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OF THE

NATIONAL SPELEOLOGICAL SOCIETY

VOLUME 26 NUMBER 3

Contents

JULY 1964

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Artesian Origin of Fissure Caves in Missouri

By Langford G. Brod, Jr.

ABSTRACT

Many pits and small caves with similar but unusual characteristics exist in four eastern Missouri counties. These caves and pits exhibit pronounced joint control and have been termed *fissure caves*. The caves all lie in a narrow, northwest-trending belt about five miles wide and 40 miles long, which is approximately coincident with the Rockwoods anticlinal fold belt. Most of the caves occur in the Plattin limestone of Ordovician age. The caves are solutional in orgin and are thought to have developed under artesian conditions. In order to determine the depth of solution, the altitude of river terraces and pre-Pleistocene erosion surfaces were studied, permitting a partial reconstruction of pre-Pleistocene topography. The primary impetus in speleogenesis came from slight regional tilting in the area of the fissure caves, related to uplift of the Ozark dome. Subsurface water drained off the dome through a dipping sandstone aquifer which eventually carried it deep underground. The water was again brought near to the surface in the eroded Rockwoods anticlinal fold belt, and emerged along its flanks in a series of resurgences. The artesian water ascended from the sandstone through the overlying limestone along joints, and solution of the walls of these joints produced the fissure caves. With subsequent planation of the surface, circulation virtually ceased, and the caves filled with red clay. During the Pleistocene Epoch the caves were drained and cleared of most of their fill. Entrances formed when upper sections of the chambers were intersected by recent erosion of the surface.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to the many members of the Middle Mississippi Valley Grotto, a chapter of the National Speleological Society, who aided him in the investigation and mapping of the caves described in this paper, especially Gregory Yokum, who made available a number of his cave maps. Dr. Kenneth Brill of the Department of Geology and Geophysics at St. Louis University delineated the geology of the St. Louis area and generously made available an undergraduate thesis geology map. Jerry D. Vineyard discussed the manuscript and suggested several important reference sources. George W. Moore read the manuscript and made many valuable suggestions.

INTRODUCTION

During the course of investigations for the Missouri Speleological Survey, many unusual caves and pits were encountered in the western section of St. Louis County. Most of these caves are small but so distinctive that they prompted further study. Several pit type caves in adjacent counties have similar characteristics. The writer believed that in spite of some differences the caves all had a common origin, and in that case other members of the group might exist. Likely areas were investigated, and a fairly large group of caves having the requisite characteristics were found. This group of caves was carefully studied, and this paper details the results of that study.

Most of these caves have passages which are typically high and narrow, so the term *fissure caves* has been applied to members of the group. A list of these caves is given in table 1, along with some pertinent data.

TABLE 1 — CHARACTERISTICS OF THE FISSURE CAVES.

Cave Name	County	Entr. Altitude	Vert. Range	Length (Feet)	Geol.	Fill	Entrance Type
Frog Pit	St C	560	26		P		g
Nightowl Pit	"	540	22	20	P		m
Totem Pole Pit	"	540	41	25	P		g
Turtle Pit	"	580	26	80	K-D		g
Bunch Cave	Frk	750	75		P		g
Bald Hill Chimney	St L	580	21	20	K		horiz
Brother Hubert's Pit	"	700	60	40	P	red	c
Catacomb Cave	"	730	44	300	P	red	d
Hilltop Cave	"	550	27	75	P		d
Horneker Cave	"	650	55	700	P	red	b
Indian Cave	"	750	27	40	P		f
New Rankin Cave	"	550			K		
Rankin Cave	"	670	24	390	K	red	e
Salia Cave	"	610	30	700	P	silt	b
Schlemper Cave	"	650	16	60	P		k
Three P. M. Pit	"	730	50	90	P		l
Tower Pit	"	750	64	200	P		b
Wyman Cave	"	750	20	40	P		l
Berger Pit	Jeff		40		P		b
Boemler Cave	"	750	23	85	P		d
Cedar Ledge Pit	"						
Crankshaft Pit	"	620	85	400	P-J	red	g
Ehlers Pit	"	790	80	44	K-D-P		c
Fools Pit	"	650	80	30	P		b
Fox Cave	"	670	85				b
Friedman Cave	"	600	30	700	P	red	
Hammach Pit	"	790	40	100	P		b
High Ridge Pit	"	700	35		P		b
Highway Pit	"	520			P		b
Hoene Hole	"	570	46	1000	P	red	e
Lostmouth Cave	"	710	20	600	P	org	e, j
Meyer Cave	"	680	27	50+	P	red	d
Model T Pit	"	690	113	55	K-D-P		c
Omagollee Pit	"	700	21	20	K		h
Pleasant Valley Cave	"	700	110	5000	P-J	red	b
Plegge Pit	"	600	42		P		b
Price Hollow Fissure	"	650	17		P		b
Rice Cave	"	610		3000	P	silt	
Rogers Cave	"	670	32	100	P	red	k
Schneider Cave	"						
Shower Pit	"	700	60	40	K		b
Unnamed Pit No. 1	"	700					
Unnamed Pit No. 2	"	800					
Wilson Pit	"	760	47		P		g
Zimmerman Pit	"	670	24		P		g
Alcove Cave	"	540	20	15	P		horiz
Anderson Cave	"	690	50	150	K?	silt	horiz

key: for entrance type, see Fig. 4

THE FISSURE CAVE REGION

The fissure cave region is hilly, wooded, and generally somewhat rugged. The location of this region and its relation to various political and topographic features is shown in figure 1. The area lies at the edge of the Missouri Ozarks, typified by a well-dissected upland surface (Branson, 1944).

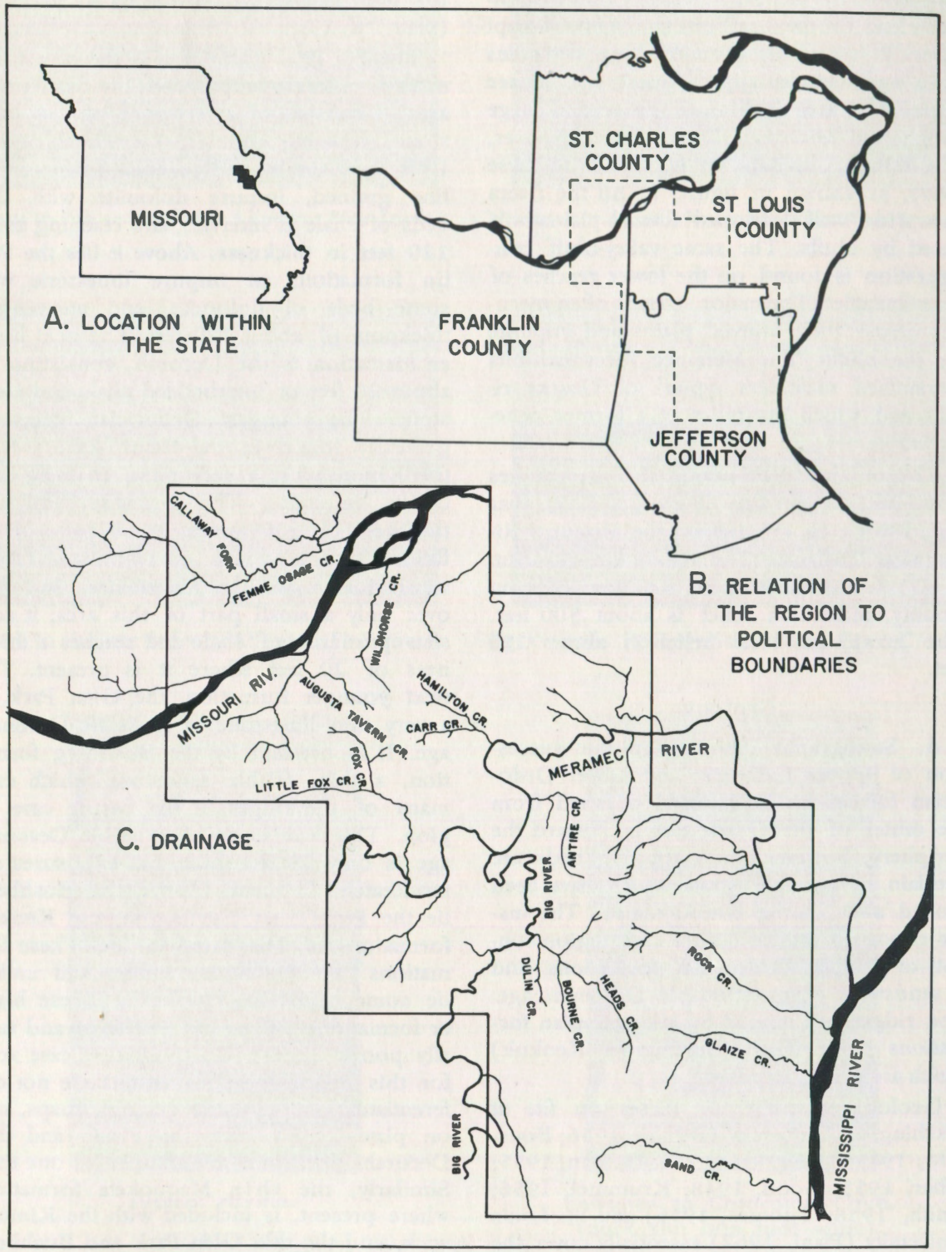


Figure 1.

Location maps and drainage map of the fissure cave region, eastern Missouri.

Topography typical of the region is pictured in figure 2; a topographic contour map of the region is shown in plate 1.

The cave region is terminated on the northwest by the St. Charles County highlands and on the southeast by the Mississippi River. It is roughly 40 miles long, five miles wide, and includes approximately 200 square miles. The area is drained by several large rivers: the Missouri River, Meramec River, Mississippi River, and by tributaries to these rivers, as shown in figure 1. All the rivers have wide, well developed alluvial plains bordered by bluffs. The same valley-bluff configuration is found on the lower reaches of the tributaries. The major streams often meander across their alluvial plains and impinge on the bluffs. The Meramec River exhibits entrenched meanders typical of Ozarks rivers and which are relics of a former peneplanation.

The minimum altitude in this area ranges from 380 feet on the Mississippi River near Kimmswick to 450 feet on the Missouri River near Defiance. The maximum elevation is 975 feet at the crest of a hill in Jefferson County. Maximum relief is about 500 feet. The maximum local relief is about 250 feet.

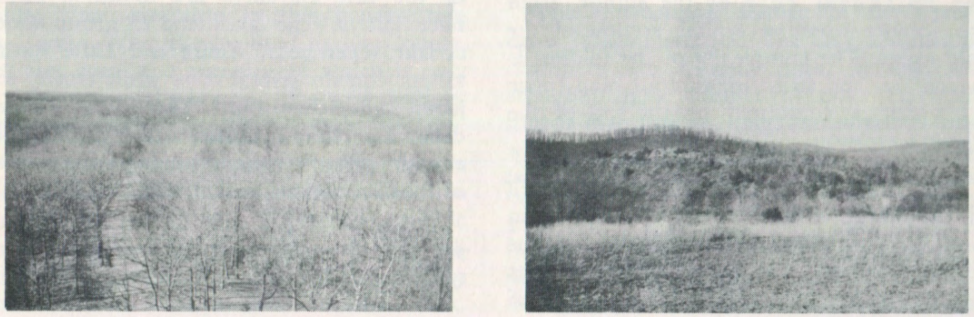
Geology

A. Stratigraphy - A stratigraphic succession of Upper Cambrian and Lower Ordovician formations is exposed outward from the center of the Ozark dome. Toward the periphery, however, these dipping beds are overlain by younger strata which have been eroded away in the central region. The major exposures in the fissure cave region consist of Upper Ordovician formations and a sandstone of questionable Devonian age. The ridges are capped by Mississippian formations (Fern Glen, Burlington, Keokuk) which are poorly exposed.

Geologic maps from theses on file at Washington University (Bethke, 1956; Bousfield, 1949; Danielson, 1956; Doman, 1955; Faber, 1955; Good, 1948; Krummel, 1956; Smith, 1958; Thomas, 1956) and St. Louis University (Piani, 1962) essentially cover the fissure cave area with only a few minor gaps. All of the geologic maps show the Upper Ordovician formations in great detail, and it is in these formations that most of the known caves of the area occur. A composite geologic map of the entire area has been prepared from the individual maps (plate 2).

The St. Peter formation is the oldest formation generally exposed in the fissure cave area. It consists of a very pure, porous sandstone averaging about 130 feet in thickness. It is overlain by the Joachim formation, a fine grained, impure dolomite with thin beds of shale at intervals, and reaching about 120 feet in thickness. Above it lies the Plattin formation, an impure limestone with some beds of dolomite, and attaining a thickness of about 120 feet. The next higher formation is the Decorah, consisting of about 20 feet of interbedded shale and limestone. The youngest Ordovician formation generally found in the fissure cave area is the Kimmswick, a very pure, coarsely crystalline limestone. The formation attains a thickness of 100 feet in some parts of the fissure cave area. An even younger Ordovician formation, the Maquoketa, is found over only a small part of this area; it consists primarily of shale and reaches a thickness of 20 feet where it is present. The next younger formation, the Glen Park, is a very thin limestone of possible Devonian age. It is overlain by the Bushberg formation, a thin, friable sandstone which caps many of the ridges in the fissure cave region. This sandstone of possible Devonian age is only 20 feet thick, but exposures are moderately frequent. Above the Bushberg lie the Fern Glen, Burlington, and Keokuk formations of Mississippian age. These formations cap the higher ridges and underlie some undissected uplands. These higher formations are greatly weathered and usually poorly exposed in the fissure cave area; for this reason these formations are not differentiated on the thesis geologic maps, nor on plate 2. Likewise, the Plattin and thin Decorah formations are mapped as one unit. Similarly, the thin Maquoketa formation, where present, is included with the Kimmswick, and the thin Glen Park and Bushberg formations are mapped as part of the undifferentiated Mississippian formations.

View to the south from Allenton Fire Tower. View to the east from Allenton Fire Tower.



View to the north from Allenton Fire Tower. Rockwoods Reservation along Carr Creek.

Typical ravine. Entrance to Catacomb Cave. (dark slit: one foot wide).

Figure 2
Typical topography, fissure cave area, eastern Missouri.

B. Structural Geology - The fissure cave region is located on the northeast flank of the Ozark dome, a roughly circular area subjected to regional uplift. Maximum uplift has occurred on the central region of the dome, causing strata in the peripheral areas to dip away from the central region at low angles.

The local dip of the beds is interrupted in the fissure cave region by folds trending northwest. The folding is a series of anticlines, synclines, and a monocline, all generally trending northwest with a few minor exceptions. The fold belt has been named the *Rockwoods Fold* by the author, from the locality where a typical section of the fold exists. The complexity of the folding is evident on the structure contour map (plate 3) which is contoured on the top of the Plattin formation.

