H. H. Hobbs III

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Contents



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# On the Definition of a Cave*

by RANE L. CURL

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

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

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

## INTRODUCTION

Why be concerned about the definition of a cave? A cave is a natural cavity beneath the earth's surface. Only a few authors have found it desirable to be more specific when they wished to describe a particular class of natural subterranean cavities. Although a detailed survey of definitions which have been given is not very enlightening, the nature of the concern which exists may be illustrated by the following selection: Bretz (1956), ". . . nor is it possible that everyone will ever agree on the definition of a cave. Is a rock shelter, broad along the hillside but shallow in penetration of the hill a cave? Is a natural bridge a cave? Is a hole that can barely be crawled into for only a few feet a cave? Is it a cave if a former cavity has become completely filled with mud and broken rock? . . . In terms of human experience, we generally think of a cave as being a natural roofed cavity in rock which may be penetrated for an appreciable distance by a human."; Cullingford (ed. 1953), ". . . Frequently restricted to those openings capable of entry by man."; Davies (1960), ". . . In the present discussion a cave is defined as mature integrated solution openings. Isolated primitive tubes and pockets are excluded from the term 'cave'."; Howard (1960), "An opening is any volume surrounded by solid rock, but not filled by solid rock . . . (it) may be filled with air, water, loose rock, mineral, clay or other debris. . . . A cave is any crevice or crevice system which fortuitously conforms to a number of poorly designated and meaningless restrictions pertaining to the size, length, availability and nature of the opening. Thus the use of this term will be limited to its occurrence as a proper noun."; Curl (1960), "Caves too narrow to traverse could be included in a cave population by imagining ourselves to be smaller than we are."; Woodward (1961), "Many caves can be entered and explored but this is not a technical requirement."

The author was led to a further consideration of this question by work on statistical relations among properties of caves in a cave population (1958, 1960). There, the concept

* Based on a paper of the same title read at the 3rd Int. Congress of Speleology, 20 Sept. 1961, Vienna, Austria.

of a "cave" had been assumed to correspond to some physical entity which could be measured in various ways. Although striking statistical regularities were demonstrated it could fairly have been asked, exactly *what* conformed to simple statistical laws? Our concepts had proved useful; we must now clarify the nature of the measures we do use.

The questions asked by Bretz will not be answered here. Indeed it will always remain that there are in principle as many definitions as there are uses for these definitions. But it is hoped that certain elementary features of the concept of "cave" will be made clearer, and the method by which this is accomplished may be of some utility elsewhere in speleology.

### The Module of a Cave

A cave is not an object. It is a space. Consequently the specification of a cave involves the specification of the boundaries of a space. Whatever specification is made, the resulting space contains, or is bounded by, a complex structure of materials which are solid, liquid, gaseous, or mixtures. It is natural, and useful for most purposes, to refer the boundary specifications to these phase boundaries between the three states of matter. However a fundamental geometrical issue becomes involved if this is attempted.

Consider the gas- or liquid-filled portion of a subterranean cavity. This occurs in many shapes and sizes but of itself has *no lower limit on its dimensions*. That is, there is a continuous class of openings including what we might call passages, tubes, crevices, fissures, cracks, and on to microscopic pores. If all of these are not to be considered, described, and explained as "cave," an arbitrary *minimum dimension* must be introduced into the definition. It is proposed, then, to specify the boundaries of a cave in terms of this minimum dimension, and it will be called the *module* of a cave.

In practice a solid shape must be associated with the module. Then a cave of a particular module becomes the *subterranean volume which may be traversed continuously by the specified shape having that characteristic dimension*. One choice for this shape is the sphere, with its diameter equal to the module. However the choice is only one of convenience or purpose. The author has referred to this imaginary object as a *standard explorer* (1961) but it will be called hereafter simply an *explorer*. Other shapes which might be assigned to the explorer are the tetrahedra, or other polyhedra, forms with extensions which permit the inclusion of adjacent crevices within the cave boundary ("hands"), etc.

A cave defined by a given spherical explorer may be imagined as a space which is in contact with the real walls (phase boundaries) of the cave at only some points. A tetrahedral explorer, or other form, would permit a closer correspondence between the actual cave space and phase boundaries. However only in the limit of the module approaching zero may a cave defined in this way be coincident with the subterranean opening. On the other hand, as the module is made larger, any given subterranean opening might well be divided into a greater number of caves.

It is not proper here to settle whether cave fill, formations, water etc., are *in* or *bound* a cave. This must be specified depending upon the purpose of the definitions. The intention here is to point out the usefulness, indeed necessity, of associating a *minimum dimension* with practically *any* definition of a cave, its entrances, or other features which are not objects but extended spaces.

The exploration and description of caves by humans is an example of the application of the above cave boundary specifications, except that now the explorer is not particularly standard. Nevertheless, such caves are selected on the basis of a human module or, since all those which are enterable are given proper names, a *proper module*. Such caves will be called *proper caves* and recognized as a very limited selection of all subterranean cavities, selected on the basis of the dimensions of humans.

A cave of a given module is always completely enclosed by a cave of a smaller module, if both explorers have the same shape. If two caves of the same or different module intersect, but with the intersection too small to allow passage of the explorer between them, the intersection will be termed a cave *connection*.



### Entrances and Proper Entrances

So far it has been assumed that the explorer is not able to escape from the subterranean cavity to the surface. That is, that the cave, so specified, has no entrances. Entrances are another form of boundary to the cave space. They are, of course, a structure common to both the surface and cave morphology. It should be apparent that the same problem of specifying the boundaries of a cave in respect to its enclosing rock—the need of introducing a minimum dimension, also applies to the specification of the entrance boundary. But in this case the definitions must contain an additional arbitrariness, as an entrance boundary cannot also be a phase boundary; only "inside" and "outside" are to be distinguished.

Since all definitions of caves which have ever been offered contain the notion of "rock overhead," this suggests itself as the most natural reference for an entrance boundary. Recently the Missouri Speleological Survey has shown a "drip line" at cave entrances in their published maps (Johnson, 1960). The associated imaginary "drip surface" down along which drops fall from the most outward point possible will be adopted here to define the *entrance surface*, as it divides the space with rock above from that with sky above. This definition could also be stated more exactly in terms of the direction of the gradient of the gravitational potential.

Now if an explorer approaches an entrance surface from within a cave and is able to pass completely out through the surface, the portion of the entrance surface through which the explorer may pass will be defined as a *cave entrance* with the same module as the cave. An intermediate situation where the explorer is able to intersect the entrance surface but not completely penetrate it, will be referred to as establishing a surface *connection*. Thus a surface connection is part of a cave entrance defined for a cave of smaller module. By analogy to the terminology applied to a cave, an entrance surface through which a person is able to pass will be called a *proper cave entrance*. A proper cave may consequently have neither surface connections nor entrances, connections but no entrances, either, or both. A non-proper cave cannot have proper entrances, but may have surface connections or "ordinary" entrances. Finally, a non-proper entrance may connect to a proper cave by way of non-proper passage.

All of these relations are shown in Figure 1 where a profile of a hypothetical cave is shown being tested with spherical explorers of different module. The examples are drawn in two dimensions but the extension to three dimensions should be made in the imagination. The upper opening is meant to be only a hole in the roof of a larger chamber.

The situations depicted are as follows: (A) Cave. Subscripts indicate separate caves; (B) Connection; (C) Entrance surface; (D) Surface connection; (E) Cave entrance of same module as cave.

In this particular example it was decided to consider cave fill as a bounding surface for the cave of a given module, but to not treat stalactites as such; thus they may or may not be "within" the cave of a given module of spherical explorer. A different shaped explorer would change the details but not the principles of the definitions in this example. If the reader should care to substitute a human for a spherical explorer, he will find that the terms employed here are consistent with our ordinary experience with caves.

The situation designated (F), and the cave space so selected when the explorer may only penetrate the entrance surface for a short distance from outside is not defined above, but might be thought of as a "shelter."

### Applications

*Morphological:* The origin of limestone caves is usually studied only in terms of air filled proper caves with proper entrances. In a few cases information about a non-proper passage may be discovered by stream or air tracing, deductions from joint patterns, etc., but these methods yield only fragmentary data. The possibility remains that many clues to cave origin reside where we cannot observe them. Not only is it possible that the volume of non-proper caves exceeds that of proper caves, but it is likely that the volume of proper caves with proper

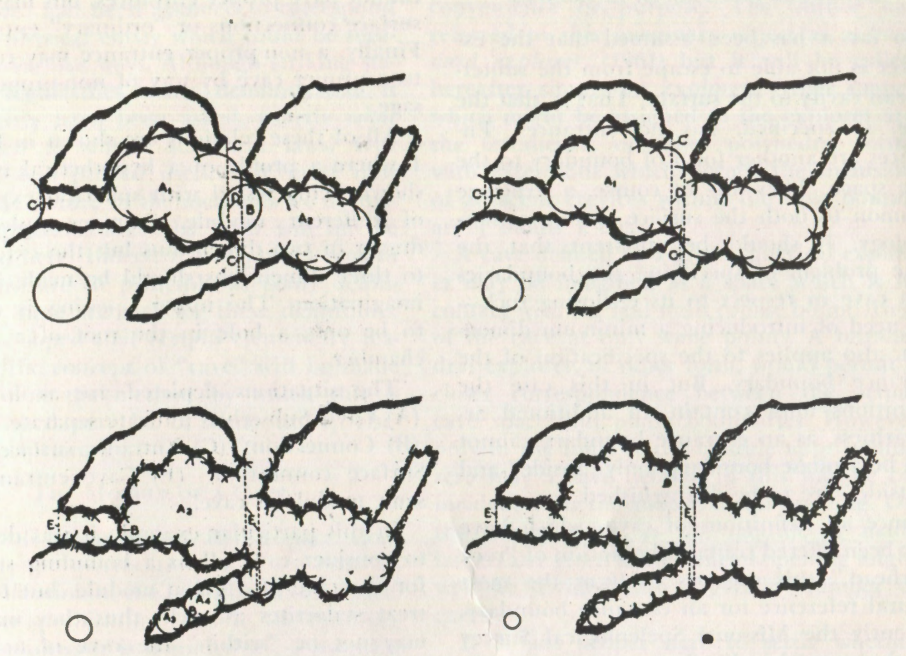

Figure 1

Examples of caves defined in a cave space by spherical explorers of different module. Also shown are the "explorer," cave and surface connections, portions of the entrance surface, cave entrances, and shelters.

entrances is only a fraction of that without. Students of cave origin may be willing to extrapolate with confidence from their observations in the available selection of caves to the remainder, but nature usually does not divulge her secrets to limited observation, and it is more likely that our present concepts are considerably biased.

As a defining module is made smaller, an explorer would be able to penetrate into an ever increasing volume of cave space. Cavities formed by the solutional enlargement of joints might be expected to exhibit features which would distinguish them from the narrow gaps in joints which have not been enlarged, and perhaps even from the primitive solutional cavities and tubes which would be explored with a different module range. Several classes of cave space might be distinguishable on this basis.

Consider the total volume of cave space under some region which is traversable by a specified spherical explorer. Include all cave space of a suitable size without regard to the existence of entrances. Imagining that this volume is measurable, plot the value of the total versus the module. If the result is the smoothly decreasing curve in Figure 2 labeled *ungrouped,* we would conclude that cave space is not naturally divided into groups by module range. But if the "stepped" result shown in Figure 2 labeled *grouped* is obtained, a classification on the basis of "caves, crevices, fissures, joints, cracks, pores, etc." might be imagined. Each of the steps represents a significant contribution to the total cave space volume over a relatively narrow module range, while the plateaus between are ranges in which there is a relative paucity of cave space.

The actual case is not now known and would be difficult to determine. Also, there are probably better measures upon which to base a division into cave types. This one is mentioned because of its possible relation to the already demonstrated order in the distribution of proper-cave lengths.

