Later rise of sea level destroyed these phreatic conditions, and the caves assumed their present state in which they are partly filled with salt water.

There are two extraordinary facts about Bermuda caves: (1) most of them contain salt water pools at tide level and these pools contain submerged dripstone; and (2) there is no fresh ground water in the islands.

Bermuda is a carbonate land mass down to minimum depths of about 100 feet. Its material has accumulated on a truncated volcanic edifice rising from oceanic depths of 16,000 feet. Most of this carbonate rock represents wind-transported beach sand, now indurated and constituting several Pleistocene formations.

There are three Bermudas in geologic literature: Greater, Older, and Younger. All differ in age, area, and origin.

Greater Bermuda was more than 12 times the present area and existed when the growth of continental ice sheets had lowered sea level to expose the bottom of a large, relatively shallow lagoon lying northward from the island group. Only about 20 square miles of this former land now survive the post-glacial rise of sea level.

Older Bermuda constitutes perhaps nine-tenth of this 20 square miles. It is largely a karst topography, now partially drowned. It was made by solutional reduction from rainfall on the wind-transported sand when sea level was lower than today. The numerous bays, sounds, harbors, and reaches represent areas of most marked reduction. The caves are all in Older Bermuda rock.

Younger Bermuda consists of marginal rows of coastal dunes, their sand indurated by percolation of lime-charged rain water from their surfaces. Cementation is less marked than in Older Bermuda rock but most of it is adequately advanced for building stone use. No karst topography exists in Younger Bermuda.

Bermuda's fresh water supply is from rain on roofs and catchment areas and from tankers. Wells universally find salt or brackish water. Yet the caves and sink holes are indubitably the work of fresh ground water, and the salt water cave pools have been formed since a time when these caves were air-filled.

The stratigraphy of the islands, as accepted in this study, consists of three eolianite formations, three marine limestone formations, and three paleosols, arranged in the following order, although nowhere is there a complete geologic section. The paleosols mark erosional unconformities and are not truly aggradational units like the marine limestones and the irregularly distributed eolian deposits.

Dunes
St. George's paleosol
Pembroke eolianite
Spencer's Point marine limestone
Harrington paleosol
Devonshire marine limestone
Shore Hills paleosol

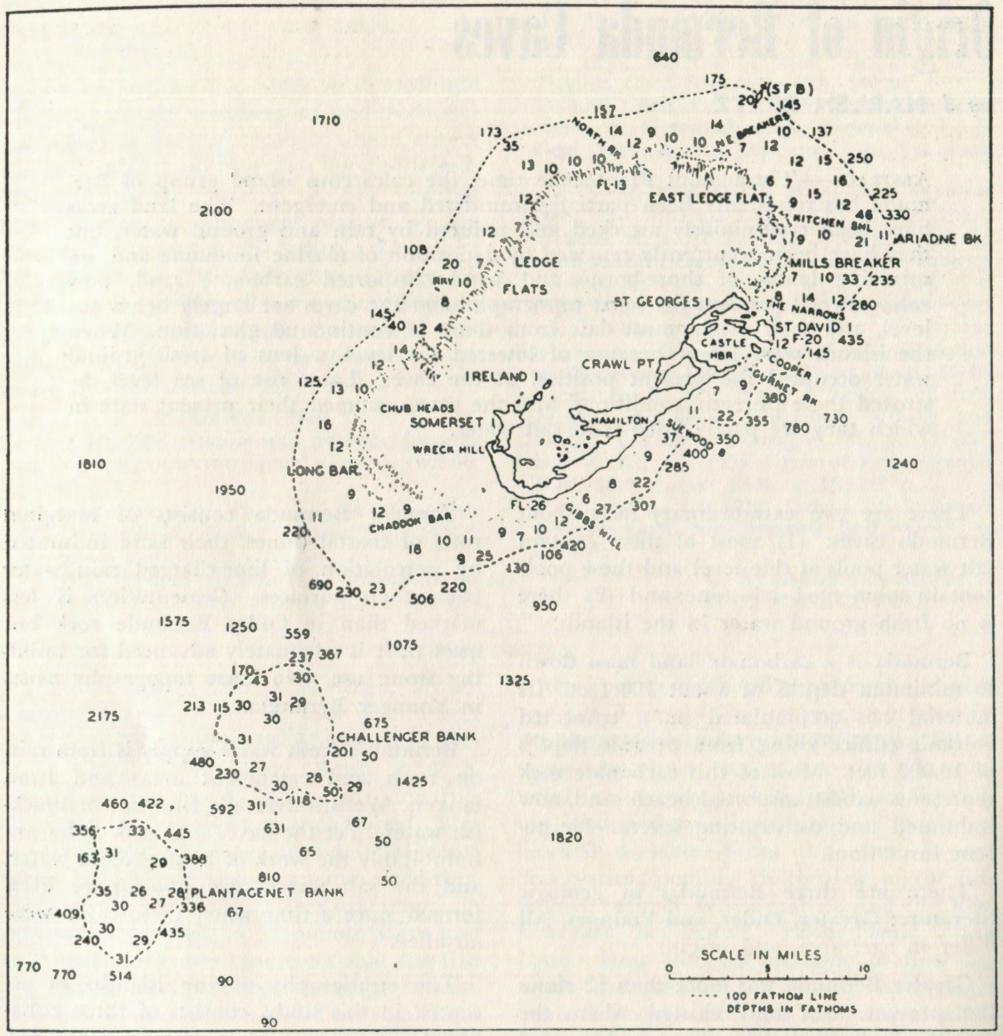

Figure 1
Bermuda Islands with the adjacent banks.

Belmont marine limestone
Walsingham eolianite
Volcanic rock

A dozen or so solutional caves in various stages of deterioration are known. They show by ceiling and wall blind pockets and sponge-work, horizontal elongation, and total lack of solutional outlines on fracture-determined, steeply inclined entrance passage walls, that they are of phreatic origin. For their making, Bermuda had to have a fresh ground water body whose water table was 30-40 feet above present tide level, an impossible condition today. Only the Greater Bermuda of glacial times could have provided it.

The Ghyben-Herzberg concept of a lens of fresh water in adequately sized oceanic islands, 42 times as deep below sea level as its water table is above (Badon Ghyben, 1889; Herzberg, 1901), is appealed to in explanation. At such times, the interior basins could hardly have existed in anything like their present dimensions. The caves appear to pre-date the long interval of solutional reduction which gave us the St. George's paleosol and the Older Bermuda topography.

Many fragmentary relics of former caves diversify the sea cliffs facing the open ocean, the large lagoon to the north, and, especially, the interior sounds and harbors. Heavy, corroded dripstone masses still decorate steep-walled concavities back under partly surviving roofs.

The steep fracture caves, which Swinnerton misinterpreted as vadose solutional cavities, all lead down to failed portions of the horizontally elongated true solution caves and are genetically ponor sinkholes. In quarries, a founder breccia is seen in rock overlying collapsed tracts of the true solution caves.

It is significant that such fracture openings occur in hill slopes marginal to the interior basins, strike parallel to their shore lines where the cave relics noted above occur, and in some cases clearly record gravity faulting of great slices of the hillside down toward the basins. These basins are in part later than the caves. They are viewed as essentially uvalas of a mature karst topography and the scattered islands and peninsulas in them as cave-containing hums.

Thus the Bermuda karst topography, partially drowned today, is also a product of conditions of Pleistocene low sea level but is later than most cave-making.

Cave history in Bermuda presents a paradox. In continental interiors, limestone caves pass from a phreatic environment to a vadose one because of deepening of river valleys and consequent lowering of the water table due to uplift of the region. But in Bermuda, it was initial rise of sea level that destroyed the phreatic conditions, drained and initiated collapse of caves, and allowed dripstone to grow. Further rise has submerged some of that secondary limestone to depths as great as 60 feet below tide level.

The Shore Hills paleosol records fully as long an exposure as does the later St. George's soil, and probably there have been two episodes of marked emergence (a Greater Bermuda) involving a fresh ground water body, cave-making, and solutional reduction of the land of its time.

This paper is only a summary statement. The detailed evidence for its conclusions will be presented in another publication.

References Cited

Badon Ghyben, W., 1889 Nota in verband met de voorgenomen put boring nabij Amsterdam: K. Inst. Ing. Tijdschr., 1888-1889, p. 21.

Herzberg, Baurat, 1901, Die Wasserversorgung einiger Nordseebader: Jour. Gasbeleuchtung Wasserversorgung, v. 44.

Swinnerton, A. C., 1929, The caves of Bermuda: Geol. Mag., v. 66, p. 79-84.

Department of Geology,
University of Chicago,
Chicago, Illinois

DISCUSSION

Roger W. Brucker, *Cave Research Foundation:* Swinnerton explained in his longer work in 1932 that, in his Bermuda paper, he had not meant to discuss at length his water-table hypothesis but to emphasize the importance of joint control.

Author: We could not satisfy ourselves that there was joint control that was effective. Swinnerton mistook hillside gravity sliding for joints. We saw two sets of joints in the marine limestones, but the joints hadn't been opened much by solution. There are caves down which one can crawl that I call collapse ponors, but these do not have joint control.

William E. Davies, *U. S. Geological Survey:* Dr. Bretz, may I draw you out on one thing please? You said, I believe, that the water gradient in Bermuda was about 1 in 300 toward the sea, and that the caves developed along a phreatic slope such as this. How is this slope related to the development of the caves? Wouldn't the development be near the top of this zone of saturation?

AUTHOR: No, I did not specify the position below the water slope at which the cave development took place.

RICHARD R. ANDERSON, *Bell Telephone Laboratories:* Did you say there was one large cavern under the entire surface which collapsed to leave the residual island mounds?

AUTHOR: No, a complex of caves. These hills occur all over the Bermuda island group; they are what are called *hums* or residual hills left in a region otherwise lowered by rain-water solution.

GEORGE W. MOORE, *U. S. Geological Survey:* Could the paradox of the Bermuda caves be resolved if the caves were formed, not during glacial times of low sea level, but during a former interglacial period when sea level was even higher than it is today? Former shorelines along the Atlantic coastal plain which possibly formed during the Sangamon Interglacial stage are 30-40 feet above sea level and might correspond with the time of cave development in Bermuda.

AUTHOR: There being no fresh ground water in Bermuda today, I see less chance for any when sea level stood still higher.

Changing Concepts of Speleogenesis

by WILLIAM R. HALLIDAY *

ABSTRACT—Theories on the nature of the origin and development of limestone caverns underwent systematization in the United States in 1930 as a result of the publication of an important deductive study by William Morris Davis. For some years thereafter, controversy existed as to whether caves are a result of a "one-cycle" process occurring wholly in the vadose zone or a "two-cycle" process having its first phase in the phreatic zone. Field work by many investigators in recent years has indicated some features of caverns which clearly were formed in the phreatic zone and others which were formed in the vadose zone, but this has by no means resolved the controversy.

Comparison of the features of individual limestone caves with those of nearby caves that are at a different stage in a genetic sequence and comparison with caves in different regions suggest that the terms "one-cycle" and "two-cycle" should be abandoned. Emphasis instead should be placed on the specific nature of features of individual caves derived from processes occurring in each of the phreatic and vadose zones. Only in the broadest terms can it be said that all limestone caves develop in the same way, and terminology which suggests that this is true should be replaced by descriptions of individual speleogenetic sequences.

Thirty years ago, William Morris Davis (1930) presented an important deductive study of the origin of limestone caverns. Although others had at least glimpsed the concepts which Davis outlined in this paper, his contribution resulted in a profound, almost revolutionary alteration of concepts on the origin and development of limestone caves. Its implications were so far-reaching that it is fitting today, 30 years later, that we reconsider not only these implications, but their significance in the light of later research which his paper stimulated.

The present paper will not review the concepts of speleogenesis expressed before 1930, nor will it restate the finer details of Davis' concepts. It will suffice to condense his 150 pages into the statement that Davis postulated two types of origin for limestone caves. One of these occurred during a single geomorphic cycle, as a result of the effects of subsurface water acting on interstices of limestone during a fairly early phase of the geomorphic cycle, with downcutting and perhaps subterranean stream piracy soon causing the caves to be drained. The other type developed rather late in the geomorphic cycle, primarily through deep phreatic solution, and these caves were exposed as a result of subsequent uplift which superimposed a second geomorphic cycle on the history of the region. His terms for the caverns produced in these two hypothetical ways were "one-cycle caverns" and "two-cycle caverns."

Close perusal of his paper leaves little doubt that Davis was referring to geomorphic cycles in the use of these terms, rather than cycles within caves as has come to be assumed widely. Perhaps somewhat because of the manner of his arrangement of material, many investigators have come to infer that Davis deduced that his theoretical "one-cycle caverns" were produced exclusively by solution and corrasion above the water table, as contrasted to the "two-cycle caverns" developed below the water table. Despite his summary entitled "four-epoch history of one-cycle caverns" which, alone, might lead to such a belief, this was not entirely the case. Reference to speleogenesis below the water table is encountered

---

* Paper read by Philip M. Smith, National Science Foundation

repeatedly in his discussion of "one-cycle caverns," particularly in the section on development of cavernous passages in one-cycle caverns in porous limestones. In retrospect, it appears that Davis perhaps placed too much emphasis on solution beneath peneplains and not enough on that by shallow subwater-table streams in dense limestones, perhaps in part because he was misinformed about the nature of certain cavernous limestones (Swinnerton, 1932). But it is clear that Davis considered the possibility of different kinds of speleogenesis, and specifically considered, for example, the possibility that some one-cycle caverns which developed beneath the water table might produce what he termed an "imitation of a two-cycle cavern."

It is also of note that Davis emphasized the discontinuity and filamentous irregularity of the water table in dense limestones "even in a late stage of an erosion cycle". He also pointed out that until considerable maturity of the water table had developed, the height of the air-water contact in small, new passages of the first erosion cycle would vary, as a result of such factors as rainfall, surface flow, passage size, slope, and perhaps configuration, so that the water table in such regions would not have a simple surface. This does not mean that all his related deductive concepts are fully acceptable today, such as his belief that in dense limestones, a typical cavern passage newly developed in the first erosion cycle would acquire a "free upper surface" at "some such size as a garden hose or a stovepipe". Nevertheless, it seems apparent that Davis envisioned different mechanisms of speleogenesis occurring under different circumstances although his advanced age precluded his developing this topic by the study of large numbers of caverns in different areas. It was his conclusion that there is little evidence of origin of important caverns through the mechanism of water with a "free upper surface", although he noted the effects of such streams in the subsequent development of certain cavern patterns.

In 1932, Ralph W. Stone published a revision of his study of the caves of Pennsylvania in which he stated that the history of most of the caves which he had studied in that state was "divided into at least two distinct cycles". By the term *cycles,* Stone was referring to the epochs outlined by Davis (*i.e.,* phreatic origin, plus subsequent drainage) rather than to geomorphic cycles. In the same year, Swinnerton (1932) similarly wrote of Davis' theory: "The solutional phase, or first cycle, occurs during the low stand of the limestone body; the depositional phase represents the second phase . . ." when uplift has supervened.

With all due respect to Dr. Stone, who probably has done at least as much to promote the progress of speleology in the United States as any of the more publicized speleologists who were his contemporaries, it must be said that this seemingly inocuous change of emphasis in Davis' terminology was unfortunate. Ten years later J Harlen Bretz (1942) wrote: "Davis conceived of two epochs in a cavern's history: The first occurring beneath the water table and being entirely solutional, the second . . . after air enters the cave." At that time, the concept of phreatic solution as the key to understanding the origin of limestone caverns was still in need of support. Bretz re-emphasized and produced evidence that most of the limestone caverns which he studied had been developed below the water table, and that free-surface streams merely modified them. At that time, incidentally, Bretz apparently still believed that most important caves probably developed beneath peneplains as Davis had postulated, even though Swinnerton had previously pointed out that except for artesian flow, there is little hydrostatic head and consequently little movement and solution by ground water beneath a peneplain (Swinnerton, 1932). Bretz also stated that he was "introducing the concept of an epoch of clay filling in normal cave history", between the earlier phreatic and the later vadose epochs. Unfortunately, some speleologists have confused his careful use of the term *epoch,* also used by Davis, with Davis' use of *cycle,* and have termed this the "three cycle theory", thus misconstruing both Davis and Bretz.

This tendency has become widespread, and has even been incorporated into standard references, so that the term "one cycle theory" to the average speleologist now means the concept that a cave is of vadose origin, and "two cycle theory", the concept that caves are developed below the water table and later drained by down-cutting or uplift. As Stone stated in 1932: "In the first cycle they were being excavated and were filled with water. In the second or present cycle they are filled with air and some of them are slowly being filled with travertine". With the advent of the use of aqualungs for exploration and study, the term "one cycle phreatic cavern" might also have been anticipated, but to the best of my knowledge, we have been spared this.

The situation has slowly become more confused. Davies (1957) has termed the intermediate clay fill epoch of Bretz a "third cycle", and on at least one occasion the outline of speleogenesis in Appalachian caves by Davies (1957) has been termed the "four cycle theory". If this tendency were to be carried to its logical end, the term "six cycle theory" would be applied to Bretz's (1956, p. 165) outline of the history of Marvel Cave, Missouri; "seven cycle theory" to Green's (1958) study of certain caves of the Uinta Mountains, Utah; "eight cycle theory" to my recent outline of speleogenesis in the Sierra Nevada of California (Halliday, 1957); and so on up to a "twelve cycle theory", since at least that number of changes in subterranean history have been recorded (Halliday, 1954). Actually, it has not been established and seems doubtful that any single speleogenetic period of cavern history alone represents a complete geomorphic cycle.

It seems fair to say that the concepts outlined by Bretz in 1942 have probably had as much impact upon the progress of speleology as did the paper by Davis twelve years earlier. Bretz outlined methods for determining the history of individual caverns, and enthusiastic use has been made of this approach. As the years have passed, however, it has become more and more apparent that strict conformance to this approach also has certain flaws.

In the more recent American and British literature, at least, there is a strong tendency for insistence that the solutional features of limestone caverns must be classified either as phreatic (developed beneath the water table) or vadose (above the water table). Since the water table of limestone regions is far from simple, both in pattern and in concept, it is not surprising that controversies have arisen over classification and nomenclature. This is perhaps more apparent in personal communication than in perusal of the literature, suggesting that it may be hampering the publication of valuable studies.

Davis' deductive study emphasized the importance of deep circulation of ground water, and hence phreatic speleogenesis at great depth as opposed to that close to the water table. This was soon challenged by several authorities who believed that deep phreatic speleogenesis was exceptional if it occurred at all.

In his 1942 study, Bretz noted that Davis had proposed the term "water-table stream" as well as "subwater-table stream". Davis considered the latter important in speleogenesis, at least in some caves in limestones which he inferred to be porous. By a terminology employed widely today, the subwater-table streams of Davis and Bretz are —or ought to be—considered phreatic; but this is by no means accepted universally, and strong arguments for classing them as vadose have been advanced.

In 1932 Swinnerton stressed the speleogenetic importance of "lateral flow in the upper zones of the water table," a concept which he had expressed somewhat less clearly in 1929. Emphasizing the zone of fluctuations of the water table, he termed these water-table or subwater-table streams "vadose" even though at times of heavy rainfall, he stated, no free air surface existed. As Warwick (1953, p. 55) has cautiously outlined this controversial subject: "Opinion varies whether such flooded passages are part of the phreatic zone. Theoretically this depends on whether the flooding is below the general water-table, but this is not always possible to determine." Similarly, Bretz (1942; 1956) has listed ceiling channels as vadose phenomena, and argued in support of this seeming contradiction.

A somewhat different method of speleogenesis was proposed by Malott (1932; 1936), now generally termed the invasion theory of cavern development. Malott concluded that the caves which he studied owed most of their characteristics to invasion of small, primitive, poorly developed network-type phreatic caverns by intermittent flood waters and other surface flow, which might or might not have a free surface within the cave.

Other workers have proposed variations of the mechanisms mentioned above, but those already discussed seem to be the most important contributions to date. Let us then consider the rhetorical question: what is the result of the accumulation of data through the years, and of the differing theories which it has spawned?

First, it is well to reiterate that the article by Davis was a deductive study, outlining various possibilities and urging field studies which its author could not personally carry out. Davis himself pointed out (1932, p. 606) that certain caverns were not in accord with the emphasis he placed on deep phreatic solution, and undoubtedly he anticipated that many of his deductions would be modified as the result of later information.

Secondly, to a speleologist with little field experience in the areas discussed by Bretz, Davies, Malott, and Swinnerton, it seems curiously evident that each appears to have drawn reasonable conclusions from the evidence observed in specific geographic areas, but that the stratigraphic, geomorphic, and structural conditions of the areas studied by these investigators differ markedly.

Inasmuch as the surfaces of these areas have not all had the same geomorphic history, it does not appear logical to expect the history of their caves to have been necessarily identical.

The student of the origin and development of limestone caverns of the western United States and Pacific islands is blessed by diversity in conditions of speleogenesis. The caves of California present particularly fruitful contrasts, although the systematic study of large areas of the state is just begun. In a recent publication, I pointed out how different were the origins of many of the caves of the Sierra Nevada (Halliday, 1957). One type of cave commonly found in the vertical or steeply tilted limestone of the Sierra Nevada has horizontal passages. Often these caves have flat, horizontal sections of ceilings which sometimes are stepped, indicating a series of pauses in the lowering of the level of the regional or local water table. As intimated by Davis (1932, p. 606) in the case of similar caverns in Virginia, and emphasized by others before and since, these caves show marked control by the water table.

An entirely different type of cave is found more rarely in California. Good examples are the White Chief Caves at the foot of a cirque high in the Sierra Nevada. These shallow, largely graded caverns appear to have been developed through the agency of periodic invasion by surface waters which, intermittently at least, filled them completely. In addition, however, these caves show many remnants of a pre-existing, somewhat three-dimensional network of phreatic origin similar to that cited by Malott. It is also my personal belief that Boyden Cave, 180 feet above the south fork of the Kings River, also owes most of its development to invasion. A slot at the entrance to the cave is caused by recent downcutting by the cave stream attempting to keep pace with the river, but the largely-graded remainder of the cave (originally a relatively minor part of the Church Cave system) appears to be due to invasion by nearby Windy Gulch Creek when this creek intersected an earlier phreatic cavern at a level close to that then occupied by the nearby river.

Still other caverns in the Sierra Nevada show patterns characteristic of a phreatic origin and a profusion of phreatic speleogens (solution features) extending to considerable depth, with little or no evidence of even short halts in the descent of the water table during regional downcutting. Whether these features are a result of deep phreatic solution or of shallow phreatic solution paralleling the dropping water table is an unanswered question, but most observers seem to favor the deep phreatic theory.

It is possible that some heavily-fluted, tubular California caverns, hundreds of feet below erosion surfaces, may have been formed through deep artesian solution, but no satisfactory evidence is yet at hand.

In the recently-emerged, poorly consolidated coralline limestone of southern Okinawa the characteristic cavern pattern is a graded branchwork superimposed on an earlier network. Some of the caves are a little above the water table, and dry. Others contain streams which are almost graded. Still other caves appear to extend to considerable depth below the water table. In my limited experience with the last group, I did not find any submerged aerogenic speleothems like those of Bermuda, nor did I find horizontal ceilings like those of the California caves mentioned earlier. At least one Okinawa cave shows modification by invading flood waters in the form of a distinct type of hackly, pitted surface at a horizon a few feet below the main part of the cave, and on the lowest part of the main level, but the remainder of this cave and most of the others appear to have been formed by solution by shallow subwater-table streams.

The idea that limestone caverns may not all have the same history is not new. Both Davis and Swinnerton alluded to it, the latter stating his belief that: "although deep phreatic caverns exist, most of the large cavern systems (which he studied) were, at the time of their formation, closely related to the water table level" (Swinnerton, 1932). Many recent students of caves, including Bretz (1956), have pointed out that not all caves of a given area have the same speleogenetic sequence. It has been suggested that many of the differences of opinion expressed by different observers can be resolved by considering the differing factors which operated in the areas studied by each.

A synthesis of these differing theories can be achieved only by study, comparison, and interpretation of the individual characteristics of each cave and cave region. This is essentially what Davis urged 30 years ago. As mentioned earlier, this type of study received great impetus from the 1942 paper of Bretz, which was also of value in that it completed the work of Davis in disproving the idea that ordinary streams were responsible for the characteristics of most caves. Now, however, it appears that insistence upon classifying speleogens as either phreatic or vadose is somewhat hampering further progress, and the wide deviation of the use of the terms "one-cycle" and "two-cycle" from their original context has also introduced artificial barriers.

It is probably fair to say that a considerable number of speleologists in both the United States and Great Britain who hold differing views on these matters of terminology and classification have independently evolved surprisingly similar views of speleogenesis which basically are a synthesis of the concepts originally outlined by Swinnerton and by Davis, with specific modifications where needed. There seems to be less and less divergence of basic concepts, and more and more argument over classification and terminology, which can be carried to the point that two authorities holding similar views are unable to recognize their agreement.

CONCLUSIONS

It is proposed that the time has come for the substitution of a more descriptive approach to speleogenesis than the mere use of phrases like "one-cycle" and "two-cycle" or "vadose" and "phreatic." It seems desirable, for example, to speak in terms of a free surface or lack thereof, of turbulent or smooth flow, of degradation or aggradation of clastic fill, of flow primarily under the influence of gravity or of hydrostatic forces, of primary and secondary permeability of the bed-rock, of shallow and deep subwater-table flow, of a stationary or descending water table, and the like; not to mention renewed emphasis on the nature of the water table in given cases.