The dominant structure of the fold belt is the Eureka-House Springs anticline. An accompanying syncline parallels the anticline to the southwest. The Eureka-House Springs anticline is asymmetric; the dip northeast of the crest is relatively low (only a few degrees), but on the southwest (synclinal) side dips up to 25 degrees are found (Doman, 1955). Another important structure, the Sand Ridge monocline, lies south and southeast of the Eureka-House Springs anticline. The Herculaneum fault, which is roughly colinear with the Sand Ridge monocline, begins in the southeastern corner of the geologic map and extends to the Mississippi River lowlands. The southwest (upthrow) side of the fault is displaced a maximum of 20 feet within the mapped area. The Wildhorse Creek anticline is northwest and approximately on the axis of the Eureka-House Springs anticline beyond an intervening saddle. Other small anticlines and synclines are scattered about the area.

To the east and northeast beyond the structurally disturbed area the beds dip to a maximum depth in the Illinois Basin (Weller, 1945). The limit of the Ozarks region is not far from the folding and is considered to be coincident with the outcrops of Mississippian formations (Branson, 1944).

CHARACTERISTICS OF THE FISSURE CAVES

A. Location - The fissure caves were first encountered and recognized as a distinct type in western St. Louis County. Additional caves of this type were discovered in adjacent regions of northern Jefferson County, northeastern Franklin County, and southwestern St. Charles County.

The caves occur in rather hilly terrain. Forest cover in the region is common, and all known caves of this group occur in forested areas. Cave entrances are often on hillsides formed by ravines which constitute headwaters of creeks or in creek valleys. Few of the cave entrances are found in major river valleys. The caves tend to group about certain watersheds; Antire and Little Antire valleys contain several caves while closely adjacent valleys have none. There is also a tendency for two or more of the caves to occur in groups; nine groupings among 24 of the fissure caves are known.

Locations of presently known fissure caves are plotted on figure 3. A number of caves of possible fissure type occuring in the area are also shown on the map and differentiated by symbols.

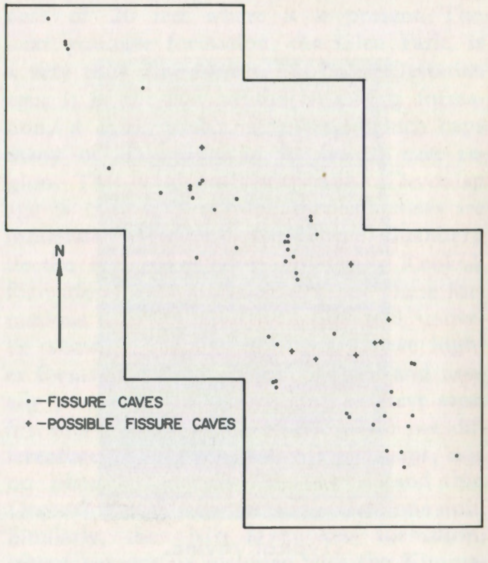


Figure 3.
Locations of fissure caves plotted on an outline map of the fissure cave region.

B. Entrances - The entrances to the fissure caves usually occur in the cave ceilings, forming either pits or steep rubble slopes. Only a few of the caves have adit entrances, and in these cases upper, pit type entrances also exist.

Entrances may be anywhere on the hillsides, from the bottom of ravines to almost the crests of hills, but generally partway up the hills. In the few cases where entrances are at or near the bottoms of hills, they are usually still fairly high with respect to the main surface drainage in the same vicinity. One exception to this general rule is Totem Pole Pit in St. Charles County, 40 feet deep, the entrance of which is only 25 feet above the bottom of a well developed stream valley.

The entrances are usually small, with little or no surrounding rock outcrops. In some cases they simply consist of an abrupt hole in the forest floor. In many instances migration of the soil from around the entrance into the cave has produced a small sink. Typical configurations of various entrance types are shown in figure 4.

C. Structure of the Caves - The fissure caves may be roughly grouped into two classes: (1) the pit type, and (2) the passage type. These two classifications do not represent different kinds of caves but simply denote two extremes of a spectrum of types including many intermediate forms. The pit type caves are simple pits with no horizontal passages and having limited lateral development. In the passage type caves there is greater lateral development, although the term "pit" may still be retained as part of the cave name.

The outstanding feature of the fissure caves is joint control. The cave passages or chambers are typically high, narrow, and straight. In a number of cases caves are higher than they are long, and entrances form where the ceiling is intersected by the surface. Ceiling heights range between one and 90 feet, and the total depth of one pit is 113 feet. The ceilings of the caves are often irregular in height, and abrupt changes of 15 to 20 feet are not uncommon. Floors are also usually quite irregular. Bedrock floors are

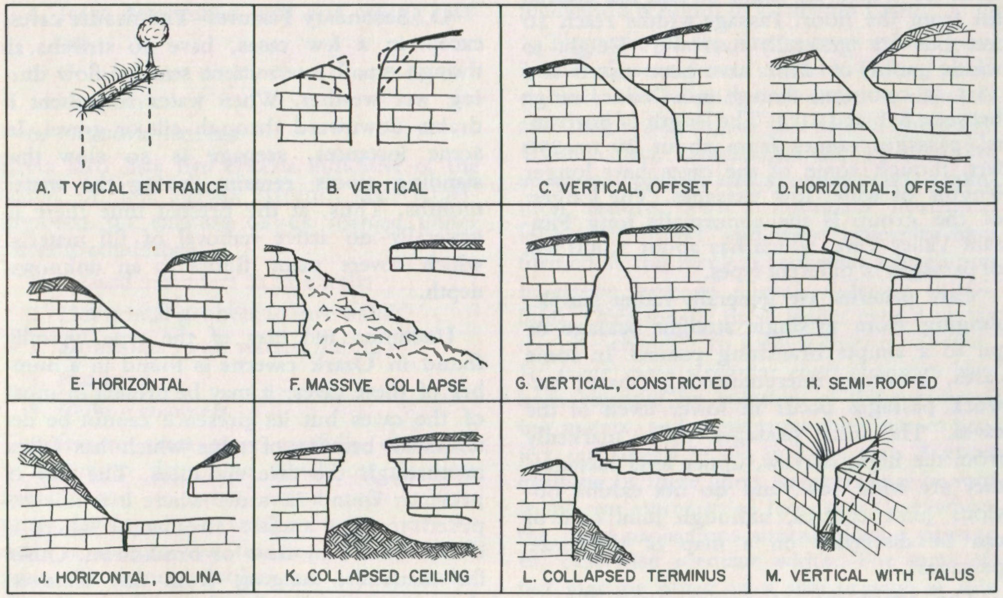


Figure 4.
Entrance diagrams of fissure caves.

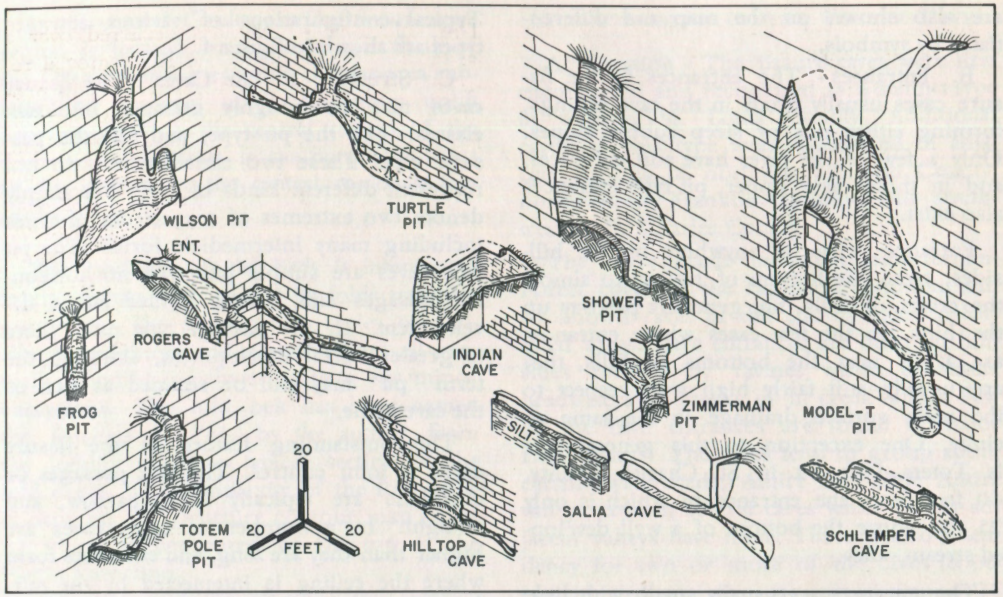


Figure 5.
Typical fissure caves.

rare and are found only occasionally where the irregular bedrock projects above fill material or where an active stream has cleared fill from the floor. Passage widths reach 10 feet but are generally narrower. Height to width ratios of 25:1 have been noted and 15:1 is common, though most values range between 5:1 and 10:1. The length of horizontal passages ranges from about 20 to 250 feet, though some of the caves have longer lengths of wide, low passages. The longest of the group is the abnormally long Pleasant Valley Cave, which has about 5,000 feet of passages of different types.

Cave patterns are generally rather simple, ranging from a single straight passage or pit to a simple branching pattern. In some cases, however, interconnecting (maze) network passages occur in lower levels of the caves. The maze passages differ markedly from the high, narrow, upper level passages; they are wide, low, and do not exhibit obvious joint control, although joint control can be discerned on a map of the maze passages.

The structures of representative fissure caves are shown in figure 5. No one single cave is typical because of individual variations which exist among members of the group.

D. Secondary Features - The fissure caves, except in a few cases, have no streams, although small intermittent streams flow during wet weather. When water is present it drains downward through silt or gravel. In some instances, seepage is so slow that standing pools remain during the wetter months. Thus, at the present time there is generally no active removal of fill material which covers many floors to an unknown depth.

Unctuous red clay of the type typically found in Ozark caverns is found in a number of these caves; it may be present in most of the caves but its presence cannot be determined because of talus which has fallen in through the cave entrances. The clay is presently found in areas where it is not exposed to free surface streams or where it is not buried by talus or breakdown. Other fill materials, ranging from fine textured clays to coarse sand and gravel, are found in many of the fissure caves. Common brown silt, probably of recent origin, is found in most of the caves near entrances or along the banks of streams.

Speleothems are somewhat scarce in the fissure caves and not expecially noteworthy, although some are unusual, such as the hanging rimstone cascade in Catacomb Cave. Large amounts of wall flowstone are often found, probably because the narrow dimensions of the caves prevented free hanging speleothems from reaching any appreciable size.

SPELEOGENESIS OF THE FISSURE CAVES

A. Developmental Conditions - One of the primary questions of speleogenesis is whether the caves initially developed as a result of solution under completely subaqueous (phreatic) conditions or as the result of subterrenean free surface (vadose) streams. Bretz (1956) lists six criteria indicative of solution which have been found in Missouri caves:

1. Spongework
2. Wall and ceiling pockets
3. Bedding and joint plane anastomoses
4. Joint determined wall and ceiling cavities
5. Continuous rock spans across cave chambers
6. Network patterns

Bretz also lists five criteria indicative of the action of free surface streams, later superimposed on existing caves formed under phreatic conditions:

1. Incised meanders in cave walls
2. Horizontal grooves in cave walls
3. Dome pits (with vertical fluting)
4. Pendants
5. Ceiling channels

The fissure caves were carefully examined in order to determine which criteria were present and to what extent such criteria were developed. After evaluation of the data, it appears that the caves have formed primarily through solutional activity under phreatic conditions.

Primarily, the fissure caves consist of solutionally enlarged joints or groups of joints. The solutional activity has occurred over a large area of the joint but has removed relatively little depth of wall material, thus producing the typical high, narrow cross-section. Passages in these caves occasionally terminate by becoming impassably narrow. In many cases the effect of joint control is immediately apparent. The effect is especially evident on a cave map, as in the case of the Catacomb Cave map (figure 6). The joints enlarged by solution may intersect at any angle from 30 degrees up to about 160 degrees, above which angle the effect becomes difficult to distinguish. The walls of the passages usually continue linearly up to the point of intersection. At smaller angles of intersection the walls lying between the two passages meet at an acute angle to form a sharp, angular cusp. Some cave passages exhibiting the higher angles of intersection proceed in a zigzag fashion. Passages sometimes continue on past the point of intersection, forming a wall slot or a small side passage. Some high narrow passages are slightly inclined from the vertical, indicating that the joint on which these passages formed was slightly inclined from the vertical. A good example of this inclination is found in Catacomb Cave.

The walls of the fissure caves exhibit gently curved, contiguous surfaces. Ceiling pockets and small domes several feet in diameter and height are found in a few of the caves. Upon closer examination the walls exhibit solutional pitting, and spongework is a common feature. Some nominally horizontal ledges are found, and these appear to have formed as the result of solution acting upon limestone beds of slightly differing solubilities. Occasionally these ledges extend across the cave chamber to form a continuous span. In some cases irregular chert stringers have been exposed by solution of the surrounding matrix, and these ropy chert masses project out several inches into the cave. A good example of these chert stringers may be seen in the rear extremity of Horneker Cave, where the chert projections almost block a passage of otherwise adequate width. The same effect may be noted in a side passage of this same cave in conjunction with bedding plane anastomoses. In many of the caves fossils have been exposed by differential so-

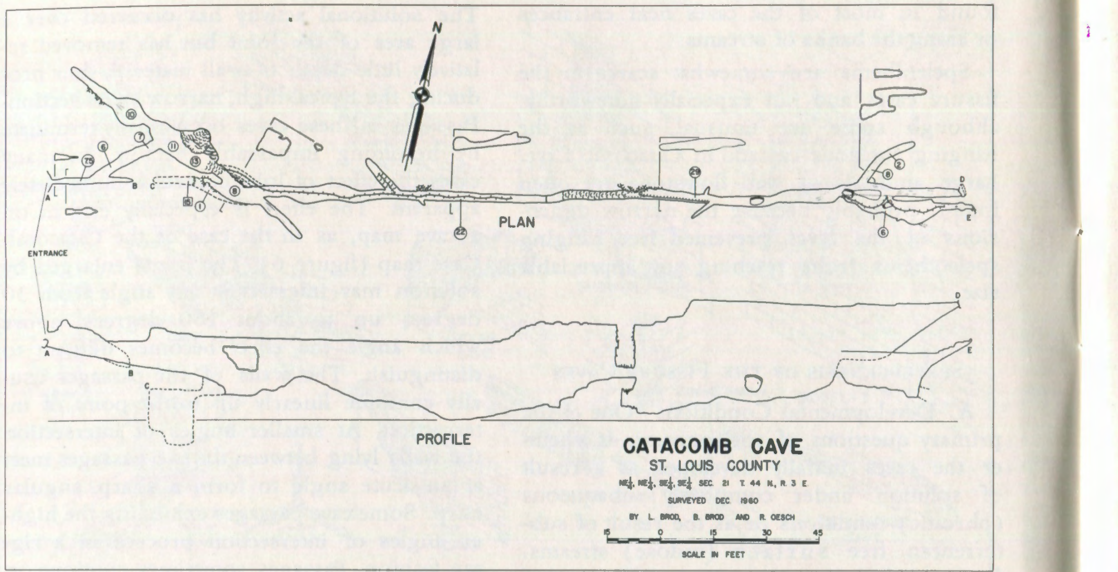


Figure 6.
Catacomb Cave — a typical fissure cave surveyed in plan and section.

lution. In Catacomb Cave exposed cephalopod fossils project several inches beyond the matrix rock into the cave. In Boemler Cave concretionary masses apparently of limonite and brachiopod fossils have been similarly exposed.