*Statistical:* In two earlier articles the au-



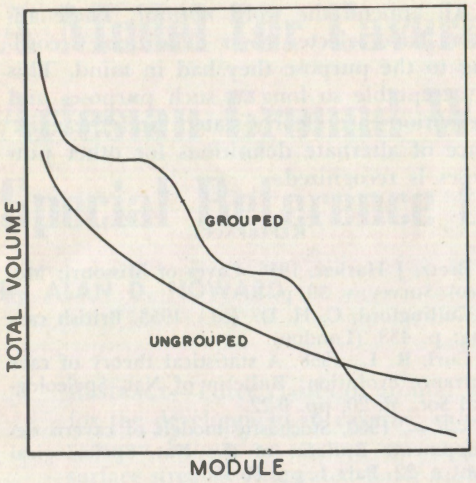


Figure 2

Possible results of measuring total cave volume as a function of the defining module.

thor considered statistical relations among properties of natural air-filled proper caves with proper entrances (although without so identifying them at the time) and deduced some properties of proper caves without proper entrances. To do this the number of proper entrances and the surveyed proper length of caves were used. Measuring length and entrances on the basis of their being proper serves to select a most consistent cave population for analysis; that is, it rejects data such as artificial entrances and connections found by digging or air or stream tracing, or by geological deductions, or entrances surmised or dug into, as not being equally well known for all caves in the population. The present considerations make clearer the reasons why proper length was a suitable variable. Entrance forming processes acting on a non-proper (though air filled) cave *cannot produce proper entrances,* and consequently this whole class of caves and entrances may be omitted from consideration without affecting the relations found in the remainder. Whether the geomorphic constants found for caves of West Virginia and Pennsylvania depend upon the module is not clear. The number of cave entrances, and cave lengths, may not vary in the same proportions as the module is changed; so for the present they should be considered as proper geomorphic constants.

*System specification:* The module concept leads naturally to defining a cave-space volume or *system* for a number of other applications. For example, in cave meteorology it is necessary to consider the heat balance on a cave. That is, a volume of cave space is selected and all the thermal fluxes are measured at the boundaries of the system, while the thermal accumulations are measured within the system. The boundaries for such a thermal system may be placed arbitrarily, although the use of a specified module provides a consistent selection. Similar considerations might apply to ecologic studies where it is necessary to account for biogenic energy which is passing through or accumulating within the cave boundaries.

The "father of modern biospeleology," E. G. Racovitza (1907) was concerned with the module question. He referred to the habitat of cave fauna as the "domaine souterrain" which he divided into *"Les grottes accessible à l'homme,"* and *"Les fentes étroites inaccessibles à l'homme,"* concluding that the *real* domain of cave fauna is to be found in the latter.

## Discussion

Selecting specific, or arbitrary, definitions may at first thought seem to allow an investigator to reach any conclusion he wishes. But this is not true. Such apparent arbitrariness of definitions is in fact basic to the scientific method. People are weighed minus their shoes and their height measured excluding their hair; the yield of wheat from a farm is measured per acre, but excludes the roots, stalks and chaff; the positions of the planets are discussed sometimes with respect to their centers and sometimes with respect to their surfaces. In essence, we make our definitions and then attempt to determine whether they are useful; that is, functionally or statistically related. Considerable "pruning" or rearrangement of the definitions may be necessary before a significant conclusion can be reached, which then only applies to the defined variables. So it is with caves.

There has been a need for unique definitions of cave and cave entrance for purposes of both description and for quantitative manipulations. It has been proposed here to define these in terms of a *module* assigned to a *standard explorer,* the shape of which is in turn selected for convenience or purpose. Likewise the materials which are to be considered as boundaries to the explorer (rock, breakdown, fill, water, speleothems . . . ?) must be separately selected. This then leads to definitions of *cave space, cave entrance,* and *connection* on the basis of a given module, which have the virtue of being consistently selected or measured and hence usable in precise statements. To designate caves or entrances traversable by humans the word "proper" has been suggested, which makes the surveyed lengths used in previous work, *proper lengths.* The distinctions "natural" or "artificial" may be applied separately.

Returning to the examples of definitions given in the introduction, we may tabulate what each author specified in each of the above categories in his definition of a cave. They are given in the order *a.* Bounds, *b.* Explorer, *c.* Module, *d.* Entrances, and *e.* Purpose:

Bretz (1956) and Cullingford (1953), a. Rock and fill, b. human, c. proper, d. unspecified, e. descriptive; Davies (1960), a. Solution surfaces, b. unspecified, c. larger than "primitive tubes," d. unspec., e. theory of origin; Howard (1960), a. Solid (original) rock, b. unspec. c. not stated but apparently small, d. not required, e. descriptive; Curl (1960), a. Rock, fill, and water, b. human, c. proper (and possibly smaller), d. proper, e. statistical theory of evolution; Woodward (1961), a. Rock and fill, b. water, c. "freely flowing water," d. not required, e. theory of origin.

All append the word *natural.* These authors have selected their definitions according to the purpose they had in mind. This is acceptable so long as such purposes and definitions are clearly stated, and the existence of alternate definitions for other purposes is recognized.


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# A Model for Cavern Development Under Artesian Ground Water Flow, With Special Reference to the Black Hills


**by ALAN D. HOWARD**



ABSTRACT—Three classes of ground water flow within limestone are responsible for the development of caverns: *subsurface stream, integrated water table,* and *artesian.* Subsurface streams are comparable in method of flow and properties to surface streams. Integrated water table flow occurs as lateral flow at the top of a nearly planar water table. Artesian flow of ground water is through enclosed solutional cavities in the completely saturated zone where there is no free water surface. In the Black Hills of South Dakota structural situations have promoted the development of artesian ground water circulation through limestone, and all three of the above classes of ground water flow are involved in the ground water movement through the limestone. Caverns formed through the action of the last two categories of flow within limestone are similar, but criteria are given to distinguish between the two classes of origin on the basis of cavern morphology. These criteria are applied to Wind Cave in South Dakota, and the balance of evidence indicates an artesian origin of the cavern system.


Using the present ground water conditions in the Black Hills it is possible to develop a theoretical model for artesian ground water movement and cavern development which result from certain topographic and geologic conditions where a hydraulic potential is present across a limestone unit.

Three intergrading classes of ground water flow may be contemporaneously involved in active artesian cavern systems. Using common terminology these classes may be referred to as *subsurface stream, integrated water table,* and *artesian.*

For the purpose of this paper I define the *water table* as the upper boundary of any subterranean body of water or zone of saturation. Thus many of the streams and pools of water in caves would necessarily represent perched water tables.

Cavern development of the first type is characterized by the presence of free-surface subterranean streams with a relatively steep gradient. Malott (1922) has outlined the suite of cavern characteristics generally resulting from the action of subterranean streams. These include: coarse, stream-worn cavern sediments; current produced wall flutings; simply connected cave passages which are sometimes in a trellis arrangement; and an irregular downhill cavern gradient. The theoretically distinguishing characteristics of this pattern of ground water flow are: thinness of the zone of ground water movement, that is, the subterranean stream; the steep, irregular profile of the water table along the direction of ground water movement, which is the stream longitudinal profile, and this is minutely controlled by the bed of the stream; and lastly the poor integration of ground water levels between adjacent streams.

Contrasted to the above is cavern development by lateral movement of ground water along an integrated water table.

By an *integrated,* or *coordinated,* water table I mean a ground water-atmosphere surface which describes between and along the cavern passages a fairly regular surface, for example, that of an irrigation network or canal system without dams or gates compared to that of mountain streams with rapids and waterfalls. The driving potential for ground water movement is a slight gradient of the water table. Streamlines of flow are nearly parallel to the water table and average discharge and associated solution decrease with depth (White, 1960; Davies, 1960; and Ewers, 1962). The necessary presence of a well-defined water table for this type of cavern development implies earlier stages of solutional activity by either subterranean stream or artesian ground water movement. If, because of some physiographic control, the ground water level remains stationary for an extended period, a well-defined cavern level may be expected to form, but if the water table fluctuates, cavern development will occur over a wider interval. Where a stable physiographic situation has allowed sufficient solution to occur to create a nearly flat water table, this ground water regime may be distinguished from the previous case by several criteria:

1. The upper boundary of the completely saturated zone, namely, the water table, is nearly flat and of simple contour, that is, integrated.

2. The passage floors, which are the lower limit of solution, may be uneven, and generally this lower boundary does not directly determine the configuration of the water table.

3. Solutional passages may be multiply-connected, and will, like the water table, be well integrated with each other.

Caverns formed as a result of integrated water table flow should exhibit some of the following characteristics: distinct cavern levels, nearly horizontal; a tendency for major cavern passages to be aligned along the strike in dipping beds; where passages cross the stratigraphic dip, the passages should remain essentially horizontal even though cutting across the structure (Appendix 1); absence of coarsest cavern sediments, but clays and silts deposited from suspension may be expected; and in larger cavern systems there should be an abundance of phreatic features (Bretz 1942), for example, spongework, natural bridges, network, or multiply-connected passages, ceiling pockets derived from high stands of water, and if the water level changes, a multi-level cavern.

In artesian cavern systems ground water flow has been structurally and stratigraphically constrained to flow at an altitude well below the static water level.

Where movement of water is by artesian pressure, no true water table for the artesian unit exists, because structural and stratigraphic impediments to vertical circulation prevent establishment of a water column equal to the pressure head within the unit. The static water level is the altitude of the top of the theoretical equilibrium water column. In such cases water flows under pressure in a manner analogous to water flow within pipes, as opposed to the open-channel flow of the previous cases. Water velocity through an artesian cavern system is probably very slight. Therefore a near absence of coarse sediment transported by traction or turbulence may be expected, through suspended detritus may be brought into the cave and deposited. Characteristics of artesian caves are those given by Deike (1960) and by Bretz (1942) for his "deep phreatic" zone: for example; spongework; a complex, three dimensional network of passages where the passages are formed at intersects of joints and the more soluble limestone zones; ceiling pockets and intimate interconnections between cavern levels; cavern passages following stratigraphy and structure, that is, not necessarily horizontal; and a down-dip orientation of the cavern system as a whole.

All of the three types of ground water movement discussed may be expected in some artesian situations, as in the case of ground water circulation in the southern Black Hills. A section extending from Beaver Creek within Wind Cave National Park, southeast of Beaver Creek near Buffalo Gap Pass cut the southeastern flank of the Black Hills domal uplift with local dip to the southeast. However, a small anticlinal flexure is present near Buffalo Gap (Darton and Page, 1925). Ground water flowing within the limestone seems to be prevented from vertical flowage into the overlying sandstone by shale horizons at the upper limestone boundary (Appendix 2). The combination of the resistance to erosion of the Pahasapa



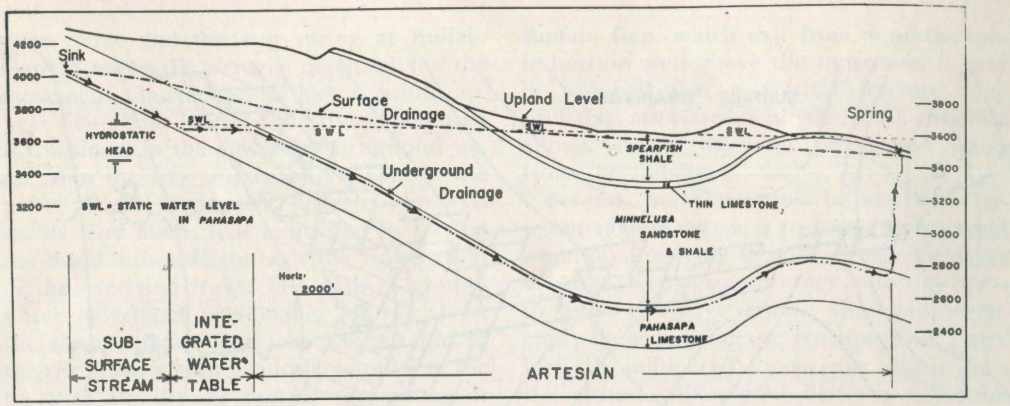


Figure I

Geologic cross section through the southeastern flank of the Black Hills, showing ground water conditions. Vertical exaggeration 6⅔x.

limestone and the overlying Minnelusa sandstone compared with the easily eroded Spearfish shales overlying these two resistant units has created an altitude differential between the ground water collection area to the northwest, in the Pahasapa limestone exposures and the discharge point at Buffalo Gap. Almost all streams originating in the central portion of the Black Hills which cross the Pahasapa exposure in the southeastern Black Hills lose their drainage to subterranean flow within the limestone and probably to a lesser extent to similar flow within the Minnelusa sandstone. This underground drainage then comes to the surface as artesian springs around the outer margins of the Black Hills, for example, the springs shown at Buffalo Gap, and springs at Hot Springs and Cascade (Fig. 1).

The assumed localization of ground water flow within the upper portion of the Pahasapa limestone is based upon the almost total absence of solutional cavities in the lower levels of this formation, where it is presently exposed. It cannot be decided at present whether this is the result of a difference in solubility of the upper and lower portions of the limestone, or to density factors in ground water flow concentrating solutional activity within the upper levels of limestone.