By outlining individual, regional, and worldwide speleogenesis in such terms, our progress will escape blind alleys of needless controversy. Too many vital questions remain unanswered to afford the luxury of setting up additional artificial problems for the sake of argument. Emphasis must be placed on the interpretation of the specific nature and sequence of cave features, and upon determining the exact conditions which caused their presence. Only in the broadest sense can it be said that all limestone caves develop in the same way—or in one of two ways—and terminology which suggests that this is true should be replaced by descriptive data based on the individual speleogenetic sequence observed in each case.

References Cited

Bretz, J H., 1942, Vadose and phreatic features of limestone caverns: Jour. Geology, v. 50, p. 675-811.

—— 1956, Caves of Missouri: Missouri Geol. Survey and Water Resources, ser. 2, v. 39, 165 p.

Davies, W. E., 1957, Erosion levels in the Potomac drainage and their relation to cavern development: D. C. Speleograph, v. 12, no. 4, p. 1-5 (*repr.* Speleo Digest, 1957, p. 2-32—2-36).

Davis, W. M., 1930, Origin of limestone caverns: Geol. Soc. America Bull., v. 41, p. 475-628.

Green, D. J., 1957, The Dry Fork cave system, Uintah County, Utah: Salt Lake Grotto, Natl. Speleol. Soc. Tech. Note, no. 43 (*repr.* Speleo Digest, 1957, p. 1-119—1-124).

Halliday, W. R., 1954, The speleogenesis of Neff Canyon Cave, Utah: Salt Lake Grotto, Natl. Speleol. Soc. Tech. Note, no. 5.

—— 1957, The origin of the limestone caves of the Sierra Nevada of California: Western Speleol. Survey, Misc. Ser. Bull., no. 3, serial no. 11 (*repr.* Speleo Digest, 1958, p. 2-36—2-40).

Malott, Clyde, 1932, Lost River at Wesley Chapel Gulf, Orange County, Indiana: Indiana Acad. Sci. Proc., v. 41, p. 283-316.

—— 1937, Invasion theory of cavern development (abs.): Geol. Soc. America Proc. for 1936, p. 323.

Stone, R. W., 1932, Pennsylvania caves: Pennsylvania Geol. Survey Bull., ser. 4, no. G-3, ed. 2, 143 p.

Swinnerton, A. C., 1929, Changes in base-level indicated by caves in Kentucky and Bermuda (abs.): Geol. Soc. America Bull., v. 40, p. 194.

—— 1932, Origin of limestone caverns: Geol. Soc. America Bull., v. 43, p. 663-694.

Warwick, G. T., 1953, The origin of limestone caves: *in* Cullingford, C. H. D., *ed.*, British Caving: London, Routledge and Kegan Paul, p. 41-61.

Western Speleological Survey,
1117 36th Avenue N.,
Seattle, Washington

DISCUSSION

Charles R. Warren, *U. S. Geological Survey:* As a geologist who has only incidental speleological background, I am confused by the use that seems to be made of the terms vadose and phreatic. "Vadose" means above the water table, or water in unsaturated rocks. "Phreatic" would include all water below the water table, both near the water table and deeper as in artesian conditions. "Phreatic" would include perched water tables — anything that would contribute water to a well. If you use these terms in any other way, you're privileged to do so as long as it is clear what you mean, but I suggest you avoid the terms or use them in these, the accepted senses.

J Harlen Bretz, *Univ. of Chicago:* Would it satisfy you if we used the term *perched* along with the word phreatic?

Warren: That could be true in many cases. The existence or absence of a free air surface at the top of the phreatic zone also may be a quite significant point.

Bretz: A cave-floor stream could exist above the water-table level?

Warren: It would be the local water table—it could be a perched water table but as long as it is a flowing stream, to me, it's phreatic because it is a continuous body of water, and water that is flowing laterally is not moving straight down as vadose water in essence does.

Bretz: Then the floor of a cave stream which is above the regional water table is characterized by phreatic conditions?

Warren: The word phreatic is derived from the Greek word for *well,* and if the water would seep laterally into a pipe placed there, it is phreatic water.

Richard R. Anderson, *Bell Telephone Laboratories:* At what angle would water moving downward stop being vadose water?

Warren: At the point where the openings of the rock become saturated with water.

Bretz: If the water in the bottom of the stream is penetrating cracks and leaking down to unsaturated rock, what kind of water is that?

Warren: The part that is in the stream is phreatic. As soon as it gets below the perched water table to the point where there is air between water moving by laminar flow so that there are saturated conditions, then it ceases to be phreatic.

Roger W. Brucker, *Cave Research Foundation:* I share Dr. Halliday's concern in this problem. Finch suggested (Colorado Sci. Soc. Proc., v. 7, p. 193-252, 1904) that three zones are important in ground water circulation: a zone of percolation, a zone of discharge, and a static zone at depth. This places emphasis on a dynamic concept of the water table which is probably best expressed as a piezometric surface.

George W. Moore, *U. S. Geological Survey:* In Meinzer's original definition of the words *phreatic* and *vadose* [U. S. Geol. Survey Water Supply Paper 489, p. 38, 1923] they were intended to apply to permeable rocks. The situation in limestone may be more complex and the words therefore lose some of their applicability. A stream flowing in a cave passage above the top of the zone of saturation cannot be described in these terms without some ambiguity.

William E. Davies, *U. S. Geological Survey:* Answering a point in this paper, if Dr. Halliday will recheck his source he will find I have used the word *stage* in application to the development of limestone caverns rather than *cycle* as implied. Cycle denotes return to the point of starting and subsequent repetition. Stage is better than epoch because epoch, in the geologic sense, connotes a time element. Erosion in karst is a straight-line process to destruction, though certain stages may have distinct characteristics. I feel there are normally four such stages in karst and cavern development.

Arthur L. Lange, *Cave Research Associates:* I agree with Dr. Halliday when he maintains that each cave can come about differently. Even in the case of limestone solution caves, considered apart from other types: these are the result of the combinations and alternations of structures and processes. We can try to detect common processes such as submerged solution, or free stream solution, and we can attempt to map the initial joint and bedding patterns and classify these; but trying to discover some universal pattern of cave-making is like trying to find the universal story plot. Such an over-generalization would be useless.

Davies: I do not agree and feel there is one way in which most caves have formed, and we must find that way. We will all agree that most of them formed by the solvent action of water, and I think if we continue working we will find that most caves can be tied to a certain sequence of events. If not we will have chaos; there will be 5,000 different ways to form caves.

Origin and Geologic Relations of Breathing Cave, Virginia

by GEORGE H. DEIKE, III

ABSTRACT—Thirty or more caves occur in the folded Tonoloway, Keyser, and Helderberg limestones in the southwestward extension of a synclinal segment of the Bullpasture River Valley in west-central Virginia. The limestone formations, dipping less than 30°, plunge northeast beneath Devonian shale and are again exposed in Bullpasture Gorge water gap. Subterranean drainage crosses the structural grain and resurges at four springs in Bullpasture Gorge.

Breathing Cave, on the northwest side of the valley, in which four miles of passages have been surveyed, is a rectangular maze of strongly joint-controlled passages in a limited stratigraphic zone. The cave is confined to a 77-foot section of shaly limestone between two sandstone beds and is little affected by numerous minor folds and faults. It follows the dipping flanks of a syncline through a vertical range of 340 feet.

The major caves appear to have developed below the water table, in an artesian situation, confined by sandstone interbeds. Caves near spring outlets tend to be horizontal, regardless of the attitude of the bedding, and evidently they formed directly below the water table. Breathing Cave, which is far from the ground water outlet, exhibits deep bedding-controlled development, but it contains some evidence of horizontal enlargement caused by former stable positions of the water table.

INTRODUCTION

Breathing Cave, Virginia, has attracted the attention of members of the National Speleological Society for more than 15 years. The complex pattern of interconnected passages challenged explorers, and evidence of saltpeter mining near the entrance encouraged Burton S. Faust to undertake research into the history of the mining. The reversing air currents from which the cave takes its name, originally noted by Faust (1947), have been studied by Donald N. Cournoyer and were described by him in a short paper (Cournoyer, 1954).

In January 1954, members of the Nittany Chapter of the Society, including the author, first visited the cave and undertook a survey. This study was made a Society project in 1956, and 22,000 feet of passages were surveyed with compass and tape. The survey included many virgin passages in the northern end of the cave beyond a 42-foot drop, and the cave is still not fully explored. I. K. Nicholson has recently conducted surface explorations in the area which led to the discovery in March 1958 of the Butler Cave system which is considerably larger than Breathing Cave and is only partly explored and mapped.

The present study is a portion of work done for a Master's Thesis at the University of Missouri. Field work was done during parts of the summers of 1958 and 1959. The author is indebted to his wife, Ruth, and to various members of the Nittany Chapter, especially John L. Haas, for help in the field, and to members of the D. C. Chapter cabin committee for making their facilities near the cave available.

GEOLOGIC RELATIONS

Breathing Cave is in the southwestward extension of the synclinal valley of the Bullpasture River in west-central Virginia (fig. 1). Devonian Oriskany sandstone and overlying Onondaga and Millboro shales crop out in the valley along the axis of the syncline which plunges to the northeast. Except for a few patches, these rocks are entirely eroded away in the extension of the valley southwest of Bullpasture Gorge. Here a broad area of Upper Silurian and Lower Devonian limestone is exposed. Beneath the limestone lies resistant Ordovician and Silurian sandstone and shale which form the ridges surrounding the limestone outcrop. Bullpasture Mountain is an anticline through which Bullpasture River has cut a gorge to reach its junction with the Cowpasture River. Breathing Cave is located on the southern slope of Jack Mountain, on the northwest side of the valley, where the limestone dips 12-20° E.

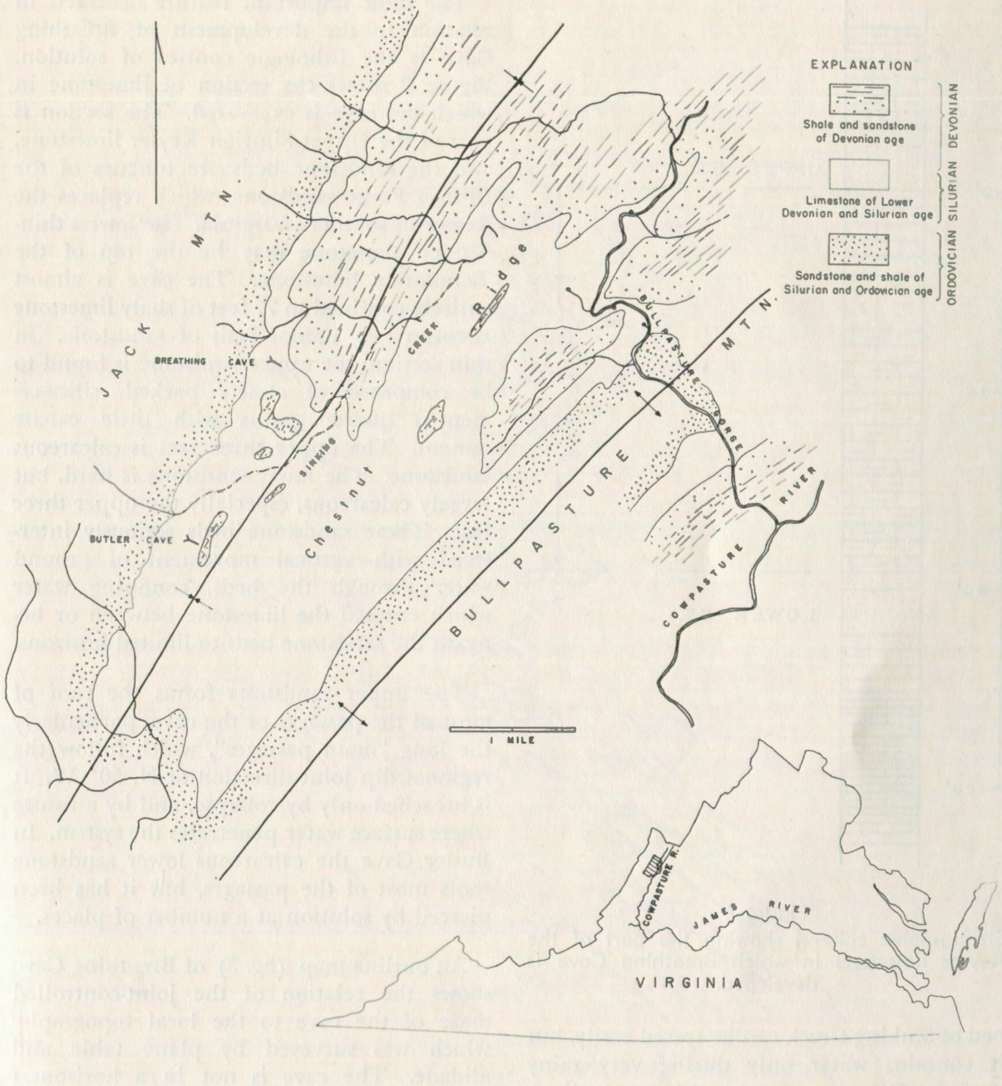

Figure 1
Location and geology of the Breathing Cave area, Virginia.

Streams flowing from the ridges sink near the limestone contact, and permanent surface streams occur only on the shale outcrop. The

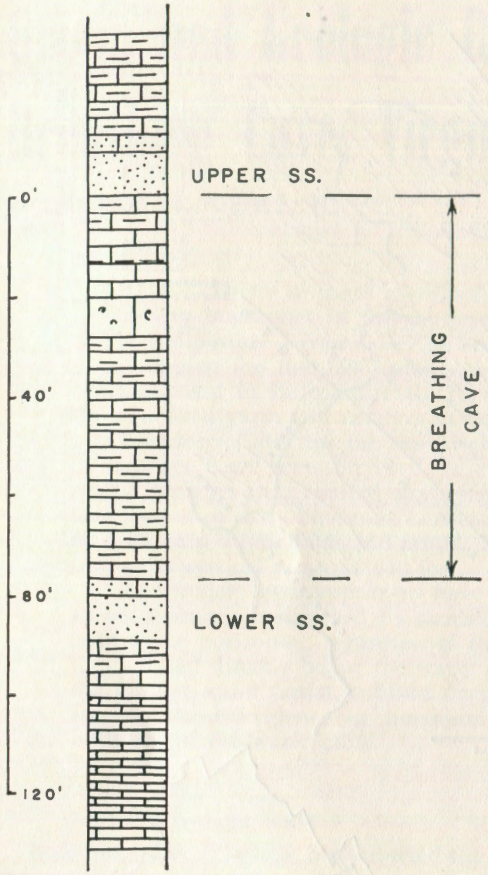

Figure 2
Stratigraphic column showing the part of the Keyser limestone in which Breathing Cave is developed.

bed of Sinking Creek can be traced easily, but it contains water only during very rainy periods. Other stream channels on the limestone are obscure.

Ground water from the limestone valley rises at four springs at the northwest end of Bullpasture Gorge. This is the lowest point of limestone outcrop and has long been base level for the underground drainage. The flow from these springs, measured in July 1959 to be about 20 second-feet, is approximately enough to account for all the rain which falls annually on the limestone and mountain slopes combined. These must be the only important outlets.

The most important feature observed in relation to the development of Breathing Cave is the lithologic control of solution. Figure 2 shows the section of limestone in which the cave is excavated. The section is part of the Upper Silurian Keyser limestone, and the sandstone beds are tongues of the Clifton Forge sandstone, which replaces the Keyser in southern Virginia. The lowest thin-bedded limestone may be the top of the Tonoloway limestone. The cave is almost entirely confined to 77 feet of shaly limestone between two 12-foot beds of sandstone. In thin section, the upper sandstone is found to be composed of closely packed, silica-cemented quartz grains with little calcite cement. The upper three feet is calcareous sandstone. The lower sandstone is hard, but largely calcareous, especially the upper three feet. These sandstone beds seriously interfered with vertical movement of ground water through the beds, confining water which entered the limestone between or beneath the sandstone beds to limited horizons.

The upper sandstone forms the roof of most of the passages of the cave, particularly the long "main passages", which follow the regional dip joint direction of N. 50° W. It is breached only by collapse, and by a fissure where surface water penetrates the system. In Butler Cave the calcareous lower sandstone roofs most of the passages, but it has been pierced by solution at a number of places.

An outline map (fig. 3) of Breathing Cave shows the relation of the joint-controlled maze of the cave to the local topography which was surveyed by plane table and alidade. The cave is not in a horizontal plane, but follows the bedding which strikes about north and dips about 15° to the east. The eastern side of the network is thus 150-200 feet lower than the western side, where the entrance is located. The total vertical range of the cave is about 340 feet.

Drainage is southeast, away from Jack Mountain, 4,500 feet northwest of the cave, whose crest lies at an altitude of 3,500 feet. The cave crosses the divide between two hollows on the mountain slope, and crosses beneath Red Hollow. Red Hollow, whose

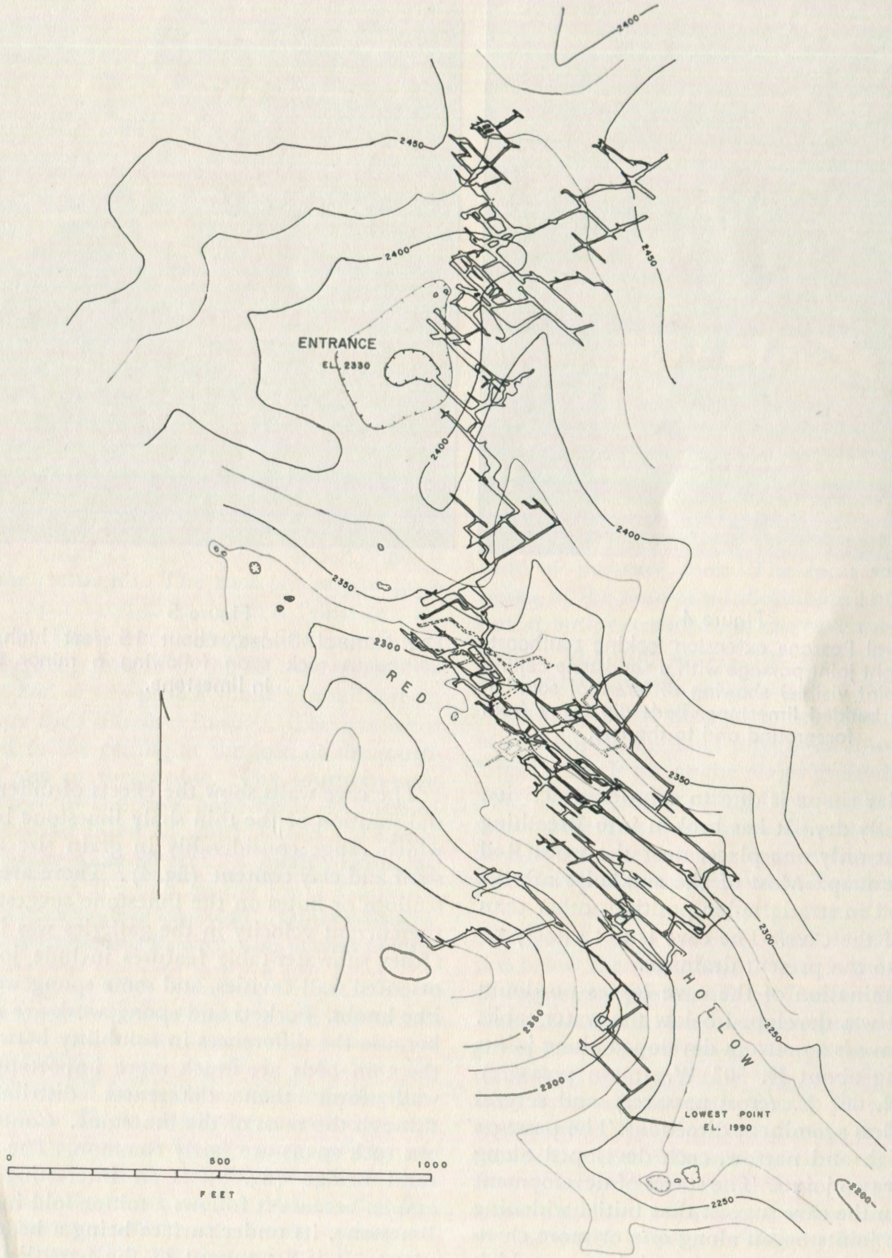

Figure 3
Map of Breathing Cave, Virginia, showing relation to surface topography.

Figure 4
Cathedral Passage extension looking southeast. A straight joint passage with a sandstone ceiling (with joint visible) showing differential solution of thin bedded limestone. Beds dip away from foreground and to the left.

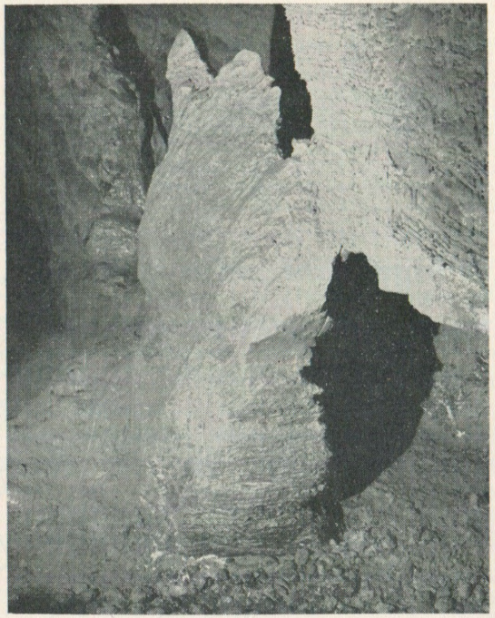

Figure 5
The Natural Bridge, about 15 feet high, a continuous rock span following a minor fold in limestone.

irregular shape is due to solutional activity, is usually dry. It has broken into Breathing Cave at only one place, near the word Red on the map. Most of the sinkholes are developed in stratigraphic positions other than that of the cave. The cave is not closely related to the present drainage.

Examination of the cave leaves no doubt that it was developed below the water table. The cave is a network developed along joints striking about N. 50° W. (main passages) and N. 60° E. (cross passages) and several other less prominent directions. The passages are high and narrow, each developed along one or two joints. The stages of development seen in the cave suggest that initial widening of the joints began along one or more channels which usually coalesced into one high passage. Several reverse faults are exposed on the cave walls, but there has been almost no solution along these. The corners at passage intersections are not rounded.

The cave walls show the effects of differential solution of the thin shaly limestone beds which range considerably in grain size and sand and clay content (fig. 4). There are no scallops or flutes on the limestone suggesting the current velocity in the galleries was low. Other subwater-table features include joint-oriented wall cavities, and some spongework-like knobs. Pockets and spongework are rare because the differences in solubility between the thin beds are much more important to wall form than differences distributed through the mass of the limestone. Continuous rock spans are fairly common. The Natural Bridge (fig. 5) is an interesting example, because it follows a minor fold in the limestone, its under surface being a bedding plane. It is a remnant of the partition between two joint passages, one of which apparently was blind. The cave also exhibits thin bands of shale which fill cracks perpendicular to the bedding and stand in relief because of differential solution (fig. 6). These were named clay fins by White (1959a).

Not all of the joints exposed in the cave have been opened by solution, but many have. From northeast to southwest across the cave system there are more than 70 parallel passages in a distance of 1,700 feet. Solution was accomplished by slowly moving water along most of the joints in this limestone zone.

The original joint passages have been almost completely filled with conglomeratic silt and sand fill (fig. 7). Cobbles 12 inches in diameter are common, and the explorable parts of the cave are open as a result of the removal of this fill by small free-surface streams.

The profile of the Cathedral Passage (fig. 8), which is a long main passage in the middle of the main part of the cave south of the entrance, shows the irregular removal of the clastic fill. The roof of the passage is the upper sandstone. Several faults are exposed. The lower sandstone is exposed only in the deep canyon in the fill near the northwest end of the profile where a small stream crosses the Cathedral Passage. The passage is filled to the ceiling at the fold at the southeast end of the profile. The southern-most passages in the cave have been emptied of fill beyond this fold which lowers the upper sandstone some 80 feet. A small stream cascades down the fold on the lower sandstone to another floor of clastic fill. Other passages, such as Cathedral Passage, also extend farther beyond this big fold but are still filled.

The limits of the explorable cave passages are not usually the limits of solution. In figure 10 the passages which end downdip (east) in fill have been extended diagrammatically. Those which are extended to the west, or updip, are largely north of the entrance, and end in rock falls which may reflect their approach to the surface (fig. 9). The passages which are shown ending in breakdown 500-1,000 feet south of the entrance, are adjacent to Red Hollow.

Figure 6
Small reverse fault exposed in Cup Room. Differential solution of beds is evident as well as "clay fins."

Figure 10 shows structure contour lines drawn on the bottom of the dipping upper sandstone, which is the ceiling of most of the passages. Thus it shows the slope and altitude of the cave roof. The local strike is north, at the nose of a subordinate anticline, but at both extremities of the cave the strike is seen to swing toward the regional strike of about N. 40° E.

