BULLETIN

OF THE

NATIONAL SPELEOLOGICAL SOCIETY

NUMBER TWENTY

November 1958

BULLETIN TWENTY

Published by

THE NATIONAL SPELEOLOGICAL SOCIETY

To stimulate interest in caves, karst, and related features and to record the findings of explorers and scientists within and outside the Society

IN THIS ISSUE . . . . November 1958

Published intermittently, at least once a year; Editor: William E. Davies, 125 W. Greenway Blvd., Falls Church, Va., Assistant Editors: Nancy G. Rogers, 2026 Key Blvd., Apt. 640, Arlington, Va.; Dr. William R. Halliday, 1117 36th. N., Seattle, Washington.

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

PUBLICATIONS include the BULLETIN published at least once a year, the NEWS appearing monthly, and the OCCASIONAL PAPERS. All members receive the BULLETIN and the NEWS.

Office Address:

THE NATIONAL SPELEOLOGICAL SOCIETY
203 VIRGINIA HILLS AVE.
ALEXANDRIA, VIRGINIA

Membership dues in effect January 1, 1958:

Family Associate	$ 2	Sustaining	$ 14
Associate	$ 4	Institutional	$ 10
Regular	$ 7	Life	$140

THE NATIONAL SPELEOLOGICAL SOCIETY was organized in 1940. It has members throughout the United States and many members in other countries. The Society is associated with the American Association for the Advancement of Science.

THE SOCIETY is a non-profit organization of men and women interested in the study of caves, karst and allied phenomena. It is chartered under the law of the District of Columbia.

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

THE AFFAIRS of the Society are controlled by an elected Board of Governors. The Board appoints national officers. Technical affairs of the Society are administered by committee chairmen who are recognized specialists in their professional fields.

LIBRARY: An extensive library on speleological subjects is maintained by the Society. Material is available on loan to NSS members at a nominal charge to defray the cost of handling.

Big Room Cave of Payne Cove

By CORD H. LINK, JR.

The relation of caverns to surface features has often been a matter for speculation. The combination of good, detailed topographic maps and accurate mapping of caverns in the Payne Cove area demonstrates the close relation of cavern and surface features. In addition the proper interpretation of surface features is a guide to location of cave entrances. Cord H. Link, Jr., is a Director of the National Speleological Society and has studied Tennessee caves for many years.

During exploration and studies of the larger caves of Payne Cove, some degree of correlation was apparent between the surface topography and the conditions in the cave beneath. It seemed that wherever the path of the cave was crossed by a surface wash or stream, the effect on the cave was catastrophic. In such regions extensive breakdown is very likely. In turn, the collapse within the cave may be reflected in the local surface topography. Most common is the occurrence of a sink hole above cave collapse and perhaps a stream capture, but there are often much larger, more general indications on the surface. These larger features may appear on topographic maps as modifications of "normal" contour lines. Following up leads of this kind in Payne Cove has led to interesting new finds, and applications elsewhere have been fairly successful.

This report also deals with an attempt to trace the waters of subsurface drainage in Payne Cove[1]. The major underground drainage of the cove resurges in neighboring Burrow Cove at Sartain Spring which contributes half the volume of the Elk River (Figure 1).

In the headwater country of the Elk River is a large system of three coves in the form of prongs. The coves are near Pelham, in south central Tennessee near the junction of Coffee, Franklin and Grundy Counties. Penetrating northward is Burrow Cove, known locally as Bursey Cove. To the east extends Payne Cove, and to the south and east lies Layne Cove which contains Wonder Cave, a widely advertised tourist attraction. Access to the region is by U. S. Highway 41, which passes near Wonder Cave and through Pelham. The region lies about halfway between Nashville and Chattanooga. The plateau area drained by these coves is just west of the Tennessee-Cumberland Valley divide. Our interest will be centered on Payne Cove — the middle prong of the system. The area maps which were the basis of studies are 7½ minute quadrangles 93 NE and SE, topographic maps published by the Tennessee Valley Authority (Figure 2).

Big Mouth Cave

Famous in the region, and noted on the TVA map, is Big Mouth Cave. Entrance to this cave was provided when surface erosion breached a curve in a large vadose channel (Figure 3). The resulting opening is about 150 feet wide by 20 feet high. Our first visit to this cave took place in 1953, during early activities of the small group which later became the Cumberland Chapter of the National Speleological Society. At that time, Thomas R. Morel, of Manchester, Tennessee began systematic exploration of caves of the region. It was found that the left branch of Big Mouth Cave proceeded generally west and north under Limekiln Hollow, and deteriorated under Payne Ridge which separates Payne Cove and Burrow Cove[2].

The right branch of Big Mouth Cave (Figure 4) was found to lead eastward along 400 feet of straight passage, to a breakdown plug under

[1] For a suggested theory of the formation of caves in deep coves, see the article on caves of middle Tennessee by T. C. Barr, Jr., National Speleological Society Bulletin 16, Dec., 1954.

[2] Deterioration consists of a lowering ceiling from which slabs become detached on contact with the cavers head or back, and a rising relative water level forming series of pools in which storm floods have deposited decaying vegetable matter which releases "marsh gas" when disturbed.