Theoretically this ground water flow may be divided into three zones characterized by ground water movement of the three types discussed previously. Where a surface stream flowing from the northwest first encounters soluble limestone, it will generally become subterranean, following solutional and erosional cavities at the base of the limestone. Such ground water movement would be steep, rapid flow of independent free-surface subterranean streams. The lower lateral boundary of this zone is where the free water surface becomes nearly flat and integrated. Note the difference in elevation of the water table between the areas where the rock units underlying the limestone are exposed, where permanent surface streams indicate the water table always lies above the lowest local points of the land surface, and the 200-300 feet deep water table within the limestone. This lower, well-defined water table and the completeness of underground drainage indicate that the present underground drainage system has existed for a long time, geologically.

The second zone of ground water flow occurs along the integrated water table toward the lowest point of this water table, presumably nearest the artesian spring. In Figure 1 this zone is greatly foreshortened, for the main component of flow is long the strike of the limestone. Caverns within this zone should be of the integrated water table type. Several cave levels associated with different previous stable stands of the water table might be expected.

The third zone of ground water movement is that of artesian flow. The hydrostatic head of about 200 feet between the

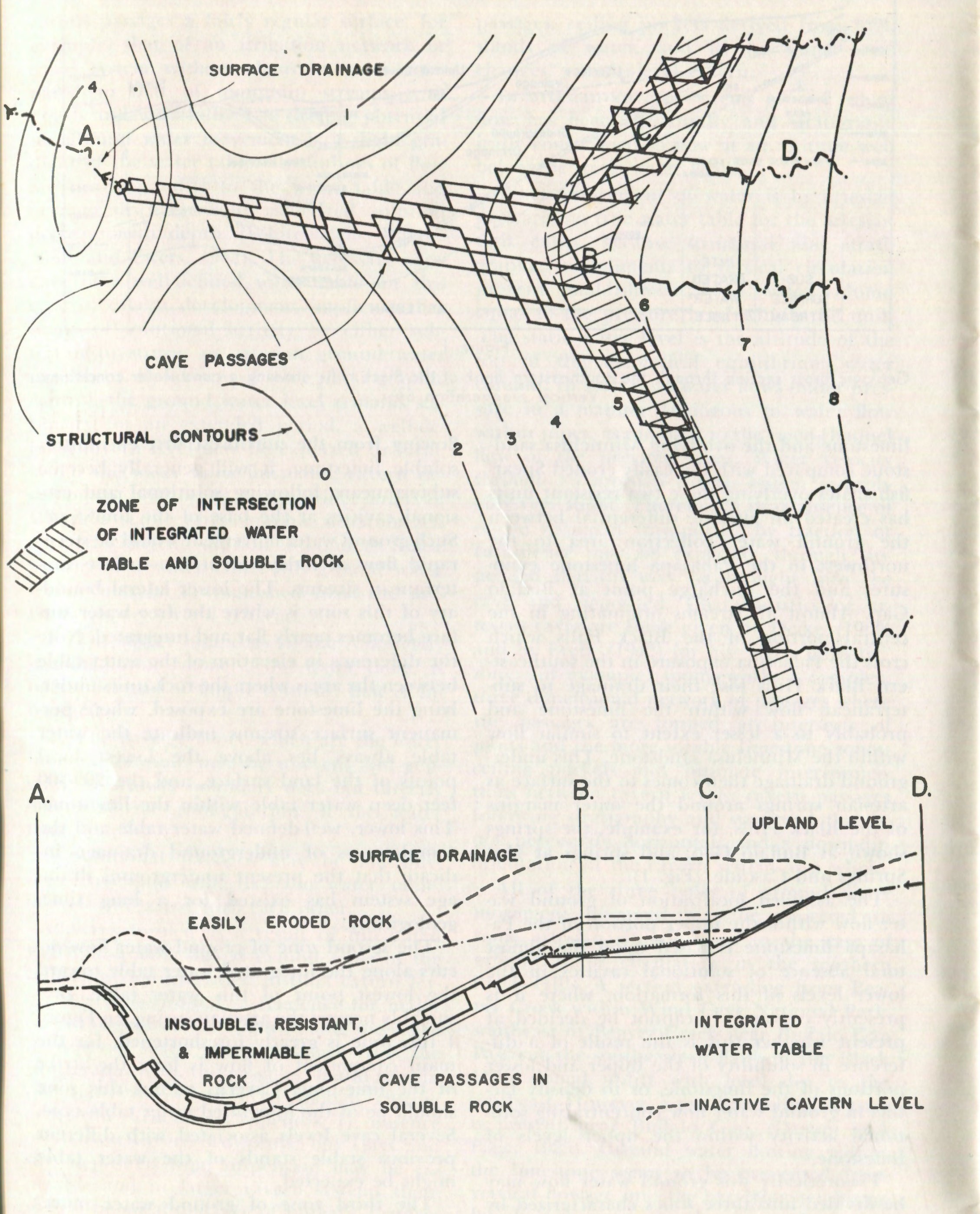


Figure 2

Theoretical properties of cavern development by artesian ground water flow.



water table and the exit spring at Buffalo Gap provides the driving potential for the movement. Based on well logs it would appear that about half of the driving potential is consumed in the movement of ground water from the free surface water table to the point in the limestone beneath the exit spring, and about half is utilized in forcing the water upwards through the constriction of the overlying rocks. The path of ground water movement presumably follows about the shortest path from the water table to the rise; such a path would be parallel to the regional dip. In the case of the springs at Buffalo Gap, which exit from a stratigraphic horizon well above the limestone, it may be assumed that a vertical fracture zone probably associated with the local anticline allows vertical discharge of ground water from the limestone.

Several conditions must be met if an artesian cavern system is to form: a structural situation involving a sealed limestone layer which connects ground water collecting areas to lower discharge points; this would generally be an asymmetric syncline, and a geologically influenced topography which gives the altitude differential between collection

TABLE 1

Criteria for Differentiation of Cave Development by Artesian Flow and Integrated Water Table

| Feature | Caves Formed by Artesian Flow | Caves Formed by Integrated Water Table |
|---|---|---|
| 1. Major controls upon cavern passage location and trend. | 1. Joint system, stratigraphy, and direction of ground water movement. | 1. Joint system, stratigraphy, water table, and direction of ground water movement. |
| 2. Trend of dominant passages and cave system as a whole. | 2. Parallel to dip. | 2. Parallel to strike. |
| 3. Controls upon vertical profile and vertical orientation along cave passages. | 3. Cavern passages follow structural configuration (i.e., may dip strongly). Passages have no vertical constraints other than stratigraphic (i.e., high, narrow passages may be found). | 3. Cavern passages nearly horizontal, following water table. A stable water table limits vertical development of passages to within a few tens of feet of the water table. However, a fluctuating water table will promote more vertical development. |
| 4. Vertical profiles of cavern passages. | 4. Irregular ceilings and floors may be expected. | 4. Rather regular ceilings and floors. |
| 5. Relation of cavern levels. | 5. Cavern levels intimately interconnected. Major cavernous zones may interchange between levels (reflecting shifting of ground water flow between cavern levels). | 5. Cavernous levels are largely independent, with relatively few interconnections. Cavernous zone should not interchange between levels. |
| 6. Cavern sediments. | 6. Little transport of detritus by traction, varying amounts of introduced fine silts and clays, with *relatively* high proportion of chemical deposits. | 6. Fine to coarse introduced detritus may be present. Generally low percentage of chemical sediments. |
| 7. Cave temperature during solution period. | 7. May be considerably higher than average annual temperature, for deeply formed caverns. | 7. Close to regional average annual temperature. |
| 8. Amount of solution per unit volume of rock within cavern. | 8. Stable ground water regime allows very large cavern systems to form. | 8. Relative instability of water levels means usually smaller amount of solution per unit volume. |

and discharge points. Because of the well-developed artesian circulation occurring at present within the Black Hills, it is reasonable to speculate that cavern formation is now taking place on a large scale within the Black Hills. If this true, then there is significance in the fact that this is occurring without much development of karst topography in the classical sense. In addition the caverns now forming will not have a direct relationship with the immediately overlying topography, but are products of larger scale patterns of drainage and structure (Fig. 2).

The accessible cavern systems within the Black Hills are not directly related in origin to the present topography and patterns of ground water flow, for these inactive caverns are 100 to 400 feet above the present permanent water levels, and are being dissected by the present topography. However, the presence of well developed artesian ground water complexes at the present time within the Black Hills allows the possibility that some of the inactive caverns within the area may have been formed by similar processes. Indeed, the possibility of an artesian origin of some of these caves has been cited before (Tullis and Greis, 1938, and Neighbor, 1954). Two caverns, Wind Cave and Jewel Cave, within the Black Hills are immediately suspect of artesian origin because of their large size, phreatic features, relative lack of cavern sediments, and three dimensional maze pattern (Fig. 3 C). However, the above features might also be found in caves formed at an integrated water table. It is therefore important to be able to distinguish between these two modes of origin by the characteristics of the cavern (Table 1). The first five criteria cited in Table 1 are based on geometrical considerations and should largely follow from the definition of the two contrasted regimes. The sixth criteria, the theoretically small transporting power of the low velocity water flowing through active artesian caverns indicates that significant detrital material would not be carried into artesian cavern systems. However, Deal (1962), although adhering to the idea of an artesian origin of Jewel Cave, argues for the previous existence of large quantities of clay fills within Jewel Cave which were subsequently removed by swiftly moving ground water. However, I find no evidence in Wind Cave for the existence of more than the present small amount of introduced sediments. However, in both these caverns the addition and removal of clay fills may have been due to ground water flow patterns subsequent to and not directly related to the flow patterns responsible for the major solution within the caverns. The 7th criterion is based upon the possibility of ground water flow in artesian circulation to a significant depth. In the Black Hills at present there are artesian springs which issue tepid water. This higher temperature, however, should not be expected to have been true for all artesian caves, but only for those formed at great depth or those in areas of high goethermal gradient. Criterion 8 is based upon the difference of stability of artesian and integrated water table flow. Artesian flow should retain a stable pattern as long as the exposed structural and drainage features remain essentially the same, even though tens or hundreds of feet of erosion or aggradation occur. On the other hand, water table levels are affected by even minor physiographic or climatic changes. To utilize these criteria a large portion of a cavern must be explored to furnish detailed data on the patterns of the cavern system and related rock structures. Also these data must be tied to accurate mapping of the passages based on rigid horizontal and vertical control.

The effect of any water level control on cavern development can be shown by a histogram relating cavern volume to altitude. In constructing such a histogram it is assumed that: (1) there has been no appreciable tilting of the rocks containing the cave since the period of formation of the cave, (2) the water table which formed the cave had no appreciable slope over the area of the cave being considered. A simple approximation is the construction of a histogram relating altitude versus occurrence of surveyed stations. This was done for Wind Cave (Fig. 4). For caverns with extensive areas of breakdown that occurred after draining of the cave, only stations from portions of cavern passages free of collapse should be utilized.

