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OF THE

NATIONAL SPELEOLOGICAL SOCIETY

VOLUME 27 NUMBER 1

Contents

JANUARY 1965

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Papers in any discipline of speleology are considered for publication in the BULLETIN. The upper limit for length is about 10,000 words or approximately 40 pages of manuscript, typed double-spaced. At least one copy but preferably two copies of the manuscript (typed, double-spaced) should be submitted to the Editor, Jerry D. Vineyard, Missouri Geological Survey, Box 250, Rolla, Missouri 65401. Photographs and line drawings, if required, should be submitted with the manuscript. In general, prints and line drawings will be photo-reduced to the size necessary for use in the BULLETIN.

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Influence of Surface Conditions On Temperatures in Large Cave Systems

By J. B. Cropley

ABSTRACT

Temperature data recorded by the West Virginia Association for Cave Studies between February and November, 1963, show that the influence of outside weather conditions extends for several thousand feet into large cave systems which have complex stream and air-flow patterns. Contrary to the popularly-held viewpoint, cave temperatures are not necessarily constant – or even approximately so – but may vary widely. Mathematical relationships which may be used to predict temperatures in caves are presented.

INTRODUCTION

The hardy explorer who finds himself wading an icy cave stream in mid-winter may reflect that the year-round constant temperature that is widely believed to prevail in all caves is more fiction than fact – and indeed it is. Cave temperatures may vary widely under the influences of surface temperature fluctuations and the varying flow patterns of air and water currents within caves. Although the relationship of the annual mean surface temperature to the cave temperatures for the same area is obscure, it is obvious that some relationship must exist, if only because caves in cold climates are colder than those in warm regions. The purpose of this paper is to explore those factors which influence cave temperatures and to develop the methods by which they may be predicted.

Between the months of February and November, 1963, members of the West Virginia Association for Cave Studies, Inc., recorded air and water temperatures in two large cave systems in Greenbrier County, West Virginia. A total of 86 temperatures were recorded in the Greenbrier Caverns and Ludington's Cave systems, at distances from zero to 6000 feet from the respective entrances. Passage conditions from dry to flooding were encountered, the latter at freezing temperatures. Streams flowed into both caves through the normal entrances. The relationships presented and discussed herein were developed with the aid of these data. Strictly speaking, they apply only to caves similar in nature and hydrographic structure to those studied here. It is anticipated that future studies will determine the extent to which these principles are applicable to caves in general.

GENERAL DISCUSSION

If one travels sufficiently far into a large cave, he will eventually arrive at a point where the temperature may be expected to remain at approximately the mean annual surface temperature for that locality. This "equilibrium temperature" is 51.6° F for the region surrounding Lewisburg, West Virginia, where this study was conducted. In order to reach an area where the temperatures are within ±1° of 51.6° F, it was necessary to enter the caves for over 5000 feet – this great distance was surprising, for it had been assumed that the influence of surface conditions would not extend nearly so far. Although the mathematical relationships developed in this report show that the location of the equilibrium temperature moves somewhat closer to the entrance in the latter months of the year, it was observed to be no closer than 5000 feet to the entrance at any time, in both Ludington's Cave and Greenbrier Caverns systems.

By comparing the temperatures observed in limestone cave systems with those which can be calculated for the interior of a very large block of solid limestone, assuming identical surface temperature fluctuations, it is possible to identify certain variables which influence cave temperatures. It may also be possible to estimate their relative importance. The average monthly surface temperature for the Lewisburg area varies sinusoidally from 31.9° F in January to 70.9° F in July. If one surface of the limestone block were exposed to such a varying temperature, it may be predicted that its interior temperature would remain very close to 51.6° F within a very few feet of its surface. There would be a time lag between the occurrence of the maximum temperature at the surface and that in the interior: the maximum temperature in the interior would occur seven days later than that on the surface for every foot of depth into the limestone. This figure illustrates the very slow rate at which heat can be conducted through limestone.

In many cases, the observed temperatures were markedly lower than the 51.6° F which was predicted on the basis of the solid limelimestone temperature response. It was inferred, therefore, that factors other than pure conduction influence the cave temperatures, and, indeed, may be more important. Such variables as evaporative cooling by less-than-saturated cave winds, and cold wintertime air and water streams, are logical candidates.

In the winter months, the average *monthly* surface temperature appears to approximate more closely the minimum temperatures to be found within caves than does the *annual* mean surface temperature. Thus, temperatures as low as 32° F were observed several hundred feet inside the caves. This observation is apparently the result of the rather large amounts of cold water carried into the caves by swollen winter streams which, in turn, are likely to reflect the average monthly temperature. Cold air currents undoubtedly contribute also, but they will be more subject to daily temperature fluctuations than will be water streams. In general, as one proceeds further into caves, the temperature will rise until the equilibrium region is reached. Local exceptions may occur, as when a colder stream joins a warmer one, but the general trend is nonetheless demonstrable.

As the year progresses and the weather becomes warmer, the cave walls will remain quite cold for a long time, because the flow rates of the streams in warm weather are quite likely to be many times lower than those of the icy streams which cooled the cave. Also, surface stream temperatures are considerably below ambient surface temperatures during the warm months of the year. Thus, heat may be carried *into* the cave at a much lower rate than it was removed only a few months before. Gradually, however, the minimum temperatures to be found in the cave will rise, ultimately approaching the annual mean surface temperature. Thus, one might expect that cave temperatures measured in the rather dry late summer or early fall might be quite close to the annual mean surface temperature, and such is the case. These temperatures may continue to rise well into the winter, until they are again lowered by the returning cold waters of the winter streams.

It was stated earlier that the effect of the conduction of heat through the limestone cave roof upon the temperatures within the cave will be to maintain the temperature essentially constant at the annual mean temperature for the area, unless other factors are present. If the only factors present are those which tend to lower the cave temperatures below the annual mean surface temperature – such as streams and air currents as discussed above – the temperature in the cave cannot rise significantly above the annual mean surface temperature. The data support the conclusion that this temperature – 51.6° F in the Lewisburg area – is the maximum attainable cave temperature.

The above observations are purely qualitative, and, although interesting, cannot be used to predict the actual temperatures to

be found within a large cave system. Nevertheless, several important variables have been identified; among these are the annual and monthly mean surface temperatures, the time of year, and the distance from the point of measurement to the nearest entrance. These variables include implicitly the effects of stream and air currents. It is desirable that these variables be combined into a statistically significant expression which can be used to predict actual cave temperatures. The derivation and application of such an expression is discussed in the next section.

Prediction of Cave Temperatures

It will be convenient to the discussion which follows if we arbitrarily divide large caves into three zones, according to the manner in which the temperatures in each respond to surface conditions. These zones may change from cave to cave, and from season to season within any one cave.

Zone I is that part of the cave immediately adjacent to the entrance. It is characterized by temperatures which vary directly with the surface temperature, and which fluctuate widely both above and below the annual mean surface temperature for the area. Zone I may extend for as little as a few feet to as much as a few hundred feet, depending upon the individual cave characteristics. Because the temperatures in Zone I are more characteristic of surface temperatures than those deep in caves, we need not consider them further.

Zone II is sufficiently deep in the cave that the entrance effects that are characteristic of Zone I are no longer present, but temperature variations still occur because of the effects of stream and air currents. Evaporative cooling by less-than-saturated cave winds can alter the temperature pattern in this part of the cave, as well as Zone I.

The rate at which the temperature of a cold, winter-time stream will rise as it flows through a cave will be proportional to the difference between the stream temperature at any given point and the bulk limestone temperature. The latter may be assumed to be the annual mean surface temperature for the area, or 51.6° F for the Lewisburg region. Following this reasoning, it may be predicted that the temperature of the water – and of the cave – will rise exponentially from the entrance to some point within the cave at which the temperatures of both the water and the cave are essentially equal to the annual mean surface temperature.

If the stream continued to enter the cave at the same flow-rate and temperature, the point at which the equilibrium temperature would be reached would recede farther and farther into the cave as the limestone in the vicinity of the cave passage became cooled. But as the flow of the stream decreases and its temperature rises as the seasons progress, the quantity of heat carried into or extracted from the cave by the stream becomes quite small in comparison with that extracted from it by the swollen stream earlier in the year. The combined effects of the now small but warm stream and the conduction of heat into the cave from the surrounding limestone will cause the cave temperature to rise exponentially until it approaches the annual mean surface temperature, or until the onslaught of cold water the following winter forces it down again.

Most, if not all, of the temperatures recorded during the course of this study were characteristic of Zone II, and ranged from 32.4° F to 52.4° F. These data were combined with the exponential effects discussed above to give the following equation, which may be used to predict cave temperatures in Zone II.

$$T = 51.6 - 20.6\, e^{-[(4.152)(10^{4})X + 0.0933Y]}$$

where X is the distance in feet from the point at which the water or air current enters the cave, Y is the time in months since January 15, and T is temperature, °F.

This relationship is depicted graphically in figure 1, which may be used to gain an understanding of the physical meaning of the equation. Figure 1 shows that the temperature in a cave rises as one travels farther into the cave, and as the year progresses. The relationship is not applicable very late

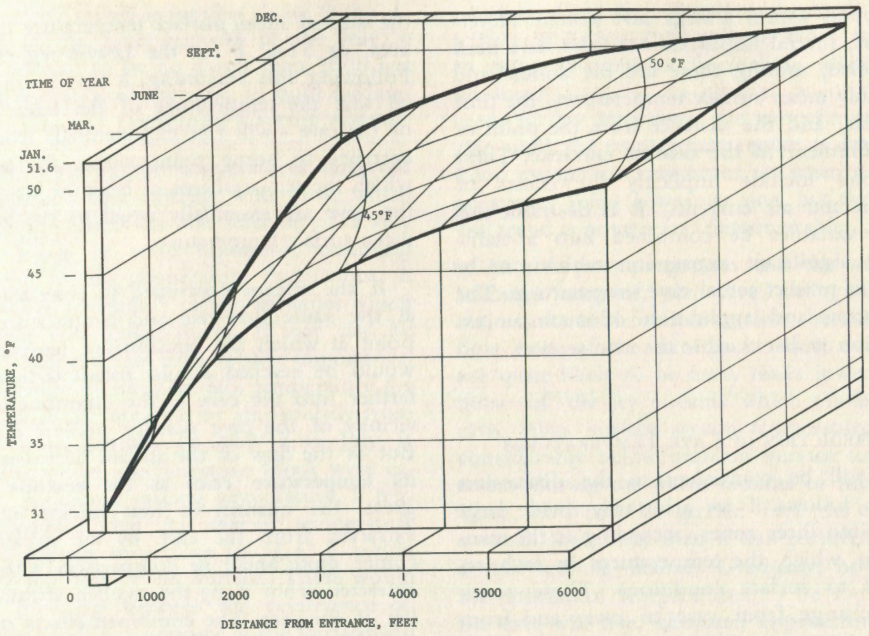

Figure 1.

Temperature response of real cave systems (Zone II).

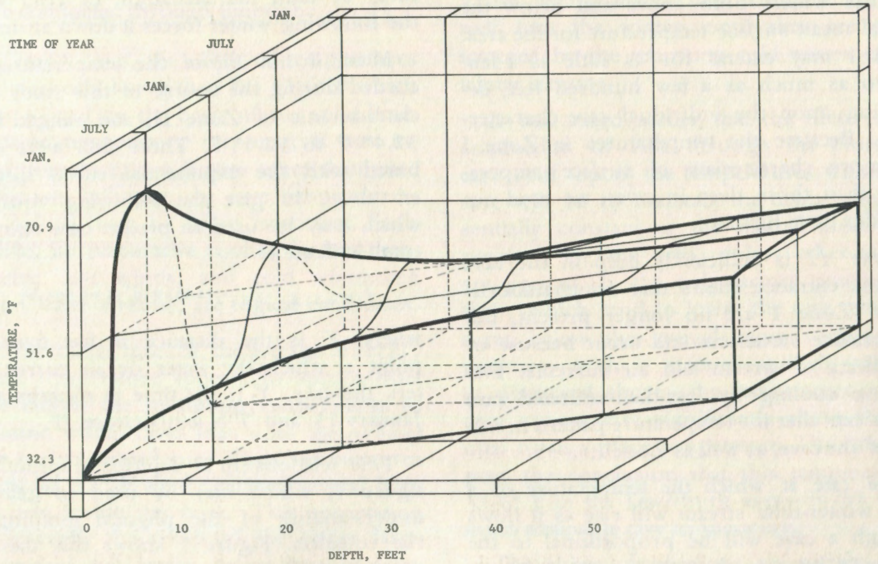

Figure 2.