Many caves are thought to begin as a maze of small openings, later integrated into a few large channels taking the major ground water flow. Although Breathing Cave is still a network there exists the possibility that water flow in the system would have enlarged some passages preferentially, as main conduits. This might be particularly true if major enlargement was accomplished by streams just below the water table. This is the mode of formation postulated by Davies (1959). The main conduits would be expected to be gently sloping, reflecting the slope of the water table. In this case the conduits, confined by sandstone beds, would lie parallel to the strike. Examination of maps and field data indicates that there are no such conduits. The drainage basin uphill from the cave is small, and flow velocities of a few feet per minute could handle the largest floods. As a result, no single large streams were developed in the system. There are some larger passages, mostly trending N. 50° W., but these are not connected to other N. 50° W. passages by large cross passages, and if any-

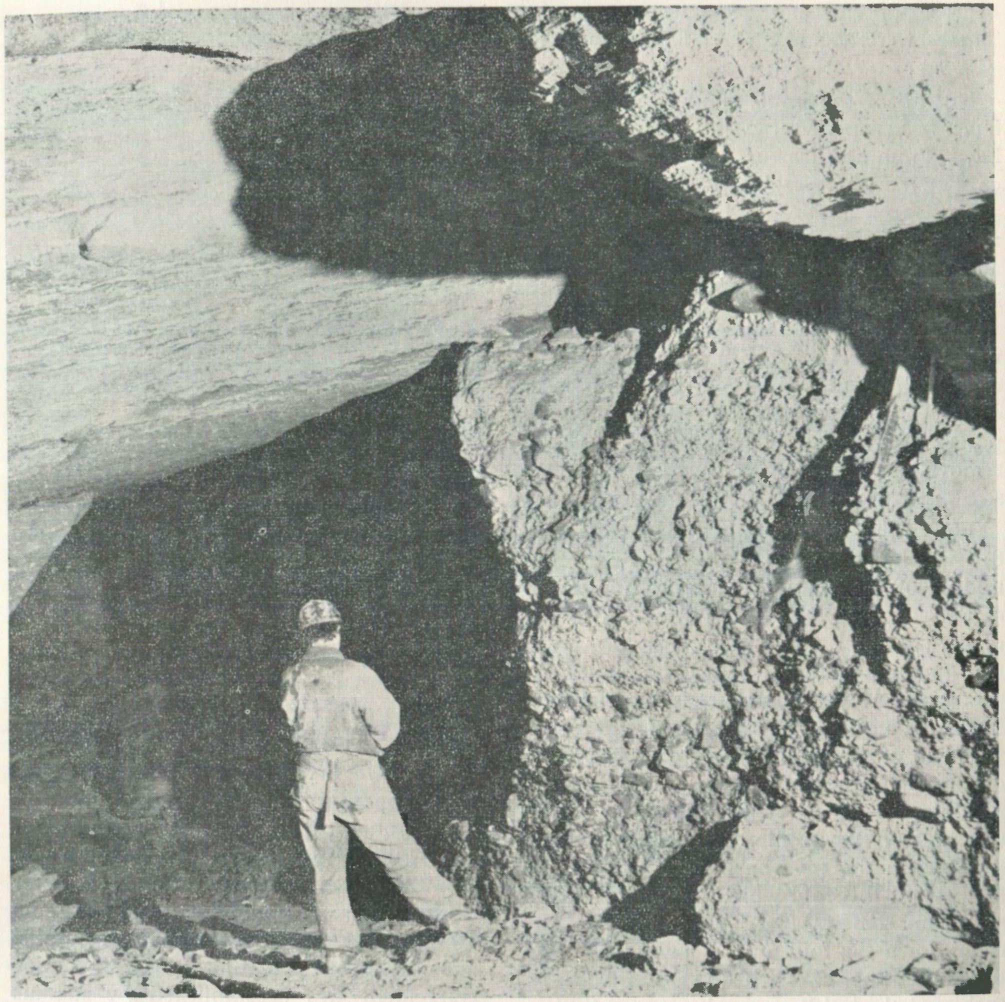

Figure 7
An exposure of conglomeratic cave fill 250 feet south of the entrance.

thing they reflect several preferred paths of flow diagonally downdip along this joint direction.

It appears that most of Breathing Cave was developed simultaneously in this confined horizon by slowly moving water.

Surface erosion has taken place in stages here in the James River drainage much as it has in the Potomac drainage. This is reflected in well-developed terraces cut on the shale of the Bullpasture and Cowpasture River valleys, and probably by various hill summit levels in the region. These features reflect relatively stable periods in the erosional history of the region. At these times the water table would stabilize also.

Even if ground water flow were too small to dissolve large main conduits in Breathing Cave, the water table must have stood at certain levels in the system during the stable periods, and this should be reflected in the morphology of the cave. Additional upward solution would then be limited by the water surface. This probably has occurred at two levels in Breathing Cave. Less than 250 feet south of the entrance, three joint passages become impassibly narrow and seem to pinch out near an altitude of 2,300 feet.

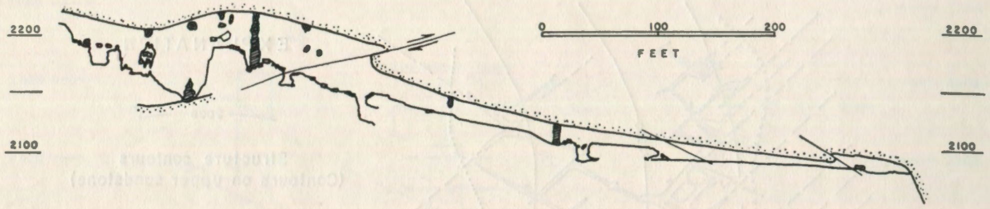

Figure 8
Profile of Cathedral Passage and extension. The ceiling is the upper sandstone. Cross passages shown as shaded openings.

An extended stable water surface seems to explain this sudden narrowing best. Several other passages north of the entrance narrow noticably at this level, although they do not end. These passages were in existence before this stable period. This situation is similar to that observed in Pennsylvania caves by White (1959b).

About 650 feet south of the entrance, lower levels are shown on figure 10 in dashed lines. In these passages, small free-surface streams flow on the lower sandstone, but the passages seem to narrow and pinch out upward at approximately 2,220 feet. The main "level" of passages (not truly level) lies about these pinch-outs, and is only connected to the lower passages in a few places. Apparently upward solution in these lower levels was limited by the water table.

It is also possible that concentrated flow of water near the water table would develop a number of passages at this level during stable periods.

Most passages are roofed by the upper sandstone and only those at other horizons in the limestone were examined for concentrations at particular levels. This confined the examination almost entirely to the cross passages, which follow joints other than the "main" N. 50° W. dip joint.

There are a large number of cross passages near the Cathedral Passage, 900 feet south of the entrance. Some of these are shown in figure 8. Most of the cross passages (18) lie between 2,120 and 2,170 feet, but few are at any single altitude, and there are commonly several of them one above another along the same joint. It is difficult to imagine that these represent levels. Several passages in the southern end of the cave have ceilings between 2,075 and 2,095 feet, but again they do not seem to reflect a water surface. If these are levels, then they are numerous and are most likely related to hydrologic conditions within the cave system, rather than stable periods of local base level of erosion.

Figure 11 presents the relationship of the caves and erosion levels in Bullpasture Valley. Present base level is the Bullpasture

Figure 9
The Pit Room, a passage which ends updip in a near vertical breakdown pile.

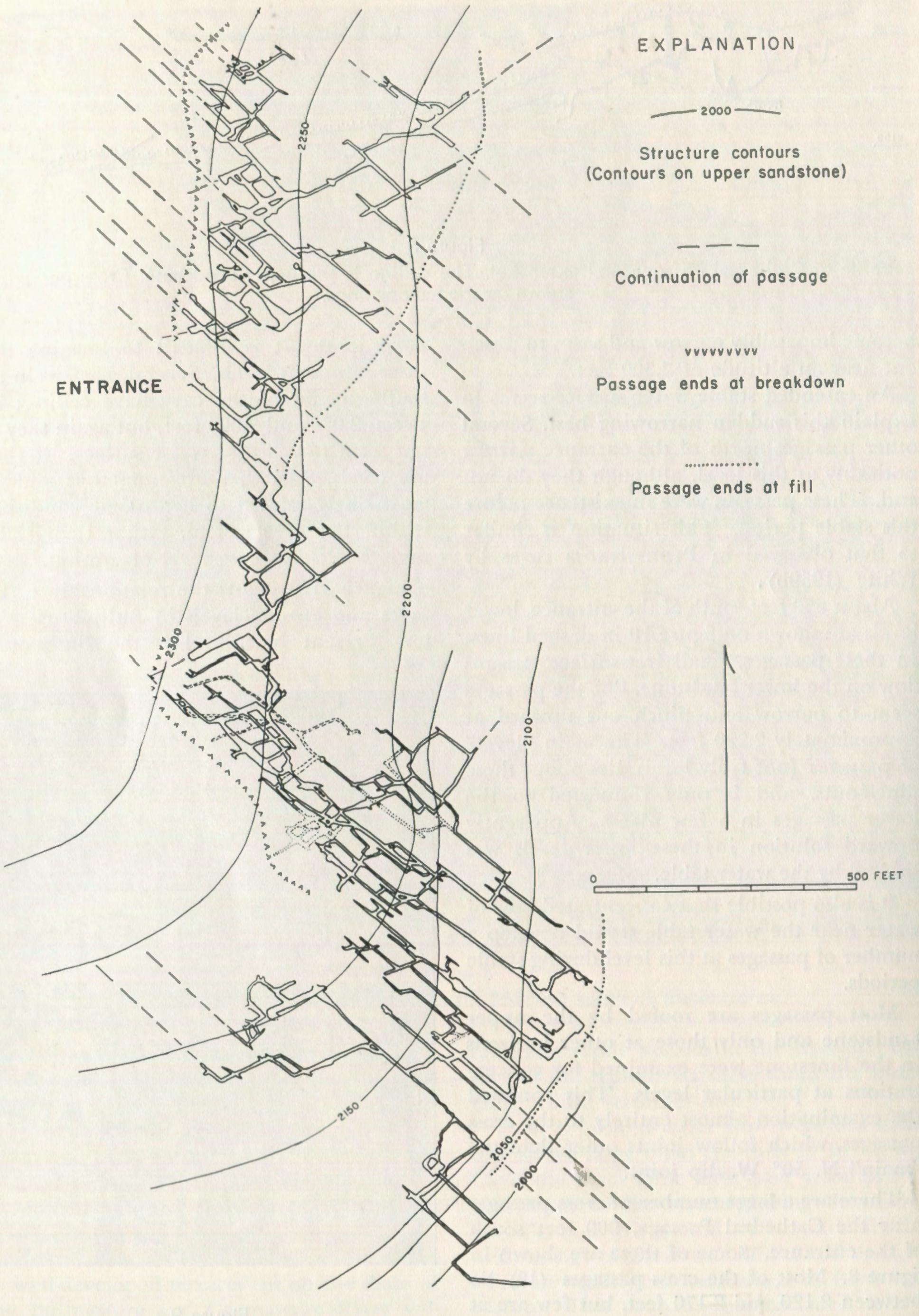

Figure 10
Structure contour map of Breathing Cave. Contours show slope of the sandstone cave roof.

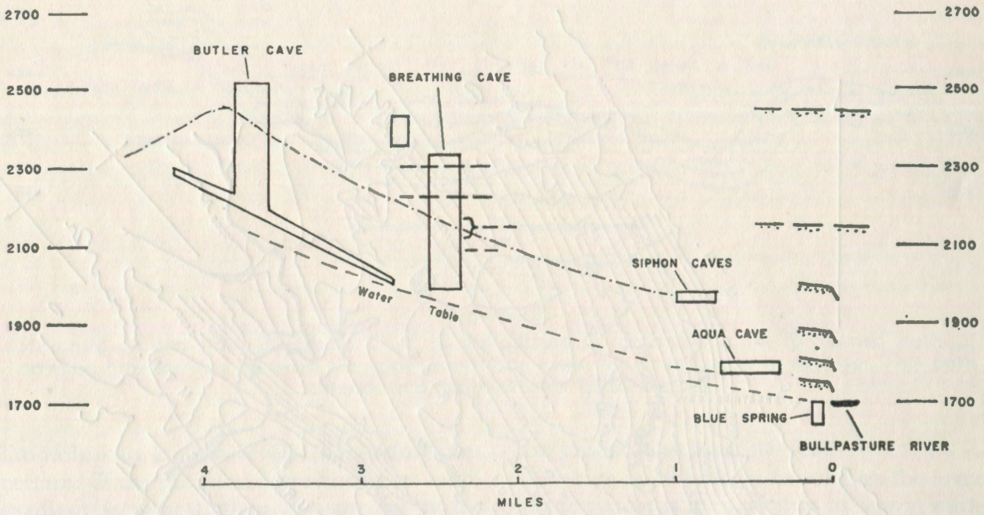

Figure 11
Vertical relations between caves and erosion features.

River at an altitude of about 1,700 feet where it crosses the limestone outcrop. Above the river the four most prominent terraces are shown diagrammatically. These are often correlated with the four glacial stages of the Pleistocene epoch. The two lowest hill summit levels, as reported by Davies (1957) in the Potomac River drainage basin and apparently recognizable in Virginia too, are also shown. The horizontal and vertical extent of several caves are shown diagrammatically with their distance from the river.

Two outlets to the present drainage are shown. One is Blue Spring which rises from a joint passage very like those of Breathing Cave. Diving has shown the passage to extend at least 50 feet below river level. The opening is not confined by a sandstone bed. It is not known whether the passage extends down the dip of the beds, or becomes horizontal, cutting across the bedding.

The other outlet is Aqua Cave, which is 70 feet above the river. The difference in altitude of these two outlets, which are both in the Keyser limestone on opposite flanks of a syncline, shows that the present active drainage is not confined to a level close to present base level. Aqua Cave, however, extends horizontally through dipping beds, crossing the axis of an anticline. It appears to be close below the second river terrace. The cave probably originated as a major outlet to subterranean drainage as this terrace was being formed, in the manner suggested by Davies (1959). Ground water is still using this conduit, presumably for lack of a connection to a lower outlet.

The Siphon Caves, located at Water Sinks, the termination of Sinking Creek Valley, are shown as one cave in figure 11, and seem to be directly below the fourth terrace level. From this cave a dot-dash line shows the profile of Sinking Creek, over its divide near Butler Cave.

To understand the relations of Breathing and Butler Caves, a few points must be made about the water table in this limestone. The two springs mentioned above, and two others not in the same limestone beds, carry all the underground water from the valley to the Bullpasture River, the lowest point on the water table in the limestone. Neither Breathing nor Butler Cave has extensive flooded passages which could be said to be below the

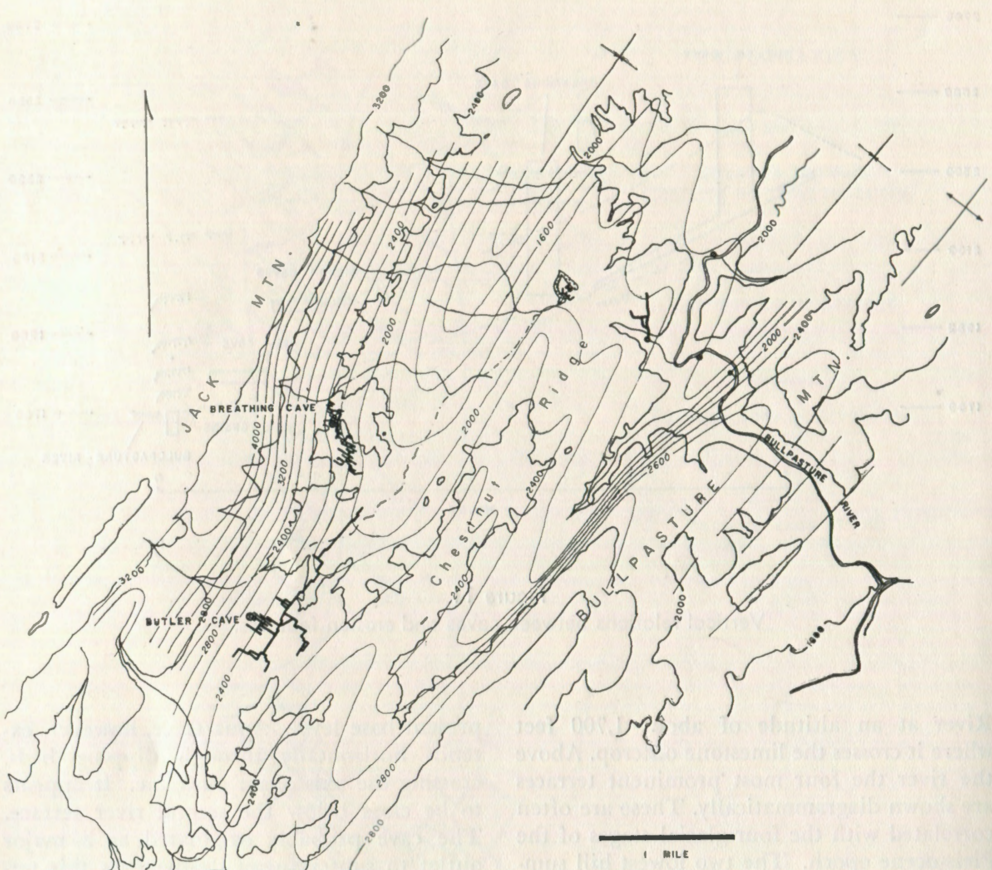

Figure 12

Regional structure contour and topographic map of the Breathing Cave area. Structure contours drawn on the upper sandstone horizon. Line maps of caves are shown.

water table. If such an inundated zone exists, it must lie below the explored caves. A hypothetical water table just below the caves is shown in dashed lines on figure 11. It has a slope of less than 100 feet per mile toward the river.

Several free-surface streams in the caves contribute to the underground drainage. These are very small, with a flow of 1/3 second-foot at a time when the springs issue 20 second-feet. The large stream in Butler Cave carries much more water in flood and is a danger to exploration downstream. Particularly in Butler Cave, there are standing pools along the stream, and these are a small part of the water which feeds the springs a relatively steady flow. Most of the storage capacity, however, is probably nearer to the outlets. If the cave systems continue to follow bedding, confined beneath the sandstone beds, then large parts of the system in low areas structurally are below the water table and act as storage chambers.

The two definite and two doubtful levels of static water tables in Breathing Cave are shown in figure 11. The spacing resembles that of the four river terraces, except that these levels are all farther above the present water table than the terraces, and the lowest two levels are questionable. Their exact relationship to erosion levels is therefore uncertain. If the postulated present water table gradient is typical, then the ancient water table would have had to slope toward the summit level at 2,150 feet to place the entire Breathing Cave system under water. Its origin would thus date from the time of this erosion level, or before.

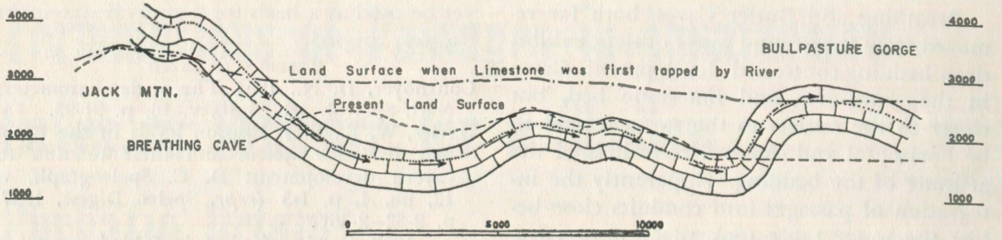

Figure 13

Structure section from Breathing Cave to Bullpasture Gorge showing the presumed path of artesian flow (arrows) beneath the upper sandstone when the cave began to develop. This path extends to a depth of over 1,000 feet.

Figure 12 shows the topography, taken from U. S. Geological Survey quadrangle maps, of the Breathing-Butler Cave area with structure contours drawn at 200-foot intervals on the upper sandstone. Rough line maps of the caves are shown. If the water in the Breathing Cave system was entirely confined beneath this sandstone, it must have moved toward the outlets at Bullpasture Gorge around or under the synclines and anticlines shown. Butler Cave, which is largely below the lower sandstone, does extend up both flanks of a syncline. Water traveling in a straight line from Breathing Cave to the gorge would have to pass beneath this same syncline at an altitude of 1,700 feet — 600 feet below the present entrance, as in figure 13. Butler Cave has a vertical range near 500 feet. It appears likely that the water did pass beneath these structures as artesian water confined by the sandstone. Breathing Cave, as explored, does tend to parallel the local strike southward, and this may reflect a tendency for the water to go around the structures, parallel to the strike and hence to the structure contours, rather than directly beneath the anticlines and synclines. The vertical development is nonetheless probably at least 400 feet.

Having an important bearing on the origin of the system is the fact that its lowest outlet has always been at the point where the Bullpasture River cut through Bullpasture Mountain anticline in the gorge. A glance at figures 12 and 13 shows that the river did not cut into the Breathing Cave horizon until it reached about 2,650 feet, about 1,000 feet above present river level. Only after the limestone horizon had a lower outlet at the gorge was a hydraulic gradient set up in the limestone, and only then did water begin to move through the rock to create the caves. The known caves lie well below this level. Presumably the higher parts of the original system have been destroyed by erosion.

Conclusions

Breathing Cave is a highly joint-controlled cave which follows dipping structures in a thin shaly limestone zone. The cave is confined beneath a sandstone interbed.

The cave was developed below the water table by slowly moving water in an artesian situation over a long period of time. Present caves nearer to the resurgences of ground water at Bullpasture Gorge have probably been developed in a thin zone close beneath the water table which existed during stable periods of terrace formation.

Breathing Cave originated at the time when the river first opened a low outlet for water in the limestone aquifer. It shows some effects of continuing enlargement when the water table stood at several different levels at different times within the cave.

Breathing and Butler Caves, both far removed from the ground water outlets, exhibit deep bedding-controlled development. Caves in the same area and limestone bed, but closer to the outlets to the surface, tend to be horizontal and shallow, regardless of the attitude of the bedding. Apparently the integration of passages into conduits close below the water table took place most effectively near spring outlets. Further research is needed to determine whether this pattern is adhered to by other caves, both here and in other geologic situations.

At present the Nittany Chapter of the National Speleological Society is surveying Butler Cave, and much other work remains to be done. Both Breathing and Butler Caves are interesting and perhaps unusual cases of lithologic control of solution. They cannot yet be used as a basis for a general statement on cave origin.

REFERENCES CITED

Cournoyer, D. N., 1954 The speleo-barometer: Natl. Speleol. Soc. Bull., v. 16, p. 91-93.

Davies, W. E., 1957, Erosion levels in the Potomac drainage system and their relation to cavern development: D. C. Speleograph, v. 12, no. 4, p. 1-5 (*repr.* Speleo Digest, 1957, p. 2-32—2-36).

——— 1959, Origin of caves in folded limestone (abs.): Geol. Soc. America Bull., v. 70, p. 1802.

Faust, B. S., 1947, An unusual phenomenon: Natl. Speleol. Soc. Bull., v. 9, p. 52-54.

White, W. B., 1959a, Speleogenesis, part II: Netherworld News, v. 7, p. 6-26.

——— 1959b, Terminations of passages in Appalachian caves as evidence for a shallow phreatic origin (abs.): Geol. Soc. America Bull., v. 70, p. 1816.

DEPARTMENT OF GEOLOGY,
UNIVERSITY OF MISSOURI,
COLUMBIA, MISSOURI

DISCUSSION

WILLIAM E. DAVIES, *U. S. Geological Survey:* We had the same trouble in attempting to correlate the terraces with levels, and we finally decided to take them not by levels but by intervals, plotting the intervals between terraces against intervals between cave levels. I believe if you did that here you could get a good correlation between terraces and levels.

AUTHOR: The correlation by intervals looks good, but I am somewhat dubious about the lower two levels of the cave because there is a series of cross passages at these levels with considerably different floor and ceiling elevations. In some places there are two of these passages directly one above the other on the same joint so that I don't know whether these can be lumped together as a level or not.

DAVIES: We found that unless they are separated by 40 feet or more they cannot be used with safety because the gradients vary so quickly in a short distance.

JOHN A. STELLMACK, *Pennsylvania State Univ.:* In the area of the cave where the saltpeter was mined there are large banks of fine silt. Can you tie these down to the history of the cave? Were these deposited while it was still filled with water?

AUTHOR: I haven't satisfied myself that I understand how some of that fill material was deposited. The fills consist of lenses of silt and sand, with a great deal of coarse conglomerate in many places. The deposits look like free-surface stream-channel deposits. The cave must have had openings on the updip side at various times throughout its history. Streams from the mountain entered these and carried in the fill. None of the fill exposures are deltas deposited into standing water. Therefore many of the deposits may be ordinary stream sediments, or at least they have been reworked by free-surface streams. There is some laminated silt which may have been deposited in standing water, but there is much work yet to be done in this field.

Terminations of Passages in Appalachian Caves as Evidence for a Shallow Phreatic Origin

by WILLIAM B. WHITE

ABSTRACT—Considerable controversy exists between advocates of the deep phreatic theory of cave origin of Davis and Bretz and advocates of the shallow phreatic theory of Davies and Sweeting. The deep phreatic theory predicts cavern enlargement along any open conduit in a lithologically suitable bed without regard to depth below the water table. The shallow phreatic theory predicts solution only in a limited zone just below the water table. The latter theory was supported by evidence found in the examination of about 25 caves in the Appalachian Mountains.

Caves with maze patterns have apparently formed by slow phreatic flow along a soluble bed. In flat-lying limestone, caves with this pattern may have considerable area, but in strata of medium dip, passages on the updip and downdip sides terminate abruptly. Hence solution is limited to a narrow zone, even though the soluble bed continues in both directions. Several caves in nearly vertical limestone have been examined. In none of these had solution extended any distance along the bedding in a vertical direction, even though a favorable bed and good partings existed in that direction. Instead the caves are limited to a nearly horizontal zone. Cross sections of caves in steeply dipping limestone show that the passages tend to be elongated along layers of good solubility. In the updip direction the cross section narrows and pinches out. In the few caves where the cross section can be traced downdip, the same thing is observed.

These data show that caves tend to maintain their horizontal pattern in spite of structure and lithology. The position of the water table is apparently the dominant controlling factor; structure and lithology seem merely to modify the ground plan and passage cross section.