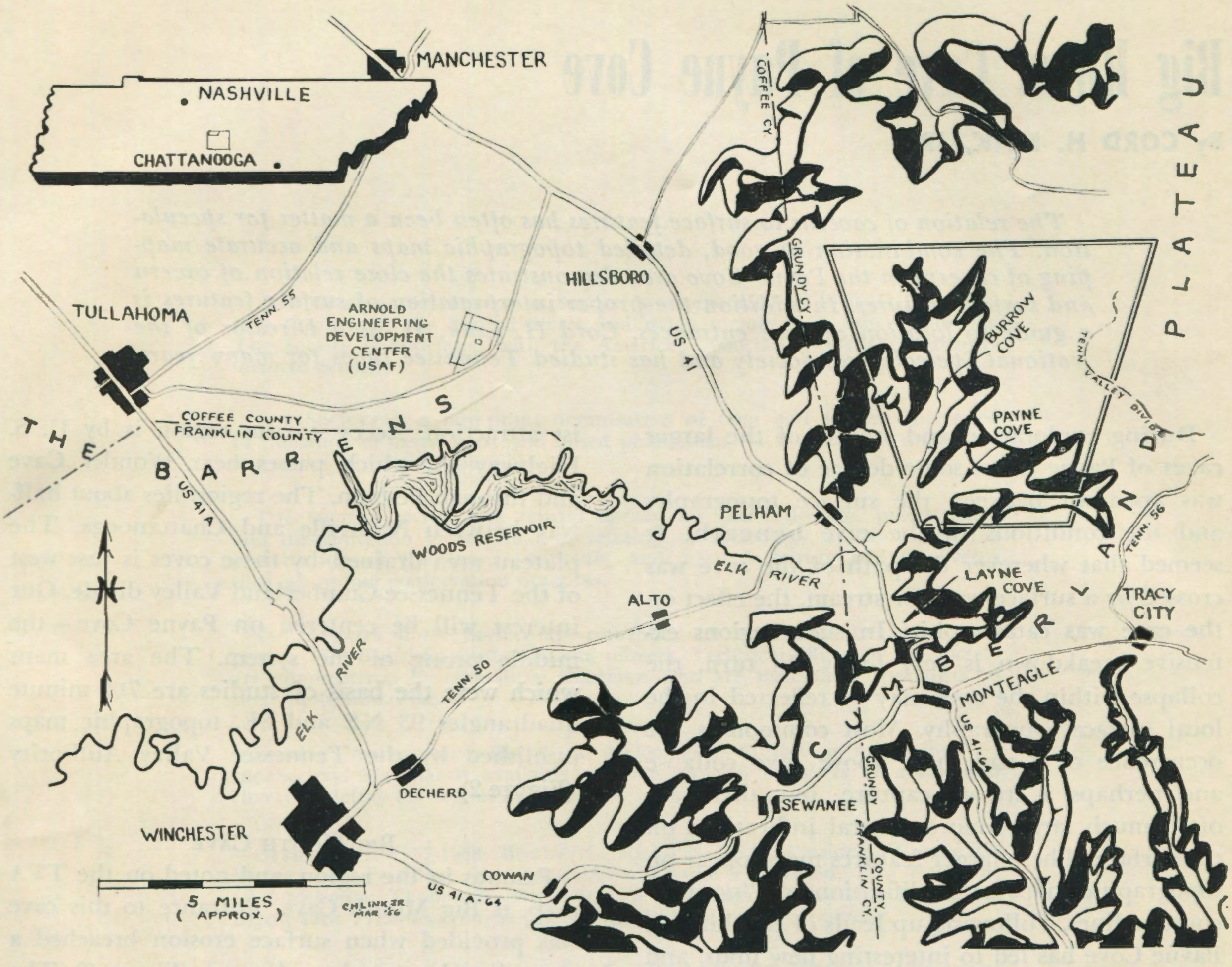


Figure 1
Map of Middle Tennessee, showing the area around Payne Cove at the head of the Elk River. The region in double lined box at right is sketched in Figure 2.

Spring Hollow. Many fruitless hours were spent in trying to work through the breakdown in following months. Surface waters from the washes outside enter via the mouth of the cave and vanish in crevices. Several acres of pasture land are drained here giving rise to a rich population of micro-organisms in the cave soils as found by T. C. Barr, Jr.

Within 50 feet of the farm lane that leads near Big Mouth Cave there is a small cave with much mud fill that was once worked for saltpeter. There are several hundred feet of interesting passages in this Saltpeter Cave. About a hundred yards away is "Bone" Cave which is named from the fact that it is a handy place for disposal of the remains of chickens which are dressed for market on the nearby farm. Recent legislation outlaws this practice in Tennessee.

Big Room Cave

Eastward across the field from Big Mouth Cave, beside the farm lane, is a small well-like opening, fenced to keep livestock from falling in. The farmer, who owns the land where these caves begin, directed attention to this cave, assuring his visitors that after a while it got big and went on and on. It was later learned that he was concerned with the possibility that the cave might make a good bomb shelter or underground factory site, and it might be worthwhile for the state to put in a farm-to-market road starting from Big Room Cave.

Our visits to Big Room Cave began in the late summer of 1953. After the descent into the well mouth and another drop to about 30 feet below the surface, a well decorated winding passage leads northward and eastward to an easy crawl-

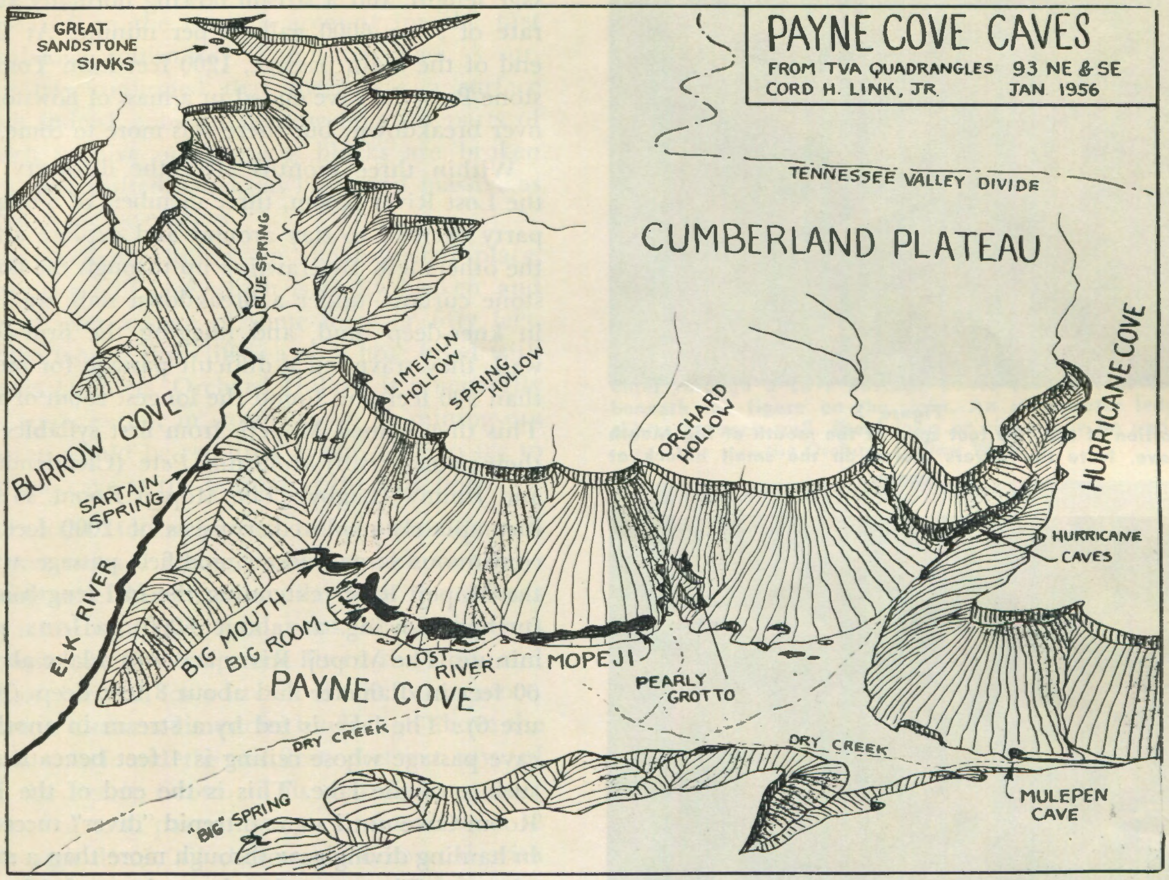


Figure 2

Perspective view of Payne Cove and Burrow Cove, showing the Payne Cove caves. The chambers marked Big Room, Lost River, and Mopeji, make up the Big Room Cave of Payne Cove.

way which opens up into the Big Room. Class 4 surveys by Tom Morel and the author set the length of this room at 1200 feet. Its width is more than 100 feet at the widest part, and its height ranges from 9 to 15 feet from the mud fill floor.