Temperature response of solid limestone.

in the year, when returning cold streams will lower the cave temperature, nor is it applicable to Zone I regions, but it may be used with some confidence in Zone II areas over much of the year.

A total of 75 temperature observations were used to develop the above equation, with the result that 72 per cent of the total observed variance in temperature was accounted for. The standard deviation of the error is ± 2.4° F, and it may be shown that the equation is highly significant from a statistical standpoint. The numerical coefficients were calculated using a step-wise multiple regression program for an IBM 7074 computer. The data collected in the study, together with the temperatures predicted by the above relationship, are presented in table 1.

TABLE 1

SUMMARY OF CAVE TEMPERATURE DATA COMPILED BY WEST VIRGINIA ASSOCIATION FOR CAVE STUDIES

Greenbrier County, West Virginia

1963

NOTES:

1. Temperatures are degrees Fahrenheit, measured with glass-and-mercury laboratory-type thermometers.
2. Distances are in feet, measured to nearest known entrance.
3. In both Greenbrier Caverns and Ludington's Cave, stream flow is *into* the entrance.
4. Key to location within caves of temperature measuring points is found elsewhere in this report.
5. For correlation purposes, time of year is taken as months since January 15, to nearest 0.1 month. Thus, 1 March is equivalent to Y = 1.5.
6. Points marked (W) are water temperatures.
7. Calculated temperatures were determined from the equation developed elsewhere in this report.

			Temperatures		
Pt. No.	Dist., ft. X	Time Y	Observed T	Calculated T'	Loc. Key
Greenbrier Caverns, 2/2/63					
1	1500	0.5	47.0	41.1	A
2	3000	0.5	43.5	45.9	G
3	4000	0.5	47.5	48.1	H
4	5000	0.5	51.0	49.1	L
5	5500	0.5	51.0	49.6	M
6	5000	0.5	51.0	49.1	N
7	5000	0.5	51.0(W)	49.1	N
8	0	0.5	36.0	------	Ent.
Ludington's Cave, 2/9/63					
9	0	0.8	31 (est.)	------	Ent.
10	1500	0.8	43.0	41.2	B
11	1500	0.8	42.1(W)	41.2	B
12	1700	0.8	44.1	42.0	C
13	1700	0.8	43.5(W)	42.0	C
14	2500	0.8	43.8	44.8	D
15	2500	0.8	38.4(W)	44.8	D
Ludington's Cave, 2/16/63					
16	0	1.0	15 (est.)	------	Ent.
17	600	1.0	32.4	36.8	A
18	600	1.0	33.4(W)	36.8	A
19	1500	1.0	41.4	41.6	B
20	1500	1.0	40.8(W)	41.6	B
21	1700	1.0	43.2	42.3	C
22	1700	1.0	43.2(W)	42.3	C
23	2500	1.0	43.5	44.9	D
24	2500	1.0	40.0(W)	44.9	D
25	3500	1.0	46.0	47.2	E
26	3500	1.0	43.9	47.2	E
27	4500	1.0	52.2	48.7	F
Ludington's Cave, 3/2/63 (Cave flooding)					
28	0	1.5	32.4(W)	------	Ent.
29	0	1.5	33.1	------	Ent.
30	650	1.5	35.8	37.6	I
31	650	1.5	32.9(W)	37.6	I
Greenbrier Caverns, 3/9/63					
32	0	1.8	52.0	------	Ent.
33	2500	1.8	42.0	45.3	Q
34	2500	1.8	39.9(W)	45.3	Q
35	3500	1.8	48.2	47.5	F
36	3500	1.8	51.1(W)	47.5	F
37	5000	1.8	52.0	49.4	R
38	5500	1.8	52.4	49.8	P

Greenbrier Caverns, About 4/1/63

39	0	2.5	36:8	-------	Ent.
40	2500	2.5	47.1	45.7	B
41	3000	2.5	47.2	46.9	C
42	5000	2.5	50.5	49.5	D
43	5000	2.5	51.1(W)	49.5	D
44	4500	2.5	50.5	49.0	E
45	3500	2.5	47.7	47.7	F
46	3500	2.5	51.5(W)	47.7	F
47	3000	2.5	43.7	46.9	G
48	4000	2.5	47.1	48.4	H
49	4800	2.5	48.1	49.1	I
50	4800	2.5	47.2	49.1	J
51	4800	2.5	47.5(W)	49.1	J
52	3500	2.5	45.0	47.8	K
53	3500	2.5	46.2(W)	47.8	K

Ludington's Cave, 4/20/63

54	1700	3.3	46.0	44.1	C
55	1700	3.3	45.3(W)	44.1	C

Ludington's Cave, 9/2/63

56	0	7.5	48.9	-------	Ent.
57	600	7.5	44.6	43.6	A
58	1500	7.5	46.6	46.0	B
59	1700	7.5	47.5	46.5	C
60	3500	7.5	49.1	49.2	E
61	5000	7.5	50.5	50.3	G
62	5500	7.5	50.4	50.6	H
63	5500	7.5	50.0(W)	50.6	H

Ludington's Cave, 10/26/63

64	0	9.4	73.0	-------	
65	1500	9.4	47.8	47.0	B
66	1700	9.4	48.2	47.4	C
67	2000	9.4	48.6	47.9	J
68	4100	9.4	50.0	50.0	K
69	6000	9.4	50.7	50.9	L

Ludington's Cave, 11/30/63

70	0 Noon	10.5	36.9	-------	Ent.
71	0 8 PM	10.5	27.0	-------	Ent.
72	600	10.5	42.1	45.5	A
73	1700	10.5	46.3	47.9	C
74	2000	10.5	47.0	48.2	J
75	2500	10.5	47.4	48.8	D
76	2500	10.5	43.6(W)	48.8	D
77	2500	10.5	48.0 soil	48.8	D
78	3300	10.5	50.0	49.6	N
79	3300	10.5	51.7(W)	49.6	N
80	3300	10.5	49.6	49.6	P
81	3300	10.5	51.0(W)	49.6	P
82	3000	10.5	49.4	49.4	M
83	3000	10.5	44.4(W)	49.4	M
84	2700	10.5	49.0	49.1	Q
85	3500	10.5	51.0	49.8	E
86	3500	10.5	50.5(W)	49.8	E

We may wish to examine the data to determine whether the above equation is equally applicable to the two cave systems, and to both air and water temperatures. The standard deviation of the error of the equation is a widely used criterion, and will be used here. The following table may be constructed:

Cave System	Standard Deviation of the Error: Using All of the Data	Standard Deviation of the Error: Excluding Point No. 1
Greenbrier Caverns, overall	±2.55°F	±2.34°F
Ludington's Cave, overall	2.36	2.36
Both caves together, overall	2.45	2.35
Greenbrier Caverns, air only	2.30	1.94
Ludington's Cave, air only	1.92	1.92
Both caves together, air only	2.07	1.93
Greenbrier Caverns, water only	3.61	—
Ludington's Cave, water only	3.16	—
Both caves together, water only	3.22	—

Point No. 1 was selected for exclusion because it was measured in the Saltpetre Hopper Room of the Organ Cave section of Greenbrier Caverns. This location is virtually bone-dry, and is protected from the normal effects of air circulation because it is relatively isolated from the rest of the cave. It is clearly an exception to the Zone II temperature response as developed in this study.

The following conclusions may be drawn from the above table:

1. The equation applies equally to both cave systems. One may infer, therefore, that it is of general applicability, and that large cave systems with complex hydrographic features respond similarly to the surface weather conditions. Nevertheless, the equation should be applied only with caution to cave systems

in locations other than the Lewisburg vicinity, because the numerical constants in the equation reflect the surface conditions. For example, 51.6 is the annual mean surface temperature; 20.6 is approximately the difference between the average January temperature and 51.6. The exponential coefficients are determined largely by the average precipitation for the area, but the exact nature of the relationship is unknown. In the absence of sufficient data for other areas to permit the empirical estimation of the exponential coefficients, the values determined here may be used. Unless the precipitation characteristics for another area are radically different than in the Greenbrier Valley (as, for example, in the Southwest), little error may be expected.

2. Air temperatures are much more predictable than water temperatures. Several reasons may be cited: many of the larger errors in water temperatures as predicted by the equation resulted from attempts to predict the temperatures of rushing, swollen, wintertime streams. Comparable conditions for air currents occur seldom, if ever. In addition, the heat capacities of the air and water streams are enormously different, and the air currents contact a much larger rock surface area; therefore, the influence of the cave walls upon air temperature will be more pronounced than water temperature.

Zone III is so remote from the entrance of the cave that no temperature variations occur except those that are initiated by the conduction of heat from the surface through the cave roof. Because of the excellent insulating properties of the limestone, temperatures in Zone III will normally be very close to the annual mean temperature for the area. The very small temperature fluctuations that do occur are related to the thermal properties of the limestone, the thickness of the cave roof, and the nature of the local surface temperature variation.

The following equation* was derived for the prediction of the Zone III temperature response. Strictly speaking, the relationship applies only to a very large block of solid limestone, one surface of which is exposed to a temperature which varies sinusoidally in the manner of the surface temperature in Lewisburg, W. Va. (fig. 3). Nevertheless, Zone III is so defined that the analogy between the cave and the limestone block temperature responses is rigorous.

$$T = 51.6 - 19.3\, e^{-0.121X} \cos[(0.0172)(t-21) - 0.121X]$$

where t is the number of the day of the year and X is the thickness of the cave roof, in feet.

The following physical properties of limestone were used in the derivation of the above equation. The numerical values are those reported by Perry (1950).

Property	Symbol	Numerical Value
Thermal Conductivity	k	0.54 BTU/ft^2–hr–°F/ft
Density	p	103 lb/ft^3
Heat Capacity	C	0.217 BTU/lb–°F

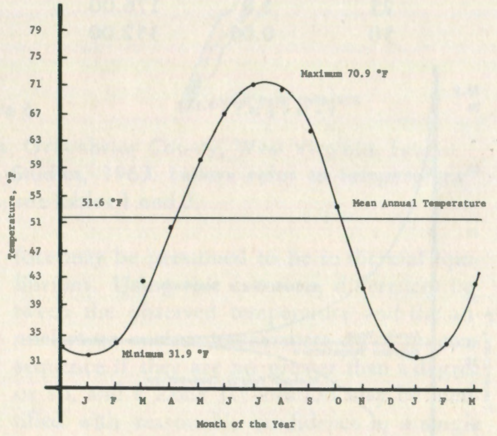

Figure 3.

Average monthly surface temperatures and average annual surface temperature compiled by the U. S. Weather Bureau of the Lewisburg, West Virginia area.

* Those familiar with classical heat conduction theory will recognize this equation as an integrated form of the diffusion equation for the one-dimensional conduction of heat through a semi-infinite solid with one surface exposed to a sinusoidal forcing temperature.

The above equation is graphically illustrated in figure 2, which shows that the temperature variation diminishes as the thickness of the cave roof increases. It is seen also that the occurrence of a peak temperature in the cave will lag behind the corresponding peak in surface temperature. It may be shown that the lag increases by about one week per foot of depth – the cave temperature will therefore lag behind the surface temperature by one year at a depth of 52 feet. The following table illustrates the rate at which temperature variations disappear as one probes deeper into the limestone. These data are shown graphically in figure 4.