INTRODUCTION

Evidence submitted in a number of papers by different authors published over the last 30 years strongly suggests that the majority of limestone caves are formed in the phreatic zone. The agreement among the authors is not so good, however, on the exact path taken by the water responsible for the enlargement of the cavern chambers. The argument has been essentially resolved into one between a deep phreatic theory and a shallow phreatic theory. The problem may be further reduced to a matter of determining under which of the two mechanisms solution operates with the greater intensity.

The deep phreatic theory proposes that major enlargement of a cave takes place at random depth through a great distance below the water table. When caves are observed to exist over a large area in flat-lying limestone with little vertical cave relief, it is suggested that there is bedding-plane control. The same horizontal pattern is difficult to explain by the deep phreatic theory in limestone with a steep dip.

Davis (1930, p. 611) recognized this problem and says: ". . . the caverns here treated [those of the Appalachian Mountains] are of particular importance because they do not support the main thesis of this essay as to the solutional excavation of caverns by ground water below the water table in the first epoch of their history; and therefore, instead of here finding confirmation of our two cycle theory, we find contradiction". Bretz (1942, p. 759) also recognized the problem and suggested that subwater-table streams may modify an older network or spongework to produce a horizontal passage in a tilted formation. It is important to note here that Bretz apparently considered deep solution to be the primary cause and the subwater-table stream to be simply a modifying factor.

Sweeting (1950) and Davies (1958) have preferred to regard a subwater-table stream with low gradient as the primary agent. It follows then that the greatest enlargement is in a zone just under the water table where this stream is moving. Deep phreatic solution is still needed to open joints to make room for the subwater-table stream, but the process has been assigned a relatively minor role. The question is thus resolved into deciding which of these two phreatic mechanisms is responsible for most of the enlargement of caves.

This paper will consider the caves of the Appalachian Mountains of Pennsylvania to see which theory fits the field evidence best. Pennsylvania is one of the few areas in which most of the caves are explored and mapped. Hence good data are available on many caves in a wide variety of rock types and structural settings. Data have been taken from Stone (1953), Haas (1958), and numerous unpublished maps and reports, as well as from the author's field work.

The author is very grateful to Bernard Smeltzer and Charles Landis, Jr., who made unpublished maps available for this study. John A. Stellmack was of great assistance in collecting field data.

GEOLOGIC SETTING

The caves discussed in this paper all lie in the Valley and Ridge Province of the Appalachian Highlands. The three main cave areas are the Great Valley, the Ordovician Valleys, and the Helderberg Belt. The Great Valley, or Cumberland Valley, is floored with limestone of Lower Ordovician and Cambrian age. Caves are developed principally in the Elbrook and Conococheague limestones. The valleys underlain by Ordovician rocks to the west include Nittany Valley, Penns Valley, Brush Valley, Kishocoquillas Valley, and Morrisons Cove. Caves lie in low hills and under the valley floors principally in the Trenton limestone. (The Trenton is used here in the old sense as including all limestone from the base of the Martinsburg shale to the top of the Beekmantown dolomite.) The Helderberg Belt is formed by the Tonoloway and Helderberg limestone groups which crop out in a sinuous band which may be traced for many miles along the flanks of ridges. Numerous caves are found in the ridges along this belt.

In this region, 262 caves have been reported. Of these, 30 have been closed or quarried away and 155 are too small (less than 100 feet) to show a well-developed pattern. The remaining 77 caves have been considered in this report.

PATTERNS OF PENNSYLVANIA CAVES

Davies (1953) has discussed the geology of Pennsylvania caves and some of their features. Caves in folded rocks are reported to be nearly linear, and to lie in a horizontal plane extending along the strike. It is instructive to tabulate the patterns as a function of dip, and the results of such a tabulation are given in table 1. The following caves are not included because of lack of data.

Aitkin Cave
Boalsburg Cave
Bruckerhoff Cave
Hennigh Cave
Redington Cave
Rockview Cave

To tabulate the cave pattern, the following classification was devised. It is intended to be purely descriptive and is based only on this group of caves in Pennsylvania.

1. Linear:
   Cave consists of a single straight passage with no branches. The linear passage may be a strike passage but is not necessarily so. The type example is Nicewander Cave.
2. Rectangular:
   Cave consists of essentially one passage with no branches. The passage has bends, however, and may even turn back on itself. The type example is Reese Cave.
3. Branchwork:
   This pattern is one in which the passage forks and divides. It more or less follows the original definition of Davis in the sense that a branchwork pattern does not have re-entrant loops, but it is not a dendritic. In the field a pure branchwork pattern is hard to find. Millheim Cave is taken as the type example.
4. Network:
   A cave in which there is multiple branching with the branches re-joining to form closed loops. The spacing of the loops is usually in the same order as the spacing of regional joints. The network may range in complexity from a few closed loops to large grids of interesting passages. It is not a common pattern in the Valley and Ridge Province although extensive caves are common in the Plateau Province to the west. Duffield Cave is a reasonably good example.
5. Irregular:
   The pattern of a cave in which passages or tubes are not well defined. This is the pattern of many of the smaller caves omitted from this report.

Like many classifications, this one does not work perfectly in close detail. Numerous caves are found in which the pattern is fairly well defined except for a slight superposition of another pattern. A cave may be linear but has several parallel connected passages giving a very elongate network. Or a cave is mainly a branchwork with a few minor closure loops. In table 1 the overall pattern is classified and secondary patterns appended. The assumption is also made that each cave is completely explored and that the map is complete. The discovery of new connecting channels could well turn a branchwork into a network, but the classification is believed precise enough for the discussion to follow.

The published literature was searched and many measurements of strike and dip were made in the field to compile table 1. In some cases published values were found to be inaccurate so one should not place too much reliance on the table, especially since it is known that structure may change even from one part of a cave to another.

The horizontal nature of most of the caves of Pennsylvania is well shown by table 1. Of the 77 caves listed, only Dales, Sharer, and Rossman show any well-expressed three-dimensional development. None of these has more than 100 feet of vertical relief. Other caves sometimes have sloping passages but for the most part remain on one plane.

The control of pattern by strike is not particularly great. Only in caves where the limestone dips more than 35° does the linear and rectangular pattern become dominant. In flatter limestone, there is no preferred pattern. Thus theorists who look for these effects in more gently dipping limestone will probably not find them. At high dip, strike-oriented patterns are common but by no means the rule.

Of the 25 caves in limestone with a dip greater than 40°, ten have extensive passage development *across* the bedding. Noteworthy among these are Reese, Conodoguinet, Fleming, and Parker caves where a single passage cuts across nearly vertical beds with no apparent strike pattern (fig. 1). Maps of the other three are given by Stone (1953). In each case there are as many passages cutting across beds as there are along the strike and yet the cave is horizontal. It is difficult to see what factor could control the location of the horizontal plane unless it is the position of the water table. The actual shape of the pattern can be explained by the hypothesis of Deike (1959) in which she gives evidence that the pattern is controlled by the quality of joints present in the rock.

TERMINATIONS OF NETWORK CAVES

Bretz (1942, p. 759) cites network caves in inclined beds as evidence of deep phreatic solution. The argument is that a network presumably can be formed only by slowly percolating ground water. Since the network exists along a sloping bed, the cave should extend deep beneath the clay fill and also updip to the surface. The updip side is presumably blocked by breakdown or travertine.

Inclined network caves are not particularly common. Table 1 shows 17 network caves of which 5 are in nearly flat lime-

TABLE 1. PATTERNS OF PENNSYLVANIA CAVES

Cave Name	*Limestone*	*Pattern*	*Dip*	*Reference*
Alexander	Trenton	Rectangular	low	6
Allensville	Trenton	Rectangular, b	low	5
Aughenbaugh	Chambersburg	Network	low	4
Carnegie	Elbrook	Branchwork	low	5
Dales	Helderberg	Vertical	low	1
Duffield	Chambersburg	Network	low	5
Eiswert I	Trenton	Rectangular	low	—
Eiswert II	Trenton	Rectangular	low	3
Elk Creek	Trenton	Rectangular	low	3
Hall	Helderberg	Rectangular, l	low	5
Indian Echo	———	Branchwork	low	2
Lincoln	Helderberg	Network	low	2
McClure	Helderberg	Branchwork	low	1
Onyx	———	Network, l	low	2
Peiper	Conococheague	Network	low	4
Sharer	Trenton	Vertical	low	1
South Temple	Conococheague	Branchwork, n	low	1
Welsh Run	Stones River	Irregular	low	5
Arnt	Helderberg	Rectangular	10SE	5
Rupert	Helderberg	Network	10	1
Goss	Trenton	Network	12SE	3
McConnells-town Quarry	Helderberg	Rectangular	15SE	3
Woodward	Trenton	Network	15S	2
Lime Sinks	Trenton	Network	16N	3
Chisel	Trenton	Branchwork, l	17SE	3
Huber Coy	Conococheague	Branchwork, n	20NW	4
Pillbox	Trenton	Network	21S	3
Tytoona	Trenton	Rectangular, s	21SE	6
Milroy	Trenton	Network	22N	3
Miller	Trenton	Branchwork, s	23SE	3
Hesston	Helderberg	Network	24SE	1
Dragon	Martinsburg	Branchwork,	25S	5
Schofer	Martinsburg	Branchwork	25S	1
Deerbone	Trenton	Branchwork	27NW	3
Carpenter	Tomstown	Branchwork, n	28E	1
Hipple	Trenton	Rectangular, l	28SE	1
Weller	Helderberg	Linear, s	29SE	3
Arnold	Helderberg	Branchwork, l	30	5
Penns	Trenton	Linear, r, s	30	6
Millheim	Trenton	Branchwork	32N	1
Hobo	Conococheague	Linear, s	37SW	1
Rossman	Trenton	Vertical, r, b	37S	1
Lost	Conococheague	Linear, b	38NW	2
Curfman	Helderberg	Irregular	40W	7
Hershey	Elbrook	Branchwork, n	40	4
Historic Indian	Trenton	Rectangular, n	40SE	2
Little Aitkin	Trenton	Network	40NW	5
Horsebone	Trenton	Linear, s	42SE	—
Stover	Trenton	Linear, s	44NW	6
Blue Springs	Helderberg	Linear, s	45NW	7
Boyer I	Helderberg	Linear, b, s	45S	—
Long Quarry	Keyser	Linear, b, s	45NW	5
Winfield	Helderberg	Linear, s	45S	6
Brubaker	Trenton	Rectangular	51SE	1
Dreibilbis	Martinsburg	Branchwork	55NW	1
Seawra	Helderberg	Linear, n, s	55	1
Crystal	———	Linear, s	56NE	2
Kooken	Trenton	Linear, r, s	50-V	3
Needy	Tomstown	Linear, s	60-V	5
Cleversburg Sink	Elbrook	Branchwork	70N	4
Goods	———	Linear, n, s	0-70	1
Gromiller	Helderberg	Network	70NW	7
Nails I	Trenton	Network, s	70N	1
Nicewander	Chambersburg	Linear, s	70NW	1
Reese	———	Rectangular	70W	1
Veiled Lady	Trenton	Linear, b	70SE	1
Siglerville	Trenton	Linear network, s	76S	3
Baker I	Stones River	Rectangular, n	V	2
Buffalo Run	Trenton	Linear, s	V	—
Conodoguinet	Beekmantown	Rectangular	V	2
Fleming	Helderberg	Rectangular	90	5
Parker	Chambersburg	Rectangular	V	1

stone, 7 cut across the bedding and remain horizontal, and only 4 appear to lie along the bedding. Of these, Goss Cave is nearly plugged with fill so that very little can be determined about it, and most of Lime Sinks Cave is below water. This leaves Rupert and Hesston Caves as examples of bedding-plane network caves of medium dip.

Rupert Cave is a network with well-developed dip passages. These range up to 15 feet high in the main part of the cave. The strike-joint passages are generally much smaller. In the downdip direction the passageways become smaller, narrower, and eventually pinch down until they are too small to traverse. In some cases they become buried by fill, but the rock walls are also constricted. In the updip direction one observes a similar thing: the central passage ends in fill, but on both sides the dip passages become constricted until they are too narrow to traverse.

Hesston Cave is a good example of a network cave in dipping limestone. A map is given by Stone (1953). The cave lies along the bedding which dips about 24°. In the central portion of the cave, passages are open and range up to 6 feet high. The cave is unusual in that for the most part it has a bedrock floor. Hence one can obtain a true notion of the passage terminations. In the updip direction the passages become more and more narrow and eventually pinch down until they cannot be traversed. In the downdip direction the dip passages also pinch down although, with perseverance, one can reach a small stream which flows in an exceedingly tight sinuous slot along the strike. All downdip passages terminate at this slot.

Therefore, both these examples of network caves developed along the dip have terminating dip passages. Hesston Cave is somewhat elongated along the strike while Rupert is elongated along the dip. In both cases there is a record of a central zone of maximum solution with no evidence of extensive flow along the dip. If one measures the width of the area of traversible passages along the dip and multiplies it by the sine of the dip, Hesston Cave has a vertical relief of 60 feet and Rupert, 45 feet. This is not what this author would call "deep" phreatic solution.

Two network caves of interest are Goods and Siglerville. These were classified as "linear networks", and in both caves, the dip is near 70°. The network extends along the strike for a distance about 10 times its width. The cave is horizontal and linear in spite of its network pattern which indicates a very slow former phreatic flow. The only explanation reasonable for these two caves is flow in a horizontal plane as a subwater-table stream.

PASSAGE CROSS SECTIONS IN CAVES OF MEDIUM DIP

Table 1 lists 19 caves in limestone with a dip between 35 and 60 degrees. Since a fair proportion of the passages are along the strike, examination of the walls of strike passages should give some information about the nature of the former flow. In some caves the shape of the cross section is controlled by the relation of joints to bedding planes. The three possibilities are shown in figure 2. If a joint is perpendicular to the bedding, breakdown blocks are easily dislodged and the cave develops the "gabled-roof" cross section shown by Stover Cave. Another good example of this cross section is in the strike passages of Historic Indian Cave. A vertical joint gives rise to the cross section of Blue Springs Cave. The general shape is triangular with the acute angle extending down dip. If the joint is along the bedding (or the cave is developed along a bedding-plane parting) a cross section similar to Seawra Cave is developed.

Cross sections of strike passages can be very complex. Figure 3 presents selected sections of Needy Cave (dip 60°) and Arnold Cave (dip 30°) taken from maps made by Bernard Smeltzer. The sections are in sequence from the entrance toward the back of the caves. The bedding exerts little influence on the cross section, and there is little evidence for deep phreatic tubes extending in the updip direction.

In all cases examined, in caves of medium dip, the wall of the passage on the updip side terminates as a smooth wall, or at least as a wall of irregular profile. The downdip extent of these passages is difficult to examine because in most cases it is filled with silt. Seawra Cave is a rare exception. One can squeeze through small holes in the floor at several points on the old tourist route and drop some 15 to 20 feet along the bedding to a series of small chambers with bedrock floors. Here the passage also pinches out in the downdip direction.

Kooken Cave is a possible exception. The limestone ranges in dip through the cave from about 50° to vertical. The cave is very uniform in altitude and follows the strike of a plunging syncline. High narrow chimneys are common at several points in the cave, extending along bedding planes. Several of these have been explored for 150 feet and two of them are known to reach the surface. There are two arguments against their being portions of a deep phreatic system. They are volumetrically much smaller than the main gallery below by a factor of 10 to 20. They show flutings and groovings and have the appearance of being almost entirely vadose in origin.

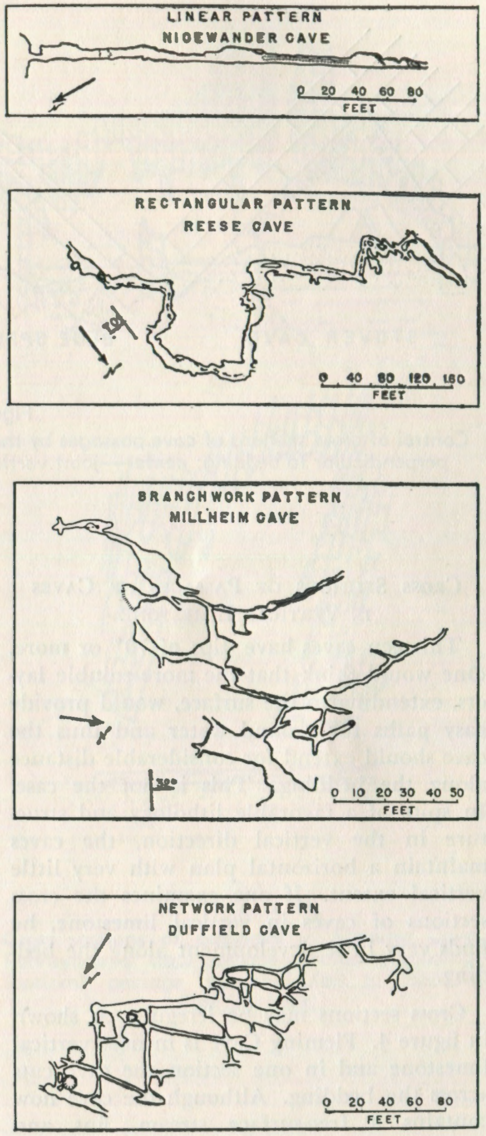

Figure 1
Type examples of cave patterns.

Notes on Table 1.

1. "Low" dip means from horizontal to 10°. "V" indicates that the dip of the limestone is merely reported in the references as being vertical. It may not be exactly 90°. Maps were available for all except Eiswert I, Horsebone, and Boyer I caves.
2. The caves are listed according to the above classification mostly as one of five types. Characteristics of another pattern type are indicated by appending a lower case letter to the name of the main pattern, thus:
   l=linear, r=rectangular, b=branchwork, n=network
   A cave which is essentially a branchwork but which has a few minor loops would be listed as "branchwork, n." The letter "s" appended to the pattern indicates that the main trend of the cave is along the strike. A few caves with vertical development are listed as "vertical."
3. References:
   1. Stone (1953), 2. Stone (1932), 3. Haas (1958), 4. Smeltzer (1958), 5. Unpublished maps by Bernard Smeltzer, 6. Unpublished maps of the Nittany Chapter, 7. Author's unpublished files.

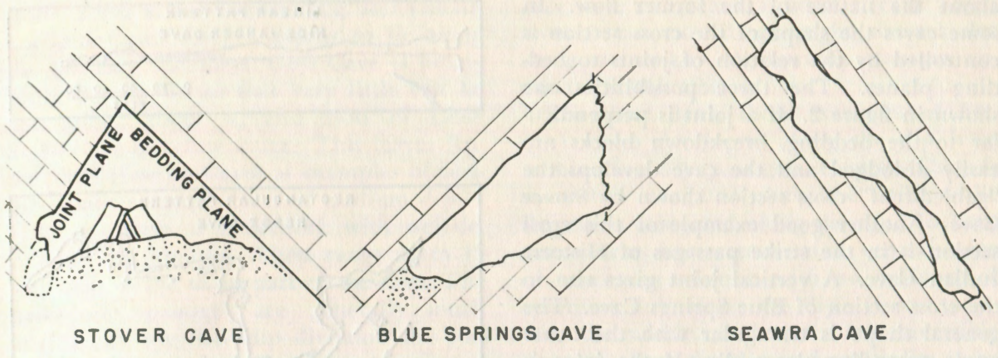

Figure 2

Control of cross sections of cave passages by the relation of joints to bedding: **Left**—joint nearly perpendicular to bedding; **center**—joint vertical; **right**—joint or parting parallel to bedding.

Cross Sections of Passages of Caves in Vertical Limestone

Thirteen caves have dips of 70° or more. One would think that the more soluble layers, extending to the surface, would provide easy paths for ground water and thus the cave should extend for considerable distance along the bedding. This is not the case. In spite of a favorable lithology and structure in the vertical direction, the caves maintain a horizontal plan with very little vertical extent. If one examines the cross sections of caves in vertical limestone, he finds very little development along the bedding.

Cross sections may be irregular as shown in figure 4. Fleming Cave is in near vertical limestone and in one section the cave cuts across the bedding. Although the cave now contains a free-surface stream, fins and pockets on the walls and ceiling suggest a phreatic origin. Note that there is no vertical development along the bedding.

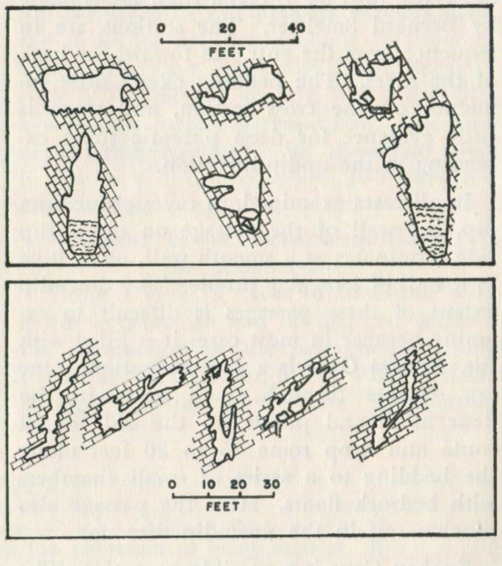

Figure 3

Cross sections of Needy Cave (upper figure) and Arnold Cave (lower figure) showing effect of bedding on passage cross sections (after Smeltzer).

Siglerville Cave and Cleversburg Sink are interesting in that they have cross sections in the strike-oriented passages that are high narrow fissures. This is especially interesting since Siglerville is a network cave and Cleversburg a branchwork. This might be evidence for deep phreatic flow, but if one examines the tops of these passages, they too terminate, and the cave has a vertical zone of major solution of only 30 to 40 feet.

Nails I Cave exhibits a smooth arched cross section in beds dipping 70°. The walls are scalloped in places and show evidence of rapid flow. There is no extension along the bedding in most places and indeed it is difficult to determine where the bedding planes are. The smoothly arched tubes extend, for the most part, along the strike, but several short tubes cut directly across the bedding.

Terminations of Passages

Although the caves discussed in this paper are relatively small, in many cases only a few hundred feet long, it is difficult to say that any of them "end". The termination of passages, especially strike passages usually takes one of the following forms: silt choke, breakdown, travertine choke, intersection with surface, syphon, and too small to traverse. The latter is often caused by the fill being too near the ceiling. Fairly complex drainage systems are known in the Ordovician limestone valleys where the distance from swallow holes to possible resurgances is many miles. Therefore most of the caves examined have the appearance of subterranean conduits carrying water along nearly horizontal planes. The caves which end in syphons still may be forming in the shallow phreatic zone beyond the syphon.

Conclusions

In this paper the following facts have been presented:

1. Most caves are horizontal, but only in limestone which dips greater than 35° do they become dominantly linear.
2. Networks along the dip tend to terminate in the up- and downdip directions limiting the area of enlargement to a thin zone.
3. Examination of the walls of passages in steeply dipping limestone shows no tendency for great extension along the dip.
4. In near vertical limestone, the passages maintain the same rounded cross section possessed by passages in caves in flatter limestone.
5. Caves seldom really "end" in the sense of being blocked by bedrock.

It is now possible to use these data in an attempt to resolve the argument between the deep phreatic and the shallow phreatic theories of origin, at least for the caves of the Valley and Ridge Province of Pennsylvania. The caves have the appearance of being part of a subterranean drainage net in which subwater-table streams moved under a finite flow velocity. There is almost no evidence for an earlier spongework or network extending along the bedding toward the surface or deep into the rock as predicted by the deep phreatic theory. Thus one would conclude that the shallow phrea-

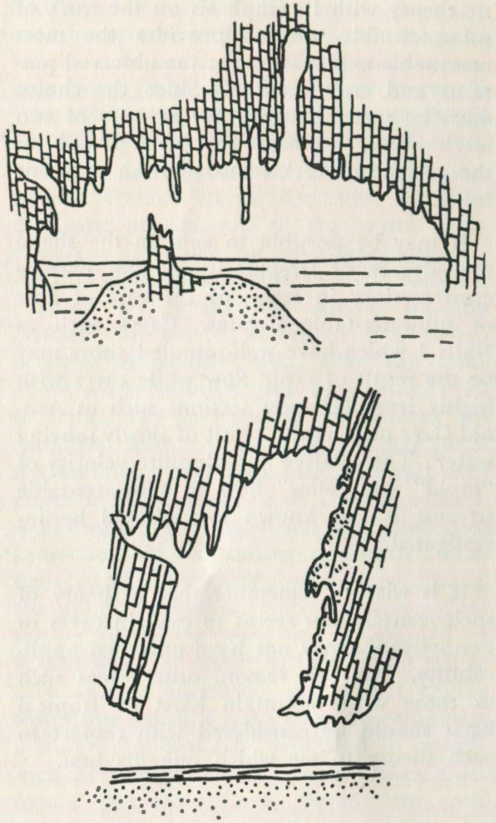

Figure 4

Cross sections of passages in Fleming Cave, Pennsylvania: (top) passage parallel to bedding; (bottom) passage perpendicular to bedding (after Smeltzer).

tic theory with its emphasis on the work of subwater-table streams provides the most reasonable explanation for the observed patterns and cross sections. Since the choice must be made between the velocity of two mechanisms, emphasis has been placed on the volume of rock removed from different zones.

It may be possible to explain the shape and degree of irregularity of the passage cross sections in terms of the rate of flow of subwater-table streams. Caves such as Nails I which have well-rounded tubes may be the result of rapid flow while caves with highly irregular cross sections such as Arnold Cave may be the result of slowly moving water. The relative and absolute velocity of "rapid" and "slow" flow in subwater-table streams is not known and should be investigated.