The north end of the Big Room is sealed with a great breakdown plug under Spring Hollow, just as is the Big Mouth Cave. Although no elevation surveys or close stratigraphic identifications have been made, it is reasonably certain that this breakdown is the same in the two caves, and that they were once one. With the collapse of several hundred feet of passage, the back of the old cave was broken, where Spring Hollow cuts across it.

During the months following our first visit to Big Room, Tom Morel made frequent trips in an attempt to work through the Spring Hollow breakdown. Giving this up, he turned his attention to the southeast end of the Big Room where several passages offered hope of continuing. The longest passage ended in massive breakdown.

Throughout 1954, Morel led frequent trips to explore and map the Big Room. In late 1954 or early 1955, Tom and his wife, Zita, were accompanied by Fritz Whitesell of Sewanee, Tennessee, who has an affinity for wet caves and small spaces. In some manner Tom and Zita forced Fritz through 80 feet of tortuous squirmway and through the breakdown. This route, originally called Morels Pass for his long efforts to find it, has since acquired the name Tombstone Pass (Figure 5) and leads into the large Lost River Room which contains the best speleothems in the entire cave system. This appeared to be virgin territory[3], with some 2000 feet of total pas-

[3] In private communications, Whitesell informed the writer that he first heard of an underground river somewhere in the (previously named) "Little Mouth" or Big Room Cave from Dr. Edward McCrady of Sewanee.

Figure 3
Portion of the 150 foot span at the mouth of Big Mouth Cave. Note the cavers seated on the small hillock at center.

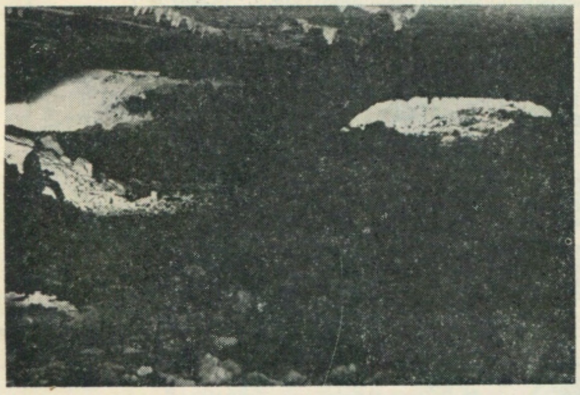


Figure 4
Looking towards the entrance of the east branch of Big Mouth Cave.

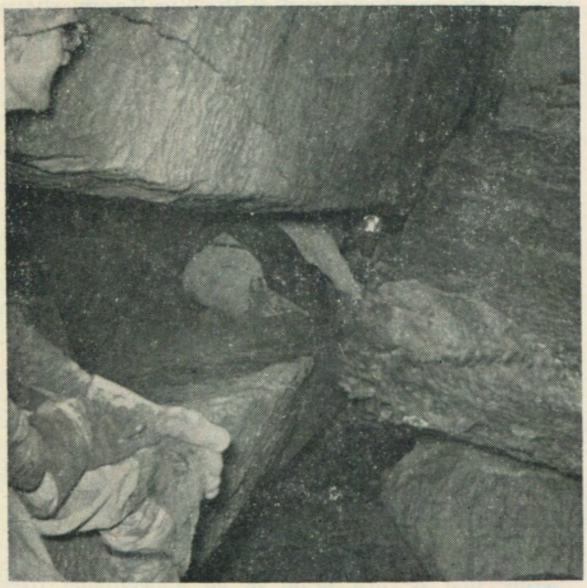


Figure 5
The beginning of Tombstone Pass, between Big Room and the Lost River.

sage length, and a stream flowing normally at a rate of some 6000 gallons per minute. At the end of the main passage, 1200 feet from Tombstone Pass, the cave ended in a mass of flowstone over breakdown; but there was more to come.

Within three months after the discovery of the Lost River Room, three members of a larger party decided to stay around and explore after the others left. By crawling up through the flowstone curtain, under a breakdown slab, wading in knee-deep mud, and hugging the firm left wall, they traversed a difficult passage for more than 300 feet and found the longest room of all. This they named Mopeji, from first syllables of their names (Bill) *Mo*loznik, *Pe*te (Clendenon), and *Ji*mmy (Bagby). The Mopeji Room, so far incompletely explored, consists of 2000 feet of continuous large vadose modified passage with the Mopeji River extending the full length and further, flowing at about 6000 gallons per minute. The Mopeji River arises in a lake about 60 feet in diameter and about 8 feet deep (Figure 6). The lake is fed by a stream in another cave passage whose ceiling is 4 feet beneath the surface of the lake. This is the end of the Big Room Cave until some intrepid "diver" succeeds in hauling diving gear through more than a mile of cave. The unexplored portions of Mopeji Room extend downstream, a route expected to lead back to the Lost River Room, via Lost River.

The above account of Big Room Cave exploration is given to show how the central theme of this paper arose. It was hoped that a continuation of the cave could be found but where to look was a problem. Our class 4 surveys, subject to doubt throughout the crawlways, and with no possibility of closure, were transferred to a topographic map. Immediately obvious was the connection between the surface washes and the cave breakdown beneath.

Topographic Map Exploration

The Mopeji Room of Big Room Cave appeared to end under a very large wash named Orchard Hollow. As there is some breakdown beside Mopeji Lake we wished to find out if there might be a connection with the wash, and equally important, to find a back door into Big Room Cave. The topographic map showed extremely strong relief, and a sharp break in the contours at Orchard Hollow. However, no wash appeared on the map to account for the first breakdown squirmway, Tombstone Pass. A surface trip confirmed that there was a surface wash indeed, a broad shallow area, in parts of which massive outcropping blocks are broken loose and shifted, blocks as large and massive as those in the cave below.

At Orchard Hollow, in the expected place, there is a cliff face which is badly broken and sagged over a span of some forty or fifty feet. At the foot of this cliff is a sink hole filled with stream boulders. Orchard Hollow is a generally dry wash, except in storm season. A mining operation would be required if one were to try to get into cave at the bottom of the sink hole.

Orchard Hollow proved to be unusually rich in cave ruins. Large expanses of rock face (the strong relief hinted at on the topo map) bear the remains of cave formations. Bits and pieces of flowstone and dripstone litter the sides and bed of the wash for a stretch of 600 feet or more. Here in a salient limestone bluff, high above the wash, was found the smallest, prettiest cave of all, the Pearly Grotto. This cave has not over 20 feet of total passage length, and ends in a 12 foot high dome, all thoroughly decorated with draperies, ropes, totem poles, cave coral, and so on. Highly polished rat trails lead on to tiny spaces.