Depth, Feet	Annual Temperature Variation, ±°F	Time Lag Days
0	19.3	0
1	16.9	7.04
5	10.5	35.20
10	5.6	70.40
25	1.0	176.00
50	0.05	352.00

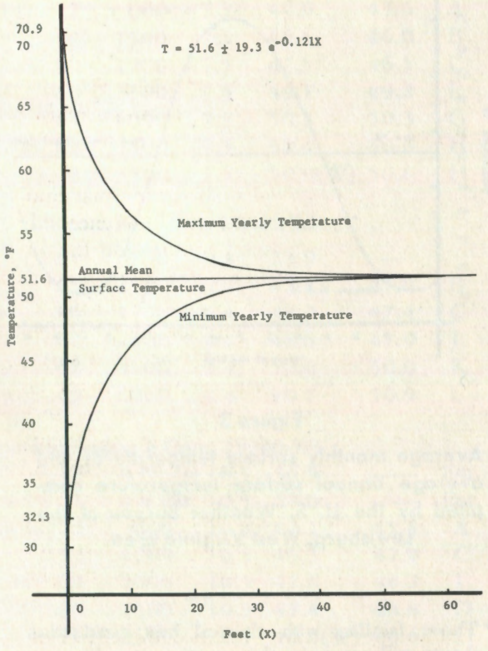

Figure 4.
Temperature distribution in solid limestone, calculated for the Lewisburg, West Virginia area.

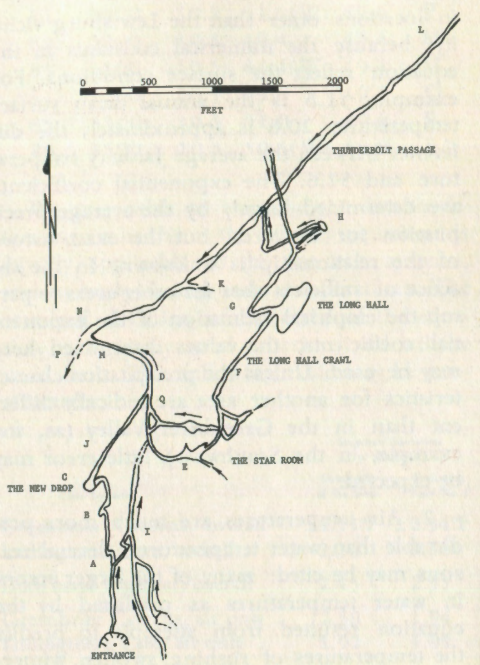

Figure 5.
Sketch map of Ludington's Cave, Greenbrier County, West Virginia, surveyed by West Virginia Association for Cave Studies, 1962-63. Letters refer to temperature measurement stations; see tables 1 and 2.

While the existence of Zone III can be predicted mathematically, no proven example of it was found in the course of the study reported herein, although several instances were noted in which the cave temperatures were very near the 51.6° F annual mean temperature. It is possible that some of these temperatures were in fact recorded in Zone III areas but the data are insufficient either to prove or to disprove the contention. One may readily establish criteria which must be satisfied before an area may be classified as Zone III:

1. Data of sufficient accuracy must be collected over a period of time to demonstrate that no temperature variations occurred that were not directly predictable solely on the basis of heat conduction through the cave roof. Normally, data of this sort would require either thermographs of exceptional accuracy, or a great many trips to the same area using laboratory thermometers of the type used in this study. In either case, instruments capable of detecting temperature differences as small as 0.1° F are desirable. Accurate knowledge of the thickness and composition of the cave roof is also required. Small departures from the published annual mean surface temperature for the area are not important, so long as the recorded temperatures are constant, because the manner in which the U. S. Weather Bureau calculates the published value may give rise to some small differences. In addition, the mean value for any given year may be slightly different from the long-term average.

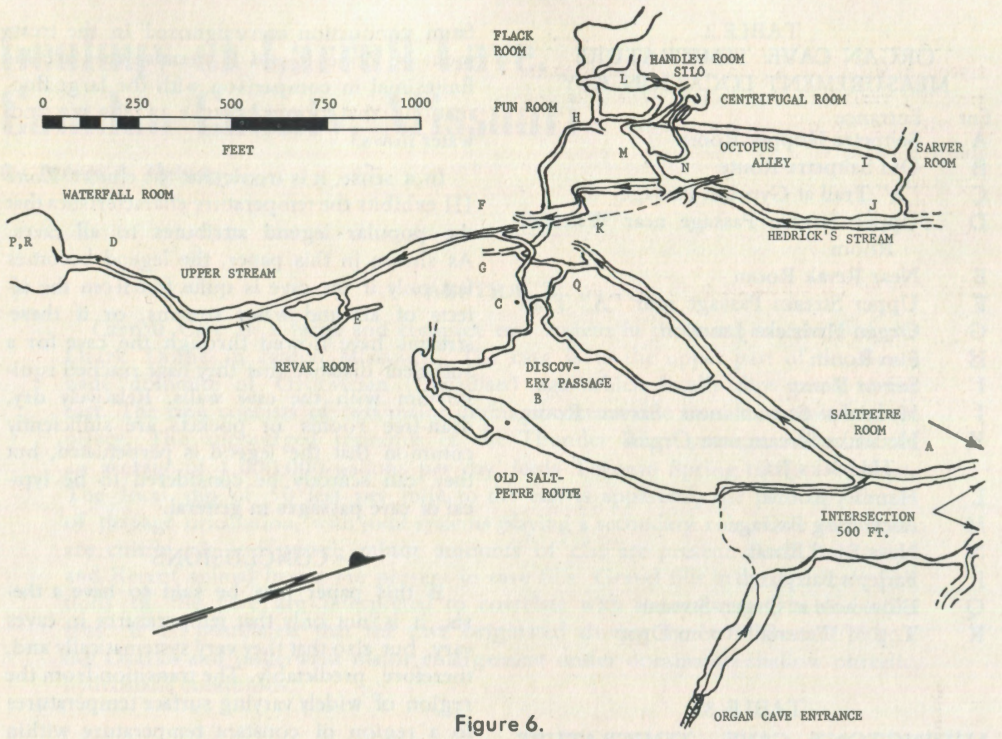

Figure 6.
Sketch map of a part of Greenbrier Caverns, Greenbrier County, West Virginia. Froma map by West Virginia Association for Cave Studies, 1963. Letters refer to temperature measurement stations; see tables 1 and 2.

2. In a passage in which a stream is flowing, the absence of thermal effects other than conduction can be demonstrated if the air and water temperatures are equal over a distance of at least several hundred feet and therefore may be presumed to be in thermal equilibrium. Using this criterion, differences between the observed temperature and the annual mean surface temperature are of no consequence if they are no greater than a degree or so, and a Zone III location may be identified with reasonable confidence in a single trip. This criterion was applied in many instances in the present study, but no instance of a true Zone III location was found. Points 42 and 43 of Table 1 are typical. A few instances in which air and water temperatures were equal were noted, but these generally were for non-flowing pools rather than for flowing streams, and the test is not reliable.

Although we have identified the effects of the conduction of heat through the cave roof only with Zone III, they will also be found in the parts of the cave nearer the entrance. Variations in cave temperature which result

TABLE 2
ORGAN CAVE: TEMPERATURE MEASUREMENT LOCATION KEY

Ent	Entrance
A	Saltpetre Hopper Room
B	Old Saltpetre Route
C	"A" Trail at Gypsum Passage
D	Upper Stream Passage near Waterfall Room
E	Near Revak Room
F	Upper Stream Passage near "A" Trail
G	Organ-Hedricks Junction
H	Fun Room
I	Sarver Room
J	Hedricks Stream near Sarver Room
K	Hedricks Stream near Organ-Hedricks Jct.
L	Handley Room
M	Ascending Passage
N	Near Sand Room
P	Farley's Fairyland
Q	Blow-hole at Organ Stream
R	Top of Waterfall Room Drop

TABLE 3
LUDINGTON'S CAVE: TEMPERATURE MEASUREMENT LOCATION KEY

Ent	Entrance
A	Start of Polar Passage
B	Last Chance Salon
C	New Drop (Top)
D	Survey Station LL6 – Lower Ludington's Passage
E	Star Room
F	Long Hall Crawl
G	Boo-Boo Boulevard
H	Robbins Falls
I	Old Drop (Top)
J	Passage between New Drop and LL6
K	Bottom of Green Stream Drop
L	Upper Thunderbolt Passage
M	Lower Lundington's Stream, near junction with Thunderbolt Stream
N	Thunderbolt Stream, near junction with Lower Ludington's Stream
P	Thunderbolt Stream, below junction with Lower Ludington's Stream (Temperature here is of combined streams)
Q	Lower Ludington's Stream, 150 feet above LL6

from conduction were ignored in the treatment of Zones I and II because they are infinitesimal in comparison with the large fluctuations that occur because of the air and water flows.

In a sense, it is ironic that the elusive Zone III exhibits the temperature characteristics that the popular legend attributes to all caves. As shown in this paper, the legend becomes fact only if the cave is quite free from the effects of air and water streams, or if these streams have flowed through the cave for a sufficient distance that they have reached equilibrium with the cave walls. Relatively dry, draft-free rooms or pockets are sufficiently common that the legend is perpetuated, but they can scarcely be considered to be typical of cave passages in general.

CONCLUSIONS

If this paper may be said to have a thesis, it is not only that temperatures in caves vary, but also that they vary systematically and, therefore, predictably. The transition from the region of widely varying surface temperatures to a region of constant temperature within the cave is not necessarily abrupt, as is commonly supposed, but may occur gradually and the transition zone may extend for thousands of feet.

One may reflect for a moment upon the importance of this extensive transition zone to the ecology of the cave. For example, the fabled constant temperature environment has often been cited as contributing to the speciation of various forms of cave life. Is it not also possible that two regions whose temperatures vary in systematically different ways might produce biologically distinguishable forms of the same basic species?

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Geology of Carroll Cave, Camden County, Missouri

By James A. Helwig

ABSTRACT

Carroll Cave is a large and complex cave system in the northern slope of the Ozark Dome in central Missouri. The cave is in the upper part of the Gasconade dolomite of Ordovician (Canadian) age which locally dips gently to the east. The cave consists of two major drainage systems due to subterranean stream piracy. The submerged terminus of the Thunder River passage, which carries an average of 1,000,000 gallons per day, feeds Toronto Spring to the northeast. The local dip of 50 feet per mile to the east is apparently the primary control of passage orientation, with joint systems playing a secondary role. Cave sediments are chiefly silt and gravel; minor amounts of clay are present. Both Pleistocene and Recent animal bones are present in cave fills. Gravel fills in the upstream portions of the cave are interpreted to correlate with a downstream facies of fine silts. It is postulated that the cave originated during the late-Pliocene uplift of the Ozarks and underwent major enlargement under dominantly shallow phreatic, hydrostatic conditions.

INTRODUCTION

Carroll Cave is a large and complex cave system in the northern slope of the Ozarks in central Missouri. The only known entrance to the cave is in the NE ¼, NW ¼, SW ¼, Sec. 18, T. 37 N., R. 14 W., Stoutland Quadrangle, Camden County, Missouri (fig. 1). The cave may be reached by State Route 7 from either Richland or Montreal, Missouri.

The entrance of the cave is a low arch in dolomite 60 feet wide and 12 feet high facing east toward the Mill Creek valley; a small stream flows out of the cave. Due to an extremely low gradient near the entrance, the water is ponded through the first 1000 feet of the cave. Because of low ceilings in this same section and a flat valley outside, heavy rains may cause water to rise to the ceiling. The cave is therefore dangerous to enter during stormy periods.

The cave extends west and north from its entrance and underlies the partially dissected areas of an upland surface which is 150 to 200 feet above the floor of Mill Creek valley. This upland surface is best observed south of the town of Montreal, although the cave does not extend this far.

The cave is in the upper part of the Gasconade dolomite of Ordovician age. The overlying Roubidoux formation (Ordovician) forms most of the upland surfaces. These formations locally dip to the east from 40 to 60 feet per mile.

Surface drainage in the area is generally to the north via Mill Creek, Wet Glaize Creek, and the Lake of the Ozarks (Osage River).

* Based on an undergraduate thesis of the same title prepared for the Department of Geology and Geological Engineering, St. Louis University, St. Louis, Missouri, 1963.