It is wise to remember that a theory of speleogenesis that seems to explain caves in Pennsylvania may not have universal applicability. For this reason, other areas such as those with mountain karst or tropical karst should be considered with respect to each theory to see which one fits best.

REFERENCES CITED

Bretz, J H., 1942, Vadose and phreatic features of limestone caverns: Jour. Geology, v. 50, p. 675-811.

Davies, W. E., 1953, Geology of Pennsylvania caves: Natl. Speleol. Soc. Bull., v. 15, p. 3-9.

—— 1958, Caverns of West Virginia: West Virginia Geol. Survey, v. 19A, 330 p.

Davis, W. M., 1930, Origin of limestone caverns: Geol. Soc. America Bull., v. 41, p. 475-628.

Deike, R. G., 1959, Orientation of cave development (abs.): Natl. Speleol. Soc. News, v. 17, p. 92.

Haas, J. L., Jr., *ed.*, 1958, New caves and extensions in central Pennsylvania since Bulletin 15: Nittany Chapter, Natl. Speleol. Soc. Newsletter, v. 6, p. 77-136 (*repr.* Speleo Digest, 1958, p. 1-1—1-41).

Smeltzer, B. L., 1958, Additional data on Shippensburg caves: Mid-Appalachian Region, Natl. Speleol. Soc., Bull., v. 4, p. 3-15 (*repr.* Speleo Digest, 1958, p. 1-42—1-69).

Stone, R. W., 1932, Pennsylvania caves: Pennsylvania Geol. Survey Bull., ser. 4, no. G-3, ed. 2, 143 p.

—— 1953, Descriptions of Pennsylvania's undeveloped caves. Natl. Speleol. Soc. Bull., v. 15, p. 51-137.

Sweeting, M. M., 1950, Erosion cycles and limestone caverns in the Ingleborough District: Geog. Jour., v. 115, p. 63-78.

DEPARTMENT OF GEOPHYSICS
AND GEOCHEMISTRY,
PENNSYLVANIA STATE UNIVERSITY,
UNIVERSITY PARK, PENNSYLVANIA

DISCUSSION

AUTHOR: One of the problems of key importance in evaluating shallow and deep solution is to determine the thickness of the zone of maximum solution just below the water table. It could be as much as 50 or 60 feet.

WILLIAM E. DAVIES, *U. S. Geological Survey*: It could be the whole interval between river terraces which in some cases is as much as 100 feet.

ROGER W. BRUCKER, *Cave Research Foundation*: It seems to me that you can account for 50 or 60 feet in Kentucky by simply considering the seasonal variations of the position of the water level resulting from changes in rainfall.

DAVIES: But it must have been very stable during cave development there and not varied seasonally. When there is much up and down movement of the water level, we get the present situation in Kentucky where there is very little cave development and simply filling of the caves with clastic material.

ALAN D. HOWARD, *Yale University*: With respect to the depth of the shallow phreatic zone, I think that it will probably be found that this will depend on the topography and the flow of water because, in a well-developed cave, solution can occur far below the surface of the water table. The topographic relation of the joints along which the cave is developing probably will determine the depth to which there will be solution.

AUTHOR: This is not a matter of determining depth below the surface because the thickness of the layer of water where most limestone is being removed might be 300 feel below the surface, but this zone may be only 50 feet thick.

HOWARD: Drill holes in the Galena dolomite in Illinois and Wisconsin find the contact between oxidized and unoxidized rock to be almost exactly at the water table, but along cavities some distance below the water table there is oxidized rock which indicates that the cavities cause a deeper flow of solution, and therefore the depth at which the oxidation occurs will be dependent on factors controlling flow.

GEORGE W. MOORE, *U. S. Geological Survey*: You suggest then that oxidation of the limestone creates an acidic environment directly below the top of the water table? This is a very interesting idea. It has been strongly suggested today that much cave development occurs at the top of the water table, so there must be something special about that zone. The change in the limestone from reducing to oxidizing conditions may be part of the answer, and I would like to suggest another possibility, although they both may operate together. The other possibility is that biological activity occurs in this zone where there is an interface between aeration and saturation. The limestone generally contains several percent of organic material which could serve as food for microorganisms living in the zone just below the water table. Carbonic and organic acids produced by the microorganisms could work with the acids formed by the oxidation of, say, sulfide minerals in the limestone to make the zone at the top of the water table especially favorable for cave development.

ARTHUR L. LANGE, *Cave Research Associates*: I don't see where any special solution gradients are needed to explain flat ceilings of caves in inclined beds. They can come about where solution goes on in water even to depth. The only special requirement is a spill-over level. A cave lake whose level is maintained for a long time by a spill-over either to the outside, or to a lower passage, will dissolve the walls and all submerged projections of the ceiling uniformly. Thus these parts of the ceiling will retreat toward the upper limit of the water surface and no farther. Were the level not maintained by a spill-over, the water surface would fall as cave volume increased and a flat ceiling would not result. I have seen flat ceilings in a number of western caves, and in several, such as Samwel and Lilburns Caves, California, and Deep Cave, Nevada, the spill-overs can be shown.

Origin and Development of Fulford Cave, Colorado*

by JOHN V. THRAILKILL

ABSTRACT——Fulford Cave, a solution cave in the Leadville limestone, consists of a series of parallel passages which extend along the strike of the beds and which are connected at their northeastern ends by a passage parallel to the dip. This passage is occupied by a stream throughout most of its length. The known passages of the cave have an aggregate length of half a mile and the cave has a vertical extent of over 200 feet.

Although development of cavities occurred in the Leadville limestone during late Paleozoic time, these cavities have since been filled with detritus, and the present cave has been excavated more recently. Erosional and depositional features within the cave indicate that its present form is due to erosion and deposition in these three successive environments, of which the principal characteristics are: (1) conditions of slowly moving ground water far below the water table; (2) conditions of more rapidly moving ground water just below the water table; and (3) air filled conditions in which only vadose water is present. It is believed that the principal cave excavation occurred during the second of these environments, probably as the water table was intermittently lowered during Wisconsin time.

INTRODUCTION

Fulford Cave is in Eagle County, Colorado, about 20 miles by road southeast of the town of Eagle. Inhabitants of the area have long known of the existence of the cave, and according to Gabelman (1949, p. 68), it was discovered by miners in the early days of the nearby mining camp of Fulford. For some time following its discovery it was visited regularly. During this period ladders were installed in several places, the Pit Entrance was excavated and timbered, and a guide service was maintained. In recent years a Forest Service trail has been constructed from a campground in the bottom of the valley to the entrances, and the cave is frequently visited during the summer months by tourists and local residents.

The cave was mapped to determine the dimensions and relative positions of the various passages and to locate accurately the more important erosional and depositional features. Traverses were made using compass and tape.

The writer acknowledges with thanks the assistance given in this study of Fulford Cave by members of the Geology Department of the University of Colorado and by members of the Colorado Chapter of the National Speleological Society. Especial gratitude is extended to Lavine Thrailkill for her invaluable assistance in all phases of the study.

GEOLOGIC SETTING

Like all limestone caves, Fulford Cave owes its existence to a favorable combination of stratigraphic, structural, and geomorphic conditions. A brief discussion of the geologic setting of the cave is, therefore, not only desirable but mandatory.

Stratigraphy.——The entrances to Fulford Cave are located in the Leadville limestone of Mississippian age. The upper Paleozoic stratigraphic section at or near the cave has been described by Johnson (1944), Gabelman (1949), and Scott (1954). There is lack of agreement among these workers, however, as to the character and thickness of the Leadville limestone in the vicinity of the cave. This writer believes Scott's figure of 130 feet for the thickness to be the correct one. If so, the cave lies entirely in the Leadville and does not penetrate the underlying Dyer dolomite (Devonian), inasmuch as the cave occupies a stratigraphic interval of no more than 90 feet.

Structure.——The areal geology of the Fulford Cave area has been mapped in reconnaissance by Gabelman (1949), and his map with minor modifications by the present writer is shown in figure 1.

The rocks in the vicinity of the cave dip to the west at a high angle. The lower Paleozoic section has been repeated by a high-angle reverse fault whose strike near the cave is sub-parallel to the strike of the beds. Gabelman believes that this fault is the southern extension of the East Lake Creek thrust fault. The lower Paleozoic rocks west of the fault are largely concealed by Pleistocene morainal material. Fulford Cave lies in the footwall of the fault only a few hundred feet east of its trace.

Slight irregularities in the strike of the steeply dipping rocks in the area led Gabelman to define two anticlines separated by a very shallow syncline. The axes of these structures plunge to the west at an angle of about 40 degrees. Fulford Cave lies just south of the axis of the syncline. The structures of the area are all of Laramide (Cretaceous-Eocene) age.

Geomorphology.——The entrances to Fulford Cave lie at an altitude of approximately 10,000 feet on the north slope of the valley of East Brush Creek, and are about 600 feet above the creek. The valley has been occupied by at least one glacier which had its terminus at a point five miles downstream from the cave.

This glacier deposited morainal material both at its terminus and in the vicinity of the cave. Three small recessional moraines were deposited in the intervening five miles.

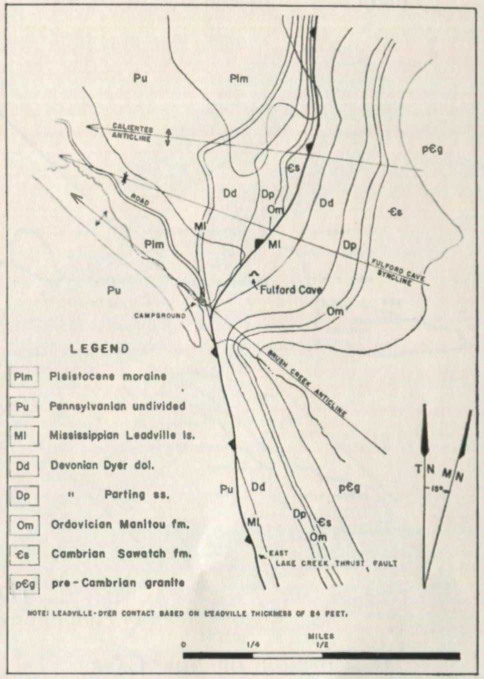

Figure 1
Geologic map of the area around Fulford Cave, Colorado (after Gabelman, 1949).

A higher level morainal deposit west of the cave was described by Gabelman (1949, pp. 24 and 26). High level glacial deposits have also been described a few miles to the south in the drainage of the Frying Pan River (Nelson, 1954). Nelson believes a horizonal surface about 300 feet above the present stream level is the pre-valley glacier floor of the valley. It is inferred, therefore, that the valley of East Brush Creek in the vicinity of the cave was deepened about 300 feet during the interval which followed the early glaciation and preceded the later glaciation.

Nelson tentatively correlates his high level deposits with Illinois drift of the midwest. The glacial deposits in the valley below the cave are considered to be of Wisconsin age by both Gabelman (1949, p. 26) and Hubert (1954, p. 72). Nelson recognized four sets of moraines and outwash plains of Wisconsin age. He concluded that the four Wisconsin glacial deposits in the Frying Pan Valley probably were deposited during the four substages of the Wisconsin (Iowan, Tazewell, Cary and Mankato). The Brush Creek drainage basin adjoins the Frying Pan River drainage basin on the north, and a close similarity in the glacial history of the two areas is probable.

---

* This paper was presented by title only at the symposium.

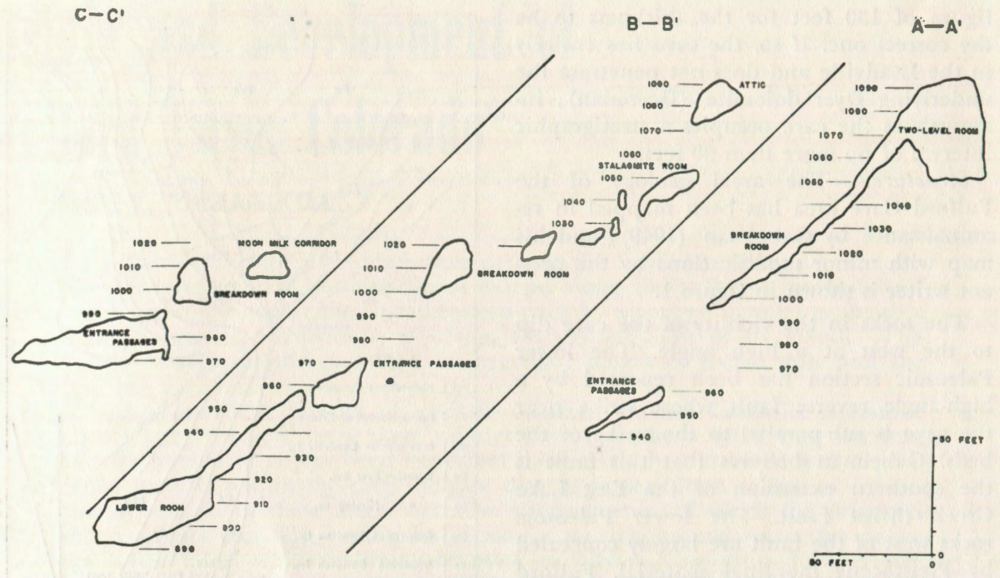

Figure 3
Cross sections of Fulford Cave approximately parallel to dip.

DESCRIPTION OF THE CAVE

Fulford Cave consists of a system of interconnected passages and rooms which have an aggregate known horizontal extent of about half a mile. The passages range greatly in size. The Breakdown Room has a total length of 300 feet and part of the Register Room is over 60 feet high, whereas there are innumerable cavities and extensions of rooms too small to permit entry. The relations between the rooms and passages are shown on figure 2.

In order to avoid negative elevations, a figure of 1,000 feet was arbitrarily assigned to ground level outside the Pit Entrance.

Disregarding breakdown, speleothem accumulations, and residual and stream detritus, the elevations of the various parts of the cave relative to the entrance are as follows: (1) the floor of the Lower Room is about 100 feet lower; (2) the floor of the southern end of the Entrance Passage is about 50 feet lower; (3) the floor of the northern end of the Entrance Passage ranges from 50 to 70 feet lower because the floor slopes steeply to the northwest; (4) the floor of the Breakdown Room is about 5 feet lower; and (5) the Stalagmite Room and the lower level of the Two-level Room have floors which lie approximately 50 feet above the datum. These relationships can be seen in figures 3 and 4.

The Cave Stream.—One of the more interesting features of the cave is a small stream which flows through the cave for a distance of about 270 feet. It enters in a small pool at the south end of the Upper Stream Passage and disappears down a small hole at the north end of the Lower Stream Passage. Its average gradient is quite steep, with a vertical drop of 80 feet between its emergence into the cave and its disappearance from it.

Little is known about the stream above and below where it is seen in the cave. At the extreme upper end of the Upper Register Room a series of small crawlways leads down to a short segment of the stream, indicating that above its emergence into the Stream Passage it follows a course approximately parallel to the Register Room. Using fluorescein dye as a tracer, the stream was found to emerge at a surface spring at the campground. The spring is 500 feet below and 2,000 feet distant from the place the stream leaves the known parts of the cave. The dye appeared at the spring about 15 hours after being placed in the cave stream.

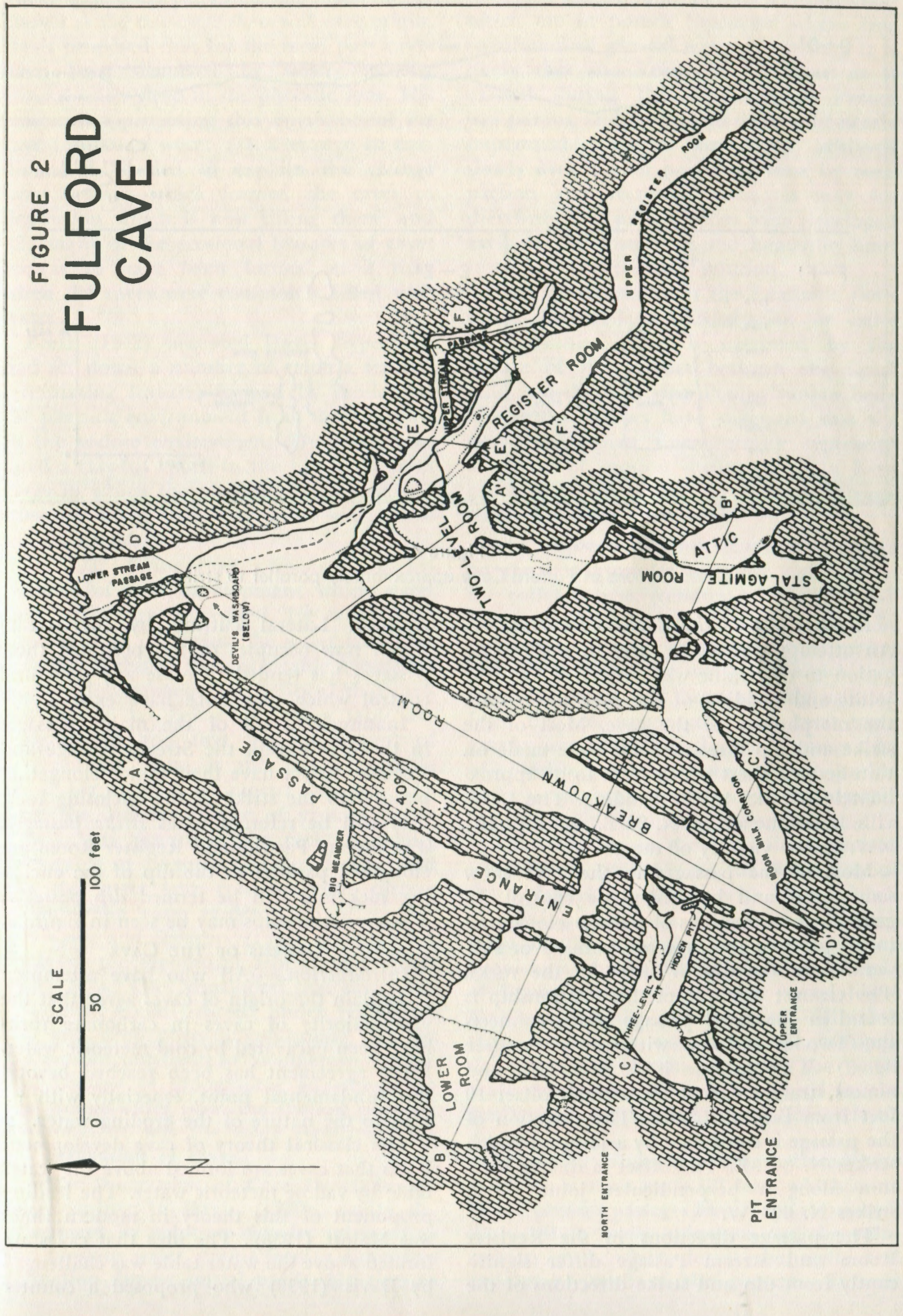
FIGURE 2
FULFORD CAVE

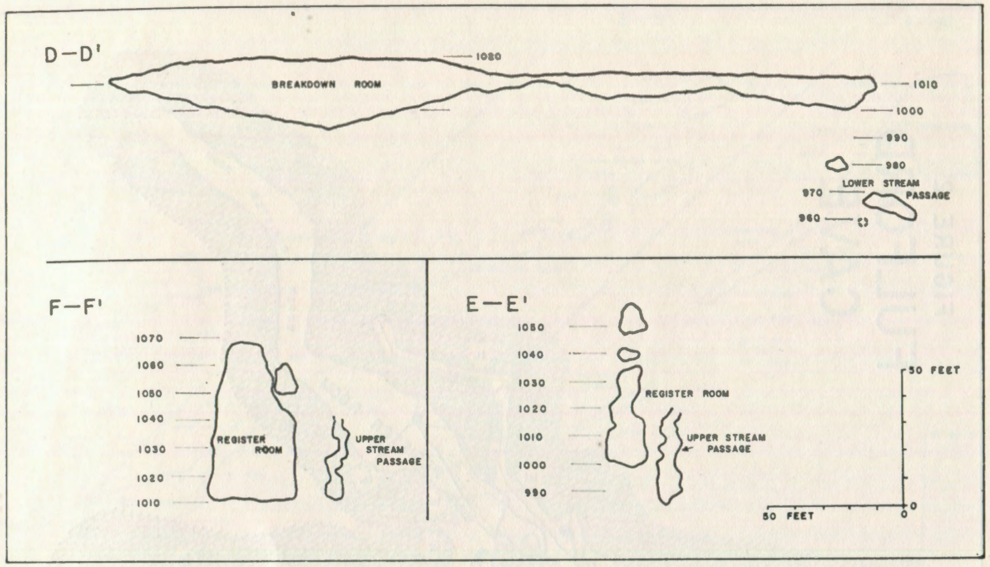

Figure 4

Cross sections of Fulford Cave approximately parallel to strike.

Relationship of the Cave to Structure.—An attempt was made early in the investigation to determine what effect, if any, the joints and bedding of the rock have upon the morphology of the cave. Most of the strike and dip measurements were made on thin beds of chert which seem to be approximately parallel to the bedding. The Leadville limestone strikes N. 2° E. and dips 40° NW. in the vicinity of the cave.

Most of the passages in the cave show some joint and bedding-plane control. In general, the directions of passage elongation in all parts of the cave are parallel or subparallel to the dip or strike of the rocks. The clearest example of this relationship is found in the small passage which connects the Two-level Room with the Attic (see fig. 2). This passage is 30 feet long and almost straight except for a small offset 10 feet from the north end. The direction of the passage is controlled by a joint set which strikes N. 30° E. The offset is due to solution along a perpendicular joint which strikes N. 60° W.

The passage directions in the Register Room and Stream Passage differ significantly from dip and strike directions of the bedrock. Lateral cutting by the stream which now occupies or has occupied these passages has tended to erase any structural control which may once have existed.

Inasmuch as all of the major passages in the cave except the Stream Passage and Register Room have their major elongation parallel to the strike of the enclosing rock, they will be referred to as *strike passages.* The Stream Passage and Register Room are elongated parallel to the dip of the enclosing rock and will be termed *dip passages.* These relationships may be seen in figure 2.

Genesis of the Cave

Introduction.—All who have attempted to explain the origin of caves agree that the vast majority of caves in carbonate rocks have been excavated by cold meteoric water. Little agreement has been reached beyond this fundamental point, especially with regard to the nature of the eroding water.

The classical theory of cave development holds that caves are formed above the water table by vadose meteoric water. The leading proponent of this theory in modern times was Malott (1938). The idea that caves are formed above the water table was challenged by Davis (1930) who proposed a counter working hypothesis which has come to be known as the *two-cycle theory* of cave origin. Davis proposed that for the most part caves have been dissolved by slowly moving ground water deep in the phreatic zone. His reasons for proposing this environment for cave formation were: (1) a change in conditions is needed to explain the change from erosion which formed the caves to deposition which is now filling them; and (2) many of the erosional features of caves appear to have been formed at a time when the caves were completely filled with water.

Bretz (1942) accepted Davis' hypothesis and set down a number of criteria for differentiating features formed by erosion in the phreatic environment from those formed in the vadose environment. He also postulated a clay-fill epoch in the history of most caves in which the phreatically formed cavities are filled with clay while still below the water table.

In 1932 Swinnerton presented an hypothesis of cave development which states that caves are excavated by water-table streams at or just below the water table. He referred to this as the *water-table hypothesis* of cave development. He believed that cavities formed far below the water table are insignificant and that the upper part of the phreatic zone is the most favorable place for cave development because: (1) here the largest volume of ground water flow occurs (assuming the rock is equally permeably in all zones and directions); and (2) the water here contains more carbon dioxide than water at depth.

Rhoads and Sinacori (1941) conducted a study of the theoretical aspects of ground-water flow. They concluded that cavity development could proceed under both shallow and deep phreatic conditions, but for the reasons put forth by Swinnerton (1932) and because of topographic adjustment to the ground-water flow, the shallow phreatic environment was the more significant for the excavation of caves.

Older Progression of Cave Development.—According to Davis (1930), cavity development by solution may be initiated as the connate water drains from a limestone formation during initial uplift. He cites as examples the caves of Florida and Yucatan, which are in porous limestone where free circulation of ground water is possible. It is likely that the Leadville limestone as it existed during the Mississippian Period was porous, and its present dense and nearly impermeable nature has been achieved slowly over a long period of time by compaction and recrystallization. It may be, therefore, that some cavities were developed early in the history of the Leadville limestone by deep phreatic solution.

Cave development in the Leadville limestone during late Mississippian or early Pennsylvanian time is suggested by the nature of the contact between the Leadville and the overlying Pennsylvanian beds. Numerous authors have suggested that the post-Mississippian unconformity represents a period of erosion during which a karst topography developed on the recently-uplifted Leadville limestone.

The depressions and channels common on the unconformity resemble sinkholes of the collapse type (cenotes). They are shallow, and associated cave passages seem to be uncommon. These characteristics, together with the fact that the surface on which they were developed had been recently uplifted from the sea, suggest that this karst topography was similar to the karst topography of Florida, which, according to Jordan (1950), has been developed by the upwelling of deeply circulating ground water.

The sinkholes in the Leadville limestone were filled, probably at the beginning of Pennsylvania deposition, with clastic debris of varying grain size and color. Although some of the sinkholes may actually have been caves which collapsed under the weight of Pennsylvania sediments, it seems likely that much of the present clastic fill other than breakdown was deposited in open depressions by stream action as the water table slowly rose. This is evidenced by the lamination and sorting of the finer clastic deposits.