Red clay has been found in a number of the fissure caves. Bretz (1956) ascribes the deposition of this clay to a later period during the phreatic phase of cave development, when gradation toward base level had lessened the velocity of subsurface circulation, allowing the clay particles to settle out of suspension. The clay particles are an insoluble residue resulting from the decomposition of limestone by surface weathering. The extremely fine particles were brought into the water filled caves by slowly circulating ground water and eventually settled. In time great quantities of clay accumulated, filling many caves to the ceiling. Filling with clay to this extent has occurred in at least one of the fissure caves. In Meyer Cave the red clay has been found about one foot below the ceiling in the entrance chamber, which has a ceiling height of 15 feet. Other caves record a considerable depth of filling with red clay. In Pleasant Valley Cave the clay is found in the upper level in a side passage off the Big Room, and in the lower level in one of the mezzanine passages. The vertical separation of these two occurrences is 40 feet. A similar situation is found in Hoene Hole where three passage levels are connected by a pit. The red clay is found in a crevice of the pit about 15 feet above a second deposit in the intermediate level. In Brother Huberts Pit the clay is found in a side passage 16 feet above a floor consisting of talus of unknown depth. In Horneker Cave the clay is found over a vertical range of 20 feet. The present day deposits of clay are mostly small remnants of the original deposit and occur on the floors of horizontal passages and isolated pockets in the walls of pits. The existence of the red clay in many of the fissure caves cannot be determined because of the difficulty of examining high, inaccessible walls or areas buried by entrance talus. The presence of red clay in those caves where it is found indicates a long period of reduced phreatic circulation.

Of the various criteria associated with free surface streams, several have not been found in the fissure caves. No examples of incised meanders or roof pendants have ever been found in any of the caves. Horizontal grooves are found only in those few caves which today possess a free surface stream, such as Pleasant Valley Cave and Lostmouth Cave. Current scallops, produced by water moving at a moderate velocity, have not been found in any of the caves. Ceiling channels have been found in Catacomb Cave and Horneker Cave. These channels are sinuous half-tubes of semi-elliptical cross section incised in cave ceilings, and resembling stream channels except for being inverted. Bretz (1956) ascribes the development of ceiling channels to a time when the original cave was filled almost to the ceiling with clay or stream deposits, forcing a free surface stream up against the cave ceiling. The channel was then formed by solution (and probably some corrosion) of the ceiling rock. The residual fill material in the vicinity of the ceiling channels in the two caves is red clay; thus the ceiling channels may be an indirect evidence of the former red clay fill extending to the ceiling.

The only other effect ascribed to free surface stream activity which has been found in the fissure caves is the vertical fluting associated with domepits. This fluting is found on walls where free falling water carves vertical grooves in the wall rock. A good example of vertical fluting is found in Anderson Cave. The fluting extends down from what appears to be an impervious layer about 20 feet above the present cave floor, and it covers a major portion of the lower walls of the cave. Some sections of the lower walls, however, are not fluted and exhibit solution pitting and bedding plane anastomoses characteristic of solution. The fluted wall is recessed about 10 inches back from the unfluted wall surface, and the fluted surfaces exhibit none of the random pitting resulting from solution. In addition, the fluting is strictly vertical, while non-fluted wall surfaces display an undulatory character. Thus, the vertical fluting appears to be superimposed on an older chamber of solutional origin.

Vertical fluting also occurs in Horneker Cave, in association with the only example of what might be termed a domepit to be found in the fissure caves. Water falling from a ceiling crevice has incised a vertical niche in one side of a joint controlled, solutional passage. The contrast between the niche and the older passage upon which it is superimposed is striking. Solution has removed softer portions of the limestone in the passage, forming spongework. In the niche where the fluting occurs spongework is absent. Moreover, the floor of the niche is about seven feet higher than the floor of the passage and is covered with water-washed chert fragments. The niche is obviously a younger feature than the passage.

The preceeding evidence indicates that the fissure caves have formed primarily by the action of solution under phreatic conditions. Vadose effects produced by the action of free surface streams have been, in all cases studied, later modifications of an existing chamber originally formed under phreatic conditions.

B. Geologic Horizons - The majority of the fissure caves are in the Plattin formation of middle Ordovician age. In fact, all known caves in the Plattin are of the fissure type. Conversely, the few caves in other formations within this area (except for those in the Kimmswick) have a non-fissure structure. These caves for the most part contain small streams and are themselves quite small.

Several fissure caves have lower level mazes, and Pleasant Valley Cave in Jefferson County is of particular interest (Yokum, 1960). This cave, with a vertical extent of 110 feet, is developed in both the Plattin and underlying Joachim formations. The obviously joint controlled entrance pit lies in the Plattin formation while the lower stream passage and maze are in the Joachim formation. Shales which occur at the formational contact are found toward the bottom of the "Big Room" in the upper level. The lower level differs completely from the upper level and has none of the characteristics usually associated with the fissure caves. This difference might be understandable in the case of the lower level stream passage which has undergone extensive vadose modification. However, there is also a contrasting difference in the "mezzanine" section of the lower level, a maze of tunnel-like tubes with no vadose features and an absence of determinable joint control. On the basis of these differences, it seems reasonable to assume that the structure of the passages is at least partially due to the difference in lithologic characteristics of the two formations in which these sections of the cave are located.

The same explanation may be extended to the entire group of fissure caves; that is: the typical high, narrow passages result in part from the lithologic characteristics of the Plattin formation, which consists generally of a hard, sublithographic limestone with a fairly high percentage of insoluble material. The character of the rock throughout the greater portion of the formation is peculiar and distinctive, being a hard matrix filled with branching tubes of a softer material of a somewhat different color. The solutional removal of the softer material leaves the harder matrix with a "worm-eaten" appearance any may have a substantial effect on the eventual solution of the matrix material itself.

Some dolomite is present in the Plattin formation, and it is in these beds that horizontal passages of the fissure caves are often developed, thus demonstrating lithologic control. A good example of this control is found in Horneker Cave in St. Louis County. The main passage is typically narrow and attains considerable height. Branching off from the main passage at right angles are a number of horizontal passages generally about five feet wide and from one to three feet high, with almost perfectly level ceilings along their entire length. The passages are generally straight, thereby indicating the possibility of joint control. These passages are developed in a thin bed of dolomite which in places is very weak and large pieces can easily be broken off. The surface of the rock can be easily rubbed to form a dolomite sand. (The original cement was probably calcite.) A similar condition exists in the dolomite found in the lower level of Pleasant Valley Cave, except that the grain structure is finer. In that case too the surface of the rock is weak, having weathered to a mudlike consistency. The structural weakening is probably responsible for the development of extensive passages in the dolomite, because in this condition the rock is easily attacked.

A small number of fissure caves are developed in the Kimmswick formation, and their form is similar to those fissure caves in the Plattin. The difference in lithology of the two limestones apparently has little or no effect, and the typical joint control configuration is found in both. In Ehlers Pit, which has an entrance in the Kimmswick and penetrates through the Decorah formation into the Plattin, a distinct change in the cave structure occurs between the limits of the Decorah contacts with the Plattin and Kimmswick formations. The entrance itself is a narrow crevice, while the main lower room is a roughly cylindrical chamber of solutional origin with solutionally enlarged joints at either end. Furthermore, the entrance and the lower chamber are offset with respect to each other; the transitional portion in the Decorah takes the form of a roughly conical chamber with its axis tilted at a considerable angle from the vertical. At least a portion of this transition has been formed by collapse of the thin, interbedded Decorah shale and limestone, and the bottom of the pit contains a large pile of the resulting breakdown. The original transitional chamber must have been fairly constricted in contrast to the larger chamber beneath. Thus this situation indicates that the shale beds have had a definite effect on the solutional development of the cave. It does not appear that the relatively small size of the entrance compared to the lower room is particularly significant, and it should not be inferred that solution produces greater enlargement in the Plattin formation. It is probable that the intermediate Decorah beds caused solution to proceed at different rates in the two formations due to differences in volumetric flow and differing flow patterns with time.

No fissure caves have been observed in the top of the Kimmswick at its contact with the Bushberg sandstone. Two pits, however, are located slightly below the contact. The walls of these pits extend vertically to the surface at which point they are abruptly terminated. Judging from this configuration it appears that these pits at one time extended up to the Bushberg contact. Although definite evidence is lacking, it is likely that the overlying sandstone had a profound modifying influence on the structure of fissure caves in the Kimmswick limestone. In the case of the two mentioned pits, the sandstone probably formed a ceiling over the pit chambers before it was erosionally destroyed.

The stratigraphic positions of the various fissure caves are shown in figure 7. The horizontal position of the various caves cannot be accurately depicted, but the figure does provide a rough representation of the relationship of the caves to geologic structure.

C. Geologic History of the Area

1. General Sequence of Cave Development - All evidence indicates that the caves were initially formed and enlarged almost to their present dimensions under phreatic conditions. These conditions obviously do not exist at the caves today, and a great amount of erosional dissection has occurred since this solutional development took place. Practically nothing is known about the area during this initial speleogenetic period. It was a time of erosional downcutting, a destruction of landforms which left essentially no clues.

The process of solutional enlargement eventually slowed and finally nearly ceased as the circulation of phreatic water slowed, because of an erosional lowering of the topography toward a base level. The caves then began to fill with the fine textured red clay. It is not known how long this fill period lasted, but it must have required a considerable length of time for appreciable clay to have accumulated.

A new phase of cave development began with renewal of the erosional processes. The erosional downcutting which lowered the land surfaces also lowered the water table to the level of the caves and lower. A renewal of circulation, in the form of free-surface streams, removed the clay fill and permitted the deposition of flowstone.

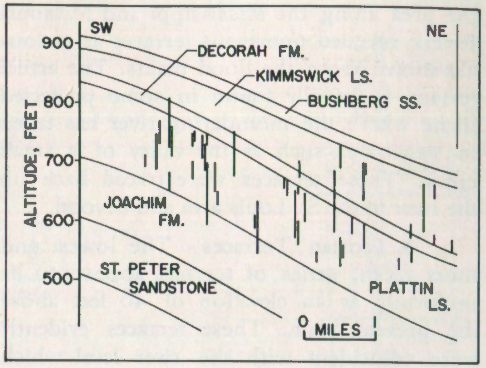


Figure 7.
Relationship of fissure caves to altitude and geologic structure on the northeast flank of the Ozark Dome.

2. Pleistocene Glacial Periods - The causative agency primarily responsible for this new cycle of erosion is the series of four Pleistocene glacial periods and the attendant drop in sea level due to the accumulation of great quantities of ice in continental glaciers. Fairbridge (1960) has delineated both the magnitude and age of the successive cumulative drops in sea level. The sea level dropped appreciably during each glacial advance and rose again when the glaciers melted. These falls in sea level were sufficient to initiate major erosional cycles, and a renewal of erosion followed each lowering of sea level. The fall in sea level at the shore caused an increase in stream gradient and this gradient propagated itself upstream, causing a renewal of erosion as it advanced. Each later glaciation caused another erosional gradient to be propagated upstream. Each of these cycles of post-glacial erosion caused the river to deepen its valley and eventually form a new alluvial plain. Remnants of the old plain were left in the form of elevated terraces along the river valley. This process has been delineated by Haag (1962). He showed how the erosion cycles formed a series of terraces which have been correlated with a similar series of marine deposits in the Gulf of Mexico. These terraces were traced up the Mississippi River almost to southern Missouri. Russell (1957) reported that in the vicinity of Forrest City, Arkansas, terraces were found at altitudes of 40, 100, 200, and 350 feet above the present alluvial plain.

A study of topographic maps covering

the area along the Mississippi and Missouri Rivers revealed numerous terraces at various elevations above the flood plains. The actual terrace is usually found in some protected niche where the meandering river has failed to penetrate, such as the valley of a small creek. These terraces were traced back up the river to the St. Louis area and beyond.

3. Peorian Terraces - The lowest and most recent series of terraces appears to lie uniformly at an elevation of 40 feet above the present plain. These terraces evidently were coincident with the river level which existed just prior to the Late Wisconsin glaciation. Radiocarbon analysis of a sample found on one of these terraces near the town of Bonfils (just east of St. Charles on the Missouri River) gives an age of 18,000 years (Howe, 1961). Being of relatively recent origin, these terraces are fairly well preserved and are found in relative profusion from above Jefferson City on the Missouri River to beyond Cape Girardeau on the Mississippi River. A number of these terraces can be found on almost every topographic quadrangle along these two rivers. They are also found on the lower Meramec River in the vicinity of Kirkwood.

4. Sangamon Terraces - A second series of terraces, smaller in number than the first, is found at a slightly higher elevation, about 70 feet above the present flood plain. These terraces correspond to an alluvial plain developed just prior to the early Wisconsin erosional cycle. The relatively small separation between these first two sets of terraces leads to a certain amount of difficulty in defining the age of the terrace. The terraces are best distinguished on topographic maps having ten-foot contour intervals. In addition, the effects of erosion may have altered the original terrace so that the determination of the original elevation is somewhat difficult. Despite these problems, a fairly large number of well defined surfaces of this age have been found along the three major rivers.

5. Yarmouth Terraces - A third group of terraces, evidently of pre-Illinoian age, is found at elevations of 140-150 feet above the present flood plain. These elevations agree closely with the elevation of Illinoian glacial till deposits found in Ste. Genevieve County about 130-140 feet above the Mississippi flood plain (Weller and St. Clair, 1928). Being older than the lower terraces, these terraces have been subject to erosional dissection for a longer period of time. As a result, there are fewer terraces and good examples occur infrequently. Enough terraces do exist at this elevation to permit a good correlation. A fairly well-preserved terrace of this age is found at the town of Chesterfield on the Missouri River.

6. Pre-Nebraskan Strath - Careful scrutiny of many topographic maps failed to reveal any well defined terraces above the pre-Illinoian elevations. Instead, the next identifiable levels occur as flattened highlands at elevations of about 240 feet above the alluvial plain. Large areas in eastern St. Louis County and Perry County are found at this height. Particular examples are the area in and around the city of Kirkwood and the area around Perryville. This elevation is identifiable as the pre-Nebraskan surface and correlates with the highest of the terraces at Forrest City, Arkansas. At Forrest City, however, this surface lies about 350 feet above the present alluvial plain. This altitude may have originally been greater due to later isostatic lowering resulting from the great weight of sediment deposited in the Mississippi embayment during the Pleistocene glacial advances and retreats. The displacement appears to diminish in southern Missouri, and the relative height of this highest surface decreases steadily northward to a stable figure of 240 feet in Perry County, as shown in figure 8.

This preglacial surface was quite extensive compared to later terraces. The surface was not as well developed as a peneplain, however.