Because the stratigraphic dip is about 7



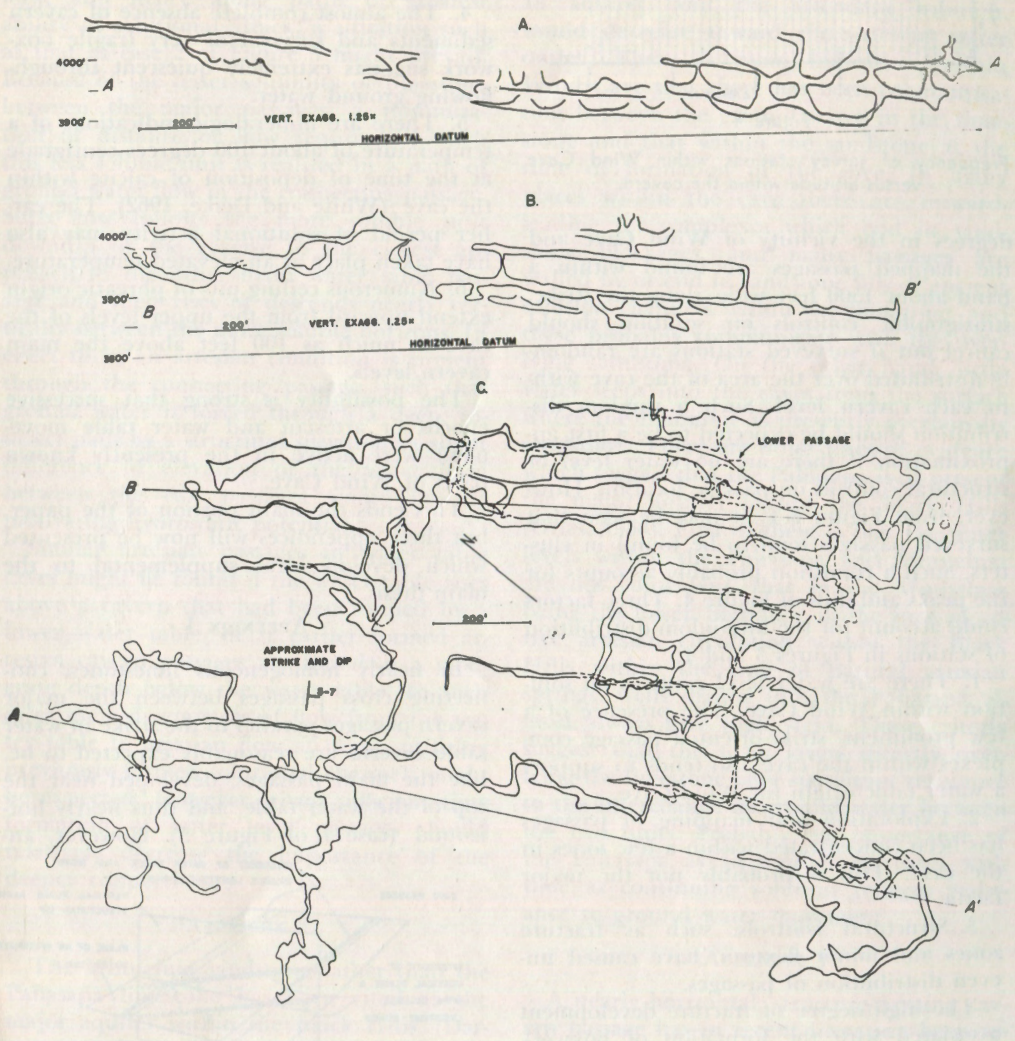


Figure 3

A generalized map of Wind Cave, and two generalized cross sections along the dip. Based on a map by Herb Conn and used by permission of the National Park Service.

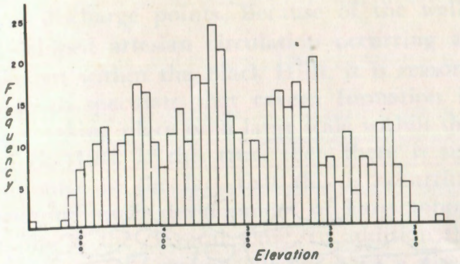


Figure 4

Frequency of survey stations within Wind Cave versus altitude within the cavern.

degrees in the vicinity of Wind Cave and the mapped passages are found within a band about 1500 feet wide along the strike, stratigraphic controls on solution should cancel out if surveyed stations are randomly distributed over the area of the cave within each cavern level. Such a random distribution should be expected to be a first approximation if there are no water level or structural controls on passage location. However, from Figure 3 C it may be seen that surveyed passages tend to be found in clusters. Such a condition probably accounts for the peaks and dips of Figure 4. Three factors could account for the unrandom distribution of stations in Figures 3 and 4:

1. There are water level controls on solution within Wind Cave. The presence of a few prominent, strike-oriented passage complexes within the cave also tends to support a water table origin for Wind Cave.

2. Exploration and mapping of passages has been concentrated within a few zones in the cave. This is probably not the major factor.

3. Structural controls, such as fracture zones and minor flexures, have caused uneven distribution of passages.

The high degree of fracture development associated with the formation of boxwork within Wind Cave and the zonal occurrence of boxwork within the cave tend to support the third factor as the cause of the uneven passage distribution.

Additional evidence supports a conclusion in favor of an artesian origin for Wind Cave (see cavern cross sections, Figure 3, A and B):

1. Zones of solution along major joints when followed laterally migrate as much as 80 feet between levels.

2. Most major passages, at least in the lower levels, follow the stratigraphic dip.

3. Cavern levels are intimately interrelated and interconnected.

4. The almost complete absence of cavern sediments and survival of very fragile boxwork suggests extremely quiescent through-flowing ground water.

5. There are mineralogic indications of a temperature of about 100 degrees centigrade at the time of deposition of calcite within the cave (White and Deike, 1962). The earlier period of solutional activity may also have taken place at an elevated temperature.

6. Numerous ceiling pits of phreatic origin extend upward from the upper levels of the cave as much as 100 feet above the main cavern levels.

The possibility is strong that successive epochs or artesian and water table movement were active in the presently known parts of Wind Cave.

This ends the main portion of the paper, but three appendices will now be presented which develop ideas supplemental to the main thesis.

## Appendix 1

In nearly homogeneous limestones, connecting cross passages between the major cavern passages parallel to the strike in water table caverns are reasonably expected to be, like the main passages, developed near the top of the water table, and thus nearly horizontal (case 1 of Figure 5). However, another possibility exists for cavern passage morphology if development of cavern passages is limited to certain more soluble zones within a dipping limestone formation. Because cavern passages will tend to form along paths of least resistance to ground water flow, and hence along paths of greatest ability of solutional attack, a situation such as that of case 2 of Figure 5 might prevail. Because of the lesser solubility of limestone between the major passages, a minimization of distance of flow required through this less soluble unit is realized in a path of ground water flow in the connecting passage. Such flow follows the more soluble unit downdip or the reverse to the closest approach to the other main water table passage and then rises or descends nearly vertically between the more soluble horizons. In effect then, an artesian condition is present through the connecting passage, such that ground water is forced through a deep, indirect path by a structural situation. A slight difference of elevation of the water level between the two passages would be the motivating hydrostatic potential.

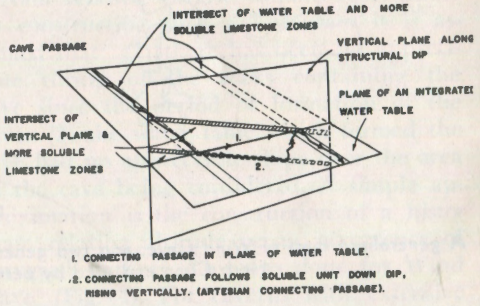


Figure 5

Two possible types of connecting passages between major cavern passages along the strike in a cavern formed at an integrated water table.
1. Connecting passage in plane of water table.
2. Connecting passage follows soluble unit down dip, rising vertically (artesian connecting passage).

Similar artesian passages in water table caves might be found if the water table rises above a cavern that had been formed by a lower water table, or if earlier formed artesian cavern passages are found at a moderate depth below the water table. In such cases some divergences of flow from the water table to artesian flow at depth utilizing previously formed solutional channels might be expected. However, given sufficient time formation of water level passages should relatively decrease the importance of the deeper connections.

## Appendix 2

The Minnelusa sandstone rather than the Pahasapa limestone has been cited as the major aquifer within the Black Hills (Darton and Page, 1925). Deal (1962) argues that the circulation of ground water was continuous between the Pahasapa and Minnelusa, and that the Opeche shale overlying the Minnelusa is the sealing unit. If this is the case then a loss of ground water from the limestone to the sandstone in the artesian zone is indicated, because almost all of the streams flowing across the limestone from the central part of the Black Hills lose all their drainage to the limestone before crossing the sandstone. This is probably accomplished by an upward seepage from the limestone to the overlying sandstone. As a consequence of this the importance of the limestone as an aquifer, and the attendant solution, would decrease toward the artesian water outlet. There is some indication within Wind Cave that there has been communication between the ground water in the limestone and that within the sandstone at the time of formation of the cave. In many places within the cave there are upward-leading pit complexes which end in sandstone blockages, and many passages are walled by or end in sandstone fills of ancient solution channels within the limestone, and these probably communicate with the overlying sandstone. On the other hand, little water seeps into the caves from the surface where the limestone is presently overlain by sandstone. There are other lines of evidence which suggest that the Pahasapa is at present the major aquifer *within* the Black Hills (Gries, 1956). First of these is that the water levels within the Pahasapa and Minnelusa are not coincident, that in the Minnelusa being the lower. Secondly, in the zone of active artesian circulation within the Black Hills within the ring of natural artesian springs, wells drilled into the Pahasapa almost always give high yield. These criteria suggest that the shaly layers directly overlying the limestone offer significant resistance to the interchange of ground water between the two units. Probably the importance of the Pahasapa as an aquifer increases with time as continuing solution reduces resistance to ground water movement.

## Appendix 3

A nearly horizontal, structure-crossing cavern passage has in recent literature been assumed to necessarily mean the influence of water table control. However, where the ground water entering a cavern system contains a heavy load of detritus, especially in the sand and smaller sizes, a horizontal control may be exerted even though solution occurs well below the water table. When such turbid water enters a large cavern system a drop in water velocity and increase in dissolved load should cause a deposition of all tractive and most suspended load. This accumulation will tend to fill in the low spots in the cavern floor, and by forcing greater velocity and turbulence at points where the ceiling of the cavern is lower, the lower and constricted passage zones will tend to dissolve more rapidly. The net result of the accumulation of sediment will be to create an upward dissolving action and the attainment of a "graded" passage of small slope. Theoretically, however, several criteria should distinguish caverns with nearly horizontal passages resulting from water level control from the present case:

1. The "sediment graded" passages should have greater and more irregular slope than integrated water level passages.
2. Remnants of former cavern sediments might be found in the latter case whose stratification provides distinguishing criteria.
3. Each major passage in sediment graded caves would have unique grades depending upon sediment input, and would tend to form at separate levels not necessarily correlating between passages, that is, the passage complexes would be practically independent.

Another similarly-acting factor leading to a nearly horizontal development of completely artesian passages might be density stratification of ground water flowing through the cavern system, either because of temperature differences or differences of concentration of dissolved or suspended load. If this density stratification tended to concentrate the more acidic ground water near the cavern ceilings, and if ground water turbulence was low, nearly horizontal cavern passages might eventually tend to form.

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# The Flint Ridge Cave System: 1957-1962


by PHILIP M. SMITH



Abstract—Systematic exploration and survey in the Flint Ridge Cave System, Kentucky, since 1947 has resulted in the physical or geologic integration of Colossal, Crystal, Great Onyx, Unknown, and Salts Caves. Passages totaling 40.52 miles have been surveyed and an additional 5 miles are known to exploration teams. Exploration between the early 1800's and 1961 which has been important to the integration of the Flint Ridge Cave System is reviewed. Concurrent with exploration, investigations have been initiated in geology, biology and hydrology. Some of the projects in these fields under the sponsorship of the Cave Research Foundation are discussed. One hundred cavers and scientists have expended 18,000 man hours in Flint Ridge since 1957.


### Introduction

The sustained exploration of Floyd Collins' Crystal Cave entered its second decade in 1957. The ten preceding years had witnessed the rediscovery and partial survey of an extensive system of cave passages discovered by Collins. Exploration practically stopped following Collins' death in 1925. Dr. Harry B. Thomas, owner of the cave, hired Harry Dennison and Ewing Hood as guides during this period but their exploration efforts were unsystematic. Many of the avenues known to Collins became almost legendary passages to the younger generation. Full scale work was resumed in 1947 under the leadership of James Dyer.

Some of the earliest exploration of this assault that has continued without interruption since 1947 was summarized by Lawrence and Brucker (1955) in their account of the National Speleological Society's Crystal Cave Expedition. After the week-long effort in 1954, exploration was continued by the handful of cavers who had been working in the cave for several years. Major discoveries, including a passage complex extending southwest from Crystal Cave into the heart of Flint Ridge, spurred the group in its work, and the exploration pace was accelerated. Explorations during the three years that followed the 1954 expedition as well as cartographic and logistic developments were discussed in a previous paper (Smith 1957).

Since 1957 exploration, survey, and research in Flint Ridge have gone forward at an increasing rate. The result is the physical integration of the Flint Ridge Cave System and the initiation of a year round research program in Flint Ridge. This article summarizes exploration that has taken place in the last five years, discusses the current mapping program and describes some completed and current research projects. Work through December, 1962 is discussed.

Most of the work undertaken in the Flint Ridge Cave System since 1957 has been under the sponsorship of the Cave Research Foundation, with the consent of the National Park Service. Until late 1960, when it was sold to the federal government, Crystal Cave was owned by Mrs. H. B. Thomas whose encouragement did much to advance the Foundation's program.