In several places in Fulford Cave there is evidence of an early fill from which some of the present passages have been excavated. This fill is easily mistaken for the solid country rock which forms the walls and ceilings of most of the passages. It only

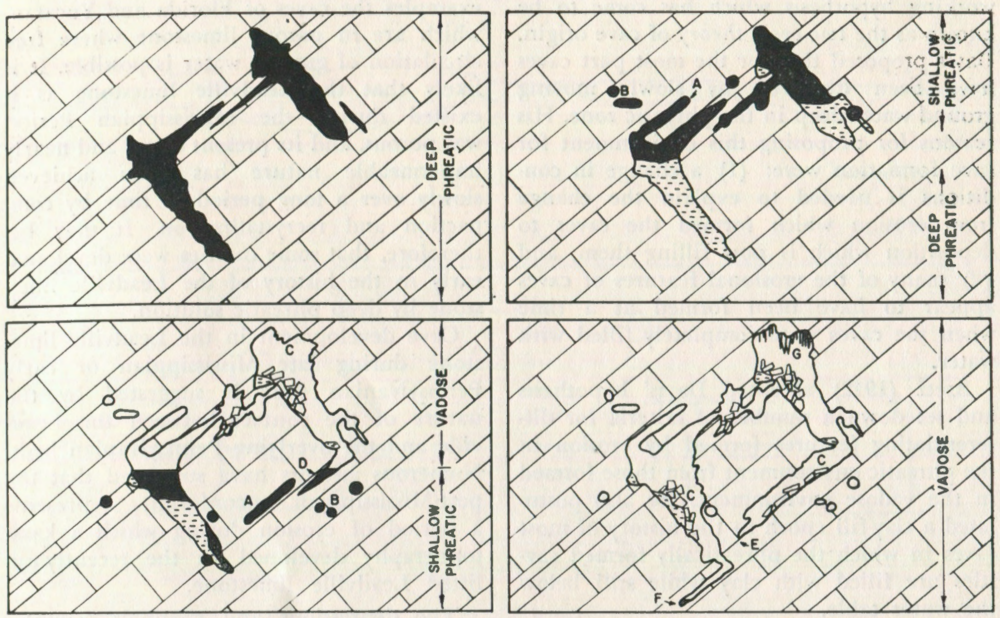

Figure 5
Evolution of the cross section of two strike passages of a hypothetical cave whose history was similar to that of Fulford Cave: **(a)** solution along joints and bedding in the deep phreatic zone; **(b)** solution and fill in the shallow phreatic and deep phreatic zones (tubular conduits at A and B); **(c)** breakdown (C) and solution in the vadose and shallow phreatic zones (tubular conduits at A and B and water-table stream cutting downdip at D); **(d)** shifting downward from E to lower passage and further cutting in vadose zone to F caused by sudden lowering of the water table (breakdown at C and speleothems at G; some remnants of phreatic fill are present).

slightly resembles the material which fills the sinkholes in the post-Leadville unconformity, since the cave fill is unstratified and consists of angular fragments of chert and limestone in a calcareous clay matrix. Although it could be a tectonic feature, it is suggested that this well indurated fill, which pre-dated the present cave passages, is the indurated remains of a clastic fill that was deposited in cavities excavated during the Mississippian period.

A progression of environments can be postulated for cavities during Mississippian time. First deep phreatic, then shallow phreatic, and finally vadose conditions would have existed as the water table fell. The cavities formed during Mississippian time can hardly be considered a part of the history of the present cave, although it is possible that one or more of the present cave passages were originally formed during the Mississippian period, then filled, and later re-excavated. It is certain, however, that most of the cave has been excavated during a second progression of environments of more recent age.

Erosion and Deposition in the Deep Phreatic Zone.—The rectangular network of passages from which Fulford Cave appears to have evolved into its present shape, and certain other erosional and depositional features of the cave, indicate that a considerable portion of the cave was excavated in the deep phreatic zone under conditions of slow water movement.

Bretz (1942) lists a number of criteria which he believes to be diagnostic of erosion in the deep phreatic zone. These include spongework, structurally controlled passages, horizontal passages in vertical beds, bedding plane anastomoses, pockets (wall, ceiling, and floor), joint determined cavities, and ceiling tubes and half tubes. This writer does not consider all of these to be valid. Spongework, structurally controlled passages, some of the pockets, and most of the joint determined cavities are features present in Fulford Cave which appear to be the result of solution in the deep phreatic zone. The rest of Bretz' criteria are interpreted as features formed in the shallow phreatic zone.

It is probable that solution at depth is controlled entirely by differences in permeability and solubility of the rock. Because the rate of water flow is low, it is doubtful that evidence of current action would be imparted to the excavated cavities. The most common effect of deep phreatic solution is simple widening of joints and bedding planes. A somewhat less common feature is removal of the more soluble portions of the rock, resulting in irregular spongework.

The close approximation of many of the cave passages to a rectangular network developed along joints and bedding planes is interpreted here as indicating solution in the deep phreatic zone. Much of this original network has been destroyed by later erosion or filled with clastic deposits, but some of the smaller passages remain. Some of these passages are tubular, indicating solution along the intersection of a bedding plane and a joint, while others are tabular, having been dissolved along a single plane.

Spongework is present on a small scale in many parts of the cave. It consists of limestone that is riddled with irregularly shaped tubes and cavities, and represents solution of the more soluble parts of the rock by slowly moving water.

Solution deep in the phreatic zone produces a type of cave ornamentation known as boxwork. Rudimentary boxwork was observed in several places in Fulford Cave, and appears to be best developed at the north end of the Breakdown Room.

There is evidence in the cave of a clay deposit that pre-dates the clastic material brought in by vadose streams. It appears to correspond to the clay fill described by Bretz (1942). According to him, it is emplaced after phreatic solution is complete but before the cave is entered by vadose streams. This fill in Fulford Cave was probably deposited while the cave was still below the water table, but it was not possible to date it closely.

Erosion and Deposition in the Shallow Phreatic Zone.—There is considerable evidence to indicate that Fulford Cave was excavated mainly in the shallow phreatic zone. It appears that some sort of water-table control is necessary to explain the orientation of the principal strike passages since their marked horizontality is not entirely due to differential solution along structural planes. In addition, there are a number of features present in the cave which have been cut by turbulent water under conditions of complete saturation. These include features which Bretz ascribes to deep phreatic erosion.

Water flow at and just below the water table is believed by Swinnerton (1932) and others to possess characteristics different from water flow deeper in the phreatic zone: (1) Shallow phreatic flow is often quite rapid, its velocity depending on the size of the openings and the slope of the water table. (2) The dissolving power of water in the shallow phreatic zone is relatively great compared to the dissolving power of water in the deep phreatic zone, because water near the water table is more highly charged with carbon dioxide. (3) The direction of principal flow is parallel or sub-parallel to the water table. Water-table slopes are usually only a few degrees or less, causing the direction of flow to appear nearly horizontal over short distances.

In general, water in the shallow phreatic zone may be considered overflow water—water that is flowing on or near the water table toward a discharge point. Also included is water some distance below the water table which is flowing more or less parallel to the water table.

The writer believes that some line of division separating the shallow phreatic and deep phreatic zones is desirable. The change from laminar flow to turbulant flow is proposed as such a division. Inasmuch as turbulent flow is usually recorded on the walls of cavities by flutes (scallops) and similar features, while laminar flow is not, it is believed that this change makes a useful, even though arbitrary, line of division. A change from laminar to turbulent flow is a function of the size of the conduits and the velocity of flow, rather than of actual distance below the water table. It should be emphasized, therefore, that so called shallow phreatic conditions (turbulent flow) may occur deeper in the phreatic zone in one place than do deep phreatic conditions (laminar flow) in another.

Among the most striking features of Fulford Cave are erosional phenomena which will here be termed *tubular conduits.* These are narrow tubes which are circular or elliptical in cross section. Where these tubes have been penetrated by later passage development the portion of the original tube that remains is a clearly defined trough on the side of the passage. The original shape of these tubes can be seen where they leave the passage to pursue their sinuous course through the solid rock. They appear to be almost identical to the tubes and half tubes described by Bretz (1942, p. 717-718). The tubular conduits of Fulford Cave differ from the forms described by Bretz in that the Fulford Cave tubular conduits display flutes almost everywhere on their walls.

Bretz (1942, p. 731) believes that flutes are formed by solution rather than abrasion, and states that their character and size are functions of the current rather than of the rock from which they are eroded. Flutes were studied as surface erosional features by Maxson (1940), and both he and Bretz agree that they represent differential erosion by turbulent vortices induced by skin friction. Although Maxson states that the vortices, and consequently the flutes, are lengthened downstream as water velocity increases, it would appear to this writer that the size of the vortices and flutes is inversely related to the velocity of the water. Almost all of the flutes observed in the tubular conduits are larger than those associated with and presumably being formed by the rapidly moving cave stream.

Inasmuch as flutes are produced by turbulent flow, they are formed in both the shallow phreatic and vadose zones. There is evidence which indicates that the water which flowed through most if not all of the tubular conduits was phreatic water. Although the general direction of most of the tubes is horizontal, a single tube may wander in any direction, even vertically, for short distances. The lower parts of the tubes have suffered no greater erosion than the upper parts, as would be the case if the tubular conduits had been formed by a vadose stream.

Many of the passages in the cave contain remnants of these tubular conduits, which range in diameter from five feet to less than a foot. At one place in the Entrance Passage as many as five may be seen at different levels. Most of the tubes in the cave follow a course that is not influenced by the present passages, indicating that the tubes are earlier than the present passages or that the passages were filled with detritus when the passages were cut. The latter is considered unlikely since any such filling would have been relatively insoluble, which would have acted as a barrier to the solutional development of the tube. Tubular conduits are much more common in the strike passages than in the dip passages, and most of them follow a course parallel to strike. A number of tubes, however, follow for some distance down the dip of the beds.

Another erosional feature attributed by Bretz to formation in the deep phreatic zone is bedding plane anastamosis. This consists of a complex pattern of small wandering channels that is confined to a single thin bed. Bretz (1942, p. 708) states that this feature represents the initial stage of deep phreatic erosion. The bedding plane anastamoses of Fulford Cave are identical to those described by Bretz. They are, however, so closely associated with tubular conduits that this author believes them to be the result of shallow phreatic erosion in which the rock structure exerted more influence over their position than in the case of the tubular conduits. Bedding plane anastamoses are present in many parts of the cave, and are especially well developed in the Breakdown Room and in the lower part of the Two-level Room.

The breakdown in most of the cave passages tends to obscure the original shape of the passages. This is especially true in the Breakdown Room and parts of the Entrance Passage. An attempt was made to visualize the shape of the pre-breakdown passages by mentally removing the fallen blocks from the floor and fitting them back in place in the ceiling. The pre-breakdown shape of most of the strike passages does not seem to be controlled solely by the structure of the rock. The original shape of the passage can be reconstructed most easily in the Breakdown Room and Entrance Passage, which are shown in plan view in figure 2, and in section in figures 3 and 4. The updip (southeast) side of both of these passages is bounded by a vertical or slightly overhanging wall whose position is determined by a strike joint. The updip side of the passage also has the higher ceiling. The downdip side of the passage is typically bounded by an indefinite wall formed by the junction of the floor and ceiling. Joints have not determined the position of orientation of this wall, which is usually more irregular than the updip wall. In spite of this lack of strike-joint control it closely parallels the updip wall.

The writer believes that the principal levels of strike passages were excavated by water in the shallow phreatic zone. Assuming that these passages were formed at a time when the discharge point for the main body of ground water was at the valley bottom as it is now (although the valley was then less deep), a gentle water table slope existed to the southwest. The strike passages were excavated by water table streams which first entered deep phreatic passages which had been dissolved along a strike joint. As the water table was gradually lowered, the stream cut down so as to maintain its position on top of the water table. Differential solubility of the limestone caused the trench to migrate downdip. Periodically, a sudden lowering of the water table caused the stream to abandon completely its former channel and, entering a lower strike-joint passage, to begin cutting a new passage. In all, four levels of strike passages can safely be inferred, and others may exist.

A downstream extension of these levels should definitely exist if this hypothesis is correct. Each level is terminated downstream, however, by breakdown and fill. Upstream, each level (except the lower one of which only a short segment is accessible) is connected by a series of small passages with the main dip passages represented by the Stream Passage and the Register Room. No continuation of the levels could be found to the northeast of the dip passages. It is therefore postulated that the water which flowed down first one strike passage and then another was supplied to the top of the water table by one or more vadose streams which flowed down the dip passages from the surface as the present cave stream does now.

There are a number of passages other than the Stream Passage and Register Room which connect the various levels. Examples of these are Moon Milk Corridor, Hidden Pit, Three-level Pit, and the slope leading from the Entrance Passage to the Lower Room. These passages are interpreted as temporary piracy routes, through which water drained from one level to another during sudden lowering of the water table. Rudimentary openings in the form of deep phreatic dip-joint passages or shallow phreatic tubular conduits probably existed prior to the piracy.

The exact relationship between the tubular conduits and the strike passages cannot be stated with any degree of certainty. It seems likely that the tubular conduits were formed some distance below the water table because the vertical relief of any one tube may be as much as 30 feet. At any one place in the cave the tubular conduits were excavated before the strike passages, since the latter were formed at the top of the water table.

Erosion and Deposition in the Vadose Zone.—Little has been said concerning the probable nature of the water table in the Leadville limestone. Because the Leadville is virtually impermeable, ground water flow is confined almost exclusively to fractures and solution openings. It has been assumed throughout this paper that the nature and abundance of these openings is such that ground water can, with only slight deviation, follow the course it would take in granular pervious material. It is probable that the water table was reflected in the cave by the surface level of water-table streams that were flowing through open passages. In the event that the water table fell too rapidly for the streams to correspondingly deepen their channels, the water-table streams would become vadose streams until they were able to re-establish themselves on top of the water table. For this reason, although the water table would appear to represent a clear boundary between the shallow phreatic and vadose zones, the relationship of the two may often be difficult to discern.

In the vadose zone, as in the two zones previously discussed, the principal mode of erosion is solution. Abrasion and other forms of mechanical erosion may locally be significant, however, and more erosion is carried on by mechanical means in the vadose zone than below the water table.

In general, vadose stream action is believed to have caused the following features of erosion or deposition in Fulford Cave: (1) greater erosion at the bottom of a passage than at the top; (2) accumulation of coarse detrital material; and (3) trench or lateral cutting of passages.

An examination of the bed of the present cave stream failed to disclose significant or diagnostic erosional features that had been produced by the stream. In the Lower Stream Passage, the stream has no well defined channel but flows through angular blocks of breakdown. In the Upper Stream Passage a small amount of polishing and etching of the rock over which the stream flowed was noted, and there are several areas of flutes on the passage walls just above the stream that have probably been produced by the stream.

An examination of the depositional record of the stream was more rewarding. Throughout most of its length the bed of the stream is littered with fragments of almost every type of igneous, metamorphic, or sedimentary rock which crops out upslope from the cave. The fragments range in size from sand to cobbles six inches in diameter. Fragments of these same rocks were noted in almost every part of the cave. Some of the larger fragments in the Entrance Passage and Breakdown Room show evidence of having been deposited by a vadose stream.

A number of interesting features of possible vadose origin are present at that part of the Entrance Passage known as the Big Meander. The passage here is crescentic in plan (see fig. 2), and appears to be the erosion remnant of a series of tubular conduits and superimposed meanders. There is a slot cut in the floor of this passage throughout most of its length. This slot averages four feet deep and three feet wide, and was cut by a degrading vadose stream. The curving wall above the slot exhibits a number of incised niches and flutes which were probably cut by a water-table stream or a low gradient vadose stream.

The most important period of breakdown probably occurred as the water-filled passages were drained, causing many of the blocks which had previously been partly supported by buoyancy to fall from the ceiling.

Many parts of Fulford Cave contain speleothems. A discussion of these vadose-zone deposits is considered beyond the scope of this paper, although they were studied in some detail during the investigation of the cave.

CONCLUSIONS

It is probable that the Leadville limestone underwent a period of cave development during Mississippian time. Cavity excavation was begun with the initial uplift of the Leadville soon after its deposition. The cavities dissolved in the limestone were filled, largely with fine clastic material, as the area was depressed during Des Moines time to form the Central Colorado Basin (Eardley, 1952, p. 232).

The uplift of the Sawatch range at the end of the Cretaceous Period (Eardly, 1952, p. 384) initiated a second progression of environments, one end result of which is Fulford Cave. It is possible that parts of the present cave consist of passages that were originally formed and filled during Mississippian and Pennsylvanian time and have been re-excavated by this later solution.

The initial solution of the second progression of environments was in the deep phreatic zone where slowly moving ground water dissolved a structurally controlled network of passages. This environment existed probably until late Pleistocene time. The location of high-level pre-Wisconsin glacial deposits suggests that the cave lay only a short distance above stream gradient at this time. Downcutting of the valley of East Brush Creek resulted in a great lowering of the water table. The varying heights of glacial outwash plains in the Frying Pan River drainage indicate that this downcutting was probably intermittent. The main strike passages (or levels) in the cave represent erosion by water-table streams during a period when the water table was being lowered slowly or not at all. Periodic sudden lowering of the water table caused lower strike passages to be excavated. This intermittent lowering of the water table probably reflects a similar intermittent lowering of East Brush Creek. These periods of slow downcutting alternating with periods of more rapid downcutting may be correlated with the substages of the Wisconsin, but it was not possible to correlate the passage levels of Fulford Cave with specific Wisconsin substages.

As the higher levels of Fulford Cave became air-filled when the water table was lowered, a vadose stream or streams flowing down the dip passages slightly modified the shape of the passages. As these streams encountered the water table they flowed along the top as water table streams. The present cave stream is confined to dip passages throughout its course in the cave. At some point below the present limit of accessibility, it turns and flows along strike to emerge as the spring at the bottom of the valley. The most probable reason it turns is that it, like the earlier streams in the cave, encounters the water table. It may, however, intersect the plane of the East Lake Creek fault and flow along the fault plane to the spring.

REFERENCES CITED

Bretz, J H., 1942, Vadose and phreatic features of limestone caverns: Jour. Geology, v. 50, p. 675-811.

Davis, W. M., 1930, Origin of Limestone caverns: Geol. Soc. America Bull., v. 41, p. 475-628.

Eardley, A. J., 1951, Structural geology of North America: New York, Harper Bros., 624 p.

Gabelman, J. W., 1949, Geology and ore deposits of the Fulford Mining District, Eagle County, Colorado: Colorado School of Mines, D. Sc. dissert.

Hubert, J. F., 1954, Structure and stratigraphy of an area east of Brush Creek, Eagle County, Colorado: Univ. Colorado, M.S. thesis.

Johnson, J. H., 1944, Paleozoic stratigraphy of the Sawatch Range, Colorado: Geol. Soc. America Bull., v. 55, p. 303-378.

Jordan, R. H., 1950, An interpretation of Floridian karst: Jour. Geology, v. 58, p. 261-268.

Malott, C. A., 1938, The invasion theory of cavern development (abs.): Geol. Soc. America Proc. for 1937, p. 323.

Maxson, J. H., 1940, Fluting and facetting of rock fragments: Jour. Geology, v. 48, p. 717-751.

Nelson, R. L., 1954, Glacial geology of the Frying Pan River drainage, Colorado: Jour. Geology, v. 62, p. 325-343.

Rhoads, R., and Sinacori, M. N., 1941, The pattern of ground water flow and solution: Jour. Geology, v. 49, p. 785-794.

Scott, K. E., 1954, Fauna and age of Leadville limestone (Mississippian) in part of west-central Colorado: Univ. Colorado, M.S. thesis.

Swinnerton, A. C., 1932, Origin of limestone caverns: Geol. Soc. America Bull., v. 43, p. 662-693.

CONTINENTAL OIL CO.,
BAKERSFIELD, CALIF.

Stochastic Models of Cavern Development

by **RANE L. CURL**

ABSTRACT—A population of caves evolves from a population of cave precursors consisting of joint systems of different complexity, which are subject to the invasion of solvent water whose source, composition, and availability vary in space and time. Although phenomenological theories have had considerable success in the identification and explanation of the succession of geomorphic processes responsible for cave development, these processes also produce manifestations in a cave population related to processes of a random or stochastic nature.

Stochastic models have been constructed to mathematically reproduce the evolution of a particular population manifestation, namely the distribution of cave lengths. Intuitively "simple" mechanisms for the rate of cave growth and decay have been used for this purpose. The theories provide a quantitative description of the evolution of cave length distributions and, conversely, some attributes of cave precursors which would lead to present-day length distributions. An estimate of the length distribution of all caves more than 100 feet long in West Virginia is used for these comparisons.

The complexity of the evolutionary process of cave populations and the urge to select evolutionary mechanisms which are subjectively simple as well as mathematically tractable are perhaps contradictory; but stochastic-process concepts are essential for a more quantitative understanding of the cavern cycle, and simple models may serve as a point of departure.

INTRODUCTION

A stochastic process is one containing events attributable to chance or randomness. The word stochastic is preferred to the other terms, as it implies the presence of both deterministic and indeterministic aspects to a process. The presence of random elements in geomorphic processes is the rule rather than the exception, though for many descriptive purposes it has not been necessary to give specific consideration to those aspects of land forms which are the product of these random elements. Some examples of the latter are the distribution and amounts of rainfall; variations in rock structure and composition; and location and type of vegetation cover. Geomorphic processes which reflect the influence of random elements are drainage patterns; meander development; stream piracy; and the development of terrain in general. Thornbury (1954, p. 114) writes: "Insequent valleys are those whose courses are controlled by factors which are not determinable. They show no apparent adjustment to structure or initial slopes and seemingly developed where they are by chance. This undoubtedly was not so but the controlling factors escape detection". It appears that insequent valleys are the result of processes in which the determinant features are more obscure than the chance features. Thornbury's reservation on the role of random elements probably arises from a desire to relate specific forms to specific processes but his phrasing might also be applied to another random process as in the toss of dice, for there too "controlling factors escape detection".

When we say that the cause of a particular landscape form is a certain process, we have stated a theory for the evolution of that form. When such a theory is made quantitative using mathematics it is often called a model because the theory then reproduces in its symbolism some behavior of the physical process. A model is necessarily a simplification of the real process. We choose events in constructing a model which are in our view simple, and the form of a model will be conditioned by the ideas already held and the understanding we have already gained. It is therefore not surprising that a model must often be modified or discarded because it can no longer, without contradiction, include all observations or because its bases are found to be not so "simple" as first supposed. A stochastic model applied to cave development must be constructed from the knowledge used in existing genetic theories.

The author has already proposed a stochastic model for the evolution of cave entrances (Curl, 1958). Stochastic models have for some time found application in a number of fields. Neyman and Scott (1959) in reviewing some of these wrote, "A few simple chance mechanisms may combine to reproduce many manifestations of a complex phenomenon.." Terrain analysis studies are the results of the stochastic processes of terrain development with the aid of statistical methods.

In the subsequent sections *cave, cave population,* the *distribution of cave lengths,* and possible processes in a stochastic model of cavern development will be defined, discussed, and applied to the evolution of cave length distributions. The derivation of the models will use the Davis (1930) two-cycle theory of cave origin which implies that cave growth, transition to vadose conditions, and finally decay, are consecutive and non-overlapping epochs. One-cycle caves (after Davis) will not be considered.

Each epoch including growth, transition, and decay, will be considered in turn, after which a composite model will be given for West Virginia caves. In particular an attempt will be made to explain the length distribution of all caves in West Virginia which is shown in figure 1. The discussion will be directed toward seeking reasonable assumptions concerning the quantitative aspects of the particular processes. Because of lack of space the mathematical development of each case has been omitted and only the results presented.

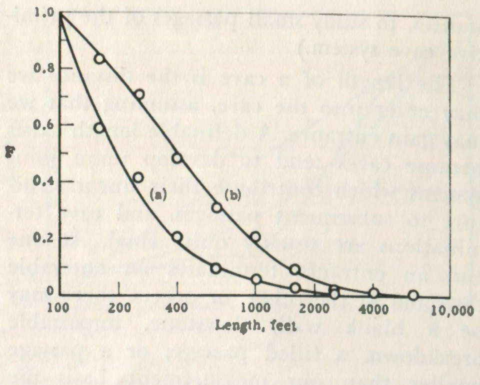

Figure 1

Distribution function of length for caves in West Virginia, where **F** is the fraction of caves longer than a given length: **(a)** all caves longer than 100 feet; **(b)** all such caves with only one entrance.

CAVE POPULATIONS

A *cave population* is an ensemble of caves related by proximity or other features useful for classification. When Davis urged the collection of better and more extensive data on certain cave features he had already implicitly used the idea of populations of caves developing by similar means and possessing similar genetic characteristics. From the limited data then available he sought to deduce population characteristics which should be observed. The existence of more extensive data today permits the population view of certain cave feature origin presented here.

The individual cave is the element or member of the cave population. It may be a single solution cavity or a fragment of an originally larger system. It does not matter whether or not it has an entrance. The fundamental basis for identifying a cave as such is the size of a human; if a different scale of measurement were used there might be no "caves", or, at the other extreme, all caves might be one cave. A solution cavity in limestone is a cave if we can get into it. Caves too narrow to traverse could be included in a cave population, if necessary, by imagining ourselves to be smaller than we are. (However it is our misfortune from the standpoint of understanding cave origin that we are unable, except in rare instances, to study small passages of the primitive cave system.)

The length of a cave is the distance we may enter into the cave, assuming that we may gain entrance. A definable length exists because caves tend to develop upon joint systems which contribute their linear structure to subsequent passages, and cave terminations are usually quite final. At one end an entrance terminates an enterable cave and at the other, or others, there may be a blank wall, flowstone, impassable breakdown, a filled passage, or a passage smaller than our measurement basis—the size of a man.