Beyond Orchard Hollow, the topographic maps indicated what might be (and were) large collapse areas, and some sink holes. A search on the ground proved that the maps failed to show all the sink holes which roughly sketched a path leading on up the cove.

One of the cove farmers directed us to Hurricane Cove, a branch of Payne Cove, where there were caves with "big" rooms in them. The Hurricane wash has here cut into an extensive cave system and quarried most of it away. The older abandoned stream bed can be found in places 30 feet higher and 100 feet to one side of the present bed. The stream has moved horizontally into the cliff and now follows a network pattern, at several levels, much like a covered rapids. The stream issues at the lowest mouth of the cave, farthest down cove, runs several hundred feet on the surface, then plunges with a roar out of sight beneath a small ledge.

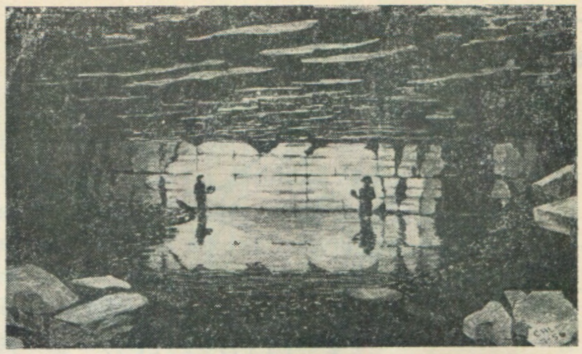


Figure 6
Mopeji Lake, the end of Big Room Cave. The lake waters enter through a cave passage whose roof is four feet beneath the figure on the right. An underwater ledge skirts the back wall. Breakdown on right may be under the Orchard Hollow Wash.

Figure 7
Mouths of the Hurricane Cave network; several larger entrances are beyond the view of this picture.

The Hurricane Cave has perhaps a dozen mouths within a distance of 300 feet along the base of the cliff (Figure 7). A cave room, complete with large speleothems, hangs bisected high on the cliff face. The small network passages are, in some places, very dry. Vegetable matter enters with each flood of the wash and the cave is inhabited by crickets, spiders, millipedes, bats and other types. Speleothems are concentrated in some small areas and are rather poor, although many cave pearls were found. In one area of dry passages, three distinct floor levels occurred, connected by slits and holes in the floors. The lowest level eventually accumulates all the stream water, and leads it to its exit. This stream is a major contributor to the underground river system of Payne Cove.

A short distance up Payne Cove from Hurricane Cove is the Mulepen Cave. The streams at the cove head, coming off the Cumberland

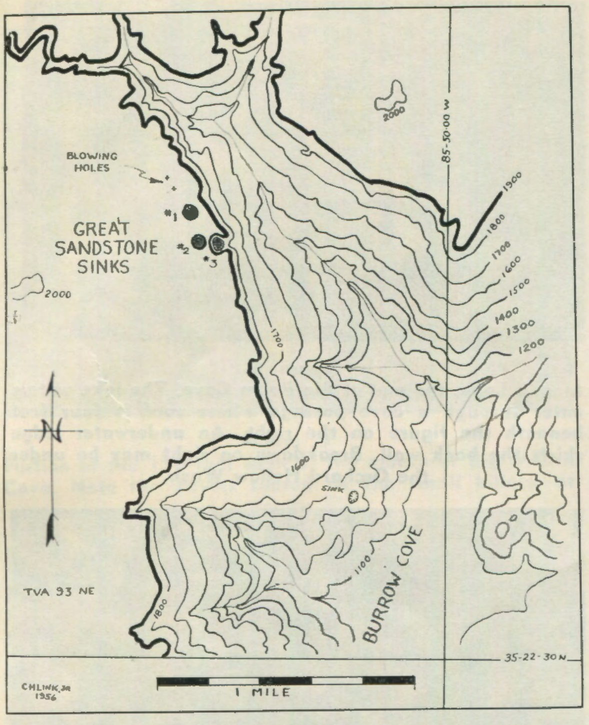


Figure 8
Topographic map of the Great Sandstone Sinks.

plateau, vanish into this cave, forming another major contributor to the subsurface streams.

Before summarizing the findings in Payne Cove, a return to Orchard Hollow is in order. The entrance to the Big Room Cave is on the property of Mr. Roberts down the cove. This cave runs under property lines to Orchard Hollow, owned by Mr. Meeks, an up-cove farmer. Mr. Meeks told the explorers that his Orchard Hollow held three caves and a pit that "must be 500 feet deep". These were later visited by a group led by Dan Bloxsom, and Meeks pointed out the locations, going along with them.

The Pearly Grotto was not one of these, nor did he recognize a description of it, nor was he shown where it is. Skeptical Bloxsom, who is experienced in the shortcomings of native estimates of cave dimensions, took along only 130 feet of rope to the "500" foot pit. Within ten minutes after entering the pit, Bloxsom was back out. He told Mr. Meeks the pit was 45 feet deep. Mr. Meeks calmly explained that the pit must have filled up recently.

Tracing the Waters of Payne Cove

Streams in the upper branches of Payne Cove enter the subsurface drainage at Mulepen Cave in Payne Cove, and at Hurricane Cove. These two make up most of the water found within the cave system. The path of the stream can be traced by following the line of sink holes until the river is found within the Big Room Cave at Mopeji Lake. From there it follows the Mopeji Passage reappearing again in the Lost River Room. From here, the sink hole trace continues across the Roberts farm with some sink holes of recent origin. Mrs. Roberts reports hearing the sound of running water under the field behind the barn, a location in line with the sink holes. On the west side of Payne Ridge, after pooling in the recesses of Big Mouth Cave, the waters issue at Sartain Spring, supplying half the volume of the Elk River. The remainder of Elk River waters come from other springs in Burrow Cove. Mr. Sartain tells how his grandfather dumped several bushels of seed gourds into the Mulepen Cave and Mr. Meeks states that his father did the "duck-on-a-plank" trick. Both duck and gourds are said to have come out at Sartain Spring. The gourd test seems practical.

Exploring by Map in Other Areas

In 1955 the Tennessee Valley Authority made available blue line manuscript copies of maps showing the upper reaches of Burrow Cove. A study of this map revealed that there were odd depressions in the Cypress Sandstone caprock near the head of Burrow Cove. A flight in a light plane over the plateau confirmed that there were indeed three large sink holes in the high resistant sandstone (Figure 8). The deepest, labeled No. 1 of the "Great Sandstone Sinks" appeared more than 100 feet deep. The day following the light plane survey, the author visited the site on foot, without any gear, except a camera. The deepest sink required ropework and was not then entered. It was about 150 feet deep. Here at these big sinks several acres of sandstone have fallen. Nearby were found two small slits in the bottom of small depressions, slits which blew cave air so warm that salamanders frisked in the leaves about the slits. This was in January, 1956,

Figure 9
Icicles in the #1 Great Sandstone Sink dwarf pilot T. F. Talbot on the ledge at center. This sink was fully explored by the author and D. Bloxsom in July 1956, by roping down the (then dry) falls just to the left of center.

with ice on the ground from the past weeks storms. Where a small stream entered the large sink, icicles were more than 8 feet long. The possibilities for caves in the area were exciting; fairly large deep water cave mouths were known to be found in Burrow Cove at the cove floor, only about a mile away. The No. 1 sink was explored in July, 1956 by D. Bloxsom and the author (Figure 9). No cave entrance was found in the sink. The nearby slits had reversed their current of air and cool cave air blew from the rocks at the bottom of the sink.