Exploration and survey are the responsibility of 70 joint venture personnel who work under the field supervision of Foundation directors and members. The joint venturers are selected because of their caving and surveying skills and their ability to participate regularly in the Foundation's program. All have entered into formal agreements with the Foundation, protecting both parties and the National Park Service in legal matters related to the work, in the management of the survey and exploration program, and in the conservation of the cave. Although joint venturers are drawn from many of the eastern states, most in the current program come from Ohio and Tennessee. Survey and exploration campaigns are held on weekends throughout the year. Each August an expedition of some 40 persons is in the field for two weeks.

Research sponsored by the Foundation has included projects in archeology, biology, geology, and history. Scientists from several universities have spent from two weeks to two summers in Kentucky, depending on the nature of the work and the financial support available. One biological project has involved daily observations for two years.

There is not space here to describe all of the individual trips or even all of the most significant campaigns which have been conducted. Only a few of those who have contributed materially to the Flint Ridge effort are mentioned here. In the five year period, 18,000 man hours have been expended by 100 cavers and scientists. At some future date an extended account of this work in the Kentucky cave region will be given.

The writer is indebted to the following for their counsel in the preparation of this summary: William T. Austin, Roger W. Brucker, George H. Deike, Robert M. Keller, John A. Stellmack, Louise Storts, William B. White, and Richard A. Watson.

### Integration of the Flint Ridge Cave System

Today the Flint Ridge Cave System is the largest known cave in the western hemisphere and one of the major caves of the world. Passages totaling 40.52 miles have been surveyed. In addition to the surveyed passages it is estimated that 5 miles of additional cave passages are known to the exploration groups. The Flint Ridge Cave System originates in five major caves and numerous smaller caves which historically have been considered separate caves. The interconnection of the caves in Flint Ridge has been suspected for many years. By 1955 the evidence was in hand even though the final physical connection was not made until 1961.

Salts Cave was probably the first Flint Ridge cave to be visited by the explorers of the Kentucky wilderness and the settlers who followed in their footsteps in the early 1800's (Figure 1). There are no clear records of the initial explorations. Dates on cave walls are as early as 1845. By 1875 persons from more distant locales were also visiting the cave. The spectacular, one-acre collapse sink entrance, the spacious northwesterly-trending, mile-long main passage, tremendous blocks of massive breakdown, and archeological remains attracted attention then as they do today. Salts Cave was the scene of two unsuccessful commercial ventures early in this century. Onyx mining was started and continued sporadically until the establishment of Mammoth Cave National Park. A commercial tour was developed but gained no real foothold, partly because of the extreme competition between commercial caves existing at the time and partly because of the inherent difficulties in developing the cave. Today the only visible signs of commercialization are the mined areas and stone stairways at two or three points near the Salts Cave main entrance and near the collapsed Pike Chapman entrance.

Unknown Cave, a second Flint Ridge cave with a natural entrance, lies to the west of the main Salts Cave passage. This cave has its entrance in a cliff in the southeastern arm of Three Sisters Hollow. The exploration history of this cave is obscure but it can be assumed that the cave was visited many times in the 1800's. Names found on the cave walls include several members of the Hunt and Lee families, local cave guides and explorers over several generations, and the name of Edmund Turner. Turner is believed to have surveyed in the cave. Unknown is not an extensive cave and was never considered an important Flint Ridge cave. The entrance passages are not large and terminate in breakdowns or vertical shaft drain complexes. Neither the breakdowns nor the shafts were explored by any of the first parties. As will be seen, their exploration has been important to the integration of the Flint Ridge Cave System.

Colossal Cave, a major complex of the Flint Ridge System, lies to the southwest of Salts Cave. Several explorers claim discovery. It is probable that parties led by Robert Woodson, Lute and Henry Lee, and William Garvin all entered the cave between 1890 and 1895. The first explored passages led to the top of the 130 foot high Colossal Dome, which, when descended, gave access to Grand Avenue, Colossal's main corridor. A nearby cave named Bedquilt was found to connect to Colossal by way of a long, low crawlway. While the date for the discovery of Colossal Cave itself must be placed around 1895, the probability is that the work in Bedquilt Cave pre-dates it by twenty years. Recently Cave Research Foundation parties have located names and dates going back to 1871 in shafts of the Bedquilt area. Two additional entrances to Colossal were developed, bringing the total to four. Today the entrance at the northern end of Grand Avenue is used most frequently.

Colossal was immediately recognized as a potential tourist attraction because of its immense avenues and vertical shafts. The fame of Colossal Cave spread rapidly through favorable notice by many writers including Hovey (1903). Throughout the commercial period, lasting until the national park movement started, exploration was continued by the cave guides. Apparently they discovered about 6 miles of cave. The commercialization was under the direction of the Louisville and Nashville Railroad which had purchased the cave in 1896.

In 1915 still another Flint Ridge cave was discovered when Edmund Turner located Great Onyx to the northwest of Unknown and Colossal Caves. The entrance was man-made; Turner had discovered a hillside breakdown terminating an impressively large avenue. The flowstone decorated entrance area and sulfate speleothems in the 4,286 foot long main passage had sufficient appeal to make the cave a potential tourist attraction. A "river route" of some 1,977 feet was also developed. This tour visited vertical shafts. Intensive exploration by the staff of commercial guides failed to uncover any significant passages beyond the avenues initially located by Turner.

When Floyd Collins discovered Crystal Cave in 1917 the fifth of the major Flint Ridge caves was opened to exploration. Collins' dual interest in exploration and commercialization occupied him continually the rest of his life. His findings were not widely known in his lifetime. Fortunately Collins took a few associates into the undeveloped parts of Crystal Cave. The knowledge possessed by these men constituted the only link between Collins' exploration and Dyer's group which commenced work in 1947.

Although Salts, Colossal, Great Onyx and Crystal Caves were the largest known caves in Flint Ridge they were by no means the only ones known to the local population. Caves such as Buzzards or Cathedral Cave near Crystal and Potato Cave west of Great Onyx are in themselves significant. Surveys during the last five years shown that the smaller caves are related to the large cave system. For example, Floyd's Cave in Three Sisters Hollow contains vertical shafts contiguous to shafts reached through the Flint Ridge System's Pohl Avenue. The small caves known prior to the end of the Ridge's human occupation are now obscured in the dense second growth forest covering Flint Ridge. They are being relocated and surveyed as time permits.

We do not know when or where the concept of a single, integrated cave system in Flint Ridge began. Surely some of the local explorers suspected interconnection of major passages. These men were handicapped by the lack of the technical equipment that now permits extended underground trips. Most of them were not able to survey, either because they did not know the techniques, the possible application, or because rivalries growing out of the competitive commercial cave business prevented assemblage of a "trustworthy" team for the work. Some workers such as Edmund Turner did relatively extensive surveying and from their notes they no doubt deduced some of the physical relationships now clearly evident.

The concept of an interconnected cave system was stated early in the century by two French speleologists. They were Max Le Couppey De La Forrest (1903) and E. A. Martel (1912). They not only foresaw the interconnection of Salts and Colossal Caves, but also predicted their eventual connection with Mammoth Cave. Their writings in *Spelunca* went generally unnoticed in the United States. Weller (1927) also noted the possibility of interconnection at the lower levels of the caves but felt that most passages would be blocked. For the most part, the several major caves of Flint Ridge were considered to be separate, unrelated caves by the visiting specialists who came in increasing numbers as the fame of the Kentucky cave region grew.

The probability of an interconnected cave system in Flint Ridge received substantial support from a series of fluorescein dye tests conducted in 1925 by the Louisville Gas and Electric Company. A dam on the Green River above Mammoth Cave had been proposed. The deeply entrenched river valley with its 300 foot high, steep-sided bluffs looked suitable for hydro-electric power generation. An engineer working for the company placed dye in a number of surface and subterranean springs and rivers on Flint Ridge to determine whether water from an impounded river would flow through the ridge, bypassing the dam itself (Figure 2). All the dye except that dumped in the surface runoff at Three Springs appeared at Pike Spring. The Three Springs dye, on the other hand, appeared at the effluent of Echo River spring, near Mammoth Cave, suggesting that impounded water could follow this route around the proposed dam. In summarizing the test R. B. Anderson concluded "... a very narrow divide, located in a dry valley, separates two major underground streams, one emptying into Green River above the site, the other below. There is consequently a grave possibility that a bypass between these two streams exists in a cave level not more than 60 feet above the level of Green River." The dye tests had positively shown the interconnection of the Flint Ridge caves at base level, as well as proving the infeasibility of the dam upstream from Mammoth Cave.[1]

Still, there was no direct evidence that man could traverse between the caves. There were rumors of connections. One has it that Floyd Collins had made some of the connections (though he probably had not) and one local legend is that he was killed in

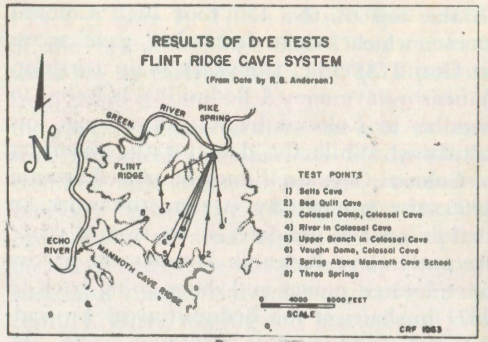

Figure 2

Sand Cave while trying to connect the Flint Ridge System with the Mammoth Cave System. Later explorers in Crystal Cave found themselves heading back into the complex already known. Examination of topographic maps and the terrain itself pointed up the difficulties in the interconnection of the caves, for the major Flint Ridge caves appeared largely separated from each other by seemingly impassable valleys. The large assault in 1954 had not produced major discoveries, and those who continued exploration received little encouragement in connecting the caves.

The situation changed rapidly when exploring parties found Crystal Cave to be the nucleus of a much larger cave system. Passages beneath Three Sisters Hollow were discovered. This hollow separates Crystal Cave from much of the rest of Flint Ridge. Beyond the Hollow lay the Pohl, Upper and Lower Turner, and Swinnerton Avenues.[2] Connected to the historical Crystal Cave by way of Pohl Avenue, these magnificent avenues, totaling 5.8 miles in length, gave explorers access to the centermost part of Flint Ridge. When the surveys of the new findings were studied three facts stood out: the subterranean crossing of Three Sisters Hollow demonstrated that cavern development in the Kentucky cave region occasionally permits travel beneath the entrenching valleys; alignment of some main avenues such as Turner and Colossal's Grand Avenues

[1] Because of the large area involved, this dye test is one of the most remarkable applications of the technique in U. S. caves. The reports contain only a little information on the methods, and much that is desired is missing. For example, the Green River stage was not noted, and there were no U.S.G.S. gaging stations operating nearby. The test should be repeated using current techniques.

[2] To avoid confusion, Lower Turner Avenue has been named Mather Avenue after Stephen T. Mather, first Director of the National Park Service. In this account some names, dating back from the discoveries, have been retained to relate the work to previous literature.



showed that many of the major avenues are parts of longer passages now segmented by valley development; vertical shaft exploration confirmed Pohl's (1955) concepts and revealed that shafts sometimes penetrated several levels of horizontal avenues, giving access to previously unexplored cave passages. Combined, these three facts suggested that it eventually might be possible to connect the major caves in Flint Ridge. On reaching the hillside termination of a major avenue, an explorer could probably find access to vertical shafts. Exploration of the shafts could lead to passages at lower elevations and these in turn could cross under a valley. Once the valley had been crossed, entry might be made into an already discovered Flint Ridge cave, or into other passages leading to known areas.

With this knowledge in hand and evidence such as the dye tests and writings of Martel and others, the Cave Research Foundation set in motion a program of systematic exploration and survey designed to describe the integrated Flint Ridge Cave System.

Close coordination of exploration and survey was an obvious requirement as the work went forward. The system of mapping in which surface topography and the cave system were shown on the same scale was already in use (Smith 1957). This series of maps did not cover the area adequately for the all-out effort in Flint Ridge. A new series, employing the same overlay principle, was developed. Taken from the U.S.G.S. 7.5 minute series, the new C.R.F. quadrangles contained exactly 30 seconds of latitude and longitude, with 225 such quadrangles making up the 7.5 minute U.S.G.S. quadrangle. The scale is 1:1200 (1″ = 100′). All the surface topography was plotted on the new base maps and existing surveys replotted on the new series. Eventually the 30 minute quadrangle series will be extended to Mammoth Cave Ridge. The system is applicable to other mapping that might be undertaken in the central Kentucky region.