Caves which have an impassable but observable connection will be considered as two caves. A corollary is that an unenterable section of a known cave is a second cave without an entrance. Some such distinction must always be made although where we choose to draw the line may vary with circumstances.

In the previous study on cave entrances, the length distribution of one entrance caves shown in figure 1, curve *b* was introduced empirically. It was thought then that the distribution of length must also be a product of a stochastic geomorphic process. However it is the population of *all* caves which is of interest in a theory of cavern development, not just those which happen to possess entrances, so the result derived by the earlier methods for all caves, shown in figure 1, curve *a*, will be used to represent the present circumstances in the state of West Virginia.

Any actual cave population is finite and therefore has a largest member, a deepest member, etc. It is convenient for the purpose of discussing generalized cave populations to overlook this fact and consider the existing population as a sample of caves from an infinite population. Distribution functions of length as in figure 1, when applied to a finite population, may yield a fraction of a cave as the number longer than some length, which just means that there is a small likelihood of that length occurring in samples of caves of the observed number chosen from the infinite "parent" population.

GROWTH EPOCH

A growth-population consists of growing and maturing cavern passages. Little is known in detail of this process. It is probably at the end of this epoch that caves have their largest size and greatest extent. It is also at this time that we can identify, at least in principle and retrospect, the parts of the primitive network which were responsible for the structure of individual caves.

The primitive system may be enlarged either continuously or discontinuously. The former means that enterable passages in the system remain always in connection and cave length grows from some single unit to include eventually the utilizable (though not the available) phreatic network. Discontinuous means that the primitive system evolves to passable size in a number of sections which may in some cases coalesce (producing a discontinuous increase in length and the loss of a "cave") before the subaerial stages commence; each forms a cave which would be associated with a larger—though intraversable—basic system. This does not include caves which are separated from a continuous growth cave by later modification. In this treatment of growth the continuous model will be used although Davis (1930) implied his preference for the discontinuous mode in writing of the "integration of small systems into few systems of larger extent".

Assumption 1. — The number of caves in a growing population remains constant.

The continuous linear extension of a cave during the growth epoch occurs at a rate which depends at least on the following circumstances: (1) The availability of water which varies from place to place, and in time, due to differences in surface drainage patterns and fluctuations in climatic conditions. Water availability is also likely to change with the size which a cave has attained, a larger system being able to divert surface drainage underground over a wider area. (2) The solvent power of water (carbon dioxide content and initial approach to saturation) will vary with time and source. (3) Corrasive power of subsurface drainage will vary with time and source. (4) The properties of the limestone in which the cave is developing are determined beforehand but our lack of knowledge of variations of the properties and their significance in cavern development requires that they be considered as stochastic variables. (5) The configuration of the primitive network influences the rate as well as the possible extent of growth.

Together these factors cause a distribution in the rate of cave enlargement. They may be divided into those that are dependent upon cave length and those that are independent of length. The first factor cited above is of the former type. The fourth and fifth may be dependent upon length because the cave could encounter, sequentially, structures of different properties and thereby have variations in its rate of growth. However, variations in structural properties may be included with temporal variations when the nature of the variability in the structures encountered does not itself depend on length.

In figure 2 three possible histories of the length of a cave are shown which, it is assumed, ended growth with a particular length at a particular time. Curve *a* results from growth at a constant rate while in curve *b* the rate of growth increased with length and in this case is proportional to length. For curve *c* time-dependent factors entered in such a way that a relatively slow rate changed subsequently to a more rapid rate. Since a larger cave may receive more solvent water it should be expected that big caves tend to grow bigger and faster, though some big caves will suffer setbacks in growth and some little caves will exhibit growth spurts. Members of a cave population would start at different lengths, grow at different rates, and end at different lengths, rather than the illustrative situation in figure 2.

Assumption 2.—The Rate of Growth of Length of a Cave is Proportional to the Length Already Attained, All Other Things Being Constant, While the Proportionality Constant Varies Stochastically with Time for Each Cave.

The rate of growth varies from cave to cave and the distribution at any instant must be complex and changing in a complex manner. However only a suitable average over the whole epoch of growth rate need be considered, as in figure 2 where all three histories have an identical average rate of growth over the period. The distribution of this average rate of growth should be more stable. Specific assumptions about the epoch-average growth rate distributions will be made in connection with examples.

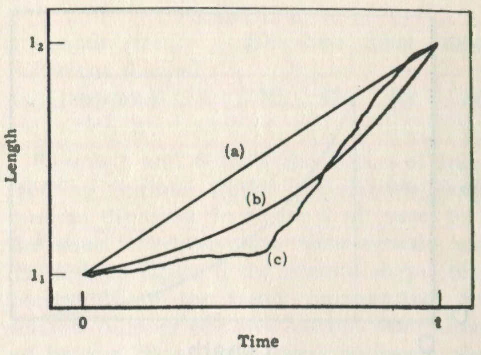

Figure 2
Mode of growth: **(a)** constant; **(b)** exponential; **(c)** possible real case.

The growth epoch starts with the caves existing at the end of the primitive stage though perhaps it is not realistic to distinguish between these stages as no special event marks the change. The treatment of the subsequent processes must be a study of the transformations of earlier populations until more is known about the origins of solutional openings in limestone. A distribution of time varying rates of growth acting on an initial distribution of cave lengths constitutes a stochastic process for the growth epoch. Each cave will increase in length, some slowly and some rapidly, and a new distribution of lengths will evolve. Caves with lengths in some range are produced by others growing into that range, and removed by growing beyond. The manner in which this evolution takes place will depend upon the superimposed growth rate distribution. A mathematical statement of this process would make an accounting of the numbers of caves entering and leaving the above range of lengths, and equate this to the rate of increase of the number of caves in the

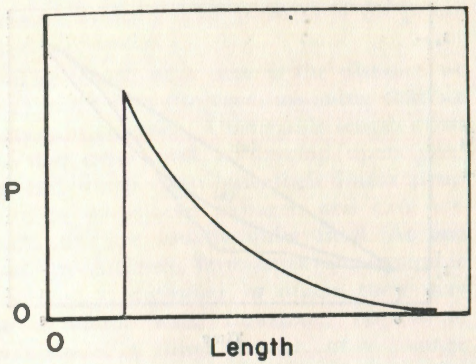

Figure 3
Exponential growth of uniform population where P is the relative frequency of caves of given length.

range. The assumptions which determine the process have already been stated. The resulting transformation equation for growth is given in the Appendix. Examples follow:

Figure 3 shows the relative frequency of caves, *P*, (the higher the curve the more frequent are caves near that length) plotted versus length, for the case when all the caves originally had the same length and the epoch-average growth rate is exponentially distributed.

If the relative frequencies of caves are initially distributed as shown in figure 4, then after some time, for *any* distribution of the growth rate parameter, the new distribution will be as shown. This case is particularly interesting because the *form* of the distribution does not change. If instead we plotted these curves as in figure 1, as the fraction of caves longer than each length for caves over 100 feet long, the curve would remain always the same during growth. There would of course be more caves longer than 100 feet, but the fractions of them would remain distributed in the same way. As this is true no matter what the epoch-average growth rate distribution is, it will be called an *invariant growth population*.

The assumptions that have been made in the above model for a stochastic growth process are of course restrictive. Also, while the evolution of one distribution (length) has been "explained", other distributions were introduced for this purpose — those for initial lengths and epoch-average growth rates. It is believed, however, that the introduction of the latter is a useful step in understanding the growth process.

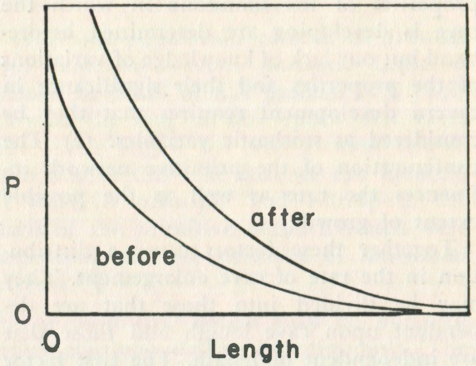

Figure 4
Invariant growth population showing new distribution after some time has passed.

Transition Epoch

The two-cycle cave origin theory states that a regional uplift, or river downcutting, brings caves above the zone of saturation following the period of enlargement of a cave system to its largest extent by solution and corrosion. It is believed (Davies, 1958, p. 27) that cave fill, collapse (breakdown), and the development of entrances occurs during this time. Water barriers may also be left in a cave while elsewhere the surface may dissect a cave into several fragments.

A characteristic modification of this transition epoch will be assumed to be the dividing of a cave into smaller caves, or fragments. A large cave may be expected to suffer more divisions than a small cave, but some caves will be undivided and others highly fragmented. Variations in the frequency and location of modification by fragmenting during transition identifies this as a stochastic geomorphic process, and associated population manifestations should be expected. Other events do, of course, occur during transition. There may be considerable loss of cave passage by filling or total removal, but here the specific effect of fill on length distributions will not be treated except later in regard to the decay epoch.

Fragmenting may be either length-preserving or length-destroying. The former is an idealization of those divisions of a cave system which destroy little net length. The latter case, which is the real situation, may be considered as superimposed decay.

Assumption 3.—Cave Fragmenting is Length Preserving.

Random fragmenting is assumed for the lack of a better hypothesis. *Random* is used to mean that divisions of the caves following the growth epoch are equally likely to occur at any point in a cave but have some average frequency of occurrence per foot of cave (much less than one).

Assumption 4.—Caves are Divided into Fragments by a Random Process in which Divisions are Equally Likely to Occur Anywhere, but an Average Frequency per Unit Length Exists (Poisson Process).

During transition some caves would not be divided at all and these would join the new population unchanged in length or number. Other caves would be divided once or more into two or more fragments. These would join the new population as shorter and more numerous caves. This process would transform the initial population to a more numerous population with a new distribution of lengths. The transformation equation for transition is given in the Appendix. Short caves can arise by either never growing very big, or by being fragments of larger caves. Both types must exist, although they are all reported as individual caves. But a cave which terminates in a short distance by breakdown or fill is probably a fragment and is likely to continue beyond (or rather, there is probably a second cave beyond).

Table 1 indicates how often caves of different lengths will be divided for a case when divisions occur at the average frequency of, for example, 0.0005 per foot of cave. Values are given for the percent of caves of a given length which will receive one or more divisions.

TABLE 1

Length (feet)	200	800	2000	4000
Percent divided (approx.)	10	32	63	86

Figures 5 and 6 show the effects of fragmenting various initial populations with random divisions. In figure 5 all caves had the same length to start. Some remain undivided. In figure 6 the general shape (exponential) of the curve representing the relative number of caves has not been altered by the transition process, although the relative number of shorter caves has increased at the expense of longer caves.

Only one model for transition modification of a cave population based on a reasonable mechanism for a change which might occur during this stage has been considered in detail. We know that caves are often terminated by breakdown and other passage closures, and it is possible to get beyond such blocks often enough to support the belief that beyond many barriers which stop exploration now there is more cave passage. This is justification for the belief that caves are interrupted and that it is permissible to consider the process as stochastic. The stochastic process of cave fragmenting tends to produce an apparent upper limit on the size of caves. By measurements of length alone it is not possible to distinguish between an upper limit on length imposed by limitations of growth or subsequent fragmenting. A comparative study of the nature of cave terminations is necessary to help decide this question.

Decay Epoch

The decay process is like the growth process; caves are changing length as part of a stochastic geomorphic process. However the agents are now not those of enlargement, but of weathering, erosion, weakening, collapse, and fill. They are primarily surface agents which act on the evolution of entrances and the filling or cutting back of points in the cave system through which they have access. It is likely that caves decay inward from points of surface intersection while the internal cave passages are relatively protected and static. If this is the

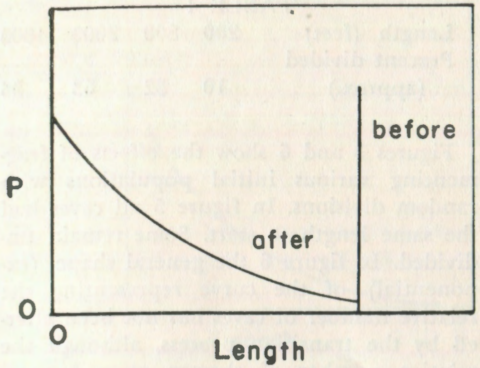

Figure 5
Transition of uniform population (**before**) to fragmented population (**after**).

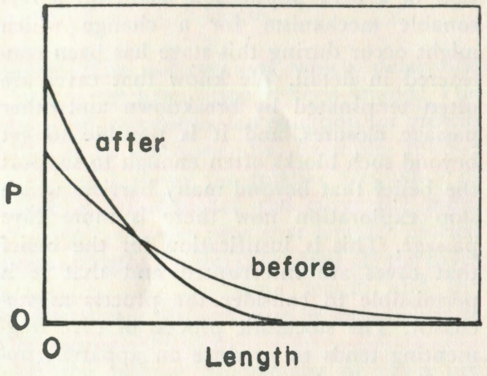

Figure 6
Transition of exponential population (**before**) to fragmented population (**after**).

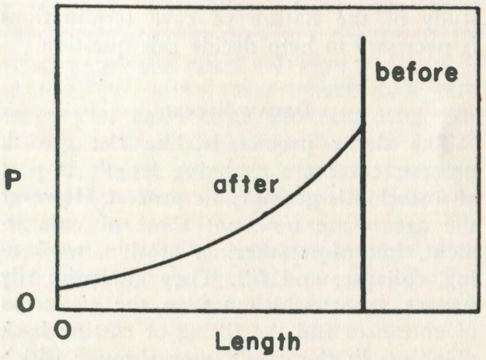

Figure 7
Exponential decay of a uniform population.

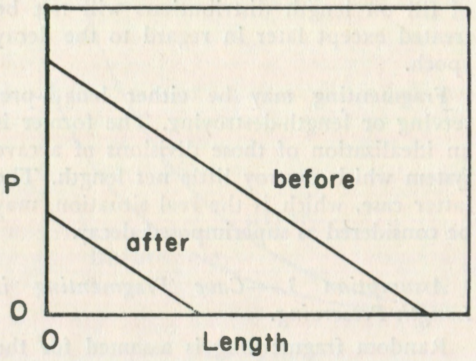

Figure 8
Invariant decay population.

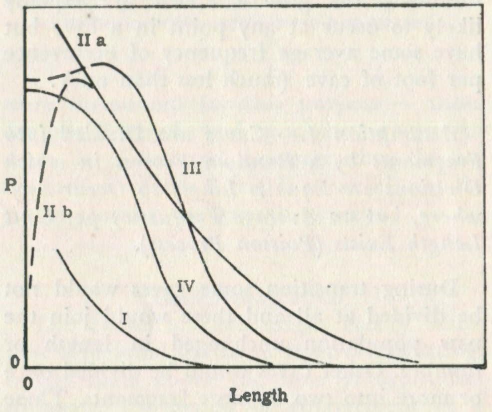

Figure 9
Evolution of a cave population, where **P** is the relative frequency of caves of given length: **(I)** start; **(II)** after growth; **(III)** after transition; **(IV)** after decay.

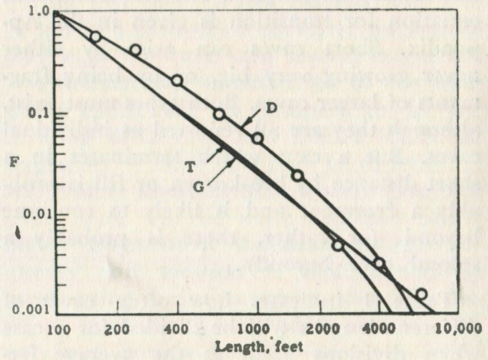

Figure 10
Distribution function of length for all caves in West Virginia longer than 100 feet: **(G)** growth population (invariant); **(T)** after transition; **(D)** after transition and decay.

case, the points of division in the transition epoch, together with the original "ends" of the cave, could be the locations from which decay proceeds. Additional intersections might be produced as the surface above is eroded with fragmenting and decay proceeding simultaneously. Such overlapping of processes will not be considered here. Since the processes occurring at divisions and ends can hardly be influenced by many of the interior passages of a cave, an appropriate guess would be that the rate of decay of a cave does not depend on its length although the rate may vary with other geomorphic influences. An epoch-average decay rate for each cave is also applicable here.

Assumption 5.—The Rate of Decay of a Cave is Independent of Length but Varies with Time.

A distribution of time-varying rates of decay acting on an initial distribution of cave lengths constitutes a stochastic process for the decay epoch. Each cave will decrease in length and eventually reach zero length. A decaying cave population moves toward a final state in which all caves have zero length. Since not only erosional removal of rock but also fill and collapse are included in decay, some zero-length caves would still be detectable. Later events may rejuvenate such caves but this complexity is not being considered. The transformation equation for the decay epoch is given in the Appendix. Examples follow:

If all caves are initially of a single length and the epoch-average decay rate is exponentially disturbed, then the population decays are as shown in figure 7. Some caves already have zero length.

If the initial relative frequency of different lengths is as shown in figure 8, then the population evolves without a change in the straight line form of the distribution no matter what the decay rate distribution. This is therefore, by analogy to the growth case, called an *invariant decay population.*

A constant rate of decay (or growth) produces simply a fixed displacement of the previous figures to the right or left depending on whether the process is growth or decay.

The conclusion from this discussion is that decay, being independent of cave length, would cause the greatest relative changes to occur in short caves.

Evolution of Cave Populations

Hypothetical Population

All of the previous models may be summarized by showing the effects each has during the evolution of a cave population. Figure 9 shows the evolutionary sequence for the length distribution of a hypothetical population. An initial population *I* has mostly short caves. Growth extends this distribution to greater length, eventually to give population *IIa.* Since it is likely that the shortest members of this population are also too narrow to enter, a modified population *IIb* is shown to represent enterable caves only. Transition modifies this by transforming long caves to shorter fragments to give population *III.* A number of short but enterable caves have also been formed and the distribution is raised near the origin. This population then decays and the distribution sinks toward zero length *IV.* Sometime during this epoch the relative number of caves of some length may increase for a while, but eventually all are gone.

Lengths of Caves in West Virginia

We return at last to a consideration of the phenomena which prompted that which is presented here: the observed distribution of the lengths of caves in West Virginia shown in figure 1b for all caves over 100 feet long and with one entrance. It has been recognized that cave entrances are accidents, and to explain the lengths of one-entrance caves requires both an explanation for the lengths of all caves, and an explanation of the way entrances are distributed among caves. The latter step was taken in a previous paper (Curl, 1958). The same data, modified slightly by the inclusion of a recently discovered cave (Culverson Creek Cave) were used to compute the distribution of length for all caves in West Virginia shown in figure 1a.

The data of figure 1a have been replotted in figure 10 using logarithmic coordinates. An "invariant" length distribution has been assumed for the growth population because the mathematical development showed that this is a distribution of great generality obtained even with a variety of quite different assumptions about initial length and growth rate distributions. An "invariant" population plots as a straight line in figure 10, and does not change during the growth epoch.

The transition epoch transforms curve *G* to *T* by causing a relative decrease in the frequency of long caves. In the case shown, the average distance between divisions (if all the caves were strung out end to end) is 2000 feet (0.0005 divisions per foot of cave). The subsequent epoch of decay is particularly hard on short caves which also constitute a large proportion of the population. A process of decay with an assumed constant loss of 60 feet from every cave produces the transformation to *D*. Many caves will have decayed below 100 feet and be no longer represented in the population now shown.

The parameters were chosen to make the final curve *D* agree with the characteristics of the data. Considerable flexibility existed in producing a good correlation since the two processes of transition and decay affect the long and short caves respectively, most strongly. However it was still necessary that the direction of the effects of transition and decay be in accord with the long and short cave properties of the data before a model could be used. This, then, is a possible model for the evolution of the West Virginia cave population.

Conclusions

All geomorphic processes, and in particular the processes of cavern development, are stochastic processes by virtue of elements of chance or randomness which enter into them. In the evolution of a cave population certain manifestations may reflect the operation of relatively simple chance mechanisms and a study of these can be useful in gaining a better understanding of the basic processes.

Stochastic models for the growth, transition, and decay epochs of the cave population of West Virginia, based on a two-cycle geomorphic history, have been proposed and compared with data. Modern knowledge on cave development has been used to guide the choice of assumptions. An "invariant" growth population was found which turned out to be very similar to the data, and the subsequent predictions of the effects of simple transition and decay models improved the correlation. The numerical values for the transition fragmenting frequency, 0.0005 per foot, and the decayed length, 60 feet, for West Virginia caves, seem reasonable in the absence of better data to check them.

The alternative to a stochastic model is to maintain that every cave is unique and that no processes may be identified as acting in common upon all caves. On inspection many cave features can be ascribed to very particular circumstances for that cave, but to criticize stochastic models in the light of such observations is to claim that a prediction of a cave feature (length) could have been made. This is more than any present theory attempts to do and is irrelevant, if not impossible, according to stochastic theories.

More observational information on the mechanisms of cave growth, the nature and causes of cave interruptions, and the effects of surface degradation on cave modification will be needed before the validity of the models presented herein can be finally ascertained.

References Cited

Curl, R. L., 1958, A statistical theory of cave entrance evolution: Natl. Speleol. Soc. Bull., v. 20, p. 9-22.

Davies, W. E., 1958, Caverns of West Virginia: West Virginia Geol. Survey, v. 19A, 330 p.

Davis, W. M., 1930, Origin of limestone caverns: Geol. Soc. America Bull., v. 41, p. 475-628.

Neyman, J., and Scott, E. L., 1959, Stochastic models of population dynamics: Science, v. 130, p. 303.

Thornbury, W. D., 1954, Principles of geomorphology: New York, John Wiley & Sons, 618 p.

Shell Development Co.,
Emeryville, California

DISCUSSION

Richard R. Anderson, *Bell Telephone Laboratories*: You assume that the rate of growth is dependent on the length. I would think it would be more closely related to the number of terminations.

Author: The number of terminations to a cave is statistically related to its length. In addition, length is more readily obtained from data. The fact that great simplifications have some utility implies that a great many other variables "average out" in some sense, or they don't enter into population manifestations in the same way they do in individual caves.

Alan D. Howard, *Yale University*: Let's suppose we consider the breaking up of caves as the dropping of bombs in a random manner. If there are two types of caves, those with a single long passage and those with a maze pattern, doesn't it seem more likely that you will produce more fragments from the single-passage cave than from the network cave?

Author: A maze cave is a "multiple-connected" cave and a linear cave is "simple-connected". In the latter you can take a ball of string and run it around, tying it together anyway you want, and still be able to pull the mesh from the cave. As you observe, if a multiple-connected cave is divided, it is still possible to have just one cave. My models apply only to simple-connected caves (or passages) but these constitute the majority. Again, many of the peculiarities of the members of these populations are submerged in the averages which are taken.

William B. White, *Pennsylvania State University*: I would like to return to your statement that the rate of increase of cave length is proportional to the length, which would mean that the length of a cave increases exponentially with time up to the end of growth. What transition is necessary to terminate growth to keep the length of the cave from going to infinity?

Author: Yes, the length of the cave would go to infinity in time, so we must consider the reasons why caves are relatively short. We could say that geologic control is the answer, but this is a weak argument because there is always much jointed limestone that doesn't have any caves in it. I have solved the problem by assuming growth of all caves in a population to cease at the same time. If it didn't, the processes of growth, transition, and decay would overlap and considerably confuse the picture. If anyone works out an alternative model, I would be quite interested. I chose to take the simplest case.

Anderson: This is presumably a continuous process. I would think there are caves being both created and destroyed now. Do you believe that these processes must happen at different times?

Author: The different populations could certainly exist simultaneously, even in a relatively small area.

Anderson: Then did you say the ones you were studying were all of the same population?

Author: I have confidence in feeling that they are. In the previous paper on cave entrances, I considered a basic parameter of these populations for all caves (with entrances) over 100 feet long, over 500 feet long, and over 1000 feet long. If anything is going to be different about different groups of caves, these ought to have included different types of caves. This basic population parameter turned out to be the same for all these groups of caves in West Virginia.

Howard: Have you done anything with smaller groups within the larger total to see if over a smaller areal range there might be significant variation?

Author: Only in the earlier paper. Too few data is the difficulty if small groups are concidered. If a way could be found to look at individual caves for properties which would include or exclude them from the local homogeneous population then something might be said about smaller groups. It is not at all obvious yet what these properties would be.

APPENDIX

The following equations were derived from the assumptions given in the text and used in applying each model:

GROWTH:

$$P_2(L)=\int_0^\infty \exp(-\mathbf{u}t)P_1[L\exp(-\mathbf{u}t)]P(\mathbf{u})d\mathbf{u}$$

where $P_1[L\exp(-\mathbf{u}t)]$ is the probability density distribution of initial lengths evaluated at $L\exp(-\mathbf{u}t)$; $P(\mathbf{u})$ the distribution of the epoch-average growth rate $\mathbf{u}$ (and $dL/dt=uL$); and $P_2(L)$ the resulting length distribution. Statistical independence of $\mathbf{u}$ and initial length has been assumed.

TRANSITION:

$$P_3(L)=$$

$$\frac{e^{-IL}}{1+I\mathbf{l}}\left\{P_2(L)+I\int_L^\infty [2+I(l-L)]P_2(l)dl\right\}$$

where $P_2(l)$ is the length distribution at the end of growth; I the average number of divisions per foot of cave; $\mathbf{l}$ the average length of the cave in the population prior to fragmenting; and $P_3(L)$ the probability density distribution of L resulting from transition.

DECAY:

$$P_4(L)=\int_0^\infty P_3(L+\mathbf{v}t)P(\mathbf{v})d\mathbf{v}$$

where the terms are as defined in the growth case except applied now to the population before and after (some) decay. The distribution of the epoch-average rate of cave decay is $P(\mathbf{v})$ (and $dL/dt=-v$). Statistical independence of $\mathbf{v}$ and length has been assumed.