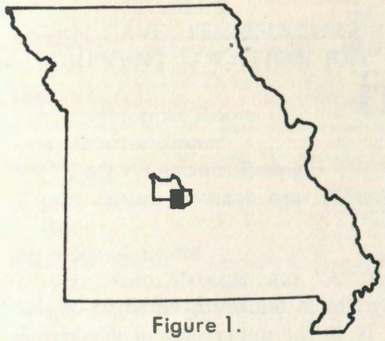

Figure 1.

Index map of Missouri showing location of Camden County and Stoutland Quadrangle.

Methods and Previous Work

Cave passages were surveyed by compass and tape. Brunton or Silva compasses and cloth-metallic or steel tapes were used. Passage details were sketched by eye on the traverse framework. Heights of large domes were checked by rangefinder. No line of levels has been established anywhere in the cave.

The position of the Forks, 7265 feet from the entrance (see fig. 2), was checked by Paul Wightman with low-frequency radio direction-finding equipment and found to be 250 feet (± 50 feet) horizontally in error. The gross error to be expected at the two ends of the map may therefore be 700 and 900 feet, at distances of 22,000 and 26,000 feet respectively from the entrance.

The original cave maps (on file with the Missouri Speleological Survey) were drafted by Dave Hoffman, Jerry Vineyard, Gregory Yokum and the writer on a scale of 1 inch to 100 feet. The maps were photoreduced by the writer to line drawings on a scale of 1 inch to 1000 feet (fig. 2).

Stream-flow volume was obtained where a stream occupied a uniform channel by measurement of cross-sectional area and average velocity. Rosette diagrams were constructed after Barnholtz (1961), but using a 180° rather than 360° diagram.

The detailed surface geology of the area surrounding the cave has yet to be worked. Only general information on the stratigraphy of the Gasconade formation is available.

White and Stellmack (1959) have described a new type of speleothem, the spathite, from Carroll Cave. They also discuss the unusually high percentage of aragonite in the speleothems.

For some years the cave has been the object of paleontological and archaeological study by Dr. Oscar Hawksley and students of Central Missouri State College.

Acknowledgements

The writer sincerely acknowledges the generous advice and support of the members of the Missouri Speleological Survey; of the members of the St. Louis University Chapter of the National Speleological Society; of Dr. Kenneth G. Brill, Jr., of the Department of Geology and Geological Engineering, St. Louis University; and of many other individuals who have contributed to what is here presented. I also wish to express a debt of thanks to the late Charles Carroll, whose name was given to the cave and whose friendship was freely given to Missouri 'cavers'.

Description of the Cave

For the purposes of description, the cave may be divided into three units: the Carroll River passage; Upper Thunder River passage; and Lower Thunder River passage. All descriptively named points in the cave that are mentioned in the text have been marked on the map (fig. 2). Passages which are described as "upper level" are those developed at the general level of the ceiling of the major passage which they intersect.

Carroll River Passage

The Carroll River passage is 13,000 feet in length from the Bridge to the entrance. Except for a 150 foot section nearest the Bridge, it is drained by a small stream, Carroll River, which flows out of the entrance. The 1000 foot entrance passage is low and nearly water filled and provides access to the Mountain Room, largest room in the cave. This room contains side passages on an upper level, large domes, joints enlarged by solution, and large piles of breakdown and scree.

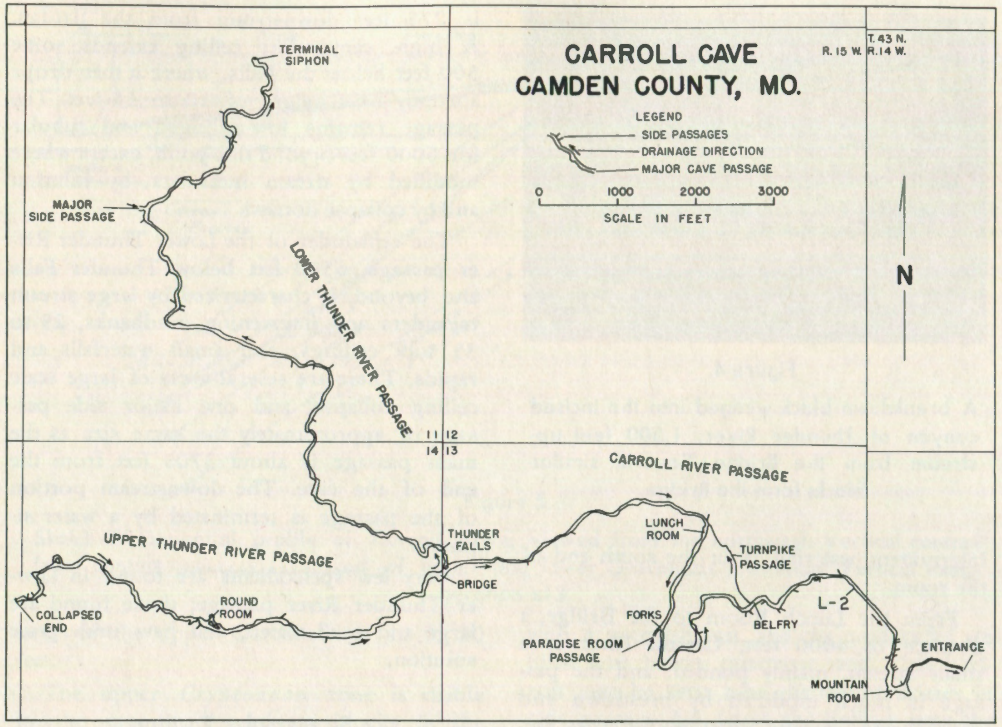

Figure 2.

Map of Carroll Cave, Camden County, Missouri

The mile of passage between the Mountain Room and the Belfry has a remarkably uniform subrectangular cross section. It contains prominent horizontally grooved walls and a uniformly ascending stream bed, causing a gradual decrease in ceiling height.

The Belfry is a large dome and ceiling channel complex which cuts across the main passage and is connected with the upper level Turnpike passage. The Turnpike passage drains from the Belfry to the northwest and into Carroll River at the Lunch Room, 3000 feet upstream from the Belfry.

Between the Belfry and the Forks the ceiling becomes progressively lower. At the Forks (fig. 3), the Paradise Room passage intersects the Carroll River passage at a small angle. The ceiling in the Paradise Room passage is 20 to 25 feet high, and this height is generally maintained in the main passage between the Forks and the Lunch Room. This section of passage leads up to the Lunch Room in a series of domes, natural bridges, flowstone and dripstone deposits.

The Lunch Room is a collapse room developed along a joint striking N. 56° E. An

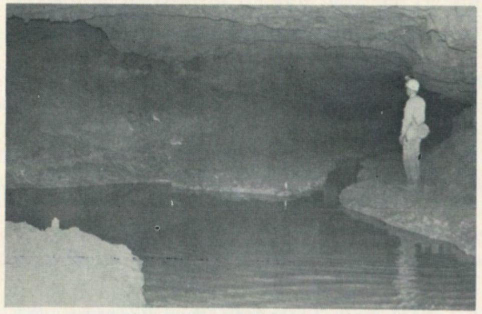

Figure 3.

The Forks. Upstream Thunder River lies to the right, Paradise Room to the left.

Figure 4.

A breakdown block wedged into the incised canyon of Thunder River, 1,500 feet upstream from the Bridge. Several similar blocks form the Bridge.

intermittent waterfall is in the south end of the room.

From the Lunch Room to the Bridge, a distance of 4000 feet, Carroll River is a small stream, mainly ponded, and the passage is much modified by breadown and speleothems, causing variations in cross section. The Bridge is just beyond the stream divide between Carroll River and Thunder River.

Throughout the Carroll River passage large banks of silt are exposed. Thin layers of sand and gravel are present in some areas.

Upper Thunder River Passage

The Bridge is formed by large breakdown blocks spanning the canyon of Thunder River where it intersects Carroll River passage. The first mile of Thunder River passage upstream from the Bridge is an incised meander canyon (fig. 4). The section of Thunder River passage furthest upstream is characterized by large collapse areas, abandoned meander channels such as the Round Room, and gravel-silt fills. The passage is terminated by a collapse blockade through which Thunder River percolates, 8800 feet upstream from the Bridge.

Lower Thunder River Passage

The portion of Thunder River passage downstream from the Bridge is 12,800 feet in length. Thunder Falls, eight feet high, is 275 feet downstream from the Bridge. A high, canyon-like ceiling extends some 500 feet below the Falls, where it then drops abruptly to a height of 10 to 15 feet. The passage remains low-ceilinged and tubular for 6000 feet beyond this point, except where modified by stream meanders, by solution and by collapse domes.

The remainder of the Lower Thunder River passage, 6500 feet below Thunder Falls and beyond, is characterized by large stream meanders and intervening mudbanks, 25 to 35 foot ceilings, and small waterfalls and rapids. There are several areas of large scale ceiling collapse, and one major side passage of approximately the same size as the main passage is about 3700 feet from the end of the cave. The downstream portion of the passage is terminated by a water siphon.

Very few speleothems are found in Lower Thunder River passage; those found are large and mud-coated, and have undergone solution.

Stratigraphic Position

Carroll Cave is entirely within the Gasconade dolomite. The Gasconade is approximately 300 feet thick in the area of the cave (from well data, Mo. Geol. Survey), and it is overlain by the Roubidoux formation. Both formations are of Canadian (Lower Ordovician) age. Because of the local dip to the east in the area of the cave, it is of interest to determine if the cave maintains a constant stratigraphic position throughout its length.

Hendriks (1941; pers. comm.), working in the adjoining Macks Creek Quadrangle, reported two algal *Cryptozoon* zones as markers in the upper part of the Gasconade: the upper zone, 100 feet below the Gasconade-Roubidoux contact; and the lower zone, 130 to 145 feet below the top of the Gasconade. The Missouri Geological Survey uses the upper zone to distinguish the upper Gasconade from the lower Gasconade. On this basis, well logs from the Ozark Fish Hatchery in Secs. 24 and 25, T. 37 N., R. 15 W. (this area lies 1 to 2 miles south of the cave), indicate that the thickness of the upper Gasconade is 40 to 80 feet.

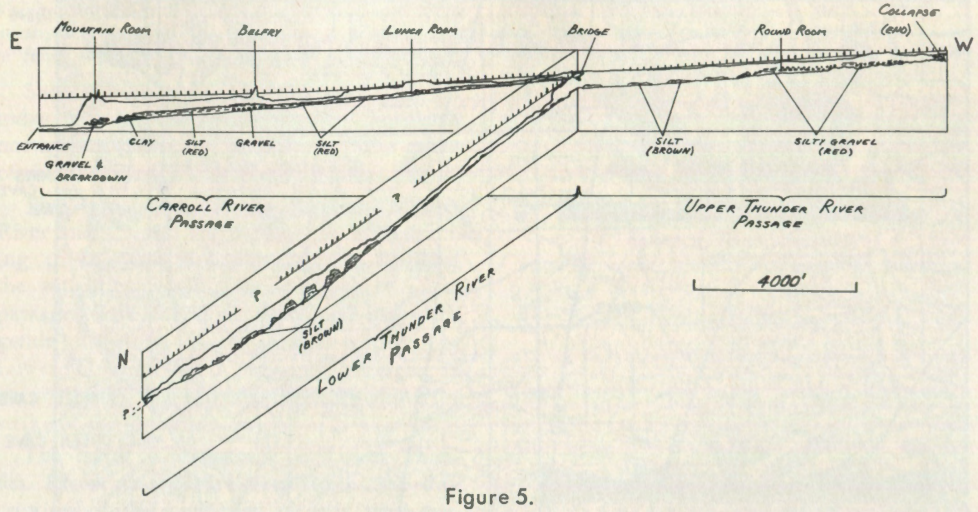

Figure 5.

Sketched tangential profile of Carroll Cave, viewed from the northwest. Vertical control from contact ııııııııııııııı of upper and lower Gasconade formation. Vertical exaggeration x13.