Initially, two areas where passages of separate caves were in close proximity received major exploratory attention. One was the Overlook-Big Canyon complex of Crystal Cave, a series of vertical shafts, canyons, and shaft drains only 500 feet from Salts Cave's Pike Chapman entrance area. Over a two year period numerous parties were put into the shafts and canyons, but none of the leads were found to head toward Salts Cave. For a while a particularly promising prospect was the top of Big Canyon which was on about the same level as the Salts passages. Explorers met disappointment after difficult technical climbing, and then returned over the long route through the Lost Passage to the Collins' entrance of Crystal Cave.

Concurrently with the Overlook-Big Canyon effort, teams were dispatched to Argo Junction, a spacious room where the southern ends of Upper and Lower Turner Avenues meet. Argo Junction is not far from Colossal Cave's Grand Avenue; the two are separated by an arm of Eaton Valley. In a crawlway off Argo Junction stalactites had been removed from the ceiling and stacked under a ledge by some unknown earlier explorer (Figure 3). Tales told by local residents recounted a breakthrough from Colossal into a decorated passage that fitted the description of our discovery. This seemingly obvious connection proved a cul-de-sac. By a longer route, the area was approached once again. From the Gravel Avenue complex west of Turner, parties led by Brucker, Robert Keller, Larry Ball and Chet Hedden explored Candlelight River. This 4,000 foot stream complex drains a series of shafts located along the northern side of the valley between Turner Avenue and Colossal Cave. No connection with Colossal was found. A natural divide of the base level streams, two siphons and frequently fluctuating air currents make the area scientifically interesting.

In Crystal Cave explorers had been repulsed by the gypsum-choked canyon and crawlway to the left of Scotchman's Trap. When other efforts to connect Crystal with Salts failed it seemed as if new efforts should be made left of Scotchman's Trap. David B. Jones and John J. Lehrberger made grueling, 20 hour trips 6,500 feet to the south, only to return with the report that additional exploration was required. Except for one trip in 1962 the work has not been continued. This area remains incompletely surveyed and explored, awaiting challenge by new teams.

In late 1959 a survey of Colossal Cave was

Figure 3

Broken stalactites left by an unknown explorer of Flint Ridge circa 1890-1920. CRF photo by W. T. Austin.

begun. The older maps made at the time the cave was owned by the Louisville and Nashville Railroad had provided a generalized knowledge of the cave's orientation but with more systematic work in other parts of Flint Ridge, it was necessary to resurvey Colossal Cave. The old maps of the main avenues proved to be accurate in most details. As survey and exploration proceeded, many additional passages were located. A number of these had been previously explored. Published small-scale maps did not align well with the new data, and exploration teams were faced with uncertainty when trying to determine whether they were in fact in new passages.

The Colossal River area, for example, was wholly inaccurate, apparently a sketch rather than a survey. The Colossal River, when finally rediscovered, was intensively examined for it seemed as if it might lead to other passages beneath the valleys of the Ridge. New river passages have been discovered and partially mapped, but none of the discoveries have led to avenues which cross under valleys.

First success in the integration of the Flint Ridge Cave System came when William T. Austin and Lehrberger discovered a connection between Crystal and Unknown Caves. Two paralleling galleries descriptively called the Upper and Lower Crouchway connect Pohl Avenue at one end, and a series of shafts on the other. Breakdown in the inactive vertical shafts made exploration of the terminations of these passages hazardous. Above the shafts is Unknown Cave.



Whether the shafts had been explored earlier is doubtful because of the inherent difficulties in the climb. Had some explorer of an earlier generation pushed exploration in Unknown Cave it is likely that much more of the Flint Ridge Cave System would have been known years ago.

The Flint Ridge System consisted of three major segments in 1960: the Crystal-Unknown complex; the Colossal Cave complex; and Salts Cave. After the sale of Great Onyx Cave to the federal government parties commenced work there, hoping to connect this cave to the Crystal-Unknown part of the System. Most promising leads terminated in breakdown or sediment-filled avenues, and shafts proved unproductive. To date Great Onyx Cave remains physically separate. Eventually it may be connected to the rest of the System. None the less, the geologic integration is clear. It is included in the surveyed mileage because of its geologic relationship to the physically integrated system.

While larger teams continued exploration and mapping in several areas Lehrberger pushed exploration in Salts Cave. He found a new series of passages below the well-known main gallery. The full extent of his important discovery is not known to this day for much more work must be done before all of the areas are explored and mapped. One important find was an undisturbed passage containing artifacts left by the Pre-Columbian gypsum miners. These early people had removed sulfates from Salts and Mammoth Caves and for a time worked in lower Salts Cave. Whereas Lehrberger had made his way to the lower areas through a tight crawlway in which he had moved breakdown blocking the passage, the Indians had probably gained access through a larger entrance, now unknown and probably closed.

Throughout 1960 and 1961 parties were dispatched to virtually all parts of Flint Ridge. Surveys mounted at such a rapid rate that drafting became a very major endeavor. In 1960, 8.6 miles of cave were surveyed by the joint venture teams. In 1961, 11.1 miles of cave were surveyed.

The work was spurred onward by the connection of Salts and Colossal Caves in August, 1960. Working from Colossal Cave, Lehrberger, David Deamer, and Marlin Werner climbed up from the river passage they were exploring into passages that Lehrberger had previously explored from Salts Cave. Many hours later the weary party emerged at the Salts Cave entrance. With this connection the Flint Ridge System was comprised of two large segments.

The connection of the two segments came a year later. During the August field program, parties again returned to the Upper and Lower Crouchways that had already yielded one connection. A group headed by Keller with Deamer, Werner, and Judy Powell checked the termination of the Lower Crouchway. Deamer moved a 40 pound rock, revealing a tight muddy crawlway. This was surveyed to a two foot wide, ten to twenty foot high canyon that Lehrberger had found from Salts Cave. Pushing on, Keller's party climbed up a pit to a passage on a higher level. The presence of Indian artifacts confirmed that the party was indeed at the end of Indian Avenue, over two miles from the entrance of Salts Cave. This linked as a single, traversable, connected cave system Crystal, Unknown, Colossal, and Salts Caves. Equally important, the connection allowed independent surveys that had been extended many miles from different entrances to be connected at a common point.

The August 1961 discovery was a crowning triumph of 100 years of exploration in Flint Ridge and gained for the explorers a lasting place in the annuals of speleology.

### Other Exploration

In all parts of the Flint Ridge Cave System discoveries of consequence have been made in the last five years. Their significance lies not in their contributions to the cumulative Flint Ridge mileage, but in the great variety of undisturbed cave environments available for study. These passages are the laboratory in which the processes responsible for so vast a cave system will be worked out.

Individual rooms or galleries, less lengthy than the long avenues, vary greatly in dimension. One of the most spectacular discoveries is Ralph Stone Hall. This room is about 300 feet long, 80 feet wide and 50 feet high. It has a breathtaking vista.

Other discoveries have included Ralph's River Trail, a 1,587 foot long canyon with a small stream. Along the Trail are a series of anomalous shafts located well inside the edge of the overlying capping beds. Black Onyx Avenue, reached from Black Onyx Waterfall adjacent to Pohl Avenue, is another significant discovery. In Pohl Avenue itself, the scene of extensive work, the southwestern end of the passage contains a difficult series of siphons, hazardous breakdown, and other obstacles. It has not been explored.

A survey party working in lower Salts Cave explored and surveyed to a window 60 feet above the bottom of a 140 foot vertical shaft. On the opposite side of the pit was a passage that was known to the early explorers in Colossal Cave. This second connection between Salts Cave and Colossal Cave was surveyed by triangulation but to this date the pit has not been crossed by man.

Several small caves located on the Ridge have been explored recently. Work in Floyd's Cave, started some years ago (Smith 1957), has shown this cave to be a segment of passage adjacent to Pohl Avenue. Cathedral or Buzzards Cave has been mapped in connection with a biological project. Potato Cave west of Great Onyx Cave was explored in 1961 and found to be a series of shafts with no passable exits.

## Research

While the extraordinary opportunity for speleological research in the Kentucky cave region has long been recognized, it has only been in the past decade that the singular significance of the Flint Ridge Cave System has emerged. Prior to this time, Mammoth Cave had been the only large cave system available for study. The difficulties of undertaking many kinds of research in a cave used for touring are obvious. With the discovery of extensive undisturbed areas in Flint Ridge and with the growing realization that in time it would be understood as an integrated system, workers began to see Flint Ridge as a large natural laboratory for research.

Concurrent with exploration and survey programs, research has been initiated. In all disciplines descriptive work is required. On the basis of an overall review of research opportunities (Cave Research Foundation, 1960), priority was given to geology. A biological study has been started. A project in regional history is in progress.

Vertical shafts have been of continuing interest throughout the last five years. Surveys have confirmed the findings of Pohl (1955), showing that for the most part the shafts are located beneath the edges of the Flint Ridge caprock. Brucker (1960) cited a few anomalous situations, but in each case the variations from the normal pattern of development can be explained. Brucker also examined the relationships between shafts and other cave features. He has concluded that vertical shafts are a major input for water entering the cave system. When the water reaches base level it commences lateral flow, enlarging passages in the process. R. A. Waston (1957) compared vertical shafts to other features having similar names (such as the *gouffres* of France). A detailed study of the Overlook complex forms the basis for his comparative studies and for observations on the morphology of shafts.

The accumulation of survey data and increased knowledge of the whole cave system have led to an examination of passage terminations. Many once longer avenues in Flint Ridge have been segmented by entrenching valleys, reentrants, and sinkholes. The segments are termed truncated passages; their ends, terminal breakdowns. Brucker (forthcoming) has carried forward the analysis of these features.

George H. Deike has spent two years studying the morphology of the Kentucky cave region. Special attention is now being given to the relationship between cave passage orientation and bedrock fractures. The work extends beyond Flint Ridge; 200 square miles are under intensive study, including a portion of the sinkhole plain to the south of Mammoth Cave National Park, Flint and Mammoth Cave Ridges, and the region north of the Green River to Cub Run. The work includes mapping and study in the caves, surface geology, and aerial photo interpretation. The work will continue through most of 1963 before conclusions are drawn.



Smith (1961) has considered the fluctuations of the Green River with respect to their effect on base level drainage in the Mammoth Cave region. Analysis of gaging records shows monthly changes in river height of five to ten feet, and annual variations as great as 30 feet with maxima of 57 feet (Figure 4). The constant variations in river stage are felt to be a major factor in the integration of passages at the upper limit of the saturated zone.

While these investigators have been concerned with the general description of the Flint Ridge Cave System, three mineralogists have directed attention to the secondary deposits. The sulfates especially gypsum, are one of the characteristic features of the area, and carbonate speleothems are found at most terminal breakdowns. Benington (1959) has described in detail a transparent stalactite. The major phase is mirabilite. A new mineral ($2Na_2SO_4 \cdot CaSO_4 \cdot 2H_2O$) occurs as a minor phase. A second new mineral found in Flint Ridge is the metastable salt $Na_2SO_4 \cdot 7H_2O$, described by White and Benington (1962). These two Cave Research Foundation members are continuing the description of the sulfate minerals in Flint Ridge. Eventually a comprehensive work on the family will be prepared. Some carbonate minerals have also been examined. Siegel (1962) worked in Great Onyx Cave, describing calcite-aragonite ratios in some speleothems there. He found calcite to be the dominant carbonate in the samples examined (Figure 5). Aragonite is also present in alternating sequence with the calcite. Further study must be carried out before the factors responsible for the alternating sequence can be explained.

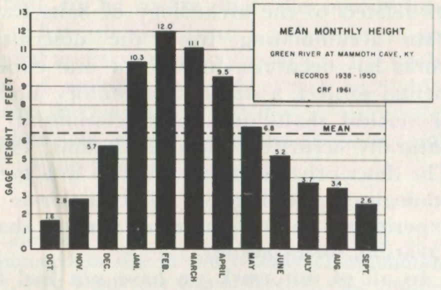


Figure 4

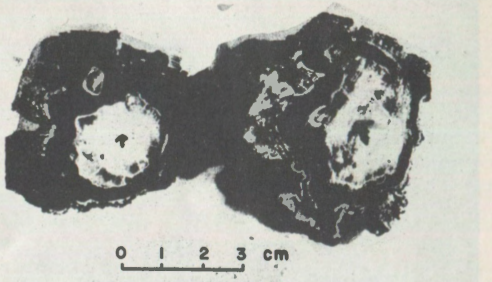


Figure 5

Calcite (light areas) and aragonite (dark bands) in a stalactite, Great Onyx Cave. CRF photo by Fred Siegel.