Map studies have guided other field efforts of the Cumberland Chapter. The beautiful Deerlick Falls, in the canyon at the cove head in Layne Cove, was first visited when unbelievably high bluffs were noticed on the topo map, just a short way down the cove. Deerlick Falls has been called a "cave with the roof off".

The grandeur of the Trinity Sinks at Mitchell Cove was first suggested by the map of the region which indicated a depth of about 120 feet. The single sink shown on the map proved to be three sinks connected by high shoulders, and the third of these sinks produced a virgin cave, discovered by the author who noticed the motion of ferns in the breeze from a small slit that invited digging into. The source of the air was found in the nearby Moscow Subway pits, named from the observation that the trains seldom run there.

A remark on the combination of slit, cave, and pit is called for here. Seasonal alteration of cave winds is a common observation. Vertical pits and interior caverns serve as heat exchanging stacks, between the earth and the atmosphere. In summer, warm outside air enters the column at the top of the pit, is chilled, grows denser and descends, to blow from any exit at a lower elevation, often a cave mouth. In winter, cool air enters the lower end of the system, is warmed, rises, and blows from the upper vent. The peculiar random shattering of rock noticed in some caves such as Wet Cave near Sewanee, Tennessee, is explained by this mechanism. This cave has fairly large air passages connecting to the surface at the top of water falls that feed the cave stream. In winter, warming-stack action is sufficient to draw large masses of cold air into the lower parts of the cave, especially at the mouth. Freezing of the rocks will produce the shattering observed which is similar to that seen around waterfalls outside. Ice has not been reported in Wet Cave, perhaps due to the lack of observers willing to face the rigors of a wet cave in freezing weather.

Conclusion

Whether for the purpose of tracing underground stream channels or for the sake of exploring for new caves, the detailed topographic maps are most valuable. Some of the uses and results obtained have been outlined above. Progress is obtained by a close integration of map studies and detailed knowledge easily (and only) obtained by visiting the sites directly. The maps provide the clues, the caver must develop the art. It is great fun being a detective when the clues are too big to conceal. Greater use of the topo maps is recommended as an adjunct to, not a substitute for, the more common methods, such as asking the natives. Where logging operations are under way, the loggers usually know more about pit and cave locations than the natives, since they get closer to more territory and (literally) lay it bare. But field searches guided by mapped clues have produced caves in the natives back yard.

The Big Room Cave of Payne Cove has paid the price so often exacted from a friendly cave which reveals its secrets to hard workers. A dead end passage, an extension of the entrance passage, used to have a dozen fine large rimstone pools, of regular smooth crescent shape that caused them to be labeled "Moon Pools" by the early explorers. On a recent visit, nearly all of these were found to have been carefully broken out at the deepest point by someone who simply wanted to see the water run. Fortunately the rigors of travel in this cave are such that few people have gotten past the Big Room without a guide. The Lost River Room is slowly gaining a floor coating of spent carbide, but is otherwise in good shape.

ACKNOWLEDGMENTS

The efforts reported here arose from interest first generated by conditions in the Big Room Cave of Payne Cove in Grundy County, Tennessee. Field trips were possible only through the support and companionship of fellow members of the Cumberland Chapter. Special thanks are due Dan Bloxsom, the outstanding pitman of this group, who can walk over tremendous amounts of rugged country in amazingly short time, and who originally urged the group into the activity of "cove beating" for caves even before maps had been acquired. Search by map arose as a defense against the great labor of walking over *all* the ground that might have a cave in it — or might not. Aerial photography by the author, over rugged cove country, was accomplished with the excellent piloting of Thomas F. Talbot of Birmingham, Alabama, formerly a member of the Cumberland Flying Club of Tullahoma.

A Statistical Theory of Cave Entrance Evolution

By RANE L. CURL

The question of the number of caves that may exist in a region or a country is one that is often raised by both laymen and scientists. In the past many estimates ranging from mere guesses to those based on empirical deductions have been proposed. To these estimates is now added a statistical approach which gives a more substantial foundation to the postulated number of caves. Rane L. Curl was introduced to cave exploration during the summer of 1952 in Charleston, W. Va. While at the Massachusetts Institute of Technology as a graduate student he was chairman of the Boston Chapter of the National Speleological Society. At present Dr. Curl is on the research staff of Shell Development Company in Emeryville, California.

INTRODUCTION

The natural creation and destruction of cave entrances are geological phenomena depending on the stratigraphic, meteorologic, hydrologic, mineralogic, etc., relations of a region in which caves occur. The existence of an entrance to a cave suggests from a statistical point of view that there is a *process* of entrance creation. The discovery of second entrances from within known caves suggests that there is a complimentary *process* of entrance destruction. It follows that there must be caves which have either not gained or have lost entrances and which are therefore unknown.

This conjecture is supported by the discovery of new caves in excavating and mining and by the appearance of a karst area having sinkholes *apparently* without traversable caves at their bases. The most common estimate is that there are ten times as many undiscovered as there are known caves. Folsom (1956) refers to approximately five thousand known caves in the United States and suggests upwards of fifty thousand unknown caves. The implication is often that these are mostly unreported caves with entrances, though this notion is not necessary and is indeed unlikely.

Supporting evidence of a logical nature is presented here for these otherwise empirical conclusions. Originally this study began after it had been noticed that since there are caves with one, two, and more entrances, there logically should be caves with no entrances. Such a notion found immediate support from the evidence mentioned above, but intriguing questions remained with regard to the number of such caves and their properties. It seemed that it should be possible to use data on the number of caves with one, two, or more entrances, and to *extrapolate* to find the number without entrances. This is, in essence, what has been done in this paper, although there is now a great difference between the first crude attempts and the present analysis based upon hypotheses concerning entrance evolution.

It was evident from the beginning that a mathematical relation would have to be "fitted" to the available information, in order to carry through an extrapolation. The main question was how this should be done. Although the earliest arbitrary functions considered gave an answer, they left the impression that the result was essentially meaningless. By what criterion was the extrapolation to be considered realistic? An example of the result of such an extrapolation, based upon an almost arbitrary mathematical relation is shown in Table 1. The mathematical relation in this case is called the *Poisson frequency distribution* (Cramer, 1955). It is a formula describing the manner in which items (caves) are sorted into different groups (groups of caves, each for a different number of entrances). The mathematical relation was fitted to the *observed frequencies* and then the expected frequency of caves with no entrances was calculated.