The upper *Cryptozoon* zone is visible in the cave in breakdown blocks in the Mountain Room, Lunch Room, and in a large collapse dome approximately 1500 feet from the end of Upper Thunder River. The zone is visible in the passage walls near the ceiling of the Lunch Room. This algal zone is a poor marker, however, due to its apparent irregularity in thickness and the difficulty of making positive identification. Because the algae are silicified, they are resistant to erosion and solution, and may be found littering the cave floor but cannot be found in an accessible position in the cave walls or ceiling. The cave does, however, lie at the general level of the upper *Cryptozoon* zone, approximately 60 feet below the overlying Roubidoux basal sandstones, with the exception of the Lower Thunder River passage (fig. 5). That passage contains no algal fragments and lies entirely in the lower Gasconade. The lower *Cryptozoon* zone is either absent in the area studied or has not been observed.

A thin, persistent, mudcracked clay horizon forms an excellent marker bed in the Carroll River passage. The clay is white with a greenish cast, and the mudcracks are filled with brown quartzose sand. This horizon may be seen near the top of domes in side passage L-6 (near the Belfry); near the ceiling of the Lunch Room; and near the ceiling at the Bridge. At the last locality, the clay has been removed, leaving a polygonal "boxwork" of the sand filling. This horizon lies a foot or two above the *Cryptozoon* zone.

Immediately above the mudcracked horizon is a thin, dark gray layer of "ropy" chert with a rusty coating. This chert layer is very prominent on and near the ceiling of Upper Thunder River passage. The small brachiopod *Syntrophina campbelli?* Walcott (Ulrich and Cooper, 1938) has been collected from this zone. Unfortunately, fossils are rare in the Gasconade except in chert zones.

Neither the *Cryptozoon* zones, the mudcracked horizon, nor the ropy chert layer have been observed in the Lower Thunder River area. The absence of all of these markers, coupled with the eight foot drop of Thunder Falls, leads the writer to believe that this area of the cave lies entirely in the lower Gasconade.

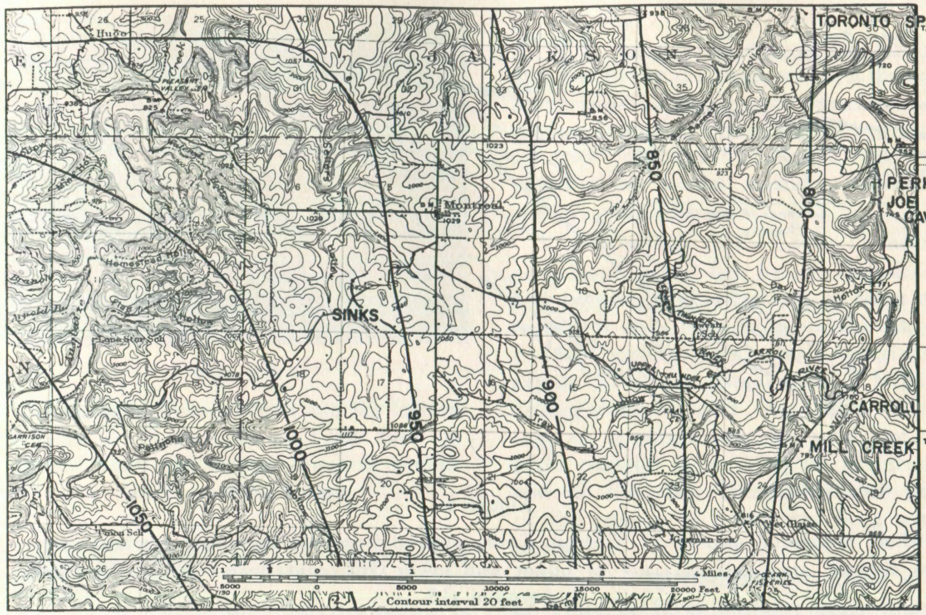

Figure 6.

Relationship of Carroll Cave to topography, structure and hydrology (U. S. Geological Survey, Stoutland Quadrangle, Missouri). Structure contours after Missouri Geological Survey and Water Resources, unpublished map. Datum: Base of Roubidoux-top of Gasconade. Structure contour interval 50 feet.

With the exception of the Lower Thunder River passage, therefore, the cave maintains a nearly constant stratigraphic position (fig. 5).

Relationship of Cave to Structure

The cave is in the northern slope of the Ozark dome, but in the local area gentle anticlinal folds predominate over the regional dip. Structure contours on the base of the Roubidoux have been drawn on the topographic sheet along with a line drawing of the cave (fig. 6). Twelve miles west of the cave is a gently northward plunging anticlinal structure striking N. 9° W. (according to unpublished Mo. Geol. Survey structure map of Missouri). To the west of the cave, the Gasconade rises to 1200 feet; in the syncline to the east, it drops to an elevation of 700 feet. The structure falls 500 feet in 15 miles for an average dip of 33 feet per mile. In the immediate vicinity of the cave, the dip is 50 feet per mile to the east (fig. 6).

The Decaturville structure lies 10 miles west-southwest of the cave, just to the east of the anticlinal axis. This is an intensely faulted and folded domal structure with pegmatite cropping out at its center. The structure is believed to be of the breccia-punch type and of local influence (M. H. McCracken, pers. comm.). Dietz (1963) has attributed the structure to meteorite impact.

Shepard (1905) believed that the Decaturville dome played an important role in the formation of springs in the surrounding area:

"Studies of the counties adjoining Camden, particularly on the west, northwest, north, and northeast, indicate a general dip of the strata toward the dome. The water from the catchment basin around the dome therefore meets in a trough, at considerable depth, the circulating water from the outside area, and the body of water thus gathered from the drainage on both sides, being under pressure, is forced up to the surface. Where erosion has cut sufficiently deep into the valleys of the Big Niangua, Osage, and Auglaize Rivers,

which surround the pegmatite hill on the west, north, and east, great springs issue at a distance of from 8 to 15 miles from the granite outcrop."

Shepard's facts remain essentially correct today, but for the substitution of the gently northward plunging anticline in the place of the Decaturville structure as a dome.

The orientation of the Upper Thunder River and Carroll River passages, both draining to the east along the eastern flank of the anticline, can be seen in figure 6. These passages have therefore developed down the gentle dip slope of the local structure. The Lower Thunder River passage is elongate in its northerly, downstream direction along the strike of the structure.

The major side passage in Lower Thunder River passage, referred to in the description of the cave, has recently been surveyed for 5200 feet by Hoffman (pers. comm.). It extends northwest, oblique to the apparent dip slope. This represents a drainage direction (southeast) almost opposite to that of Lower Thunder River, although it is similar to the general drainage directions of Upper Thunder River and Carroll River.

Figure 7 shows that the Upper Thunder River passage is prominently aligned in an east-west direction and is best related to the local dip rather than to joint systems (to be described immediately).

The rosette diagram of the Carroll River passage (fig. 7) includes the 1000 foot length of the Turnpike passage. There are three directions of preferred development: east-west; between N. 20°-50° E.; and between N. 30°-50° W. The east-west elongation again is interpreted to be due to the local dip. The northwest and northeast alignments are believed to be due to joint control and are evident in two straight sections of passage: the section between the Forks and the Lunch Room, trending northeast; and the Turnpike passage, trending northwest.

Hendriks (pers. comm.) reports two joint systems in the Gasconade dolomite in the Macks Creek Quadrangle to the west: N. 20°-30° E. and N. 40°-50° W. The joints exposed in the cave, in the Mountain Room and the Lunch Room, strike generally N. 50°-60° E.

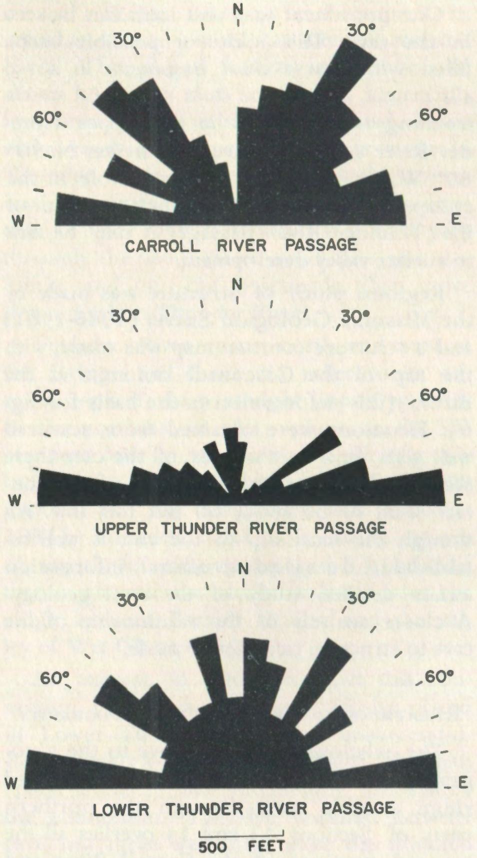

Figure 7.

Rosette diagrams of passage orientation in Carroll Cave.

The rosette diagram of Lower Thunder River passage (fig. 7) illustrates passage development in many directions. The diagram might be interpreted as an expression of six different joint sets; however, this appears unlikely.

The east-west elongation of all three passages is outstanding. In the Lower Thunder River passage, this elongation is due primarily to the section from 5000 to 7000 feet below Thunder Falls. This section drains west, opposite to the local dip. The uniform flat, low ceiling in this section suggests development along a bedding plane; if the local dip is flattened in this area, a westerly drainage may be possible for some distance.

One prominent east-west joint can be seen in the cave. This joint (or possible fault), filled with coarse chert fragments in a red silt matrix, blocks the ends of several south-trending side passages in the Upper Thunder River area. This structure strikes N. 70°-80° W., and appears to play a role in the collapse blockade of the upstream end of the Thunder River passage; it may be due to surface valley development.

Regional study of structure was made by the Missouri Geological Survey (1946-1961) and a structure contour map was made, with the top of the Gasconade dolomite as the datum (this information is the basis for fig. 6). Elevations were obtained from scattered well data, and in the area of the cave these seem to be in error. Elevations of the contact seem to be about 60 feet too low. Although the local dip to the east is well established, detailed structural information awaits detailed study of the areal geology. A closer analysis of the relationship of the cave to structure can then be made.

Relationship of Cave to Topography

The relationship of the cave to the topography can be seen in fig. 6. The flat-topped ridge running west through the northern parts of Sections 13 and 14 overlies all the mapped portions of the Carroll River and Upper Thunder River passages. The southernmost portions of passage, at the Mountain Room and again at the Forks, underlie noses of this ridge.

It is interesting to note that side passages are more numerous where the cave lies nearest surface slopes and hollows; and that very few side passages are found beneath the center of the flat upland areas. Most of the side passages contain small streams and have been considerably enlarged by them. In addition, the side passages contain evidence in their ceilings of phreatic development in the form of Bretz's (1942) criteria of spongeworks and half-tubes (fig. 8). The irregular orientation, upper level position and phreatic features of the side passages examined indicate that the earliest stage in the history of the cave was one of phreatic solution of a planar area of favorable lithology. After

Figure 8.
Ceiling half-tube cutting across an Upper Thunder River side passage (second passage from upstream end of cave).

the major passages had been enlarged and as the cave lay very near the water table, dome formation could occur in the vadose zone above side passages. Vigorous development of domes and side passages might possibly be due to greater water influx at the Roubidoux-Gasconade contact, where favorably situated topographically; this would parallel the situation in Kentucky, where domes are found beneath the Cypress sandstone near plateau edges (Pohl, 1955; Smith, 1957). The domes at the end of side passage L-6 occupy a similar topographic and stratigraphic position. It therefore appears that the optimum locations for side passage development lie between major subterranean drainageways and points where pre-existing phreatic networks lie nearest the surface, especially where capped by sandstones.

The formation of the Turnpike passage, the anomalous northwesterly draining upper-level side passage which connects the Belfry and the Lunch Room (fig. 2), might then be explained in this way: Water migrating through the soil above the Belfry found near the surface a joint-determined phreatic network through which it could move laterally to the northwest and into the Lunch Room. Continued solution in the Belfry area, perhaps from both above and below, served to form the large dome which exists today and to expose the Turnpike passage.

The Lower Thunder River passage lies beneath the headward extensions of Davis Hollow in Sections 11 and 14. The passage "V's" to the west where it crosses beneath these surface valleys. It is not known if this relationship is significant or coincidental. The major side passage is now known to trend northwest and extends beneath the northern edge of the 1000 foot elevation upland surface in Section 10.