As a part of the mineralogical studies the blackish deposits on the ceilings of Salts and Mammoth Caves were examined. Hovey (1912) and others have attributed the deposits to manganese. First analysis showed that there was no manganese present, and that the material was an organic compound coating on gypsum. Further laboratory investigation of the black material revealed that it was soot. There seemed to be a relationship between the deposits in the passages and artifacts left in the caves by Pre-Columbian Indians. A sample from Salts Cave gave a radiocarbon determination of 3075 ± 140 years BP. Benington, Melton, and Watson (1962) have discussed the correlation of this date with two dates obtained by the National Park Service on artifacts, and other conclusions that can be drawn from the work.

The probable importance of mineral development in ceiling breakdown in Flint Ridge passages prompted William B. White and Elizabeth L. White to study the process in detail. Upper Turner Avenue was chosen as the type locality for the Whites' study, but the same features are seen in many other parts of Flint Ridge and in Mammoth Cave. Features commonly caused by the mineral development are irregular fractures in walls and ceilings, fallen blocks often containing visible veins of sulfate minerals following the fractures, symmetrical fill piles beneath ceiling breakout domes, curved plates of bedrock seemingly peeled from the ceiling (Figure 6), and, thin splinters of rock removed from ceilings along bedding planes. All of

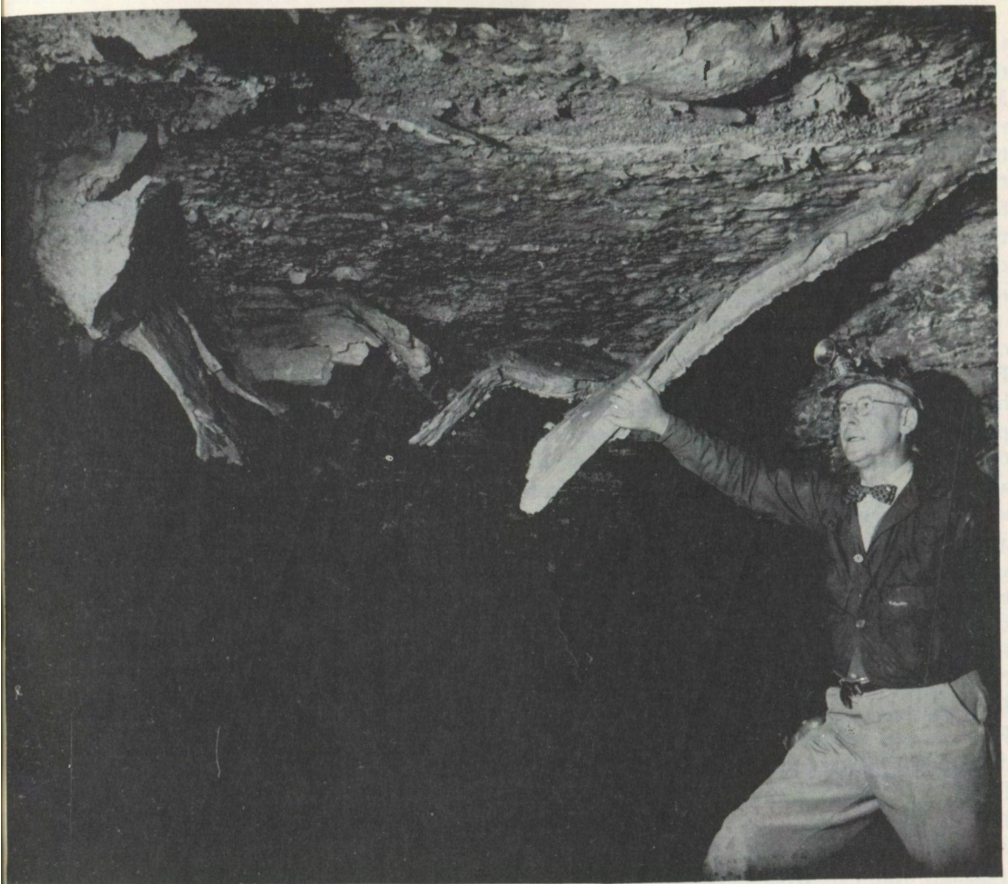

Figure 6

Curved Plate Breakdown in Turner Avenue, Flint Ridge Cave System. CRF photo by W. T. Austin.

these are caused by wedging during mineral development. Dilute sulfate solutions are responsible. When these oxides reach the zone of aeration around a cavern passage, they form gypsum by reaction with the limestone rock. Other forms of breakdown and responsible processes are also under study (White and White, 1962).

A comprehensive biological investigation, a study of the ecology of Cathedral Cave, has been undertaken by Nicholas (1962) and his assistants on a daily basis. This small cave is near the Collins' entrance to Crystal Cave. Twelve quadrants comprising about 35 per cent of the cave surface have been established. Since 1960 the animals have been marked and observed to study daily and yearly movements, predation patterns, etc. The study will continue through 1963.

In addition to these projects, the Cave Research Foundation has initiated studies in clay and manganese mineralogy, a recording program of the oral history of the region, and also botanical and pharmacological studies related to the archeology of Salts Cave. Data accumulating from the descriptive works has been responsible for one experimental project, a study of laboratory models of vertical shafts and their relationship to naturally occurring features (Reams, 1962). The descriptive work has led also to a methodological examination of two kinds of experiments in the studies of vertical shafts (Watson, forthcoming).

In all of our work we have not had the benefit of a comprehensive basic reference describing the physical geography and geology of the central Kentucky cave region. A summation of knowledge of the Flint Ridge Cave System and the region is in preparation. It will include much new data from the work of the last five years, and will review all major references to the area. It will form a basic reference for the region.

While the work undertaken or supported by the Cave Research Foundation constitutes a major part of the research in Flint Ridge, other investigators have pursued studies in Flint Ridge through arrangements with the National Park Service. John Hall (1962) has studied the life history of the Indiana bat *(Myotis sodalis)*. Thomas L. Poulson and Robert Henshaw have pursued ecological and physiological studies. Thomas C. Barr and his associates at the Institute of Speleology, University of Kentucky, have carried on ecological studies in Flint Ridge and Mammoth Cave. Donald Haynes, Paul Richards, and Richmond Brown of the U. S. Geological Survey have in near completion new geological maps and a water supply paper on the area. All of these scientists have contributed to an understanding of the cave system and its fauna.

## Conclusion

Today the investigator in Flint Ridge can travel freely through the passages of the system, making use of seven entrances to reach areas worthy of study. Finding and describing this interconnected cave system has made it possible to begin a rational description of both the cavern process in general and the history of the Flint Ridge cave complex in particular. While it is interesting to review activities in Flint Ridge from a historical standpoint it is perhaps more important to be aware that the accomplishments have derived from a persistent, open-minded and systematic approach to the problems of making the vast cavern available. Future success in Flint Ridge is totally dependent on man's continued freedom and will to inquire boldly.

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# SHORTER CONTRIBUTIONS

Short papers reporting new techniques, procedures and methods, papers of timely importance and discussions of previous papers are presented in the Shorter Contributions Section.

# Scintillites: A Variety of Quartz Speleothems

by DWIGHT E. DEAL

ABSTRACT—Speleothems formed by the deposition of euhedral quartz crystals on solutional chert remnants occur in Jewel Cave, South Dakota. They are unlike any other known occurrences of silica in caves and I propose the name "scintillites" to be applied to them and to other similar speleothems.

## INTRODUCTION AND DESCRIPTION

Sparkling red to red-brown speleothems composed entirely of quartz occur in Jewel Cave, Jewel Cave National Monument, on the west flank of the Black Hills, South Dakota. The speleothems have roughly the shape of branching helectites (Fig. 1), occur on the underside of chert ledges, and reach lengths of 40 millimeters and diameters of 8 millimeters.

The speleothems are composed of two parts: a core and an outer coating (Fig. 2). The cores make up the bulk of the speleothems and are composed of red-brown microcrystalline silica. An outer coating, 0.5 to 1.0 millimeter thick, of reddish to transparent euhedral quartz crystals up to 0.5 millimeter in diameter covers the microcrystalline cores.

## ORIGIN OF THE CORES

Jewel Cave is dissolved out of the cherty Pahasapa Limestone of Mississippian age (Deal, 1962, pp. 17-29). A considerable amount of the chert has been removed by solution and much of the chert exposed in the cave has a pitted and irregular surface similar to karrenfelder developed on limestones. The cores of the speleothems are red-stained remnants of chert nodules and bands in the Pahasapa limestone. I have previously described this staining (Deal, p. 100), which is found in a zone up to six millimeters thick behind and parallel to many of the exposed chert surfaces.

## SOURCE OF SECONDARY SILICA

There has been a considerable amount of silica deposition in Jewel Cave. Most of the silica cements fine grained fills and is found only in the cave passages below the cherty layers of the Pahasapa limestone. This led me to suggest that the silica was dissolved from the chert in the upper levels of the cave and simultaneously deposited in the underlying fills, having been transported by sinking density currents of silica-laden water. Euhedral quartz crystals up to three millimeters in diameter also occur on limestone surfaces in the vicinity of the silica-cemented fills (Deal, pp. 99-100).

George Moore (personal communication) has pointed out that it is difficult to conceive of the chert layers as a source of the silica deposited on the cores of the speleothems, which occur within the cherty zone itself. Higher bands of chert might have been the source, but since the entire Black Hills area was blanketed by extensive volcanic sediments in Eocene time the silica may well have come from the leaching of these sediments by ground water.

At this time I am not certain that the solution of the silica from the chert and its simultaneous deposition in the fills 50 feet lower is chemically feasible in the cave environment. It may well be that the source of all the silica was the Eocene volcanic material.

Both the solution of the chert and the deposition of the euhedral quartz must have taken place in a subaqueous environment.

Since there are no secondary coatings on the quartz of the subaqueously deposited calcite that is found throughout the cave, the formation of the silica speleothems must have been nearly the last event that took place before the final draining of fluids from the cave.

### Relationship to Boxwork

The occurrence of boxwork in the Black Hills caves has been discussed in detail by Deal (1962) and White and Deike (1962). The same thin veins of coarsely crystalline, brown calcite that occur in the Pahasapa limestone occasionally occur filling fractures in the chert. This is found in the area of the silica speleothems. The nature of the solutions that dissolved the chert was such as to not dissolve the coarsely crystalline, brown calcite veins and to leave the chert cores attached to the calcite veins protruding from the cave walls. Euhedral quartz was then deposited on both the chert remnants and the brown calcite veins (Fig. 3).

### Other Occurrences of Silica in Caves

Occurrences of quartz in the fills of all the major Black Hills caves and of euhedral quartz in Wind Cave, South Dakota, is reported by Deal (p. 100). Euhedral quartz in Wind Cave is also noted by White and Deike (1962, p. 81). Tullis and Gries (1938, p. 265) report large amounts of opal associated with globulites and anthodites in Wind Cave, and Johnson (1919, p. 18) reports euhedral quartz in Bethlehem Cave, South Dakota.

Euhedral quartz veins are reported to occur in Warrens Cave, Florida (Lou Hippenmeyer, personal communication). Euhedral quartz cave coral is developed on top of, and has the same appearance as the calcite cave coral in Lehman Caves, Nevada (George Moore, personal communication). Photographs of boxwork composed of silica occurring in Bozkov Cave, Czechoslavakia, have been published by Skrivanek and Valasek (1959).

None of these occurrences bear any resemblance to the silica speleothems in Jewel Cave. Because of the highly reflective nature of the speleothems described in this paper, I am proposing the name "scintillites" for them. It is my intent to apply this term to any highly reflective, all-silica speleothems having exterior forms similar to stalactites, stalagmites, or, as in this specific case, helictites.

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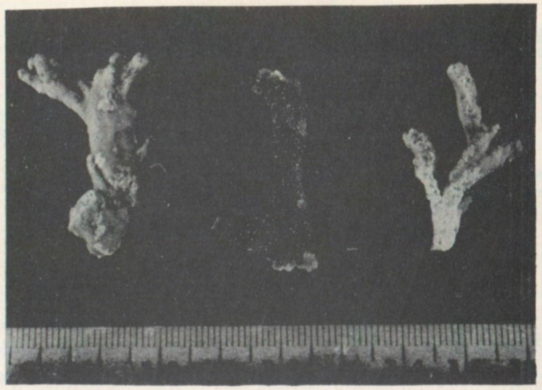

Figure 1

Three "scintillites." The scale is in centimeters and the small patches of white material on the speleothems are subaerially deposited calcite.