This use of an arbitrary though well known statistical distribution seems insufficient to provide *understanding* of the processes which may have occurred in nature to produce the observed distribution of caves by number of entrances. In addition, the characteristic parameter of the

TABLE 1.
Comparisons of Observed Frequencies of Caves of West Virginia with the Poisson Distribution Giving the "Best Fit" to Data

Number of entrances	0	1	2	3	4	5
Observed frequency	—	228	25	3	1	0
Expected frequency	893	226	29	2	0	0

Poisson formula was found to vary with the average length of the group of caves for which it was computed and hence it lacked the desirable feature of being a fundamental parameter of *all* the caves. Furthermore, other equations could have been fitted and there would have been little reason to prefer one in particular.

Following this first approach a simple mechanism of entrance evolution was assumed. The variable of cave length was not included and the resulting mathematical equation turned out to be the same Poisson formula which had been used first on intuitive grounds. Thus, Table I also represents the "fit" of a theoretical method based upon a simple mechanism. Two things were then observed which led ultimately to the theory in its present form. Firstly, it was noticed that the Poisson formula predicts fewer caves with multiple entrances than had been observed. Secondly, and more important, it was noticed that the multi-entrance caves are, in general, *longer caves* than those with one entrance. It thus became apparent that length was an important variable. As a result, the complete theory leads to a method of predicting the relative lengths of unknown caves as well as their number.

Statistical Theory of Entrances

We will not speak here of the peculiar histories and properties of individual caves. If we did, we would find that each probably could be argued as having some aspect which seems to place it out of the realm of applicability of a statistical theory. There would still remain, however, the group phenomena — properties of the whole ensemble of caves which cannot be attached to the individual members of the group. The *average number of entrances* is clearly such a property as are also the probability relations developed here. Although we will not be able to indicate what may happen to any given cave, we will speak of what is likely to occur to a group of caves with the passage of time.

Consider a large number of caves distributed over an area of relatively uniform geology, climate, and topography. A continuing *random* or *stochastic process* of formation or reopening of entrances and closure of entrances will be taking place. The agents of these processes are, in general, associated with surface erosion phenomena and, to a lesser extent, with the nature of the caves in question. The assumption will be made here that this process is taking place on a fixed population of caves of invariant lengths. The truth of this depends upon the relative time scales of external and internal changes. The assumption implies that the genesis of cave entrances is much more rapid than the genesis of internal cavern features. This is likely as the surface, where entrances form, is subject to a much harsher environment, involving more rapid chemical and physical weathering.

We start, then, with a population of caves of different lengths and with zero, one, or more entrances, at some instant of time. As time passes, the initial conditions of these caves with respect to numbers of entrances will change. In some given length of time, a few caves will lose entrances, a few will gain entrances and the rest will remain as they were. Let us consider each of these processes in turn, in order to deduce the logical form of a stochastic theory of entrance evolution.

In a large number of caves with one entrance, a certain fraction of the entrances will be closed in some interval of time. It is reasonable to say that in double the time interval about twice the number of caves will lose an entrance, as long as in either case the total number losing entrances is small compared to the total number of caves. Furthermore, if all of this group of caves had two entrances, it is apparent that the number of caves which would *lose an entrance* would be about twice that for single entrance caves, in the same interval of time. This presupposes that all present entrances are equally likely to close, an assumption which might not be quite true, but which will be taken as a first approximation. We therefore state the following hypothesis:

The probability (or fraction) of caves with n entrances losing one entrance in a time interval Δt is equal to $sn\Delta t$.

The proportionality constant s is a function of the influences of the environment.

As the length of a cave increases, it becomes ever more likely to possess those features which are conducive to entrance formation. While it may not be proper to say that the formation of an entrance is equally likely along every foot of a cave — we usually observe entrances at the terminations of caves — it is reasonable to assume that some related properties associated with entrances such as joint intersections, approaches to the surface, length relative to topographical scale, and others, are functions of the length. Therefore we might expect that on the average caves of twice the length would be twice as likely to gain an entrance in some time interval. This likelihood would also be proportional to the time interval, as in the case of losing entrances. We therefore state the following hypothesis:

The probability of caves of length l gaining an entrance in a time interval Δt is equal to $rl\Delta t$.

The proportionality constant r again depends on the environment.

It is possible that the existence of an initial entrance influences the creation of subsequent entrances, but if the new entrances are reasonably separated from the first, this effect should be negligible. In this analysis, such an effect will be assumed to be absent.

The remaining possible event of caves neither gaining nor losing an entrance follows from the previous two.

The probability of caves of length l and with n entrances neither gaining or losing an entrance in a time interval Δt is equal to $1\text{-}ns\Delta t\text{-}rl\Delta t$.

These relations define the mechanisms involved. It is now necessary to consider how they act in order to create the existing distribution of cave entrances among caves.

At some instant of time, t, we would find that there exists in a population of caves a certain number, f_n, with n entrances; another number, f_{n-1} with $n\text{-}1$ entrances, and still another number of caves, f_{n+1} with $n+1$ entrances. We are interested in determining how many caves with n entrances there will be after some time interval Δt. Instead of discussing the actual number of caves corresponding to a certain num- of entrances, we may speak of the probability of caves having n, $n\text{-}1$, or $n+1$ entrances. If the interval of time Δt is so short that the event of a cave gaining or losing two or more entrances is extremely small compared with gaining or losing only one entrance, it follows that the probability of obtaining caves which are of length l and have n entrances at time $t + \Delta t$, $p(l,n,t+\Delta t)$, will depend upon:

(a) The probability of caves of length l with $n\text{-}1$ entrances at time t, $p(l,n\text{-}1,t)$, *and* the probability of such caves gaining an entrance, $rl\Delta t$,

(b) The probability of caves of length l with $n+1$ entrances at time t, $p(l,n+1,t)$, *and* the probability of these caves losing an entrance, $s(n+1)\Delta t$, and

(c) The probability of caves of length l with n entrances at time t, $p(l,n,t)$, *and* the probability of these caves neither gaining or losing an entrance, $1\text{-}rl\Delta t\text{-}sn\Delta t$.

Further mathematical development may be found in the appendix. It suffices for this discussion to state that an equation may be obtained which describes how the probability of having caves with n entrances varies with time, if we know the distribution of lengths. It may be solved numerically if we are given the lengths of all the caves and the initial distribution of entrances among the caves. It would be found that the probability of finding caves with n entrances would approach, in time, a value depending only on n, r, and s, and independent of time. This would be a mature population of caves in regard to entrance development and we would speak of the process as then being in *statistical equilibrium.*

When statistical equilibrium is attained, the probability distribution of entrances does not change with time. This does not mean that the opening and closing of entrances has ceased or slowed down, but rather that they appear and disappear at such relative rates that the probable number of caves with some number of entrances remains fixed. The actual number will vary about this value as a mean. For example, if we look at the cave population at different times, we may find that sometimes there are no caves with three entrances, and at other times there are one, two, or more caves with three entrances. The data we have on the number of caves with one, two, or more entrances is only one of a multitude of different possible arrangements. The time process occurs on an extremely large time scale for which reason we are not conscious of these fluctuations. It is possible to calculate the relative frequency with which other arrangements would occur and thereby obtain an estimate of the variation of f_n about the mean over a long time. These estimates are given in Tables 2 and 3 and are discussed in more detail in the section dealing with results and conclusions.