7. Pliocene Surface - Remnants of an even earlier surface are found at a number of locations in the fissure cave region at altitudes of about 800 feet, approximately 150 feet higher than the preglacial strath and 370 feet above present base level. A well preserved remnant of this plain is found at Pond, Missouri. Numerous other remnants scattered over a large area

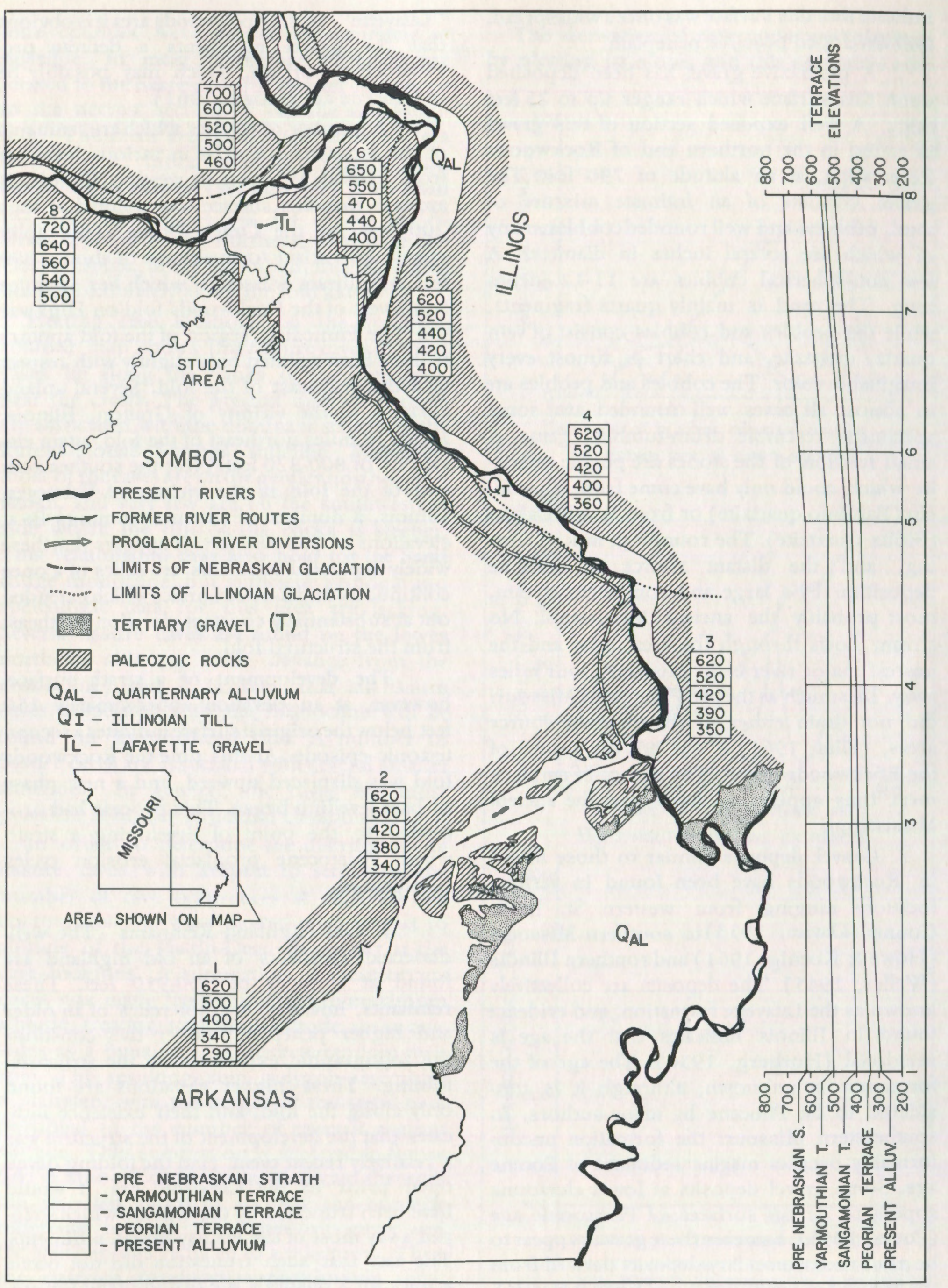


Figure 8.
Pleistocene and Tertiary features of eastern Missouri.

indicate that this surface was once a widespread, well developed possible peneplain.

A distinctive gravel has been deposited upon this surface which ranges up to 25 feet thick. A well exposed section of this gravel is found in the northern end of Rockwoods Reservation, at an altitude of 790 feet. The gravel consists of an intimate mixture of sand, pebbles, and well rounded cobbles, many of which are several inches in diameter. A few non-spherical cobbles are 11-12 inches long. The sand is mainly quartz fragments, while the pebbles and cobbles consist of vein quartz, quartzite, and chert of almost every imaginable color. The cobbles and pebbles are in almost all cases well rounded and some specimens resemble drum-tumbled gems. A small fraction of the stones are purple quartzite which could only have come from Wisconsin (Baraboo quartzite) or from South Dakota (Sioux quartzite). The rounding, lack of sorting, and the distant source all indicate deposition by a large and competent stream, most probably the ancient Mississippi. No stream flows through the area today and the nearest major river is the Missouri, four miles away. Inasmuch as the pre-Pleistocene Missouri did not drain either of the quartzite source areas, (Flint, 1961) it was not the source of the Rockwoods gravel. The agency of emplacement thus appears to have been the ancient Mississippi.

Gravel deposits similar to those found in Rockwoods have been found in various locations ranging from western St. Louis County (Davies, 1953) to southern Missouri (Howe & Koenig, 1961) and southern Illinois (Weller, 1945). The deposits are collectively known as the Lafayette formation, and evidence found in Illinois indicates that the age is preglacial (Horberg, 1956). The age of the formation is unknown, although it is considered to be Pliocene by many authors. In southeastern Missouri the formation unconformably overlies marine sediment of Eocene age. Some gravel deposits at lower elevations appear to lie on surfaces of Pleistocene age (Potter, 1955); however these gravels appear to be reworked secondary deposits derived from the earlier Lafayette formation (Bretz & Harris). Unfortunately there has been no differentiation of the various deposits and all are termed "Lafayette". In the Rockwoods area it is obvious that the gravel represents a definite pre-Pleistocene horizon, which may possibly be of Pliocene age (Howe, 1961).

A number of patches which are remnants of the same surface exist in various localities from central Missouri to western Illinois. It appears that this surface was uplifted at least 200 feet on the Ozark Dome. This uplift raised the surface to an altitude of about 1000 feet at Sullivan, Missouri, which lies 30 miles southwest of the Rockwoods fold on Highway 66. The immediate region of the fold appears to have been uplifted only slightly with respect to areas northeast of the fold. Several upland surfaces in the vicinity of Grafton, Illinois, about 30 miles northeast of the fold, attain elevations of 800-820 feet. Near the southeastern end of the fold in the vicinity of Valmeyer, Illinois, a number of flattened summits lie at elevations of 760-780 feet. It appears that these widely separated remnants are relics of a once continuous undissected surface which extended out at substantially constant elevation northeast from the structural fold.

The development of a strath surface, however, at an elevation approximately 150 feet below the original surface indicates a second tectonic episode. At this time the Rockwoods fold was displaced upward, and a new phase of base levelling began. This process had proceeded to the point of developing a strath when Pleistocene proglacial erosion cycles commenced.

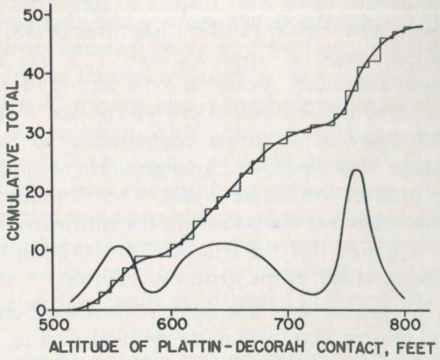
9. Old Highland Remnants - The well-dissected remnants of an old highland are found at altitudes of 900-950 feet. These remnants, however, are not relics of an older and higher peneplain; rather they constitute the topographic expression of the structural folding. These higher elevations are found only along the fold, and their existence indicates that the development of the structure was a relatively recent event. Had the folding developed prior to the Cenozoic Era, it would have been truncated by the erosion which stripped away most of the Pennsylvanian sediments. The fact that such truncation did not occur argues for a relatively late origin of this feature.

D. Distribution of the Fissure Caves - The locations of all known fissure-type caves in four counties were plotted as accurately as possible. In most cases cave entrances are located to the nearest fourth quarter section, or to the nearest second of latitude and longitude. The caves are distributed more or less in a line, or more correctly a narrow band extending northwest (see figure 3). This band lies approximately along the strike of the strata dipping to the northeast away from the Ozark Dome. More important, this band also lies approximately along the fold axes.

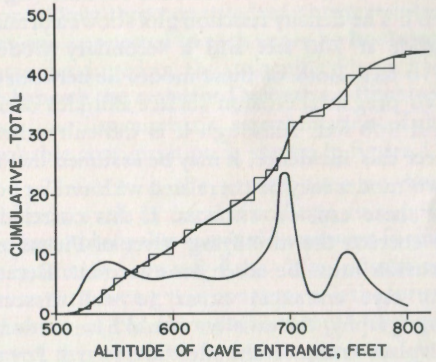
Plotting cave locations on the structure contour map shows that fissure caves in most cases lie along the flanks of the anticlines, near the crests. The greatest number of caves are associated with the dominant structure, the Eureka-House Springs anticline. Moreover, most of the caves are on the gentler northeastern flanks, and very few are on the southwestern side where the dip of the rocks is steeper. This relationship may also hold for the Sand Ridge monocline, but sufficient geologic and speleologic data for this area are lacking. Several fissure caves are found on the lower northeast side (at some distance from the monocline) and it is likely that all fissure caves associated with the monocline will be found on its northeast side. A number of fissure caves are associated with several smaller anticlines. In general, the caves are most prevalent at higher structural elevations.

In order to determine the distribution of fissure caves with respect to structure, the number of cave occurences at each 10 foot contour interval were plotted with respect to altitude of the Plattin-Decorah contact at the cave locations. A summation of these occurences was made from minimum to maximum altitude, treating structural altitude at the cave sides as a function of a discrete random variable. The resulting sum polygon resembles a stairstep, with the height of the steps proportional to the number of caves at a given altitude. This summation is depicted in figure 9A. A smooth curve was constructed through the stairstep function so that the numeric difference between the continuous curve and the stairstep was reduced to a minimum. Thus the stairstep produces approximately equal positive and negative excursions with respect to the curve. This smooth curve represents the cumulative distribution function.

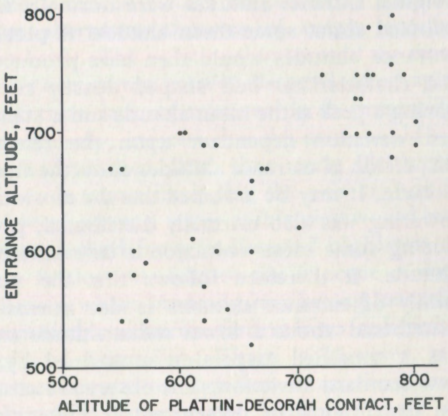
The derivative of this curve was obtained by plotting its slope, and this new curve con-



A. DISTRIBUTION OF CAVE LOCATIONS



B. DISTRIBUTION OF CAVE ENTRANCES



C. SCATTER DIAGRAM OF ENTRANCE ALTITUDES WITH RESPECT TO STRUCTURAL ALTITUDES

Figure 9.
Distribution diagrams of the fissure caves.

stitutes the density function of the cave distribution. The amplitude of this second curve represents the relative frequency of occurence of fissure caves with respect to structural altitude. The density function has three peaks, the major peak at approximately 750 feet and two secondary peaks at 650 and 550 feet, referred to the Plattin-Decorah contact. A careful study of locations contributing to these peaks was made, but no significant secondary parameter could be found. Contributions to the peaks are derived from the entire area and it appears that the trimodal distribution is a characteristic of the group as a whole.

A similar plot was made of the distribution of fissure cave entrances with respect to entrance altitude, treating the number of occurrences as a discrete random variable (figure 9B). The density function plot shows a primary mode at 700 feet and a secondary mode at 750 feet. Both of these modes lie between the two preglacial erosion surface altitudes of 650 and 800 feet. Although it is difficult to interpret this incidence, it may be assumed that the two modes may be correlated with one or both of these erosion surfaces. If this correlation is correct, the modifying effect of Pleistocene erosion must be taken into account. Because the cave entrances occur in well dissected topography, the erosion would have tended to displace entrance altitudes downward. For the sake of argument, it may be assumed that the original entrance altitudes were normally distributed about some mean altitude. A plot of entrance altitudes would then have produced the characteristic bell shaped density curve having a peak at the mean altitude and a standard deviation dependent upon the relative dispersion of entrance altitudes about the mean altitude. It may be assumed that the erosional lowering was also normally distributed, producing some mean reduction in cave entrance altitude. It therefore follows that the new family of entrance altitudes is also normally distributed about a lower mean altitude and has a modified dispersion as defined by a new standard deviation. The observed statistical distribution of present entrance altitudes shown in figure 9B does not exhibit normality, and this discrepancy may be caused by one or more of the following reasons:

1. The original, pre-erosion surfaces were not normally distributed.

2. The erosional lowering was not normally distributed.

3. The entrance altitude data is biased.

There is a distinct possibility that the first two hypotheses are both true because of inhomogeneities in the geologic formations. A scatter diagram of entrance incidence with respect to both topographic altitude and structural altitude of the Plattin-Decorah contact was prepared (figure 9C). This diagram shows that there is a definite linear relationship between entrance altitude and structural altitude. The equation of a line which best fits this postulated relationship, the mean square regression line, was found by the method of least squares, based on the choice of structural altitude as the independent variable:

$$A = 222 + 0.653\,S$$

where A = entrance altitude
S = structural altitude of Plattin-Decorah contact

The regression line was utilized in computing the correlation coefficient r, where r is defined

$$r = \sqrt{\frac{\sum (A - A)^2}{\sum (A_k - A)^2}}$$

$$\text{where } A = \frac{\sum_{1}^{n} A_k}{n} = \text{mean entrance altitude}$$

A_k = altitude of a specific cave entrance
n = total number of cave entrances

Computing the correlation coefficient by this means gave the value $r = 0.75$. With $r = 0$ random dispersion and $r = 1$ corresponding to a perfectly linear relationship (all points on a line), the resulting correlation coefficient of 0.75 implies a significant relationship between entrance altitude and the geologic structure. Thus, although initial altitudes may have been normally distributed, subsequent erosion has modified this original entrance distribution to reflect the bias introduced by geologic structure. The choice of the Plattin-Decorah contact as an index of this structure is purely arbitrary. It is possible that the use of some other formational contact would produce an even larger correlation coefficient.