Hydrology

The Carroll River passage contains a small stream which has been named Carroll "River" because of pools one to three feet deep and several hundred feet in length found in it. The water is contributed from side passages and from seepage in areas of secondary mineralization. A major contribution is made by the waterfall in the Lunch Room during wet weather. It is apparently connected rather directly with the surface.

Stream flow measurements made by the writer in Thunder River yielded figures of 825,000 gallons per day near the upstream end and 1,375,000 gallons per day above Thunder Falls. The former figure is believed to be more accurate.

A projection of the Upper Thunder River passage westerly beyond the collapse at the upstream end would bring it beneath the upland plateau south of the town of Montreal (refer to fig. 6). The plateau is in the Roubidoux formation, which consists of both sandstone and dolomite, and is capped by a thick residual soil. It is not known if the beds of sandstone in the Roubidoux are of sufficient thickness and continuity to serve as a true plateau cap beneath the soil cover. The plateau lies at an elevation of about 1040 feet and is pitted by large shallow sinks, all of which are blocked. These sinks must be the source of the water in Thunder River. Here the top of the cavernous Gasconade dolomite lies at an elevation of over 950 feet. Water may here pass through the Roubidoux sandstone and dolomite and into the Gasconade, then move down dip into Thunder River.

Thunder River turns north and west at the Bridge and flows 2½ miles to its terminal siphon. In a straight line three miles to the northeast of this siphon, in the SW ¼, Sec. 30, T. 38 N., R. 14 W. (fig. 6), is Toronto Spring, which flows 4,490,000 gallons per day (Beckman and Hinchey, 1944). Thunder River is a major source of supply for this spring and it is believed that a phreatic connection exists under the ridge between Barnett Hollow and the valley of Wet Glaize Creek.

An attempt in 1962 to prove this connection by the use of fluorscein dye placed in Lower Thunder River was unsuccessful. Recent work by Vineyard and Hoffman (pers. comm.) has successfully established the connection. The dye required between two and three weeks to move the minimal three mile distance from the cave to the spring. Since Toronto Spring is on the opposit (north) side of Wet Glaize Creek from the cave, the conduit carrying Thunder River water must be at some depth.

History of Thunder River

Sufficient evidence has now been gathered to show that the Upper Thunder River and Carroll River passages have a similar history and were formed as one, and that Thunder River has been subject to piracy at the Bridge by the Lower Thunder River passage. The list of evidence is as follows:

1. The upper parts or levels of the two passages form a continuous, down-dip, easterly trending drainage channel if they are considered separately from the present lower level of Thunder River Canyon. These upper levels are similar in their size, ellip-

tical configuration, and presence of phreatic features, *e. g.* natural bridges, solution domes, spongework, and (often modified) tubular side passages.

2. The uniformly large size of the Carroll River passage calls for a large, unidirectional flow of solvent waters during its period of major enlargement. This water was phreatic, probably under hydrostatic head, and must have been supplied by Upper Thunder River passage. The dip of the Gasconade formation to the east supplied the gradient. The Carroll River passage must predate the canyon of Thunder River at the Bridge. It is difficult to visualize the enlargement of the passage without a large phreatic flow, a flow which would have been diverted down the higher gradient Lower Thunder River passage if a connection existed.

3. At the Bridge, a large scale ceiling channel the full width of the Carroll River passage connects in a straight line with a similar channel in the ceiling of the Upper Thunder River passage. This indicates integration of the two passages during their formative stages.

4. For 4500 feet upstream from the Bridge, Thunder River flows in a canyon of steeply incised meanders. This section contains small falls and rapids; and 275 feet downstream from the Bridge is eight foot Thunder Falls. Thunder River upstream from the Falls has been rejuvenated by the piracy. The canyon-like ceiling which extends 500 feet downstream from the Falls indicates that vertical piracy (and Thunder Falls) started at this point. Tube-like, low-ceilinged passages downstream from this point are entirely dissimilar from the canyons above.

The location of the Falls below the point of capture (the Bridge) is possible because in subterranean piracy the initial leakage of water may be primarily lateral. The relationship of the water table to Lower Thunder River at the time of piracy must have played a role in determining the level of lateral movement of water away from Carroll River passage. Incised meanders show that the piracy must have taken place very near the level of the water table.

5. The large deposits of chert gravel with a red silt matrix found in Upper Thunder River passage contrast sharply with the chocolate brown muds of Lower Thunder River passage. But the large deposits of red silt in Carroll River passage may be a likely downstream facies of these coarser sediments (fig. 5).

6. The stratigraphic position of the Carroll River and Upper Thunder River passages places their ceilings in the upper Gasconade. Lower Thunder River has developed entirely in the lower Gasconade.

The actual piracy can be reconstructed as follows:

a. A meandering, free-surface stream occupies the Carroll-Thunder River passage.

b. This stream slowly loses its water to a largely pre-existing primitive cave passage, Lower Thunder River passage. This primitive passage may have been a tributary to the major side passage previously mentioned.

c. The stream is totally diverted; as the water table lowers sufficiently, Thunder Falls is formed.

d. The incised canyon is cut above the Falls and the Carroll River passage is left isolated and without its major source of water.

The evidences of the piracy are most convincing and force the postulation of major enlargement of the Lower Thunder River passage under hydrostatic, shallow phreatic conditions by means of the water pirated from Upper Thunder River. These shallow phreatic conditions fluctuated to allow the deposition and solution of secondary formations in Lower Thunder River passage, and the terminal siphon gradually retreated to its present position as local downcutting lowered the outlet of the waters. Large quantities of mud were brought into the passage by Thunder River and by side passages. This mud coats the walls of the Upper Thunder River canyon as far upstream as the Round Room, and its deposition throughout the Thunder River passage must have been contemporaneous with the incision of the canyon upstream from the Falls, extending up to the present time.

Stratigraphy of Cave Fills

Cave sediments in the Upper Thunder River and Carroll River passages were examined in detail; these sediments are the subject of a more complete paper (Helwig, 1964). The sediments in Lower Thunder River passage were examined only briefly.

The fill of Upper Thunder River passage is composed entirely of gravel and silt, with very minor amounts of sand. The best exposures of fill occur in two places: (1) in the mouth of an upper level side passage, third to the left going upstream from the Round Room; (2) in an abandoned meander slot on the right side of the passage 500 feet from the end of the cave. These fills are 13 and 15 feet in thickness respectively and very similar in content.

These sediments have been deposited in irregular layers as stream channel, cut and fill sequences. A fine to very coarse chert gravel with a red silt matrix constitutes 60 to 70 percent of the sediments. This gravel is termed the Thunder River gravel by the writer because it is characteristic of Upper Thunder River fills and may be seen in many places (fig. 9). The chert is angular to subangular, white to dark gray, and maximum particle diameter is two inches. The silt portion of the fill is somewhat clayey and very uniform; it may be finely laminated or contain thin sand partings. Glauconite fragments are present in some layers. The tops of the fills are invariably capped with a thin layer of fine dolomite sand which apparently collects by slow disintegration of the ceiling rock.

In the section of Thunder River passage from the Round Room to the Bridge is a generally thin (0-2 feet) layer of chocolate brown sandy silt. This is a later deposit, overlying those previously mentioned where they occur together. The vertebrae of a snake have been removed from this layer but cannot be identified as to type or age (Hawksley, pers. comm.).

The sediments exposed in the Carroll River passage range from clay to cobble and boulder size in a complicated series of beds and facies. The red unctuous clay described by Bretz (1942) may be found in a basal

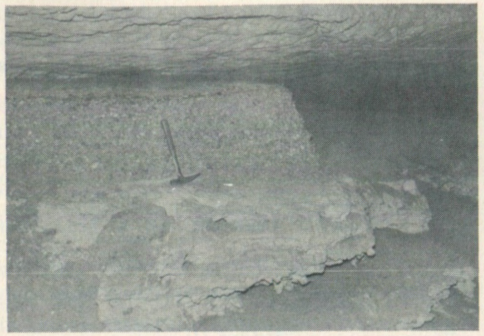

Figure 9.

Exposure of Thunder River gravel near the ceiling of the Round Room.

position immediately upstream from the Mountain Room. This clay is covered by a dark, soot-like crust and may easily be overlooked. Differential thermal analysis indicates that this clay is an illite.

The Mountain Room contains a sedimentary record of a complex history. A prominent ripple-marked silt horizon lies about 25 feet above the stream level in the southeast end of the room. Horizons of botryoidal "popcorn" deposits on the walls also appear related to a former higher stand of water (at this period of development, the entrance passage was 20 to 30 feet underwater, and the cave was a spring). Large fallen ceiling blocks, chert fragments containing *Cryptozoon,* and blocks of Roubidoux sandstone occur in conical collapse piles beneath domes and ceiling slots. The presence of bone fragments in the chert rubble records a period of direct or nearly direct openings extending to the surface. Some of these bones have been identified by Hawksley (pers. comm.) as *Odocoileus virginianus,* common white-tailed deer. The upper end of the Mountain Room contains a well-indurated fill of coarse cobbles, suggestive of an older period of surface openings.

The remaining sediments of the Carroll River passage which have so far been distinguished may be seen in the slumped sections of fill between the Mountain Room and the Belfry. Going upstream, the following sequence is observed: (1) red to brown silt,

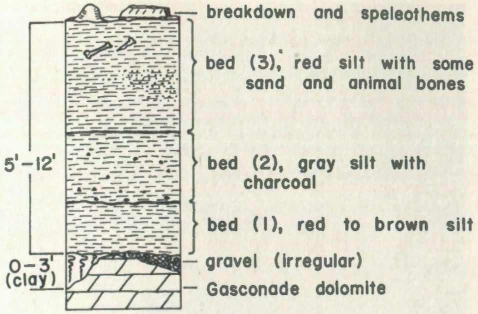

Figure 10.

Columnar section of Carroll River passage fills.

basal; (2) gray to dull brownish gray silt containing charcoal fragments; (3) variable red to brownish-red silt (fig. 10). These sediments may vary over a short horizontal distance, but for bed (2) which is consistent. Bed (3) may contain layers of gray silt similar to (2); the gray color is apparently due to organic content. Bed (3) also contains fine sand partings in some areas, producing a shaley splitting habit (fig. 11). Irregular contributions to the fill are found: a deltaic deposit of white medium gravel in the area in front of side passage L-2; and in a cobble deposit near the Belfry. The red silt, bed (3), lies directly above the latter deposit at a point 150 feet downstream from the Belfry where a human ulna was found in the silt (identified by O. Hawksley). The age of this find has not been established.

The upper red silt, bed (3), appears to be continuous through most of the Carroll River passage. This silt yielded the articulated skeleton of a dire wolf, *Canis dirus*, in the Lunch Room (Hawksley, pers. comm.). This indicates a late Pleistocene age for the deposition of the uppermost sediments in Carroll Cave. That the wolf and the human remains are found in the same or very similar beds may be significant, or may be explained by reworking of the silt or by deposition of remains while the silt was in a liquid state prior to compaction.

Bones of *Arctotherium*, a mid-Pleistocene bear, have also been found (Hawksley, pers. comm.). These remains were fragmentary and may have been derived from another deposit on the surface.

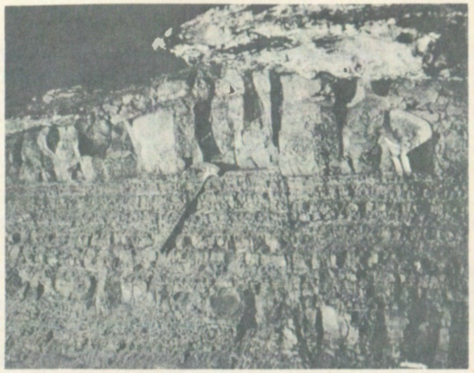

Photo by J. Vineyard

Figure 11.

Bed (3), the red silt, in a section 1000 feet upstream from the Mountain Room. Note shaley splitting in the lower half of the bed.