Geometrical Basis for Cave Interpretation

by **ARTHUR L. LANGE**

ABSTRACT—The shapes of cave structures can be a key to understanding the evolution of the cave, since they are the result of erosive and depositional processes acting on the cave boundaries. Any future outline of a uniformly dissolving or encrusting cross section of wall, ceiling, or floor is generated by a circle rolled with its axis everywhere in contact with the initial outline. The envelope described by the circle represents the new contour, and the radius is dependent on the mass transfer rate and the duration of the action. In the case of the three-dimensional body, a generating sphere will yield the correct form. This procedure is a geometrical interpretation of the differential equations expressing the event.

Sharp projecting corners will remain sharp while dissolving and will round off when encrusted. Inside corners will round off under solution and remain sharp during deposition. The resultant topographies of complex wall pattern are typical of the scalloped solution-work and bulbous encrustation found in caves where corrasion, gravity, and other directional agents have not modified the basic mechanism.

Plane walls, inundated stalactites, and right-angled ceiling blocks serve as examples of simple geometrical structures. Solution pockets, mammillary crusts, domes, gours, crusted strands, and wall niches are examples of more complicated forms. A cave stream flowing normal to a cross section and an evenly circulating water body or film are cave media in which the process of uniform mass transfer can be closely approximated.

Cave structures are the units of underground topography: the domes, potholes, stalactites, scallops draperies—the individual forms that make up the underground scenery. These features are not necessarily confined to caves, but usually they are found best-displayed in the favorable climate and near-laboratory conditions that we meet there.

William Morris Davis (1899) conceived a language in which to frame all landscape. He showed that a given geologic *structure*, subjected to a physical *process* acting over a period of time, results in a *stage* of evolution. For example, if a level plain is uplifted and exposed to stream dissection, a stage of landscape characterized by steep-walled gorges comes about. We can profit by applying this way of thinking to the interpretation of cave landscape.

Our time reference is arbitrary. The initial structures may be flat ceilings exposed by rockfall; they may be the fallen rock itself, or open joints, or any other geometric configuration underground. Any of these initial structures can conceivably undergo a diversity, even a succession of physical processes. Floodwaters invade the cavern to dissolve its ceiling upward and to cause the fallen blocks on the floor to shrink away like ice cubes. Dripping water in one season may drill holes in the limestone or mud floor; in a drier period it more likely would deposit calcite to initiate a column. A long list of constructive and destructive processes could be drawn up.

Each process has two alternatives: to remove material or to add it. Where water seeps down a joint, the joint walls may dissolve back to form a dome; or under different conditions the water may deposit calcite at the open end of the initial joint to build a stalactite. Here, the dome is in form the solutional counterpart of the stalactite, a so-to-speak "negative stalactite". The same initial structure and physical process have participated; only in the one case the water is acidic, in the other, alkaline. Examples of other processes are: film-flow, turbulent flow, flow with corrasive load, condensation,

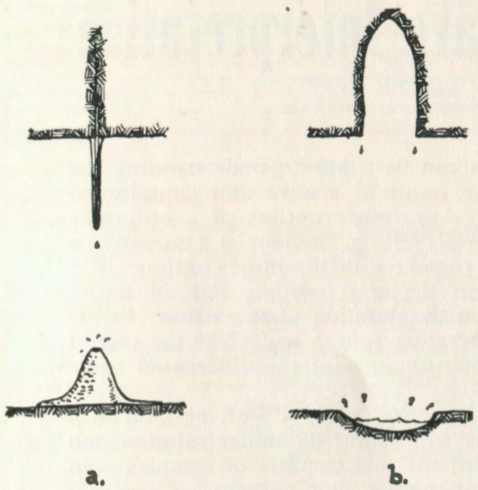

Figure 1
Cave structures resulting from water dripping from a ceiling joint: (a) stalactite and stalagmite —depositional, positive; (b) ceiling dome and floor pit—solutional and negative.

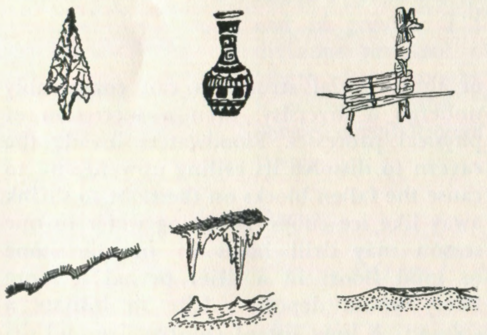

Figure 2
Artifacts formed by removal, addition, and rearrangement of material, compared with speleofacts formed by solution, deposition, and shifting.

and oscillation movements. Each has its negative and positive expressions, depending on whether material is removed or added (fig. 1).

Since the present approach is deductive, we need a deductive language or a framework of terms which conveys the natural relationships we are discussing. We must put aside the inductive, usually descriptive, field terms until they are needed in the eventual comparison of observation with theory. To begin, we shall borrow an analogy from archeology.

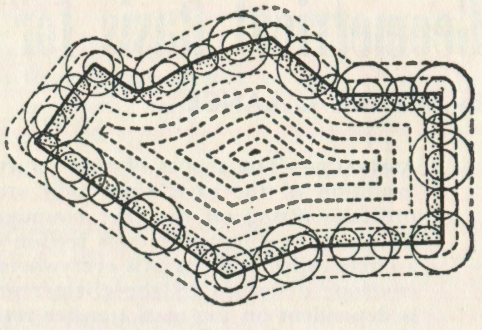

Figure 3
Speleofact contours generated by rolling circles whose radii depend on duration and rate of transfer. The heavy outline is the cross section of an initial structure of solid interior. Two outer speleothem stages and eight interior speleogen stages are represented.

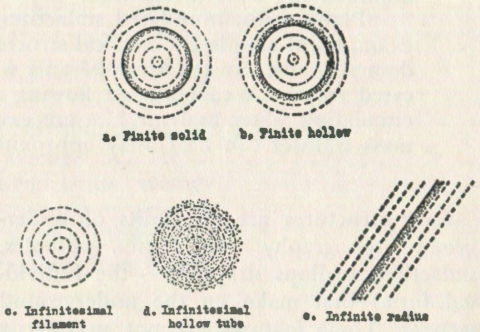

Figure 4
Cylindrical speleofacts in cross section. Solid side of initial structure partly shaded.

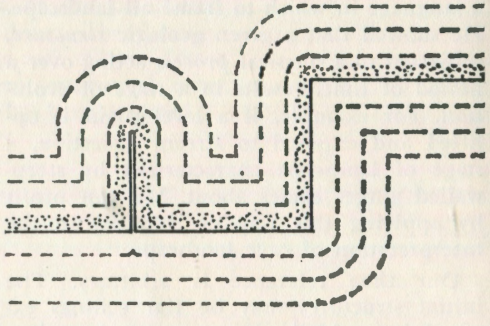

Figure 5
Speleofacts resulting from solution and deposition acting on a ceiling block and slot.

An *artifact* is defined as "anything made or modified by human art". The noun does not specify whether the initial stone or fabric was chiselled out or embellished with dyes, beads, or frills; nor does it tell whether anything at all was added or subtracted—but rather merely rearranged, like the molding of clay or the weaving of an animal figure from a willow twig. As a parallel, I call the modified cave structure a *speleofact,* meaning "cave-fashioned," and define it as being "a cave structure formed by transfer of mass between the fluid and the solid". It does not specify in which direction the mass moves: whether it leaves the cave wall to wash away with the stream, whether the stream encrusts its shore with calcite, or whether the rippling water merely shifts the sand back and forth to build a ripple-mark. Stalactites, stalagmites, shields, cave coral, potholes, ceiling tubes, floor slots, sandbars; these are all examples of speleofacts (fig. 2).

The speleofact has two aspects; namely, the *speleogen* and *speleothem.* I have defined the speleogen as being "a cave structure formed by transfer of mass from the solid to the fluid"; that is, by removal of material (Lange, 1955). Examples are potholes, floor slots, ceiling domes, joint cavities, scallops, rills, and wall niches. *Speleothem* I have redefined to fit into this framework: "a cave structure formed by transfer of mass from the fluid to the solid", or by accretion of material. This definition is somewhat more inclusive than George W. Moore's original one (1952), since I do not limit it to chemically-deposited structures. Mud stalagmites, sandbars, cave coral, calcite stalactites, helictites, and draperies all would be speleothems for the purposes of my discussion.

By alternation of conditions, a speleogen frequently becomes encrusted. In this way wall scallops are often seen decorated with a fringe of cave coral, after their generating stream has receded. Conversely, stalagmites can be dissolved by rising water (deSaussure, 1955). In either case, the result should be called a *compound speleofact.* Many speleofacts observed in caves appear to have been repeatedly compounded, perhaps seasonally.

With this general framework of structure, process, and time-stage or speleofact in mind, we can begin to consider particular examples. The most fundamental cave process is that of *uniform mass transfer.* It denotes that removal or deposition proceeds equally, without favoritism, over the entire exposed surface of a given structure. Such a condition is approximated underground where a stream flows perpendicularly to the cross-section of the form being studied. Its effects are also approached where water circulates rather randomly around an object.

In my introductory paper on cave interpretation (Lange, 1959), I have presented the general equation for the form of all speleofacts resulting from uniform transfer—plus or minus—acting on any arbitrary initial structure. The equation was derived from physical postulates. This equation has a very simple geometric meaning. It states that the successive stages are described by rolling a sphere around the surface of the initial solid structure, or, in two dimensions, by rolling a circle along the outline of a body. The center of the sphere or circle should remain in contact with the boundary. The radius is determined by the rate of mass transfer and the duration of the process (fig. 3). By analogy, if the outline of the initial structure corresponds to the hedge around a front yard, the successive strips of lawn that must be cut with a lawn mower correspond to the successive speleofact outlines.

The most fundamental two-dimensional structure is the cross-section of a circular cylinder. In caves, this might be a section of a stalactite, or of a hollow solution tube. If the stalactite is submerged by rising water, it may dissolve away uniformly, or perhaps enlarge by encrusting. The rate of change is independent of radius. The hollow tube, if re-submerged, may encrust to the point of filling completely, or it may enlarge by dissolving again, at a rate independent of its radius (fig. 4 a, b).

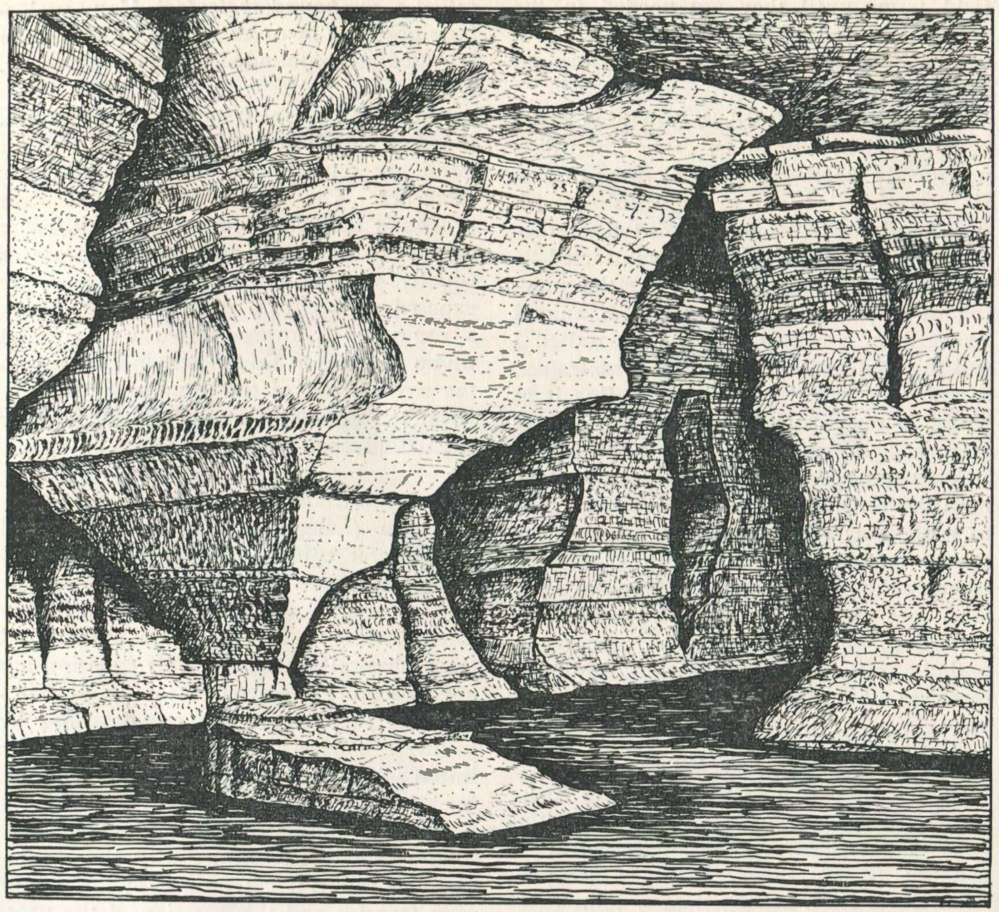

Figure 6
The preservation of right-angled corners during solution by a cave stream in Murray Cave, Ontario (drawing by A. Lange from photograph by John Kirwan; permission to publish granted by Cave Research Associates, copyright owners).

The limiting case of the infinite circular cylinder is the plane wall (fig. 4 e). A submerged wall, inundated or subjected to sheet flow, will advance or retreat uniformly. The opposite limit is the infinitesimal filament or filamentary tube (fig. 4 c, d). In enlarging, these become finite cylinders and proceed as such. Thus, by a crude approximation, the tubular stalactite may encrust or the filamentary hole may dissolve radially.

Any irregular initial structure can be represented by combinations of finite, infinite, and infinitesimal circular cylinders. For example, in the case of the right-angle step (a common ceiling-block outline), subjected to solution, the inner corner will round as it recedes, just as a sector of the infinitesimal tube would consume its walls. Meanwhile, the outer corner of the step remains square (fig. 5). When encrusting, the outer corner rounds while the inner remains square. Solution results in a cusp; deposition, in a mammilary form. An initial slot, such as a finite ceiling joint, dissolves dome-like; its inner end rounds, while its bases remain angular (fig. 5). The hanging sheet encrusts like a contracted version of the initial step, forming a U-shaped protuberance in cross-section.

The irregular initial structures undergoing uniform transfer can now be readily predicted, recalling the lawn-cutting analogy. With solution, we obtain the scalloped, cuspate topography typical of solutional cave walls (fig. 6 and 7), and borne out by model experiments with dissolving salt blocks (Lange, 1959). When encrusting, the mammilary or bulbous-type relief develops (fig. 8). These are beautifully demonstrated in outdoor travertine deposits, where logs, rocks, and leaves are found coated with tufa. One example, near Quincy, California, contains a dissected travertine pocket in which manganese-stained stalactite casts have been encrusted with a two-inch thickness of calcite (fig. 9).

Uniform transfer is not confined to submerged conditions. Solution and deposition occurring with homogeneous seepage through porous rock walls or from condensation may account for some of the wall forms I have described.

A fascinating case of uniform transfer occurs frequently on a pool surface. When the water is saturated, evaporation and carbon-dioxide release take place at the air boundary, allowing calcite to deposit uniformly around the pool outline. The result is a decorative crusted strand of the prescribed form (fig. 10). In Boydens Cave, California some pools are almost completely sealed over by their encroaching strands.

In some cases a zone of exaggerated solution occurs along the water surface of cave lakes and streams, resulting in indented "nips", or "water-level horizons". In plan view, this speleogen shows the concave weak zones scalloped out and separated from each other by the cuspate projecting remnants of less-fractured rock. Thus, the water-surface speleofact has its positive and negative counterparts in crusted strands and water-level nips, respectively.

Figure 7
Cuspate wall and ceiling topography in Samwel Cave, California (from photograph by Nancy Slusser).

At points where a pool spills over, deposition is favored, since carbon-dioxide release and evaporation are increased with agitation. The spillover points, therefore, are projected radially outward and upward, forming the circular arcs of dams, convex downstream. The individual spillover is distributed over an increasing perimeter, and adjoining dams coalesce to form a terrace of rimstone pools, or gours. Gours are common in caves as well as in hot springs and travertine deposits. Havasu Creek in Grand Canyon displays many examples of gours, whose outlines follow these convex patterns (fig. 11).

Modifications of gours occur to complicate their form. When flow decreases so that spillover does not occur uniformly over the dam, localized small gours build upon the perimeter of the main dam. And where spillover does not occur, deposition proceeds in the manner of crusted strands, extending the dam inward (fig. 10). The interplay of these variations on the basic process gives rise to different types of gours, including the beautiful crenulate or "pie crust" form.

Another type of gour occurs in which only solution of bedrock plays a role. If solution is locally discouraged at the spillover of a rock pool, its basin may widen and deepen elsewhere while the original barrier remains intact. These so-called "negative gours" can be seen in Forest Glen Cave, California, and in Montezuma Well Cave, Arizona. On surface limestone, they have

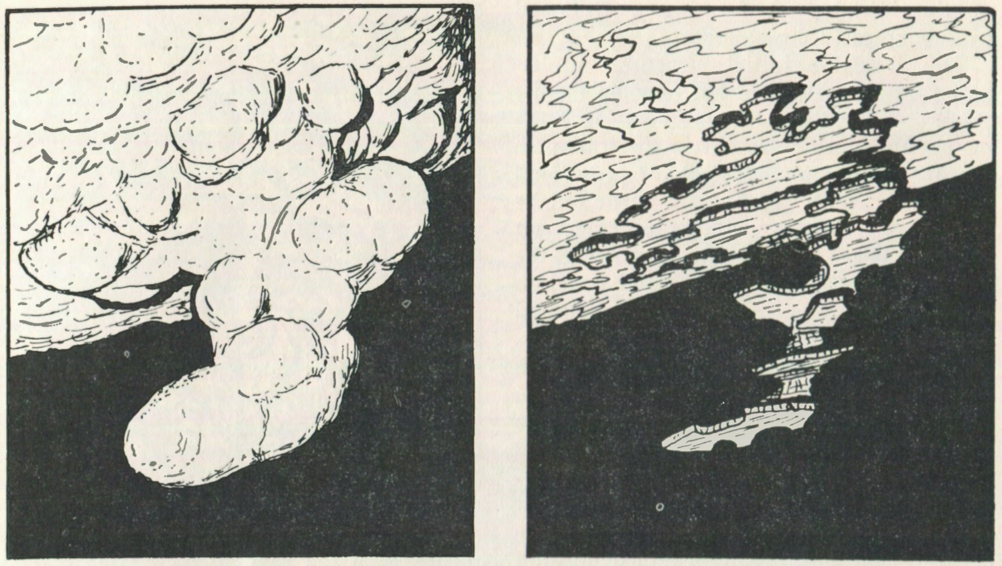

Figure 8

Left. Mammillary pendant in Goshute Cave, Nevada, approximately 3½ feet high. The entire cave below a discrete level is encrusted in this way, suggesting uniform deposition under submerged conditions. **Right.** Author's reconstruction of bedrock structure which might have resulted in this speleothem. These thin-bedded, notched projecting layers are typical of the solutional topography in the upper parts of Goshute Cave (from photograph by George Mowat).

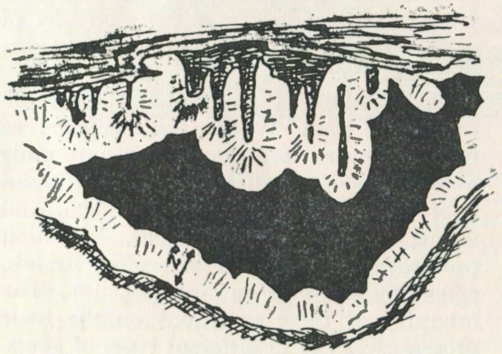

Figure 9

River-cut section of stalactite casts covered by a two-inch thickness of travertine. Casts are stained black by manganese oxide (near Quincy, California).

Figure 10

Crusted strands around a dry pool in Samwel Cave, California (from photograph by Nancy Slusser).

been designated *tinajitas* (Smith and Albritton, 1941).

I shall conclude this list of speleofacts with examples of compounded types. When a cave changes from a solutional to a depositional phase, we expect the earlier speleogens to become buried by the overlayers of speleothems, either sub-aqueous or sub-aerial kinds. Compound speleofacts of this sort abound in decorated caves, for we often discover encrusted tubes, fringed joints, and ceiling blocks covered with draperies. Less frequently, but not rarely, we enter a cave which has been submerged or re-dissolved by increased dripping, so that speleogens appear superimposed upon the speleothems. If this re-solution proceeds to the point where the speleothem is completely removed, we may detect in the resulting country-rock speleofact the "ghost" of the speleothem. "Ghost" forms can sometimes be distinguished from first-order speleogens, since their outer corners will bear the roundness which is characteristic of the formerly encrusting speleothems. In figure 12, a pure speleogen step form is contrasted with a "ghost" speleothem. Samwel Cave contains anomalous projecting ledges and floor hummocks of country rock betraying the former presence of flowstone and stalagmites. Here and there, vestiges of the flowstone are still to be seen.

Uniform transfer is by no means the only process operating to alter the geometry of cave structures, but it is the simplest to evaluate. This deductive method of geometric analysis must be extended to more complicated cave and surface problems, such as those of filmflow, directional transfer, concentration gradients, corrasion, clastic sedimentation, and simultaneous processes. We could then conceive of a set of rules for the interpretation of cave structures whereby the geologic history preserved in the subtle angles and nuances of underground topography could be faithfully read.

REFERENCES CITED

Davis, W. M., 1899, The geographical cycle: Geog. Jour., v. 14, p. 481-504.

deSaussure, Raymond, 1955, The solution of speleothems: Cave Studies, no. 8, p. 33-38.

Lange, A. L., 1955, The role of caves in dating Grand Canyon: Plateau, v. 27, p. 1-6.

—— 1959, Introductory notes on the changing geometry of cave structures: Cave Studies, no. 11, p. 69-90.

Moore, G. W., 1952, Speleothem—a new cave term: Natl. Speleol. Soc. News, v. 10, no. 6, p. 2.

Smith, J. F., Jr., and Albritton, C. C., Jr., 1941, Solution effects on limestone as a function of slope: Geol. Soc. America Bull., v. 52, p. 61-78.

CAVE RESEARCH ASSOCIATES,
BERKELEY, CALIFORNIA

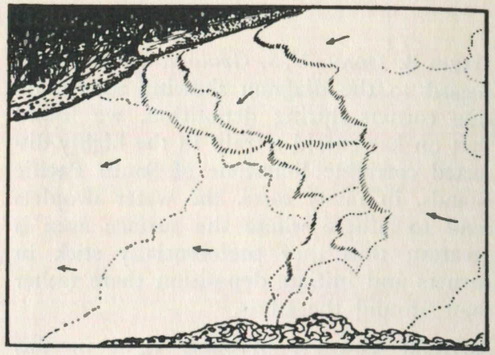

Figure 11

Travertine gours in Havasu Creek, Grand Canyon, Arizona.

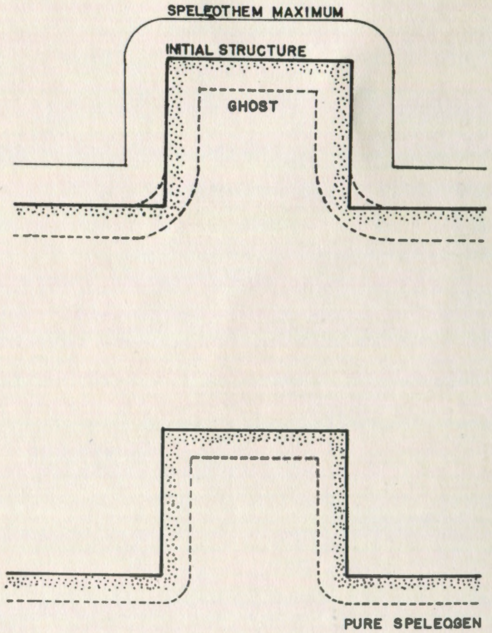

Figure 12

Upper. Speleofact formed by solution of an encrusted step. Shading indicates interior of original bedrock form. **Lower.** Pure speleogen derived by dissolving of initial step directly. Note smaller radius of curvature of inside corners.

DISCUSSION

David B. Doan, *U. S. Geological Survey*: In regard to the diagram showing square inside corners during deposition, we found that on karrenfeld terrain in the highly dissected corraline limestone of South Pacific islands, in many cases, the water droplets tend to adhere where the surface area is greatest; thus they preferentially stick in corners and initiate deposition there rather than around the edges.

Author: You are probably right in this case, but it is far from the conditions of uniform transfer to which the present paper is confined, and we cannot expect the same geometry to result.

Rane L. Curl, *Shell Development Co.*: One example of uniform mass transfer is an undulatory wall with a sine-wave curve. If the rate of solution on every point is the same, in a short time cusps will develop. Under deposition, similar cusps will form, but they will be offset half a wave length.

Alan D. Howard, *Yale University*: Why in some cases do underwater deposits have smooth surfaces and in other cases irregular crystalline surfaces?

Author: Why coarsely crystalline surfaces form rather than smooth surfaces is a matter of physical chemistry rather than a matter of geometry. The apparently smooth forms are in reality envelopes of minute crystals, whereas the clusters of large dogtooth spar crystals, for example, from a distance would also show a smooth envelope. This envelope would obey the rules of uniform transfer. The principal of uniform transfer is best approximated where the grain size is small compared with the dimensions of the structure under study.