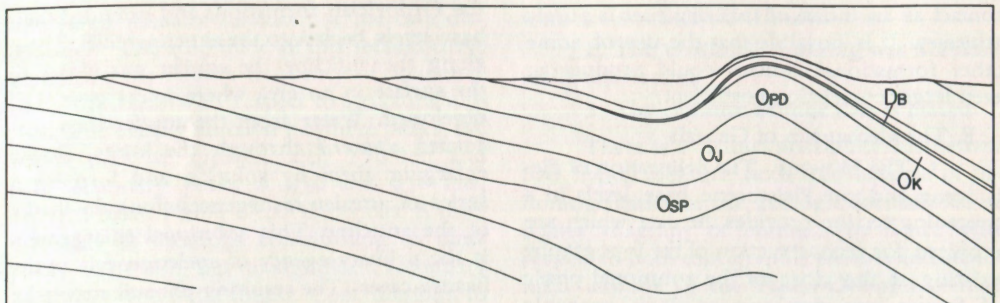
E. The Mechanism of Genesis

1. The Impetus - The delineation of Pleistocene and pre-Pleistocene base levels in a preceding section provides the data which are required for reconstruction of the topography existing at the close of the solutional phase of fissure cave development. It is probable that the valley altitudes in the area corresponded to the altitude of the pre-Nebraskan strath. At this stage the fissure caves, wholly or partially filled with clay, still lay beneath the water table. The existing strath constituted the latter phase of an erosional cycle which was initiated by an uplifting of the Ozark Dome. The uplift was accompanied by an increased tilting of the strata on the edges of the dome, including the region southwest of Rockwoods fold. Prior to the uplift, the strata would have lain at a gentler angle and the present locally exposed Ordovician formations would have been intact and undissected far into Franklin County. The various formations, emerging at a very low angle of dip, were erosionally truncated to form the essentially flat surface existing at that time and were thereby exposed over a considerable area. The permeable St. Peter sandstone was thus exposed and filled with ground water; little circulation occurred, however, because of a low hydraulic gradient.

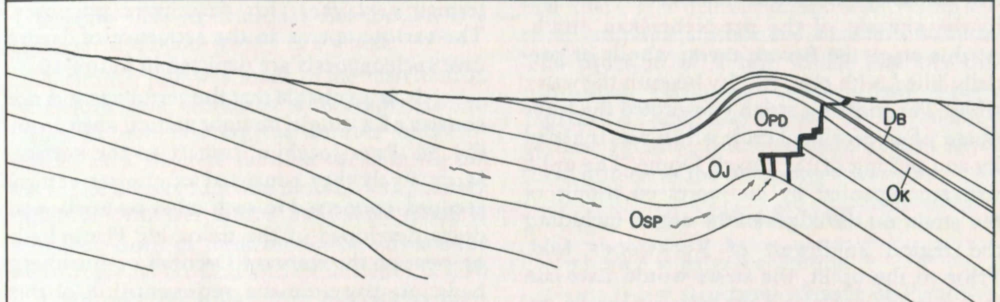
When the uplift occurred, the slight dip of the strata was increased, and the exposed truncated outcrops were lifted with respect to the anticlinal fold. This relative displacement created a hydraulic gradient in the sandstone aquifer. Northeast of the outcrops the ground water was carried deep underground by the dipping sandstone beds. However, it was entrapped and prevented from coming to the surface by the relatively thick sedimentary formations. This situation existed except at the Rockwoods fold where the Ordovician rocks in the fold projected over 100 feet above the then-existing lowland surface. Although the various strata maintained a nominally constant thickness over the anticline, local valleys, developed during a prior erosional period, existed in many places. These valleys breached the Ordovician formations and extended their base levels back into the anticlinal fold. Thus, along the anticline the aquifer was closer to the surface in an area where joints were well developed. Water from the aquifer then percolated *upward* through the joints, slowly enlarging them by solution and forming a series of artesian resurgences along the flanks of the anticline. This solutional enlargement is the primary agency of speleogenesis of the fissure caves. The resulting phreatic networks in which this upward flow occurred have been termed *vertiducts* for descriptive purposes. The various events in the sequence of fissure cave speleogenesis are depicted in figure 10.

It is probable that the vertiducts did not consist of a single straight vertical shaft from the St. Peter-Joachim contact to the surface. More likely they consisted of shorter vertical sections connected to each other by horizontal ducts developed in the dolomitic Plattin beds or beneath the resistant Decorah or Bushberg beds. A diagrammatic representation of this probable configuration is shown in figure 11.

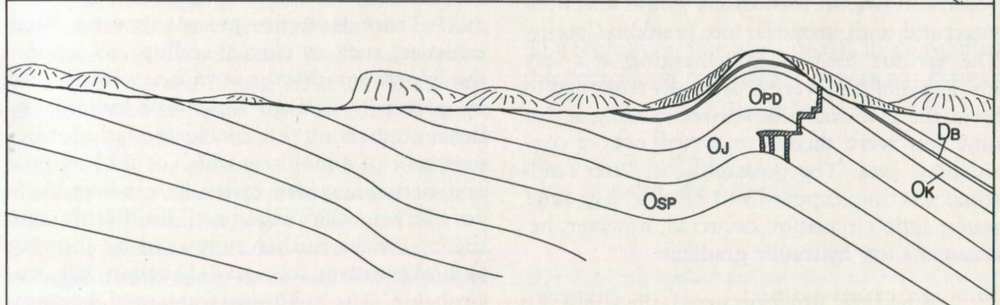
There is at the present time no direct evidence, such as current scallops, to support the hypothesis that the vertiducts were formed by primarily upward flow. The indirect evidence supporting this conclusion is the former existence of conditions which could have generated the requisite hydraulic gradient. As a corollary to this argument, the fissure cave theory can be further supported by showing that alternative theories of origin are improbable. The solutional features of the caves, their occurrence in a well dissected topography, and their lack of relationship to present-day topography, indicate that the caves could not have developed later than early Pleistocene time. It seems likely that the primary source of local ground water at this time would have been derived from undissected highlands on the Rockwoods fold or the Pliocene erosion surface, where elevated areas having low relief provided conditions favorable to subsurface ground water flow. There is, however, very little evidence for such flow under the present remnants of these old surfaces. There are fewer than 10 sinks depicted on topographic maps of the entire fissure cave region, yet an equivalent area in the Missouri Ozarks having subsurface drainage will display hundreds of



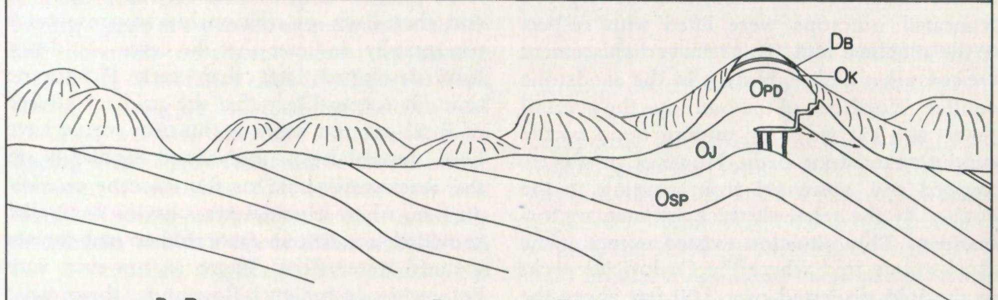
A. SITUATION PRIOR TO FORMATION OF FISSURE CAVES



B. UPLIFT AND REGIONAL TILTING - INITIAL SPELEOGENESIS



C. CESSATION OF ARTESIAN CIRCULATION - SEDIMENT INFILLING



D. RENEWED EROSION DURING PLEISTOCENE EPOCH - FLUSHING OF CAVES

Figure 10.
Phases of fissure cave genesis.

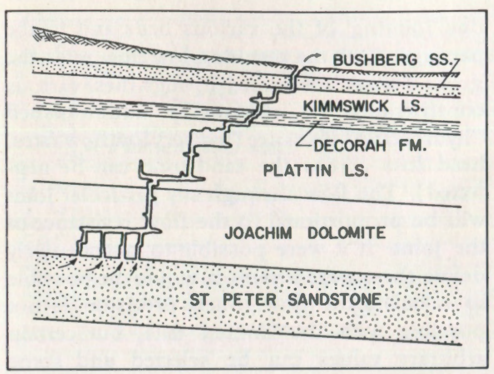


Figure 11.
Fissure cave structure, late artesian stage.

sinks. In addition, there are only two very small horizontal caves exposed in the dissected flanks of these upland remnants, while larger horizontal caves are frequently found around the periphery of upland surfaces in the central Ozarks. It appears then that the present-day remnants of these old erosion surfaces and highlands were not in general a significant factor in fissure cave speleogenesis.

If any part of these surfaces were involved, they must have been around the old periphery which has now been removed by subsequent erosion, in the vicinity of the present fissure caves. Thus, it might be assumed that the fissure caves are themselves the headwater remnants of a formerly integrated drainage system. It is then necessary to explain why the flow apparently had a large vertical component, implying a vertical hydraulic gradient, despite the fact that the water moved at a relatively low velocity. It seems incongruous that in the case of Model T Pit, for example, ground water would flow vertically downward to 110 feet below the water table without developing any horizontal passages. On the other hand, Pleasant Valley Cave has well developed network passages 95 feet below its entrance. These passages, however, extend in the opposite direction from the logical site of resurgence.

Probably the most anomalous situation is found at Horneker Cave, which lies in an abandoned meander loop of the Meramec River. This loop is an entrenched meander which attained essentially its present configuration on the Pliocene erosion surface prior to speleogenesis. The loop is about 4.5 miles long by 1.5 miles wide. Horneker Cave is situated at about the center of the neck of land enclosed by the loop. The main passage of the cave is aligned through the hill from one side of the loop to the other near the present crest. It is difficult to explain how this cave could be formed by local ground water at least 50 feet below the minimum base level at that time, and at a horizon devoid of either impermeable beds or permeable aquifers. Ground water from a higher surface would have flowed out to the river along the strike of the beds just below the water table, where the hydraulic gradient was maximum.

There are, of course, many fissure caves which by themselves do not either support or contradict any of several postulated modes of speleogenesis. It is therefore necessary that the caves be considered as a group with an implied common origin. Any theory must attempt to explain all apparent inconsistencies. Theories of fissure cave origin based on the local collection of ground water fail to provide adequate explanations for all of the group features.

2. Ground Water and the Solutional Process - One implication of the postulated theory of speleogenesis is that the fissure caves in the initial stages of development were all members of a single integrated subsurface drainage system. In that case, why did a multiplicity of resurgences form, rather than only a few favored ones? It seems likely that the large number of resurgences was due at least in part to the hydraulic impedence of the St. Peter sandstone which tended to establish uniform subsurface circulation. Thus, vertiducts in close proximity could develop relatively independently and with minimum effect upon each other.

It is possible to investigate these effects in some detail by the application of Darcy's law, which states that flow through porous media is proportional to hydraulic permeability, the cross-sectional area, and the hydraulic gradient (Todd, 1959). This law may be expressed in either its algebraic or derivative form:

$$F = \frac{kHA}{L} \quad \text{or,} \quad F = k\frac{dh}{dl} \qquad (1)$$

where k is defined as the coefficient of permeability, A is the cross sectional area of the duct, and $\frac{dh}{dl}$ is the differential hydraulic gradient, which can also be expressed as the ratio of total head H to length of duct L. The factor $\frac{1}{a}$ in equation (1) above is similar to the electrical factor $\frac{Lr}{A}$ where r is the coefficient of volumetric resistivity and the entire factor is the definition of electrical resistance of a volume of homogeneous material. Thus, by analogy the factor $\frac{1}{a}$ can be defined as the hydraulic resistance of porous media and symbolized as R. Substituting the quantity R into (1) gives:

$$F = \frac{H}{R} \qquad (2)$$

Equation (2) states that flow is proportional to head (pressure due to differential elevation) and inversely proportional to hydraulic resistance; in this form it is analogous to Ohm's law for electric circuits.

This result can be utilized in discussing the flow of ground water during the initial phase of speleogenesis. In this particular case the ground water flows first through the sandstone aquifer and then through joints and partings in limestone and shale. The sandstone and limestone beds are thus in series with respect to ground-water flow. Since in electrical circuits, series resistances add, the same concept may be applied to the hydralic situation; and (2) may be rewritten:

$$F = \frac{H}{R_s + R_1} \qquad (3)$$

where R_s is the sandstone resistance and R_1 is the resistance of the overlying limestone beds. From (3) it can be seen that even if the hydraulic resistance of the limestone approaches zero, the flow will be limited to a certain maximum value by the hydraulic resistance of the sandstone. Conversely, if the resistance of the limestone is quite high with respect to the resistance of the sandstone, it is evident that the flow will be low and essentially independent of the sandstone. In fact, this latter situation will be the condition that exists in the initial phase of speleogenesis, before any appreciable solution has occurred (assuming no prior solutional activity has occurred). Immediately following the period of uplift, upward flow through the beds was restricted to the extremely fine jointing of the various beds and to the partings. With the resulting low flow rates, the ground water was forced through these various constrictions by virtually undiminished "hydrostatic" pressure (for very low flow rates, head loss across the sandstone can be neglected). The flow through any particular joint will be proportional to the flow resistance of the joint. If it were possible to quantitatively define these parameters, it would be possible to calculate the flow. Such precision is not possible with the limited data, but certain arbitrary values can be selected and some idea of relative flows can be obtained.

In order to implement flow calculations a rather simple mathematical model of the initial speleogenetic situation was constructed, as shown in figure 12A. This model corresponds to a cross section across the strike of the anticlinal structure and adjacent regions immediately following uplift. The primary characteristics of this model are (1) a linear sloping surface, and (2) a subsurface layer of constant thickness, linearly sloping except for an anticlinal arch, and intersecting the surface at the origin. The linear (land) surface is not strictly an accurate representation; for one thing, there was a substantial area above base level at the anticline. However, it has been pointed out that the fissure caves tended to form in valleys where the base level had been locally extended back into the anticline. Thus, though not strictly accurate this representation is sufficient for purposes of calculation. The model's subsurface layer is intended to represent the St. Peter sandstone. As such, it too is not strictly accurate, but as in the previous case is sufficient for present needs.

The parameters of the two surfaces (reduced to two-dimensional form in the cross section) are taken from the actual physical situation. The origin, x = 0, is taken at the intersection of the surface of the St. Peter sandstone with the original land surface existing at the beginning of cave solution. The altitude of this intersection was approximately 900 feet (referred to present mean sea level), so that taking y in hundreds of feet gives y=9. The anticlinal arch was situated approximately 16 miles northeast of this intersection, and base level there was 800 feet, so that at x=16 y=8. With these points located it is possible to write the equation of the line which corresponds with surface elevation, h:

$$h = 9 - x/16 = 9 - .0625x \qquad (4)$$

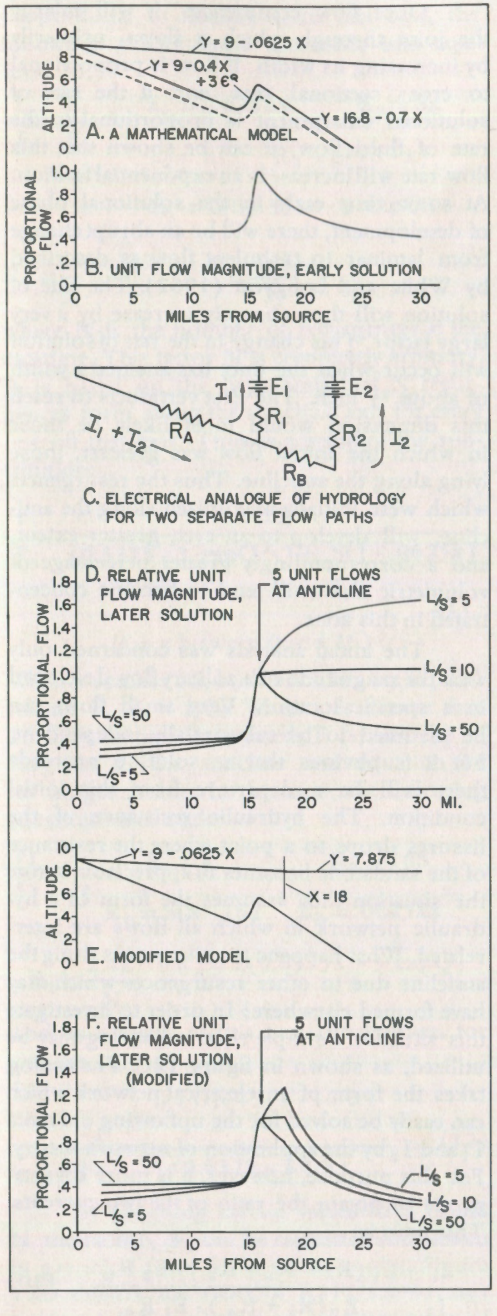


Figure 12.