The sediments of Lower Thunder River passage were examined only briefly. The major sediment is a chocolate brown sandy silt found in extremely large mudbanks through the length of the passage. Red silt and gravel derived from Upper Thunder River fills are found at and near the present level of Lower Thunder River as stream deposits. Flowstone was deposited subsequent to the placement of the major brown silt fill; the undersides of some of these speleothems have been exposed by slumping of fill. All speleothems have undergone solution and most are coated with a thin layer of the brown silt. At least two periods of phreatic and vadose conditions are therefore recorded, and it is likely that a fluctuating, gradually declining water level has operated in Lower Thunder River passage.

The sediments of Upper Thunder River and Carroll River passages record: deposition under phreatic conditions (clay) by nearly stagnant water; vigorous phreatic flow or vadose erosion removing the majority of the clay, if much clay was originally present; aggradation of coarse gravels in a basal position in surface connected areas (Mountain Room, Belfry); aggradation of from five to 12 feet of silts, somewhat laminated, probably by a "water table stream" (Swinnerton, 1933), with an Upper Thunder River facies of silty gravels. These last deposits can possibly be correlated with the ripple-marked horizon in the Mountain Room, which is indicative of peak water level during emplacement of fill.

The most recent sedimentary events in Carroll Cave are the deposition of breakdown by ceiling collapse and the deposition of secondary formations by chemical precipitation. The oxidized and pitted surfaces of some speleothems indicate at least two periods of deposition have taken place. A high percentage of aragonite has been found in the speleothems by White and Stellmack (1959).

Age of the Cave

In order to determine the age of the cave, it is necessary to consider the relationship of the cave to the water table and the geomorphic cycle, especially as recorded in clastic fills.

It has been shown that the main passages of the cave, by their size, orientation and relation to structure, and by the phreatic features found in their walls and ceilings, must have developed under hydrostatic phreatic conditions. The cave is situated in the Gasconade dolomite 40 to 80 feet below the basal Roubidoux sandstone. In the area of the cave, the Roubidoux actually contains more dolomite than sandstone (Heller, 1954). Both formations are excellent water producers throughout Missouri (Shepard, 1907; Heller, 1954). Therefore, if the cave was more than 80 feet below the water table during its major period of enlargement, it appears that much of the lateral movement of phreatic water would have occurred in the sandier Roubidoux, and not in the Gasconade. Because the Roubidoux lies nearer the surface, water could more easily enter and leave it than the Gasconade.

However, it is possible that the Gasconade formation was well-caverned, porous or jointed dolomite before major passage integration and enlargement, thus causing it to be more permeable than the overlying rocks. If this were true, hydrostatic flow could have taken place through deep phreatic channels when the regional water table lay far above the Gasconade and even above the sandstones of the Roubidoux.

Bretz's (1942, 1956) argument in favor of a deep phreatic origin for Missouri caves to a large degree is based on the presence of red unctuous clay fill. This clay, he believes, could have been deposited extensively only under the stagnant phreatic conditions existing beneath a peneplain. Davies (1960), working on Appalachian caves, has found that clay occupies the uppermost position in many clastic cave fillings. These fillings contain coarse gravel beneath clay. Davies interprets (1953, 1960) these sequences as recording fluctuating conditions during which "active subterranean streams deposit sand and gravel when the water table is low and fine silt and clay when the water table is high and phreatic conditions exist." Davies then calls for major cave development under shallow phreatic conditions prior to filling.

The question of deep phreatic vs. shallow phreatic cave formation and filling involves the position of the water table and therefore the question: Did the cave form during the present erosional cycle or in the previous erosional cycle prior to peneplanation?

Tarr (1924) and Fenneman (1938) have presented convincing arguments for Tertiary peneplanation in the Ozarks followed by late Pliocene uplift and rejuvenation. Flint (1941) points out that strath terraces in the Mississippi Valley adjacent to the Ozark region indicate a pause in the uplift. Post-glacial rise in sea level has caused aggradation of up to 200 feet of sediments in the Mississippi Valley, but less in its tributaries (Fenneman, 1938). Therefore, conditions favorable for aggradation of cave sediments existed: (1) during the peneplain stage of the previous erosional cycle; (2) during local base level formation in the Pleistocene; (3) during post-Pleistocene rise in sea level.

As shown by Davies (1960), the necessity for the peneplain stage of clay filling of Bretz is questionable. Furthermore, in cave passages of large cross-sectional area, a small rate of flow could account for even the large discharges of some Missouri springs. Clay deposition would therefore be possible during short periods of base leveling, particularly in enlarged chambers.

The red illitic clay of Carroll Cave is found only on the floor of a passage 30 feet wide and 25 feet high, at the upstream end of the Mountain Room. Clay has been found nowhere else in the cave. Red fill found in accessible ceiling pockets was run through a settling column and found to be silt. In addition, some of the silts in the upper part of the cave fill sequence have particle diameters on the order of 1/200 to 1/256 millimeters (from settling column analysis). These silts are close to clay-size, yet contain late Pleistocene animal bones and even human remains. These silts certainly were not deposited under a peneplain.

It is believed therefore that the clay could have been deposited due to: Pleistocene local base leveling; the action of large chambers as settlement basins (Vineyard, 1963); and fluctuations in head due to climatic variations.

Furthermore, the stratigraphic position of the cave argues for a shallow to moderate phreatic depth during major enlargement, although portions near the outlet of the formative waters probably developed at considerably greater depths, such as demonstrated by the depths of present outlets of some Ozark springs. The cave is therefore interpreted to be a product of the present cycle of erosion, having its origin in the late Pliocene uplift of the Ozarks.

CONCLUSIONS

The geologic history of Carroll Cave is complex and must account for many features. From the evidence cited, the following sequence of events is postulated:

1. irregular phreatic solution of a large planar area of favorable lithology;

2. major passage enlargement by generally shallow, phreatic, unidirectional flow of water down the dip of local structure under hydrostatic head (Late Pliocene);

3. reduction of head or other previously discussed conditions leading to deposition of fine red clay;

4. re-establishment of head or operation of a water table stream serving to remove much of the clay, if much was originally present;

5. fluctuation of water table allows aggradation of fill;

6. lowering of base level permits degradation of accumulated sediments;

7. piracy of Thunder River from the Carroll River passage;

8. enlargement and subsequent filling of Lower Thunder River passage by water derived from Upper Thunder River under fluctuating shallow phreatic and vadose conditions;

9. incision of Thunder River in a vadose canyon above Thunder Falls;

10. breakdown-collapse enlargement and filling of passages and two periods of secondary mineralization.

"The courses of the big subterranean discharges upstream from the springs are largely unknown. If the streams are like Echo River (Mammoth Cave, Kentucky), with large air-filled spaces above the water, it is curious that none of the numerous Missouri caves leads down to one of them." (Bretz, 1942.)

The piracy of Thunder River has provided access to the Missouri cave stream which Bretz seeks through the Carroll River passage. Nearly 1,000,000 gallons per day flow through Thunder River passage and discharge in Toronto Spring. That the major enlargement of these passages took place less than 80 feet below the water table in the Gasconade dolomite seems likely because the overlying Roubidoux formation is known to be a good water producer. The question of depth of solution and enlargement remains, however, a knotty one.

The investigation of some of the many Missouri caves known to occur in a similar stratigraphic position (Bretz, 1956) may serve to strengthen or disprove the writer's interpretation.

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ERRATA

Guilday, Martin, McCrady. Bull. vol. 26, no. 4, Oct., 1964.

p. 153, table 12, caption: P^4-M^3 to P_4-M_3

p. 161, table 20, M^4-M^3 to M^1-M^3

p. 165, legend, fig. 21: **Microtus xanthognathus**

p. 168, table 32, 2nd grouping: M_1-M_3 to M^1-M^3

p. 180, table 41, 1.3* refers to **Blarina brevicauda**

Stream Potholes as Indicators Of Erosion Phases in Limestone Caves

By Derek C. Ford

ABSTRACT

Large stream potholes studied in two sample caves in the southwest of England are entrenched in a manner that suggests two phases of development – 1. pothole drilling by a large stream; 2. elimination of the pothole by a stream of reduced volume. Remnants of other potholes are also preserved in the channel walls above the level of large stream activity. Alignment of these remnants implies an earlier channel floor that underwent the sequence of pothole drilling and elimination before the latest potholes were formed. These variations of erosive activity cannot be attributed to local geologic structure or to stream piracy and are thought to be the result of climatic fluctuations during the Pleistocene.

INTRODUCTION

The stream pothole, a deep hole drilled in the solid channel bed and having no outlet save at the top, is found in steep (youthful) river courses everywhere around the world. It has attracted attention in the geomorphological literature (*e. g.* Elson, 1917-1918; Alexander, 1932; Angeby, 1951) from which it appears that pothole form remains much the same in a great variety of rock types. The writer has seen many such potholes in limestone cave passages in Britain and the United States. In fact, the pothole* appears to be particularly frequent in caves. A part of the explanation may be that accessible caves are necessarily formed in comparatively hard and coherent rocks (otherwise they would collapse): stream potholes are best developed in the harder rock types. But it is also clear that the limestone solution process is particularly favorable to the formation of finely shaped potholes. Figure 1 is a sketch of three actual potholes (in an English cave), which later entrenchment has conveniently sectioned for inspection. The potholes are expanded in the mechanically strong limestone and blocked by much weaker shale bands, indicating the predominant role played by solution.

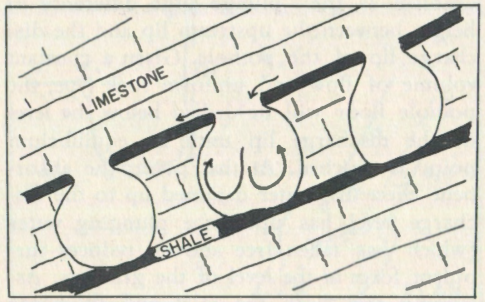

Figure 1.

Long section to show a relationship between limestone and shale strata and stream pothole formation. From an example in St. Cuthbert's Swallet, Mendip Hills, England.

* In British caving literature the term 'pothole' is often loosely applied to any watered shaft in a cave, no matter what its origin, and even to the whole cave, if its development is predominantly vertical. The sport itself may be called "potholing." In this paper, 'pothole' means only a feature formed in the manner outlined.

whether they are able to clear much of the fill and do work upon the pothole bottoms. Certainly in quieter water conditions (99% + of the time), the fill must shield the bottoms from any very active chemical or mechanical erosion.

Interpretation

The large potholes were drilled by a large stream, which established the a-a_1 channel width and lowered the channel floor from "e" (or higher), to the "a" level. There has been a reduction in the volume of flow resulting, almost invariably, in the cutting of the narrow "b" trench. Entrenchment is most vigorous at the plunge, where flow is accelerated. Here cutting down and back attains a recorded maximum of 20 feet (fig. 3). It has destroyed the verticality of the plunge, which is an important feature of the potholing mechanism. The pothole floor may still be lowered by exceptional floods, but the rate of such lowering is exceeded by downcutting in the "b" trench. The potholes are thus effectively out of action and are being destroyed. They may be termed "entrenched potholes" and, where they occur in caves, indicate at least two sequential phases of vadose stream erosion, the first of greater, the second of reduced, stream flow.

There does not appear to be an alternative explanation. Some potholes may be destroyed under constant flow conditions by "breaching". The mechanism, described by Elston (1917-1918), is illustrated in figure 4. It will be seen that the forms are very different from those of the entrenchment described above. Breaching can only occur where two potholes are drilled very close together. This is the exception in the quoted caves. A few cases do occur in Swildon's Hole but they also show the "b" trench below, and therefore post-dating, the breach. Geologic structure is not responsible. To reproduce such forms in these particular circumstances it would be necessary that the a-a_1 floor and pothole bottom be held up on resistant shale bands which the "b" trench incises without obstruction. The

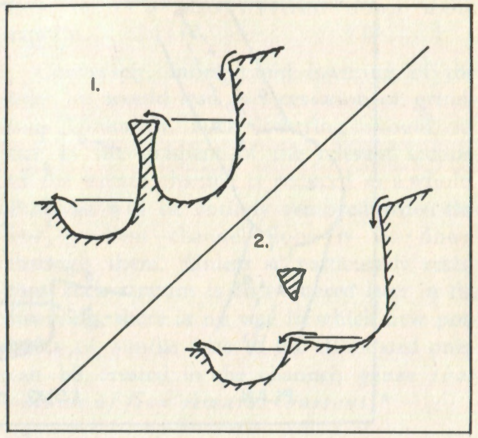

Figure 4.