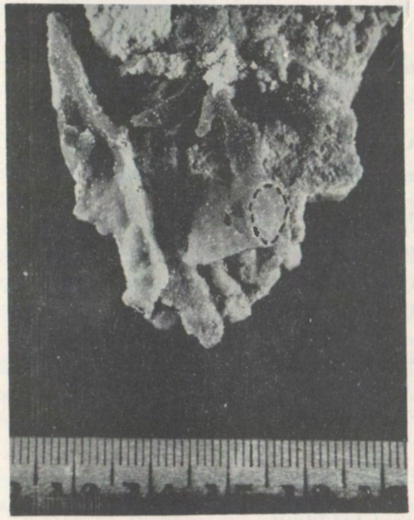

Figure 2

The underside of a chert ledge showing protruding speleothems. One speleothem has been broken to show the internal structure. The dashed line marks the boundary between the microcrystalline core and the euhedral coating. The scale is in centimeters.

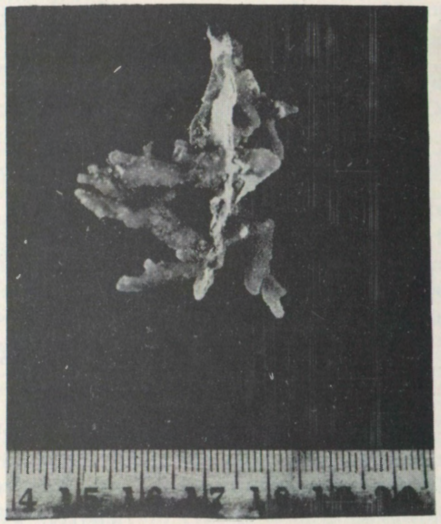

Figure 3

Scintillites developed on a vein of coarsely crystalline, brown calcite. The scale is in centimeters.

# Land Snails From the Caves of Kentucky, Tennessee and Alabama


by LESLIE HUBRICHT



ABSTRACT—Eighteen species and one subspecies are recorded, of which five species and one subspecies are known only from caves. It is believed that these latter species were originally epigean species which entered each cave in which they are known independently and then became extinct on the surface, rather than that each originated in a single cave and migrated through subterranean passages to reach its present range.


This list of cave land snails includes only species which were found within the total darkness zone of caves. In most cases they occurred in sufficient numbers to indicate that they lived and bred there. Species which were found about cave mouths or dead shells washed in are not included. Of the species listed, *Carychium stygium* (Fig. 2), and most of the species of *Helicodiscus* are known only from caves. These were found feeding principally on the guano of the cave cricket, *Hadenoecus subterraneus* (Scudder), or related species. *Zonitoides arboreus*, and *Carychium exile* were living on wood, either washed in, or carried in for walks, ladders, etc. The remaining species, for the most part, were feeding on decaying leaves blown or washed in. No snails were found feeding on bat or cave-rat guano.

That *Helicodiscus multidens*, *H. barri*, *H. hadenoecus*, and *Carychium stygium* (Fig. 2), which are known only from caves, could each have evolved in a single cave and moved from there to the other caves in its range through subterranean passageways, even if such existed, seems impossible. They were probably originally epigean species which moved independently into each of the caves in which they are now found, and later became extinct on the surface. These cave populations are probably Pleistocene relicts.

### FAMILY POLYGYRIDAE

*Mesodon appressus appressus* (Say) (Fig. 1)
KENTUCKY: Powell Co.: Bowen Cave, 1 mile northeast of Slade. Edmonson Co.: White Cave, Mammoth Cave National Park. TENNESSEE: Putnam Co.: Jared Hollow Cave, 3 miles northeast of Chestnut Mound.

*Mesodon rugeli* (Shuttleworth)
KENTUCKY: Monroe Co.: Natural Tunnel, 1 mile north of Meshack. Powell Co.: Bowen Cave, 1 mile northeast of Slade.

*Mesodon inflectus* (Say)
KENTUCKY: Hart Co.: Ronalds Cave, 2.6 miles north of Cave City; Cooch Webb Cave, 2.2 miles west of Priceville. Barren Co.: Duval Saltpeter Cave, 0.7 mile northwest of Beckton. ALABAMA: Madison Co.: Shelta Cave, 1 mile north of Huntsville.

### FAMILY ZONITIDAE

*Glyphyalinia paucilirata* (Morelet)
KENTUCKY: Metcalfe Co.: Gassaway Cave, 0.6 mile northwest of Beaumont. TENNESSEE: Dickson Co.: Columbia Caverns, 2 miles southwest of Van Leer. Warren Co.: Cumberland Caverns, 8 miles southeast of McMinnville. Perry Co. Bethel Cave, 1 mile southwest of Bethel.

*Glyphyalinia cryptomphala* (Clapp)
TENNESSEE: DeKalb Co.: Avant Cave, 1 mile east of Dowelltown; Jim Cave, 1.5 miles southeast of Dowelltown. Warren Co.: Cumberland Caverns, 8 miles southeast of McMinnville. Smith Co.: New Piper Cave. KENTUCKY: Warren Co.: Thomas Cave, near Hadley.

*Glyphyalinia sculptilis* (Bland)

KENTUCKY: Adair Co.: Saltpeter Cave, 1 mile northeast of Breeding.

*Gastrodonta interna* (Say)

ALABAMA: Madison Co.: Aladdin Cave, 7 miles northeast of Maysville.

*Zonitoides arboreus* (Say)

KENTUCKY: Powell Co.: Bowen Cave, 1 mile northeast of Slade. Livingston Co.: Shelby Cave, 2.5 miles southeast of Salem. Edmonson Co.: White Cave, Mammoth Cave National Park. Barren Co.: Vance Cave, 0.8 mile northeast of Park City. Metcalfe Co.: Gassaway Cave, 0.6 mile northwest of Beaumont. TENNESSEE: Montgomery Co.: Dunbar Cave, 1.5 miles south of St. Bethlehem. Warren Co.: Cumberland Caverns, 8 miles southeast of McMinnville. Grundy Co.: Wonder Cave, 0.5 mile northeast of Piedmont. Jackson Co.: Carter Cave. ALABAMA: Madison Co.: Aladdin Cave, 7 miles northeast of Maysville.

### Family Endodontidae

*Discus patulus patulus* (Deshayes)

TENNESSEE: Warren Co.: Cumberland Caverns, 8 miles southeast of McMinnville. DeKalb Co.: Jim Cave, 1.5 miles southeast of Dowelltown. ALABAMA: Madison Co.: Aladdin Cave, 7 miles northeast of Maysville.

*Helicodiscus multidens* (Hubricht)

TENNESSEE: Putnam Co.: Jared Hollow Cave, 3 miles northeast of Chestnut Mound. DeKalb Co.: Jim Cave, 1.5 miles southeast of Dowelltown; Avant Cave, 1 mile east of Dowelltown.

This species is known only from these caves.

*Helicodiscus notius notius* (Hubricht)

KENTUCKY: Hart Co.: Copelin Cave, 2 miles east of Millerstown. Edmonson Co.: White Cave, Mammoth Cave National Park. TENNESSEE: DeKalb Co.: Jim Cave, 1.5 miles southeast of Dowelltown. Warren Co.: Cumberland Caverns, 8 miles southeast of McMinnville.

*Helicodiscus notius specus* (Hubricht)

KENTUCKY: Barren Co.: Burnet Cave, 0.6 mile west of Park City.

This subspecies is known only from this cave.

*Helicodiscus barri* (Hubricht)

TENNESSEE: Dickson Co.: Columbia Caverns, 2 miles southwest of Van Leer. Davidson Co.: Bull Run Cave, 2.5 miles southwest of Scottsboro.

This species is known only from these caves.

*Helicodiscus hadenoecus* (Hubricht)

KENTUCKY: Barren Co.: Beckton Cave, 0.5 mile northwest of Beckton. TENNESSEE: DeKalb Co.: Avant Cave, 2 miles east of Dowelltown. Van Buren Co.: McElroy Cave, 1.5 miles northeast of Bone Cave P. O. White Co.: Indian Cave, 2.5 miles southeast of Quebeck. Jackson Co.: Hargis Cave, 1 mile north of Granville. ALABAMA: Madison Co.: Aladdin Cave, 7 miles northeast of Maysville.

This species is known only from these caves.

*Helicodiscus punctatellus* (Morrison)

KENTUCKY: Edmonson Co.: White Cave, Mammoth Cave National Park.

This species is known only from this cave.

*Helicodiscus inermis* (H. B. Baker)

TENNESSEE: Van Buren Co.: McElroy Cave, 1.5 miles northeast of Bone Cave P. O. Grundy Co.: Crystal Cave and Wonder Cave, 0.5 miles northeast of Piedmont; Saltpeter Cave, 4 miles northeast of Pelham.

### Family Pupillidae

*Gastrocopta contracta contracta* (Say)

KENTUCKY: Monroe Co.: Natural Tunnel, 1 mile north of Meshack.

### Family Carychiidae

*Carychium exile* (H. C. Lea)

KENTUCKY: Monroe Co.: Natural Tunnel, 1 mile north of Meshack. Barren Co.: Vance Cave, 0.8 mile northeast of Park City. TENNESSEE: Putnam Co.: Jared Hollow Cave, 3 miles northeast of Chestnut Mound. Perry Co.: Bethel Cave, 1 mile southwest of Bethel. Warren Co.: Cumberland Caverns, 8 miles southeast of McMinnville. Jackson Co.: Hargis Cave, 1 mile north of Granville. ALABAMA: Marshall Co.: Guffey Cave, 1.5 miles north of Grant.



*Carychium stygium* (Call) (Fig. 2)

KENTUCKY: Hart Co.: Copelin Cave, 2 miles east of Millerstown; Puckett Cave, 1 mile west-southwest of Priceville; Chattin Cave, 2 miles west of Priceville; Cooch Webb Cave, 2.2 miles west of Priceville; Buckner Hollow Cave, 7 miles east-northeast of Munfordville; Cub Run Cave, 2 miles west of Cub Run; Ronalds Cave, 2.6 miles north of Cave City; Hogan Cave, 3 miles north of Cave City; cave, 2 miles southwest of Northtown. Edmonson Co.: Mammoth Cave National Park, near river, in Great Onyx Cave; Cathedral (Buzzards) Cave, near Floyd Collins Crystal Cave; Pagoda Cave; Salts Cave, near old Pike Chapman Entrance; White Cave; Little White Cave; Dixon Cave; Proctors Cave; Martins Cave; Running Branch Cave; Blowing Spring Cave; small cave near Long Cave; Mammoth Cave: Bunker Hill, end of Audubon Avenue; Mammoth Dome, near Richardson Spring; River Hall; Violet City; Cathedral Domes; New Entrance; Frozen Niagara. Barren Co.: Indian Cave, 4 miles west of Cave City; Railroad Cave, Cave City; Burnet Cave, 0.6 mile west of Park City; Vance Cave, 0.8 mile northeast of Park City; Brushy Knob Cave, 2 miles northeast of Park City: Diamond Caverns, 2 miles north of Park City (fossil only): Short Cave, 2.2 miles northwest of Park City: Beckton Cave, 0.5 mile northwest of Beckton; Duval Saltpeter Cave, 0.7 mile northwest of Beckton; Cave Spring Cave, 1 mile south-southwest of Red Cross. Warren Co.: Bypass Cave, Bowling Green; Vails Cave, 2 miles west of Bowling Green. Simpson Co.: Hoy Cave, 2 miles north of Franklin; Steeles Cave, 4 miles southeast of Franklin. TENNESSEE: Sumner Co.: small cave in sink above White Oak Cave, 2.2 miles east-northeast of Mitchellville.

This species is known only from these caves.

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Figure 1

Mesodon appressus (Say), in total darkness zone near entrance, Great Onyx Cave, Mammoth Cave National Park, Kentucky. (Photograph by Thomas C. Barr, Jr.)

Figure 2

Carychium stygium Call, in Roosevelt Dome, Mammoth Cave, Mammoth Cave National Park, Kentucky. (Photograph by Thomas C. Barr, Jr.)



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