Flow diagrams, fissure cave region.

The subsurface layer (in reality its top surface) can be represented by two straight lines connected at x = 16 by an exponent curve representing the Rockwoods anticlinal arch. For the initial line y = 9 at x = 0 and y = 5.6 at the anticline. This elevation, however, is about 300 feet higher than the elevation of a linear slope; thus y' = 2.6 at x = 16. For the equation of the line:

$$y' = 9 - \frac{6.4x}{16} \text{ or } y' = 9 - 0.4x$$

For the exponential portion, the total rise of 300 feet is centered at x = 16. This rise can be represented by:

$$y'' = 3 \exp(Q)$$

$$\text{where } Q = (x - 16)^2.$$

The equation of the subsurface for x between 0 and 16 is:

$$y = 9 - 0.4x + 3 \exp(Q)$$

Beyond the anticlinal arch the strata dip at a nominally constant rate, and the equation is again that of a straight line. From (5), at x = 16, y = 5.6. In addition, the dip is approximately 200 feet in three miles, giving a slope of approximately 0.7. The equation of the line is thus:

$$y = -0.7x + 16.8 \qquad (6)$$

Equations (5) and (6) can now be utilized in (2). The hydraulic head, H, is simply the altitude difference between the source and resurgence of the ground water:

$$H = 9 - h \text{ or } H = .0625x$$

The St. Peter sandstone has a nominally constant thickness so that hydraulic resistance of the sandstone layer can be assumed to be simply proportional to distance; therefore R=Sx where S is a constant having the dimensional form of resistance-per-mile along the formation. In this case the factor S differs from the volumetric resistivity by having width and thickness included in it as constants. The vertical resistance of the limestone beds has also been assumed to be proportional to one linear dimension, the thickness of the intervening rock between the St. Peter sandstone and the surface. This is a very crude approximation because it does not take into account the known and unknown effects of horizontal bedding and varying permeabilities. The thickness of the intervening beds is simply equal to (h - y). The vertical (limestone) resistance is then given as:

$$R_1 = L(h - y)$$

where L is a constant of proportionality having the dimensional form of resistance-per-hundred-feet of limestone. It should be noted that L may be considered truly constant only during the initial period of speleogenesis. Once solution takes place, L will begin to decrease and continue to do so as the vertiducts enlarge.

With R , R , and H defined, (3) may be rewritten:

$$F = \frac{H}{R_s + R_1} = \frac{(y_0 - h)}{Sx + L(h - y)} \qquad (7)$$

Substituting (4) and (5) or (6) into (7) gives:

$$F = \frac{.0625x}{Sx + L(0.3375 - 3\exp(Q)} \qquad (8)$$

for x less than 16

and:

$$F = \frac{.0625x}{Sx + L(0.6375x - 7.8)} \qquad (6)$$

for x greater than 16

By assigning certain specific values to S and L, the above equations can be solved and displayed in graphic form. The ratio of S to L is important and it is necessary for L to be much greater than S in order to accurately represent the initial solutional period. Figure 12B is a plot of equations (8) and (9) for several values of L and S. It is interesting to note that the flow increases markedly at the anticline where the intervening limestone beds are thinnest.

In the preceding calculations the intervening limestone beds were treated as a homogeneous medium of low permeability. In actuality, the flow occurred through joints, or joint-bedding plane-joint combinations. Thus, as a more appropriate approximation, flow can be treated as the product of the continuous flow function shown in figure 12B and a discrete random variable of unit amplitude. The resulting distribution would take the form of discrete discontinuous amplitudes, with the continuous flow function forming an amplitude envelope.

Once flow commences, it will enlarge the joint through which it flows, primarily by increasing its width. If flow is proportional to cross sectional area, and if the rate of solutional enlargment is proportional to the rate of fluid flow, it can be shown that this flow rate will increase in an exponential fashion. At some time early in the solutional phase of development, there will be an abrupt change from laminar to turbulent flow as described by White and Longyear (1962). The rate of solution will then abruptly increase by a very large factor. This change in the rate of solution will occur when the duct has attained a width of about ½ inch. The first vertiducts to reach this dimension would most likely be those in which the initial flow was greatest, those lying along the anticline. Thus the resurgences, which were initially maximized along the anticline, will develop to an even greater extent, and a correspondingly greater percentage of volumetric flow will tend to become concentrated in this zone.

The initial analysis was concerned only with the magnitude of a solitary flow developed in a specific location. Very small flows can be assumed to be substantially independent, but it is obvious that as solution proceeds there will be a departure from this initial condition. The hydraulic resistance of the fissures drops to a point where the resistance of the sandstone becomes an appreciable factor; the situation then assumes the form of a hydraulic network in which all flows are interrelated. What happens to resurgences along the anticline due to other resurgences which may have formed elsewhere? In order to investigate this situation a simple electrical analog may be utilized, as shown in figure 12C. The analog takes the form of an electrical network which can easily be solved for the upflowing currents I_1 and I_2 by the application of network theory. For this purpose, however, it is more advantageous to obtain the ratio of the two currents. This ratio is:

$$\frac{I_1}{I_2} = \frac{E_1(R_2 + R_a + R_b) - E_2 R_a}{E_2(R_1 + R_a) - E_1 R_a} \qquad (10)$$

If F_2 is given as the upflow at the anticline, the proportional flow F_1 can be found at any point between the origin and the anticline, assuming hydraulic resistance of the limestone beds is proportional to thickness. In this case, the following substitutions are made into equation 10:

$$\frac{I_1}{I_2} = \frac{F_1}{F_2} \qquad E_1 = .0625kx \qquad R_a = Sx$$

$$E_2 = k \qquad R_b = S(16 - x)$$

$$R_1 = L(0.3375x - 3\exp Q)$$

$$R_2 = \frac{L}{N}(0.3375x - 3) = \frac{2.4L}{N}$$

where N is the number of resurgences at the anticline. This factor N is completely arbitrary. It is based on the hypothesis that N resurgences form along the anticlinal axis for every one off that axis. Thus as a result of the substitution:

$$\frac{F_1}{F_2} = \frac{0.15/N}{(0.3375 - 3\exp Q/x) + \frac{S}{L}(1 - .0625x)} \qquad (11)$$

(for x between 0 and 16)

When x reaches 16, both branches are in parallel and $F_1/F_2 = 1/N$. When x is greater than 16 the situation is inverted; F is now the resurgence at the anticline and equation 11 no longer holds. In this case, the following substitution is made:

$$\frac{F_1}{F_2} = \frac{I_1}{I_2} \qquad E_1 = k \qquad R_a = 16S$$

$$R_b = S(x - 16) \qquad E_2 = .0625kx$$

$$R_1 = \frac{2.4L}{N} \qquad R_2 = L(0.6375x - 3\exp Q)$$

And as a result of this new substitution, for x above 16:

$$\frac{F_1}{F_2} = \frac{0.15/N + \frac{S}{L}(1 - 16/x)}{(0.6375 - 7.8/x)} \qquad (12)$$

By assigning certain values to S, L, and N, the ratio F_1/F_2 can be calculated and plotted in graphical form for a variation of x. Figure 12D depicts the ratio of F_1/F_2 for various ratios of L/S, utilizing an arbitrary value of N=5. The plotted results show an interesting trend. When the ratio L/S is relatively high, corresponding to an early phase of solution, maximum flow occurs at the anticlinal crest. As expected, the proportional flow is low between the source (origin) and the anticline but reaches unity at the crest. Beyond the crest the proportional flow drops to a lower value. At a later time, when the L/S ratio is lower due to decreasing L, the proportional flow remains relatively constant beyond the anticlinal crest. For yet lower L/S ratios, the proportional flow increases above unity for increasing x, as shown by the flow curves.

It is obvious that this result is not a good representation of the true situation. The difficulty stems from a limitation of the model, which features a linearly sloping surface beyond the anticlinal crest. The old erosion remnants, however, indicate that the surface apparently levelled off at about 800 feet. This effect may be incorporated into equation (12) by assigning a constant value to E_2, the value depending on the position of the break in the slope. For convenience this position was selected to be x=18. The magnitude of hydraulic head at this point is .0625k (18) or 1.125k. In a like manner,

$$R_2 = L(h - y) = L(0.7x - 8.925)$$

When these values are substituted into the flow equation, a variation of (12) is produced.

$$\frac{F_1}{F_2} = \frac{2.7/N + 2S/L}{(0.7x - 8.925) + \frac{S}{L}(x - 18)}$$

Figure 12F was plotted for (11) for values of x between 0 and 16, (12) from 16 to 18, and (13) for values of x above 18. These curves all show a sharp break at x = 18. In addition, the curves show an inital peak at x = 16 for high L/S and a second peak at x = 18 for lower X/S ratios. It is possible that this effect may explain the odd trimodal distribution of the fissure caves with respect to structural elevation.

It may be possible to extend this type of analysis into the solutional processes. However, the difficulties involved in mathematically describing the complex structural and topographic surfaces are considerable. One possible alternative would involve the construction and operation of a laboratory scale model, operating in the manner of the salt-block analogs developed by Ewers (1962).

One of the difficulties which besets the mathematical approach arises from the fact that the ascending water did not necessarily flow vertically from the aquifer to the surface. The configuration of the flow paths shown on figure 9 indicate that the hydraulic resistance is not a simple linear function of bedding thickness. The situation is complicated by beds of differing solubilities and poorly permeable impediments.

Another primary difficulty stems from the inadequacy of the simple electrical analog to adequately depict the true hydraulic situation. In the neighborhood of a vertiduct base there would be a convergence of flow and an increasing hydraulic gradient. Effectively, this change would appear to be equivalent to a nonlinear sandstone resistance. The existence of basal cave networks in the Joachim formation tends to confirm the presence of increased hydraulic gradients around a point of resurgence, for which the networks compensated by locally lowering the hydraulic gradient.

3. Significance of Distribution

The characteristics of fissure caves in the different geologic formations supports the postulated theory of speleogenesis for these caves. This theory holds that the caves began to develop at a time when the base level was coincident with the Pliocene erosion surface. At that time the major portion of the Plattin limestone lay beneath the base level. Had speleogenesis begun later, base level would have been lower, and the distribution of caves would have been different. If, for instance, solution had begun during early Pleistocene time, there would have been less tendency for caves to form in the Plattin limestone from artesian resurgence, as at that time erosion had exposed the Joachim dolomite. The caves then probably would have tended to develop primarily in the Joachim exposures where hydraulic head was greater and the intervening rock thinner.

The structure of the fold is somewhat irregular, and in some saddle areas the beds were not arched significantly. In these areas, no fissure caves have been found. The Eureka-House Springs syncline to the southwest of the anticline, with beds at an altitude comparable to the saddle areas, also contains no fissure caves. Likewise, the high plateau areas along the fold are barren of caves. Careful study of the geologic structure has shown that in general the high plateau areas lie approximately along the crest of the fold. In these high areas there was no tendency for fissure caves to form, primarily because of the lack of hydraulic head. The intervening strata were also thicker, since these areas were untouched by erosion.

4. Caves in the Kimmswick Limestone - Another implication of the theory of fissure cave speleogenesis is that it predicts that there should be fissure caves in the Kimmswick limestone. Fissure caves are found in the Kimmswick formation, although their number constitutes less than 20 percent of the total number known. A few of the caves occur in areas where the Kimmswick lay above base level. Most of the caves, however, are on areas where the Kimmswick was present during the initial solutional period.

It appears that the primary factor which has reduced the incidence of caves in this formation is erosional removal. The formation is relatively thin along the fold and suffered considerable dissection. This dissection was particularly significant because the caves tended to form in ravines and not on interfluves where dissection was minimal. When base level was lowered, the ravines were subjected to the maximum downcutting. Thus, the upper (Kimmswick-Decorah) portions of the caves were truncated, leaving only the lower sections intact, in most cases. In fact, one example (Ehlers Pit) is known in which the upper five feet are in the Kimmswick limestone. Another pit on the opposite side of the valley is 30 feet below the Kimmswick-Decorah contact. A lateral displacement of only 150 feet would have placed the entrance above the contact. Obviously, then, dissection has been a significant factor affecting cave incidence in the various formations.

5. Depth of Solution - Inasmuch as some precise data concerning fissure cave speleogenesis are known, it is a simple task to define the maximum depth at which artesion solution took place. It is evident that solution must have occurred down to the St. Peter sandstone from which the water emerged. The sandstone arched to a maximum elevation of 580 feet on the anticline while base level was about 800 feet; thus solution would have taken place down to a depth of 220 feet. This figure is based on the assumption that solution took place only along the sub-surface crest of the sandstone, which is not necessarily the case. If solution occurred farther down on the fold, it would have taken place at greater depth, and 280-300 feet would be a possible depth.

TABLE 2 – TERRACE CORRELATIONS.

Age	Local basal altitude	Miss. R. terraces	Illinoian terraces (Horberg)
Peorian	440	Prairie	
Sangamon	470	Montgomery	Havana Strath
Yarmouth	560	Bentley	Central Illinois peneplain
Pre-Nebraskan	650	Williana	Lancaster
Pliocene	800	--------	Dodgeville

* Present local altitude is 400 feet

Another method of determining the depth of solution consists of establishing the lowest known depths of the caves at the present time compared to the old base level at the 800 foot elevation. The results of this comparison are listed in table 3. Some of the greater depths of solution in this table compare rather closely with the previously inferred depths based on the elevation of the Joachim-St. Peter contact. The computed depths of solution in this table range down to 310 feet, conditions which would definitely be described by some authors as "deep phreatic solution".