Pothole "breaching". From examples in Swildon's Hole.

"a-a_1" floor bevels shale and limestone alike, but most potholes are drilled through many shale bands with no evident blocking effect.

"Hanging" Potholes and Grooving

These are fragmentary remains in cave passage walls above the a-a_1 level, which are taken to indicate yet earlier phases of pothole erosion in higher stream channels (fig. 5). Parts of the pothole floor, "cx", are often preserved, though rarely are parts of a single pothole preserved in both walls. The grooving, "fx", dropping down to the floor fragment but not below it, leaves no doubt about the identification of the latter. Sometimes grooving alone is preserved. As such, it is not a very useful index.

As an example, figure 6 shows the distribution of hanging pothole floors in part of a major stream passage in Swildon's Hole. In this section and immediately upstream of it, 20 remnants were counted above the a-a_1 floor. Ten of them were sited above modern entrenched potholes: six were preserved at places where there has been no subsequent development of good-sized potholes and where there was no particular structural feature to locate them. The remain-

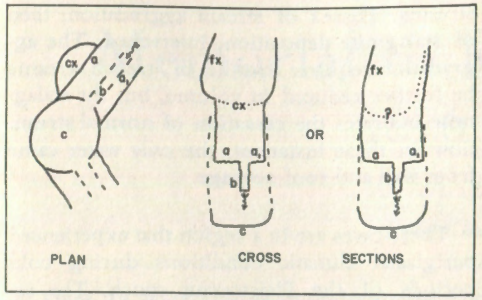

Figure 5.

Characteristic form of the "hanging" stream pothole in St. Cuthbert's Swallet and Swildon's Hole.

ing four cases were dubious: potholing may have been halted by a resistant shale band, as in figure 1. They are not considered further. In addition, there were many pothole-like groovings which lacked a "cx" floor fragment. These are also dismissed. The 16 accepted floor fragments occur at heights ranging from four to 18 feet above the a-a_1 floor. The dimensions of these past potholes were similar to the present entrenched ones.

These features are not accidents produced by a stream encountering varied structural conditions during a sustained, single phase of entrenchment to the a-a_1 level. The illustrated passage turns frequently so that there can be no simple geologic control. Some of the hanging examples that are located over modern entrenched potholes share a common vertical joint with the latter. Pothole drilling was thus arrested part way down the joint and then recommenced at a lower level.

In figure 6 massive stalagmite deposits conceal large areas of the walls and floors and elsewhere breakdown has possibly removed further evidence of hanging potholes. Nevertheless, it will be seen that the observed residuals are aligned to suggest two past stream floors above the a-a_1 level and subparallel to it. At the higher floor level, the stream passed into a passage which is now abandoned. Downstream of its junction there is only one hanging floor in the active passage.

From the interpretation presented earlier, where one level of hanging pothole is found above a modern entrenched level then (given

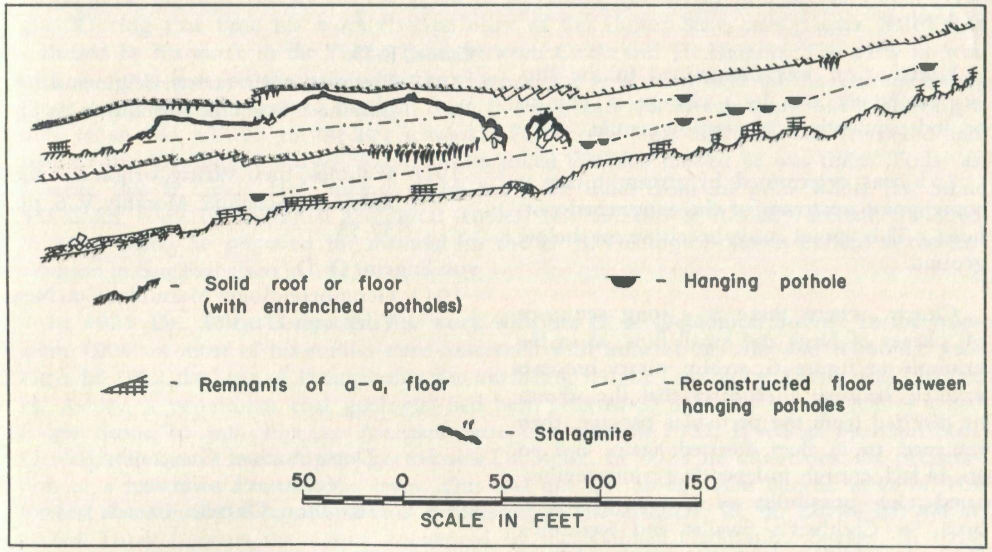

Figure 6.

Long section of a part of the main stream passage in Swildon's Hole, to illustrate the alignment of hanging potholes.

that there is no structural explanation), the following would seem to be the minimum sequence of events:

Phase 1: a large stream drills the hanging potholes.

Phase 2: stream flow is reduced and a "b" trench is cut through the potholes, to a level lower than their bottoms.

Phase 3: large stream flow is renewed. The depth of the "b" trench permits it to absorb the greater flow so that there can be no rejuvenation of the Phase 1 potholes. The "b" trench is greatly widened and large new potholes develop. The floor is lowered to the "a-a_1" level. Much of the evidence of earlier phases will be destroyed.

Phase 4: flow is again reduced and the modern "b" trench is cut.

Causes

There are two alternative explanations of the critical reduction in stream volume which allows this multiplicity of erosional forms to develop:

1. reduction was determined in the surface catchment area by a change of climate or, independently, of vegetation mantle.

2. it was determined by stream piracy at some point upstream of the entrenched potholes. This point may be above or below ground.

Clearly, where there is a long sequence of phases of large and small flow, as in the example in figure 6, stream piracy becomes unlikely because it requires that the stream be diverted from the particular passage, then returned to it, then diverted again, and so on. In fact, entirely independent evidence eliminated the possibility of stream piracy in both St. Cuthbert's Swallet and Swildon's Hole. In addition, here was plenty of evidence to show that phases of reduced flow with "b" entrenchment were not immediately followed by a renewal of the large, potholing streams. Phases of stream aggradation, then of stalagmite deposition, intervened. The aggradation requires that the "b" trench streams be further reduced in volume, but the stalagmite indicates the cessation of normal stream flow in these instances: the only water came from wall and roof seepage.

These caves are in a region that experienced periglacial climatic conditions during cold periods of the Pleistocene epoch. The sequence of phases that is revealed by a study of the entrenched and hanging potholes can be attributed to the climatic fluctuations of the Wisconsin (Würm) glaciation. Caves in periglacial areas of the United States may possess similar features.

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Memorial to Ralph W. Stone
1876 - 1964

BY WILLIAM E. DAVIES
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Over 25 years ago, as an undergraduate geologist I walked into the Pennsylvania Geological Survey at Harrisburg. My purpose was to introduce myself and announce my intention of doing a thesis on a geologic problem in central Pennsylvania. As with all undergraduates I was awed at the thought of entering the State Geologist's office; even entry to the Assistant State Geologist's office caused me to wonder if a hasty retreat was not more in order and simply let a letter announce my plans. However, as I stood at the door of the Assistant State Geologist I had little choice for Ralph Stone opened his door to leave. At this point all mental barriers disappeared, for I met a man who was interested in young people and their work. Beyond my wildest hopes, I found myself in the office of the State Geologist, George H. Ashley, with Dr. Stone at my side. I believe this was one of Dr. Stone's greatest traits for there was no one too big or small to receive his full attention on every problem and every request.

To most speleologists Ralph Stone is best known as a pioneer in modern cave studies. These came late in his life and his achievements in other fields of geology are impressive. Ralph W. Stone was born in Camden, New York on November 17, 1876. His college work gained degrees from Hamilton College (Ph.B., 1899), and Harvard (B.A., M.A. 1901). Ralph Stone began a 20-year career with the U. S. Geological Survey in 1901 as a field geologist. During that time his work covered most of the United States and Alaska. Ralph was enthused by his work in the Yukon Basin between Circle and Ft. Hamlin. The party he was with in 1905 was on the ground at the close of the gold rush days on the Yukon. Ralph Stone has a mountain named for him from this trip and his favorite story was of leaving a note in an old tabacco tin on Mt. Schwatka. Forty-seven years later this was recovered and sent to the Geological Survey; Ralph always joked that this proved he was there. Today as I write this at Circle Hot Springs I am but a few miles from the point where Dr. Stone was doing some of his initial geological studies. His interests in Alaska were later reflected in 1915 when he prepared the material for the U. S. Geological Survey exhibit at the Exposition in San Francisco in 1915.

In 1921 Dr. Stone completed his work with the U. S. Geological Survey. In the years from 1906 on most of his studies were concerned with mineral deposits and economic geology. In 1922 the State of Pennsylvania was nurturing its 4th Geological Survey and George H. Ashley, a prominent coal geologist had been selected to head the Survey. Ashley asked Ralph Stone to join him as Assistant State Geologist in 1922. It was as Assistant State Geologist that most speleologists got to know Dr. Stone. In 1928 he undertook the preparation of a report on Pennsylvania caves. This was not Dr. Stone's first interest in caves. His interest was stimulated by one of his professors at Harvard, Dr. W. M. Davis. In 1906 he visited Luray Caverns on a tour sponsored by the National Geographic Society. In 1910 while on his honeymoon in Bermuda he took his bride to Crystal Cave. In the next year Mrs. Stone was in the field with her husband and was exposed to the rigors of the then-undeveloped Morrison Cave (later Lewis and Clark National Monument.). The work on Pennsylvania caves begun in 1928 was undertaken in response to the desire of the Commonwealth to publicize its tourist attractions. At this period the Pennsylvania Geological Survey was pioneering in publications suited to the general public as well as scientists, and bulletins on scenery, road logs of geology, and popular summaries of geology of areas held a position equal to that of the old classic type of geology reports. Dr. Stone's initial report on Pennsylvania caves was an immediate success when published in 1930 and a second, larger edition was published in 1932. This publication set the format for most state speleological reports that followed in the next three decades. From 1932 on Dr. Stone, through his writings and his publicity was identified as one of America's leading speleologists.

In 1946 Dr. Ashley retired as Pennsylvania State Geologist and Ralph Stone, then 69 years of age, took over for a short period. The politics that are so common in state geological surveys were very distracting to Ralph Stone and on reaching 70 he retired from the position. Ralph's interest in the growing National Speleological Society was reflected in his term of presidency from 1948 to 1950. Ralph never missed a chance to be a friend of the Society. He encouraged many to join and always made it a point to bring the Society in when he received personal publicity for his cave work. During Dr. Stone's presidency, the Society began its period of maturity. The struggles of maintaining an infant organization were passed; membership moved upwards from about 400 to almost 1,000. After his presidency, Ralph was editor of the N. S. S. *Bulletin* for a few years and an active member of the Trustees for many years.

After his retirement as State Geologist Ralph Stone was active in many fields other than speleology. He taught courses at Wilson College, Chambersburg, Pennsylvania; participated in the Community Theater, Harrisburg, Pennsylvania; did volunteer work at the Harrisburg Hospital; and was an active member of several civic organizations.

Dr. Stone's bibliography covers 18 books and over 270 papers. His honorary awards include an Honorary Degree of Doctor of Science (Lebanon College, 1938) and Honorary Membership, National Speleological Society, 1943. Dr. Stone was active in the Pennsylvania Academy of Science (president 1939-40, editor for 13 years); Geological Society of America; American Association for the Advancement of Science; and Society of Economic Geologists.

Ralph Stone had two children. His son was killed in Algeria in World War II and this had a profound effect on Dr. Stone. On his death on May 2, 1964 he was survived by his widow and a daughter.

To those who knew Dr. Stone we will always remember him as a geologist, naturalist and humanitarian. His latter quality is well illustrated by his consideration for others. On the death of George Ashley he was called upon by the Geological Society of America to write the memorial. After completing this difficult task he resolved that no one would be put to such an effort on his part and he therefore wrote his own to spare others of the task.