Since the probabilities do not change with time at equilibrium, the parameters which determine the distribution should also be independent of time. In the statistical theory, the only parameters which enter are r, the probability *per foot of cave per year* of an entrance forming; and s, the probability *per entrance per year* of an entrance closing. The only combination of these parameters which does not involve units of time, as required by the condition of statistical equilibrium, is the ratio of r to s. This ratio will be denoted by the Greek letter lambda (λ),

$$\lambda = r/s.$$

Since r and s are functions of the environment, λ is also. We may define as a *homogeneous region* a region encompassing a population of caves which have entrances developing by a process in which λ is everywhere constant. In this study, λ has been evaluated separately for caves in different length groups in the states of West Virginia and Pennsylvania. A comparison of the values obtained indicates to what extent the areas under consideration are subject to similar conditions with regard to cave entrance development.

While λ is defined in terms of the entrance genesis phenomenon, it would be expected that it is also related to the processes involved in the internal development of caves. If λ is constant similar internal cavern features might also be expected within the area.

The statistical theory may be used to correlate data. If we take data on the number of caves with one or more entrances and on their lengths, the theoretical equation may be "fitted" to obtain the value of λ which yields the closest agreement between observation and theory. In making this "fit", it is not necessary to try to make the theoretical form "pass through" all the data points. Only one constant is available for manipulation (λ), hence only one constant obtained from the observations may be used. This number from the data is the average number of entrances per cave for all caves in an area with one or more entrances and will be given the symbol alpha (α).

The quantity λ, determined from α and cave lengths, may be used to calculate the number of caves in the same area which have, at present, no entrance. In addition, the length distribution for caves with two or more entrances may be computed and compared with observations, to obtain a check on the theory. Finally, we may calculate the length distribution of unknown caves and obtain in this way the probable number of such caves longer than any given length.

Selection of Data

Because of the relative rarity of multi-entrance caves, it is necessary to study a very large population in order to obtain meaningful results from the statistical analysis. Only two sources were found to be satisfactory.

As regards the number of detailed reports of caves, the best reference was for the State of West Virginia (Davies, 1949). The second source, with fewer caves reported, was for Pennsylvania (Stone, 1953). The former describes about 400 caves of which the information on 257 was found suitable according to certain selection rules. Of the 272 caves described in Pennsylvania, 110 were used.

Even what we are to consider a cave depends on the size of the explorer, the length of enclosed passage, knowledge of geological relations, and the extent of exploration (which may make two caves into one with two entrances). For this study, the following selection rules were used.

Criteria for selecting caves

1. The cave is reported and described in either the West Virginia or Pennsylvania reference.
2. The cave occurs in limestone.
3. Sufficient data is given to ascertain the length of the cave and its number of entrances.
4. The cave's total length is greater than 50 feet for Pennsylvania and 100 feet for West Virginia.

All the caves in each state were considered to lie in homogeneous regions. While it may be argued that this is not strictly true, it was a necessary assumption, in order to have a sufficient number of caves upon which to conduct a statistical analysis. As a result, the possible variations in λ within each state are averaged in the final value obtained, according to the contribution by each county (or homogeneous region) to the total number of caves.

The study was restricted to caves occurring in limestone. Inclusion of the few caves in sandstone and other rocks would have had little effect on the results, but for the sake of being consistent with regard to geological environment they were excluded. Some reports were found of "numerous caves" in certain areas. These and similar indefinite references were ignored.

As shorter and shorter caves are considered, some question arises as to whether they are or are not caves. In reading collected descriptions, one gets the impression of decisions to omit caves which are "short" by some indefinite standard. It is reasonable that this be done, but in order to have an accurate probability distribution for lengths, some lower limit must be placed on the lengths of caves to be included. The calculated value of λ should not depend on this limit, but the calculated number of undiscovered caves will. In the case of West Virginia, the decision was made to include only those caves which are longer than 100 feet. In Pennsylvania, where there are fewer caves and the indication is that short caves have been retained in reports, the limit was placed at 50 feet. This "rule" accounts for most of the caves which were not included.

Criteria for determining length

1. Only horizontal distances are considered.
2. Total traversable length is summed, including different levels and parallel passages.

If a total length was unambiguously stated, it was used without question. In some caves, however, the final length came about by a process of interpretation, judgment, and addition, applied to each cave. The judgment used may have introduced errors, but, because even the best reported lengths are probably accurate within 10% and reported values like "300 yards" represent even greater probability of error, it was not thought of value to refine the process.

Criteria for counting entrances

1. The entrance is natural.
2. The entrance is large enough to permit entry by an adult human being.
3. The entrance exists now or is reported to have existed, but it is now closed as a result of human activity and the cave meets all other conditions for acceptability.

Caves in quarries were excluded. They are, indeed, to be classed with the zero entrance caves. Quite a few caves have been reported in quarries in Pennsylvania and relatively few in West Virginia. Possibly this may be because of greater quarrying activity in Pennsylvania. It is also not known where entrances may have existed prior to the quarrying operation. Unless reported otherwise, they were assumed not to have existed. Entrances produced by roadcuts and other construction work fall, of course, in the same category as caves in quarries.

A vague dividing line occurs for caves which were first entered by some excavating — perhaps such a trivial thing as dislodging a small stone. By the formal definition, the latter would be an *entranceless* cave. If necessary, the definition could be modified to allow some small excavating work such as that which can be done only by hand. However, since such a fact is seldom reported, some caves are probably incorrectly included. For the purposes of the present computations, it was assumed that reporting was accurate, and caves were accepted as reported.

After the data suitable for use in the computations had been selected, the calculations were performed. This involved the determination of the average number of entrances for known caves, separate numerical computations on the data of the 367 caves tabulated, and subsequent operations to obtain the desired numbers. The magnitude of this task would have made hand computation lengthy and subject to many errors. The computations were programmed for an electronic digital computer and run with the data on caves of West Virginia and Pennsylvania in groups having different lower lengths.

Results and Conclusions

In Tables 2 and 3 are shown some of the results of the calculations. Included are the observed and theoretical frequencies of caves with *n* entrances, an estimate of the standard errors of the predictions, the value of λ determined for different length groups and the comparable results obtained by use of the Poisson distribution. The values of expected frequencies are given to the nearest tenth, though they were calculated to more places.