6. Other Modes of Speleogenesis - Great care must be exercised in assigning pits to the fissure cave group merely because they occur in the appropriate area. There is always the possibility that some of the pits may have developed through an entirely different speleogenetic process, and at a different time. The rejuvenation during Pleistocene time was a powerful factor which could have given rise to caves and pits somewhat similar in structure to the fissure caves. Merrill (1960) discusses the effect of a sandstone cap on the development of domepits in the Mammoth Cave region of Kentucky. He demonstrates how surface water percolating down through local fractures or porous zones in the sandstone cap can dissolve deep vertical pits in the underlying limestone. This explanation conceivably could be pertinent in the case of the fissure caves, inasmuch as the Bushberg sandstone is found throughout the area and is a common caprock material. The domepits described by Merrill, however, possess two distinctive features: they possess vertical flutes and are generally circular in cross section. Fissure caves, on the other hand, exhibit spongework and are generally not circular in cross section. A few of the caves of the fissure group have pit configurations approaching circularity, but the pits are always contiguous with solutionally enlarged joints, and spongework on the quasi-circular walls is common. It is believed that the somewhat cylindrical chambers of the fissure caves result from turbulence in the artesian flow during the later part of the solutional period. Any

TABLE 3 – DEPTH OF SOLUTION.

Cave	Cave Ent. Alt. -	Depth From Ent.	Lowest Cave Altitude	Depth Below 800′
Frog Pit	560	26	530	270
Nightowl Pit	540	22	520	280
Totem Pole Pit	540	41	500	300
Turtle Pit	580	26	550	250
Bald Hill Chimney	580	- -	580	220
Hilltop Cave	550	27	520	280
New Rankin Cave	550	10*	540*	260
Rankin Cave	670	10	660	140
Salia Cave	610	30	580	220
Schlemper Cave	650	16	630	170
Crankshaft Pit	620	85	560	240
Fox Cave	670	85	590	210
Friedman Cave	600	30	570	230
Highway Pit	520	30*	490*	310
Hoene Hole	570	46	520	280
Rice Cave	- - -	- -	600	200
Rogers Cave	670	32	640	160
Alcove Cave	540	- -	540	260

* estimated depth

vadose features found in these pits are superimposed on an orginial phreatic chamber.

Thus, all pits in the fissure cave region are evidently developed according to the postulated mode of speleogenesis. It is unlikely that any other pits formed by a different process will be found in this area.

The question of origin is still open to discussion in the case of Fults Saltpeter Cave. This cavern is in the bluff on the east bank of the Mississippi River in Illinois, near the town of Fults. Although the area was not studied in detail, this cave is tentatively considered to be a fissure cave, primarily because it appears to lie on the Illinois extension of the Rockwoods fold belt. This cave has other typical fissure cave features including an interior pit and narrow, joint controlled, crevice type passages. The presence of red clay suggests development prior to formation of the pre-Nebraskan erosion surface. An extremely large pothole in the horizontal entrance is obviously a vadose stream feature incompatible with the solution features found elsewhere in the cave, and the pothole is believed to represent a later modification of an original artesian cave.

In studying the wide diversity of types which comprise the fissure cave group, it has been observed that certain characteristics are generally encountered. Thus, in assigning a cave to the fissure cave group, the following criteria have been employed:

1. A pit, or crevice-sink entrance.
2. Straight passages with a high, narrow cross section.
3. Ceiling domes and walls with spongework.
4. Development in either the Plattin or Kimmswick limestone.
5. Appropriate location along the Rockwoods fold axis.
6. The presence of red clay or similar fine sediment having no lamination.

It is not necessary for all of these features to be present in a fissure cave. In any event, assignment to the group should be based on a judicious evaluation of the cave's individual characteristics.

F. Deposition and Removal of Fill - As the topography was graded to base level during late Pliocene and early Pleistocene time, artesian circulation slowed and solution practically ceased. Concurrent with degradation of the surface the fissure caves filled with red clay. With the onset of Pleistocene proglacial erosion, river valleys were deepened and cut below the old plains. Tributary ravines penetrating the anticline eventually were lowered below the elevation of the caves. The caves were then drained, and the water flowed out along bedding planes in the lower network passages. The onset of surface erosion was relatively rapid, and subsurface drainage probably followed a similar course, thus effectively flushing away much of the clay fill.

The importance of the post-glacial erosional periods can be clearly seen in examining a group of several fissure caves in Jefferson County (Pleasant Valley Cave, Crankshaft Pit). These caves open in ravines tributary to Antire Creek, which eventually flows into the Meramec River. Although the entrances are on the ravine hillsides, the lowest levels of the caves lie quite a few feet below the bottom of the ravine. In the case of Pleasant Valley Cave, the modern cave stream lies about 40 feet below the level of Antire Creek. Obviously the caves do not drain into these valleys. The question of drainage is answered by the fact that that Big River lies on the other side of an intervening hill, less than one mile away and over 100 feet lower. In addition, tributary valleys to Big River penetrate the hill to less than ½ mile from the caves. A small spring in one of these ravines may be the resurgence of the stream in Pleasant Valley Cave. It is evident that the deepening of the Big River Valley was responsible for the draining of these caves. The relationship of the caves to Big River Valley is depicted in figure 12 E. The known terrace elevations have been projected back to the caves, assuming a subsurface gradient of 20 feet per mile and a surface fall of 20 feet to the river. On the basis of these assumptions, the figure shows that the upper level of Pleasant Valley Cave could have been drained as early as the post-Nebraskan erosion. Gravel fill in the upper level might date from the Aftonian Interglacial Stage. The cave as a whole probably was not drained before the post-Kansan erosion at the opening of the Yarmouth Interglacial Stage.

In the case of Crankshaft Pit, an even later drainage is suggested. The cave probably was not drained even in part before the Sangamon erosion. Thus, this cave has been an open, air-filled chamber for no longer than about 100,000 years. Pleistocene vertebrate remains in a gravel fill near the bottom of the cave might shed some light upon this postulated date, but as yet no adequate study has been made of these remains.

It is obvious that fill removal is also a modifying factor in fissure cave distribution. It is not only necessary that the caves initially form, but in addition the caves must be in an area where later renewed subsurface circulation can carry off the filling clay. Of course, this renewed circulation is assumed to be basically vadose in nature, though the flow velocities need not be high. In a number of cases there is evidence of repetitive flush and fill cycles, indicating the variable nature of the fill removal process. Actually, most of the caves still retain an appreciable quantity of fill, and it is highly likely that the traversable portions represent only a minor fraction of the total volume of the original caves.

G. Entrance Development - The age of the fissure cave entrances is not known with any certainty, but they appear to be of relatively recent origin, much more recent than the caves themselves. The caves, even the essentially horizontal ones, develop small sinks at the entrance. The sinks act as natural funnels into which mud, stones, and vegetation naturally fall. This process will in time either plug the entrance or fill the cave. Thus, the formation of the present entrances has taken place in relatively recent time. One reason for this late development is found in the structure of the caves. As noted previously, the caves did not develop as a single vertical shaft but rather as a series of partial shafts offset laterally from each other. Such an offset was almost certain to have existed at the lower contact of the Bushberg sandstone, resulting in lateral passages in the underlying Kimmswick limestone. Thus the lower levels were effectively protected against the entry of surface rubble until erosion had effected a breach. The latter event did not occur until after extensive erosional dissection.

In almost every case the breach developed at a point where the downcutting brought the surface close to the cave ceiling. The weakened ceiling then collapsed, forming an entrance. In at least some of the caves, this collapse has occured fairly recently and very little outside rubble lies over the breakdown. Three P.M. Pit and Wyman Cave are typical examples of this case. In some other fissure caves outside rubble has filled appreciable portions of the caves. The magnitude of this effect can be clearly seen in Turtle Pit (St. Charles County) where the talus has attained a height of 15 feet in a chamber only 25 feet deep. Catacomb Cave has one of the few entrances which does not appear to have had much breakdown. One explanation for this anomaly is that the entrance passage is almost impassably narrow. In general, entrance breakdown rubble is usually found with and underneath surface rubble, and breakdown in other sections of the caves is not common.

Referring to the typical fissure cave entrances (figure 4), it is apparent that in some cases a lowering of the surface by only a few feet has produced an entrance. The hillsides are generally rather steep and erosion must be cutting down the surface at a rapid rate. An erosion rate of one foot in 1000 years probably constitutes a conservative estimate for the hillsides. Entrance ages based on this rate thus range about 2000 to 3000 years on the average. Actually some of the entrances are older than this figure, and some of course are younger. The entrance of Boemler Cave in Jefferson County was dug open by the owner who noticed a small hole.

Here again, as in the case of cave fills, entrances are a factor affecting fissure cave distribution. At least one pit without a natural entrance was uncovered and destroyed by quarrying operations. Undoubtedly more entranceless but air-filled caves are in exis-

TABLE 4 – GEOLOGIC HISTORY OF THE FISSURE CAVES.

SYSTEM	SERIES	STAGE (or note)	EVENT
Quaternary		Recent	entrance development
		Late Wisconsin	
		Early Wisconsin	valley formation and drainage of the caves
	Pleistocene	Illinoian	
		Kansan	
		Nebraskan	planation and filling of caves with clay
		pre-Nebraskan	
Tertiary	Pliocene		erosion
	Miocene	genesis of fissure caves uplift and tilting Lafayette form. deposited	Peneplanation
	Oligocene		
	Eocene	deposition in s.e. Mo., Wilcox group	
	Paleocene	deposition in s.e. Mo., Midway group	
Cretaceous		deposition of McNairy and Owl Creek formations	
Triassic			
Jurassic			
Permian			inferred erosion
Pennsylvanian		thick deposition of many formations later eroded away	last inundation of the St. Louis area, clastic rocks and coal deposited
		pre-Pennsylvanian emergence	tilting and erosional truncation of Kimmswick
Mississippian			widespread deposition
Devonian			deposition of the Bushberg sandstone
Silurian		post-Ordovician emergence	
Ordovician		deposition	Kimmswick Decorah Plattin Joachim St. Peter

tence throughout the area. If any factor tended to favor or retard entrance development in a given section of the fissure cave area, the overall pattern of cave distribution would be modified. No significant bias appears to exist; thus known cave locations probably constitute a valid sampling of the totality of all fissure caves, known and unknown.

The development of an entrance represents the latest significant event in the sequential steps of fissure cave development. The general course of this development is outlined in table 4 which depicts the significant phases of fissure cave speleogenesis.

H. Further Applications of the Theory - The conditions responsible for the development of the fissure caves in the St. Louis area may also exist elsewhere, and in that case it may be possible to find caves similar to the fissure caves. One nearby place to look for examples is around other parts of the periphery of the Ozark Dome where its regional dip is locally interrupted by an anticline. Two localities are known to exhibit this particular relationship: St. Clair - Cedar Counties in southwestern Missouri and Perry County in southeastern Missouri.

The stratigraphy of St. Clair County and Cedar County is considerably different from that of the fissure cave area in eastern Missouri. There the Middle and Upper Ordovician formations as well as the Bushberg sandstone are absent. The Chouteau group (Mississippian) is present, but it unconformably overlies Lower Ordovician formations. Despite this difference, it is known that caves exhibiting strong joint control exist in St. Clair County. Possibly the genesis of these caves is similar to that of the fissure caves.

The stratigraphy of Perry County is quite similar to the stratigraphy of the fissure cave region, except that formations above the Plattin are absent. The topography in the northeastern section of the county adjacent to the Mississippi River is well dissected, although the relief is only about 200 feet. The only formation exposed is the Plattin which in this region attains a thickness of several hundred feet. The situation is complicated by faulting along the river, but there are reports of deep pits in the river hills. Whether these pits are artesian fissure caves or vadose domepits is not known.

Summary

The caves described in this paper have developed primarily through the solution of limestone by circulating groundwater in a completely subaqueous environment. The water is assumed to have carried dissolved carbon dioxide which facilitated solution. This process is one of the commonly accepted foundations of modern speleogenetic theories. Within this general framework, however, great variation is possible, and this paper describes one such variation:

1. Prior to speleogenesis, an extensive erosion surface had formed, broken only by a chain of low hills marking a local anticlinal uplift.

2. A general uplift of the central part of the Ozark Dome tilted the erosion surface and the underlying strata toward the northeast, creating a hydraulic gradient in a sandstone aquifer below the limestone containing the caves.

3. At the anticline, the aquifer ascended close to the surface, and the artesian water ascended through joints and laterally along bedding planes to form a series of resurgences in valleys penetrating the chain of hills. Solution along these flow paths produced sizable cavities.

4. Following base levelling, the circulation virtually ceased and the cavities filled with red clay.

5. Pleistocene glaciation brought reduced sea level and renewed erosion. Local dissection lowered the water table and the clay was removed from the cavities by free-surface streams.

6. Secondary mineralization produced a variety of speleothems, most of which are calcite.

7. Present entrances formed in the cave ceilings when lowering hillsides weakened the overlying rock.

8. Drift of surface rubble into the sinklike entrances formed talus piles over the entrance breakdown.

In addition to the specific aspects of speleogenesis, several other results have accrued:

1. Solution can and does take place at depths in excess of 300 feet below the water table.

2. The alignment and distribution of caves is not necessarily related to today's topography.

3. The present-day flow of vadose water does not necessarily correspond to primitive phreatic circulation, which may have flowed uphill by present standards (at the present time water flows into, and not out of, the fissure cave entrances).

4. The importance of Pleistocene, glacial-motivated erosion is demonstrated, and the value of terrace correlations is shown.

5. The possible application of the theory to other regions is pointed out.

6. The demonstrable relationship of the caves to erosion surfaces provides a potentially useful tool for correlation and delineation of these surfaces.

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SHORTER CONTRIBUTIONS

Cave Migration of Certain Insects

By Judson D. Ives

ABSTRACT

As early as late September the Thysanuran, *Machilis variabilis,* began its cave migration into Delaps Cave, Hamblen County, Tennessee. The female mosquito, *Anopheles punctipennis,* began entering the cave for the winter months in October. The camel cricket, *Ceuthophilus gracilipes gracilipes* began its entrance into the cave in November. The insects did not penetrate the deep dark interior of the cave. The insects migrated to the cave when the temperature was between 40°F. and 50°F., and the relative humidity was between 80% and 90%. The light intensity was between 150 and 200 foot candles. When the cave and outside temperatures and relative humidities were practically the same light might have materially influenced their entrance into the cave. When the insects left the cave the increasing outside temperatures may have played a major role in their outward migration.

In regions where there are caves it is interesting to note that a number of insects pass the cold winter months in caves. In this study only Delaps Cave, also called Three Springs Cave or Buttry's Cave, is considered. The cave is located in Hamblen County, Tennessee, four miles from Russellville and 10 miles from Morristown. (For the exact location and description of this cave, see Barr, 1961: p. 242). Only that part of the cave is considered which is never flooded by the waters of nearby Cherokee Lake. This area comprises some 300 feet from the entrance. The entrance is only a few yards above the high water mark of Cherokee Lake.

Figure 1 is a map of the cave with the area indicated that is always above the high water mark. At a little over 300 feet from the entrance, the floor of the cave descends rapidly for some 50 feet where it again levels off. However, there may be an air pocket at about 550 feet from the entrance, where a side passage opens to the right. The entrance of the passage is above the level of the regular floor of the cave. By climbing up on the left side of the cave wall one can cross the main floor of the cave by a natural bridge, after which the floor of the passage ascends rapidly until the passage ends. This passage has a rather high ceiling.

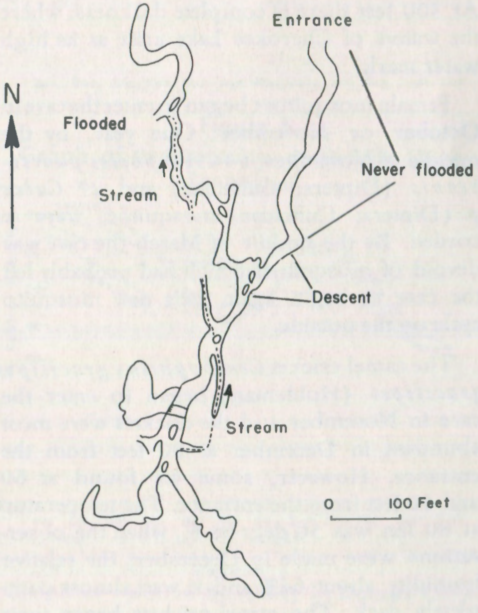

Figure 1
Map of Delaps Cave, Hamblen County, Tennessee.

In preparing for the ecological study the cave was marked off near the entrance at 20 foot intervals. To mark the 20 foot stations a transect was painted in white on the ceiling and a small iron stake was driven into the dirt floor. The height of the cave at the 20 foot intervals was from three to five feet and the average width about five feet. Station I was selected at a point in front of the cave. The cave entrance was designated as station II; 20 feet inside the entrance was station III; station IV was 40 feet from the entrance; stations V and VI were each 20 feet farther in the cave.

One day (from earliest dawn to dark) in each month of the year, beginning Nov. 1928, records were made of light, temperature and relative humidity each hour at stations I through V; occasionally temperature and relative humidity were obtained at station VI but no light readings. Inside the cave the animal count was made only on the roof of the passage. For seven consecutive months following the systematic study the cave was visited and one count made at each station within the cave each month as a check to the previous work. At 300 feet there is complete darkness, where the waters of Cherokee Lake arise at its high water mark.

Female mosquitoes began to enter the cave in October or November. One year, by the middle of November, 144 *Anopheles punctipennis* (Diptera; Culicidae) and 27 *Culex sp.* (Diptera; Culicidae) mosquitoes were recorded. By the middle of March the cave was devoid of mosquitoes which had probably left the cave to begin again their new mosquito cycle on the outside.

The camel cricket *Ceuthophilus gracilipes gracilipes* (Holdeman) began to enter the cave in November and the crickets were most abundant in December at 80 feet from the entrance. However, some we found at 60 and 40 feet from the entrance. The temperature at 80 feet was 50 degrees F., when the observations were made in December; the relative humidity about 64% and it was almost completely dark. The camel crickets began their exit from the cave in March and by the end of May at the time the study was made, the camel crickets were entirely absent from the cave (figure 2).

Machilis variabilis (Thysanura: Machilidae) began to enter the cave even in late September and were most abundant in December and January. They were practically absent from the cave by the end of April (figures 3 and 4). One December I found 358 individuals in a relatively small area of about three square feet, in the twilight region of the cave.

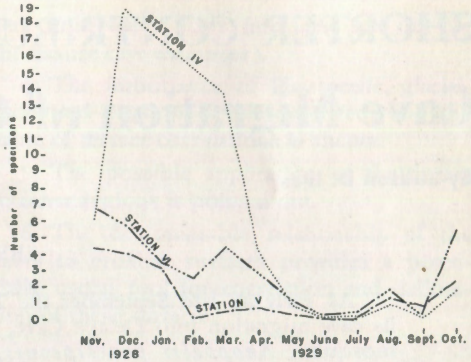

Figure 2

Cave migration of camel crickets (**Ceuthophilus gracilipes gracilipes** (Haldeman).).

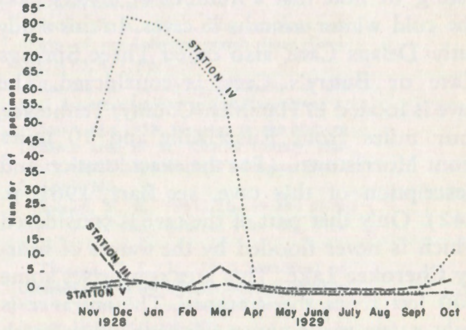

Figure 3

Cave migration of **Machilis variabilis.**

Scoliopteryx libatrix (Lepidoptera: Noctuidae) was found in small numbers during the winter months.

Snails and spiders are found near the entrance of the cave at various times during the year.

It is interesting to note the ecological conditions when the insects entered the cave in the fall and when they left the cave in the spring. These conditions are represented in figure 5 for light in foot candles, figure 6 for temperature in degrees F., and figure 7 for the relative humidity in per cent.

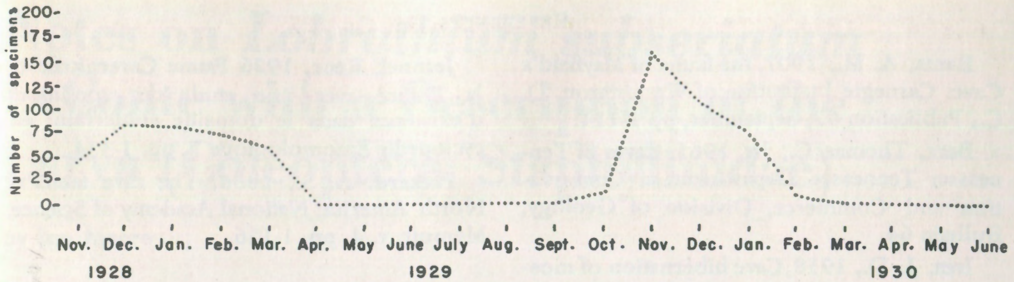

Figure 4

Machilis variabilis at Station IV.

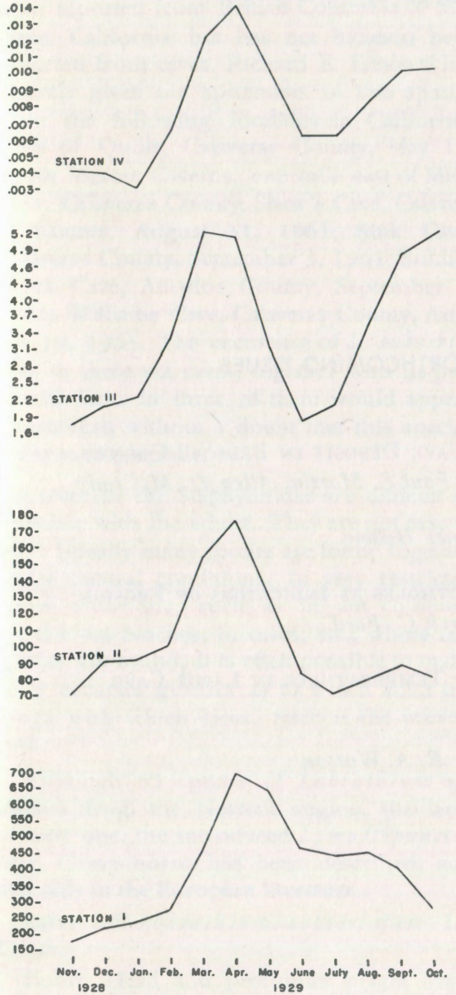

Figure 5

Light conditions at Delaps Cave in the fall, at the beginning of cave migration.

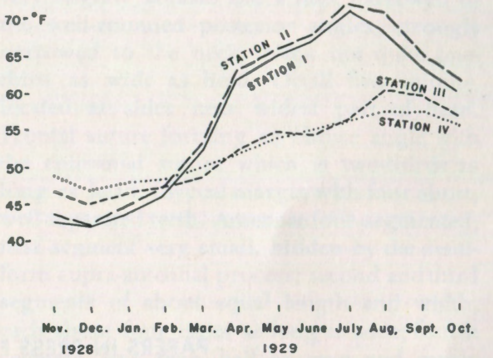

Figure 6

Graph of temperature at Delaps Cave, Tennessee.

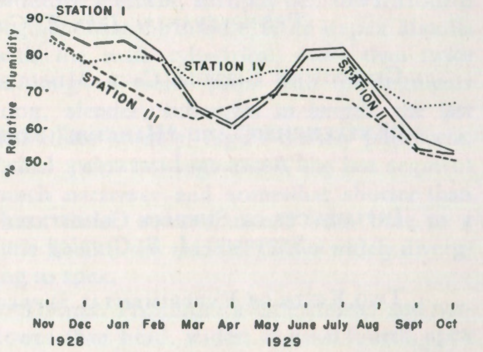

Figure 7

Graph of relative humidity in Delaps Cave, Tennessee.

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The help of students on the expeditions and the use of the facilities of Carson-Newman College for obtaining the ecological data is appreciated. Also appreciation is due the U.S. National Museum for the insect identifications.

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PAPERS IN PRESS FOR FORTHCOMING ISSUES

New Paris No. 4: A Late Pleistocene Cave Deposit in Bedford County, Pennsylvania. *John E. Guilday, Paul S. Martin, Allen D. McCrady*

Geology of Carroll Cave, Missouri. *James Helwig*

"Entrenched" and "Hanging" Stream Potholes as Indicators of Erosion Phases in Limestone Caves. *Derek C. Ford*

Influences of Surface Conditions Upon Temperatures in Large Cave Systems. *J. B. Cropley*

Two Kinds of Experimental Speleology. *R. A. Watson*

Notes on *Lobrathium subseriatum* LeConte with a Description of the Larva (Coleoptera: Staphylinidae)

By Ian Moore

Lobrathium subseriatum LeConte has been reported from British Columbia to northern California but has not hitherto been reported from caves. Richard E. Graham has recently given me specimens of this species from the following localities in California: Cave of Quills, Calaveras County, May 14, 1960; Mercer Caverns, one mile east of Murphys, Calaveras County; Shaw's Cave, Calaveras County, August 31, 1961; Sink Cave, Calaveras County, September 3, 1961; Soldier Creek Cave, Amador County, September 3, 1961; Williams Cave, Calaveras County, August 19, 1963. The occurence of *L. subseriatum* in these six caves, together with its presumed larva in three of them would appear to establish without a doubt that this species is a true troglophile.

Larvae of the Staphylinidae are difficult to associate with the adults. They are not easy to rear. Usually many species are found together under natural conditions. In very restricted faunal situations, such as in ant colonies, on the sea beaches, in caves, etc., where few species are found, it is often possible to make fairly accurate guesses as to which adult belongs with which larva. Such is the present case.

Although 63 species of *Lobrathium* are known from the Nearctic region, the larva of only one, the introduced *L. multipunctatum* Gravenhorst, has been described, and that only in the European literature.

Larva of *Lobrathium subseriatum* LeConte.

Color. Head and pronotum bright testaceous, abdomen somewhat darker, legs very pale.

Head one-fifth longer than wide, subrectangular, widest near anterior margin, thence very slightly arcuate and a little narrowed to the well-rounded posterior angles, strongly narrowed to the neck. Neck not quite one-third as wide as head. Ocelli five, minute, located at sides near widest part of head. Frontal suture forming an obtuse angle with the epicranial suture which is two-thirds as long as head. Clypeal margin with four short, well-separated teeth. Antennae four-segmented; first segment very small, hidden by the dentiform supra-antennal process; second and third segments of about equal length and width, each about four times as long as wide; fourth segment less than half as long and much narrower than third; modified seta at apex of third segment membranous, almost as long as fourth segment, abruptly bent toward fourth segment near the middle, acute at apex. Maxilla with the mala cylindrical, more than twice as long as wide; palpi with the segments long, slender, sub-equal in length; the last acuminate apically. Ligula densely pubescent. Labial palpi two-segmented, the last segment much narrower and somewhat shorter than first. Gular sutures united from base to a little behind the middle, thence widely diverging to apex.

Thorax. Pronotum a little shorter and narrower than head, widest at basal fourth, apex and base straight, sides sinuate. Mesonotum and metanotum each about as wide as base of pronotum, wider than long.

Abdomen as wide as pronotum, about as long as head and thorax. Pseudopode about as long as wide, one-third as long as first segment of urogomphus. Urogomphus three-segmented; first segment about four times as long as wide; second segment one-half as long as, and a little narrower than first, swollen apically; last segment filamentous, longer than second, slightly enlarged at apex for the reception of a long. thick terminal seta.

One specimen, "Mercer Caverns, 1 M.E. Murphys, Calaveras County, California. No. 1847 R. E. Graham, C.R.A. Inc."

One specimen, "Cave of Quills, Calaveras, Calif., Coll. R. E. Graham, 14-V-60. No. 1725."

One specimen, "Williams Cave, Calaveras Co., Calif., 19 Aug., 1963, Deep TZ, R. E. Graham."

Mr. Richard E. Graham has for a number of years been making extensive collections from American caves. He has very generously given me a number of Staphylinidae including the material mentioned in this paper, for which I am quite grateful.

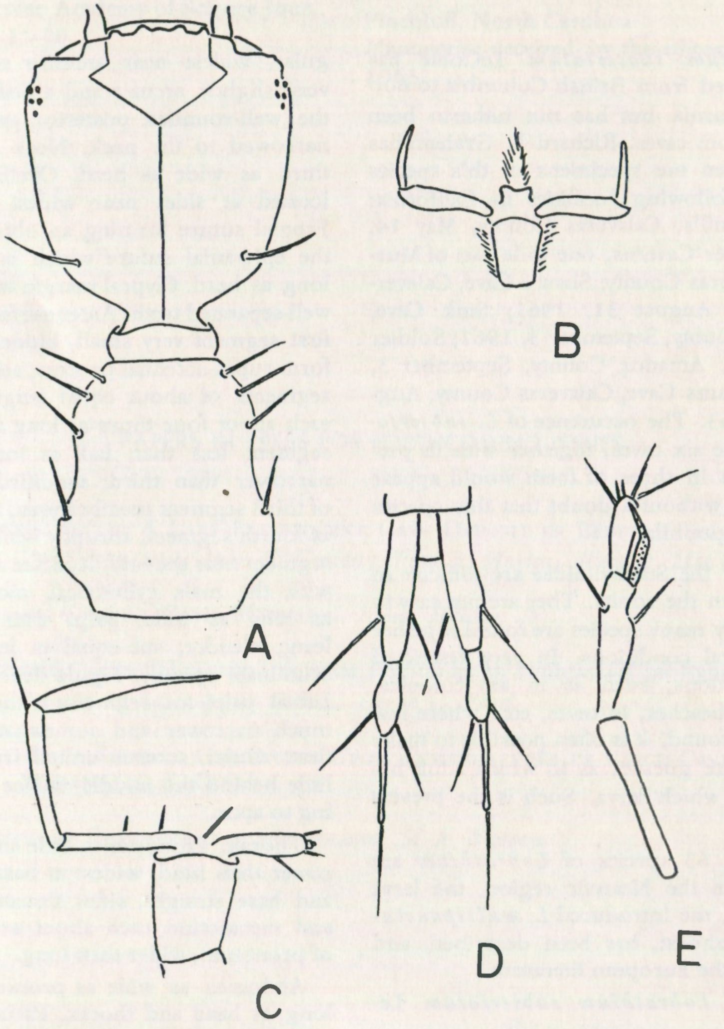

Figure
Parts of larva of **Lobrathium subseriatum** LeConte—A. Head and pronotum, B. labrum, C. maxillary palp. D. urogomphi, E. antenna.

San Diego Natural History Museum
San Diego, California
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