Table 2. Results of Calculations for Caves of West Virginia
Constants and Frequencies of Caves with and without Entrances

Caves longer than: (feet)	Number (M)	Average number entrances (α)	λ	Number of entrances (n)	Observed frequency (f_n)	Expected frequency (m_n)	Poisson Distribution λ^*	Poisson Distribution Expected frequency (f_n^*)
100	257	1.13	0.00032				0.25	
				0	(10)	2405 ± 395		893 ± 146
				1	228	228.7 ± 15		226 ± 15
				2	25	23.7 ± 4.9		28.5 ± 5.3
				3	3	3.6 ± 1.9		2.4 ± 1.6
				4	1	0.7 ± 0.9		0.1 ± 0.4
				5	0	0.2 ± 0.4		0.0 ± 0.1
500	124	1.24	0.00033				0.45	
				0	-	350 ± 59		218 ± 37
				1	99	99.9 ± 10		98.2 ± 9.9
				2	21	19.3 ± 4.4		22.1 ± 4.7
				3	3	3.7 ± 1.9		3.3 ± 1.8
				4	1	0.8 ± 0.9		0.4 ± 0.6
				5	0	0.2 ± 0.4		0.0 ± 0.2
1000	64	1.33	0.00031				0.60	
				0	-	104 ± 21		78 ± 15
				1	48	47.6 ± 6.9		46.8 ± 6.8
				2	12	12.8 ± 3.6		14.0 ± 3.7
				3	3	2.8 ± 1.7		2.8 ± 1.7
				4	1	0.6 ± 0.8		0.4 ± 0.6
				5	0	0.1 ± 0.3		0.0 ± 0.2

Table 3. Results of Calculations for Caves of Pennsylvania
Constants and Frequencies of Caves with and without Entrances

Caves longer than: (feet)	Number (M)	Average number entrances (α)	λ	Number of entrances (n)	Observed frequency (f_n)	Expected frequency (m_n)	Poisson Distribution λ^*	Poisson Distribution Expected frequency (f_n^*)
50	110	1.12	0.00035				0.23	
				0	(55)	2109 ± 562		431 ± 115
				1	99	99.3 ± 10		98.0 ± 9.9
				2	9	8.8 ± 3.0		11.1 ± 3.3
				3	2	1.5 ± 1.2		0.8 ± 0.9
				4	0	0.0 ± 0.2		0.0 ± 0.2
				5	0	0.0 ± 0.0		0.0 ± 0.0
100	78	1.15	0.00034				0.31	
				0	(50)	701 ± 208		212 ± 63
				1	68	68.1 ± 8.2		66.4 ± 8.2
				2	8	8.2 ± 2.9		10.4 ± 3.2
				3	2	1.4 ± 1.2		1.1 ± 1.0
				4	1	0.3 ± 0.5		0.1 ± 0.3
				5	0	0.0 ± 0.2		0.0 ± 0.1
500	33	1.09	0.00013				0.18	
				0	-	238 ± 135		167 ± 95
				1	31	30.2 ± 5.5		30.1 ± 5.5
				2	1	2.6 ± 1.6		2.7 ± 1.6
				3	1	0.2 ± 0.4		0.2 ± 0.4
				4	0	0.0 ± 0.1		0.0 ± 0.1
				5	0	0.0 ± 0.0		0.0 ± 0.0
1000	21	1.14	0.00016				0.27	
				0	-	79 ± 44		67 ± 37
				1	19	18.3 ± 4.3		18.3 ± 4.3
				2	1	2.4 ± 1.6		2.5 ± 1.6
				3	1	0.3 ± 0.5		0.2 ± 0.5
				4	0	0.0 ± 0.1		0.0 ± 0.1
				5	0	0.0 ± 0.0		0.0 ± 0.0

Homogeneity of West Virginia and Pennsylvania

The data for caves of the two states were calculated separately for a number of lower limits on the length. This, in effect, separated the caves into a number of groups, representing different areas within each state. As the lower limit was raised, the number of included caves decreased.

If the assumption of homogeneity made in the analysis is not justified, it would show up in a variation of λ between the groups. It is an important result that such has not been found to be the case. In fact, the constancy of the parameter λ *between* the states as well as *within* the states is quite significant. We may conclude that the caves in these states are located in essentially the same geologic and climatic region; a result agreeing with simple observation.

The deviation of λ in the two upper length groups of Pennsylvania may be due to either inhomogeneity or to insufficient data. The numbers of caves represented in these groups have decreased to 31 and 21 respectively and results obtained from such limited data is subject to error.

Now λl is the ratio, for a cave of length l, of the probability of gaining an entrance to the probability of losing an entrance. With the value of λ given in Tables 2 and 3, the product λl would have the value $\lambda l = 1$ for a cave approximately 3000 feet long. Since most caves are shorter than this, it is a general result that caves are more likely to lose their entrances than to gain entrances. Of course, the calculated value of λ is a consequence of this fact. The destruction of a cave entrance might be looked upon as the "natural" event, in that almost any collapse, slip, silting, etc., tend to fill holes which might otherwise be traversable, and it is the rarer case when these actions not only disclose an aperture, but leave its entire length traversable to a human being.

Distribution of Cave Entrances

The agreement in Tables 2 and 3 between observed and calculated frequencies of caves with different numbers of entrances is excellent. One cannot say, though, that it is *appreciably* less excellent for the ordinary Poisson distribution. In both cases λ was calculated so as to have the best agreement, but the only value that was needed from the data on entrances was the average number of entrances for caves with one or more entrances. However, based solely on the Poisson distribution, an extrapolation to find the number of caves with no entrances is unconvincing. With the statistical theory to indicate a mechanism accounting for the existence of such caves, the extrapolation may be performed with some confidence. This fact and the agreement between theory and fact support the hypotheses in the theory.

Standard errors are given in Tables 2 and 3 for the expected frequencies. If we had an *a priori* value of λ for a population of caves, we would calculate the expected frequency distributions shown in the tables. If we inspected the population, we would find that there would be different frequencies than we had calculated. This has already been explained in terms of the fluctuations about the "probable" frequencies which would occur with time in a population in statistical equilibrium. The observed differences between the expected and observed frequencies are well within the standard errors so we are given by this test no reason to doubt the proposed mechanism.

Standard errors are given also for the values of $m_{\bar{0}}$. If the theory is reasonably correct, the probability that m_0 differs from its predicted value in either direction by more than the given standard error is equal to 0.32. That it would differ by more than twice as much has a probability of 0.05.

The frequencies of "observed" caves with no entrances, given in Tables 2 and 3, refer to caves in quarries and roadcuts. It is interesting that of the eleven commercial caves reported in Pennsylvania, four were found during quarrying operations and one was found while grading for a highway. There seems little doubt that there are many more extensive caves which would be uncovered if such operations were carried on in other locations.

The ratio of unknown caves to known caves depends upon the length group considered. It is apparent from the theory that most very long caves would be likely to have an entrance. In the present cases, there are predicted to be about 20 times as many caves without entrances as with for caves over 50 feet long. For caves over 100 feet long the ratio is about 10, and for those over 1000 feet about 2. If we consider the 100 foot cave as the reasonable lower limit of our general

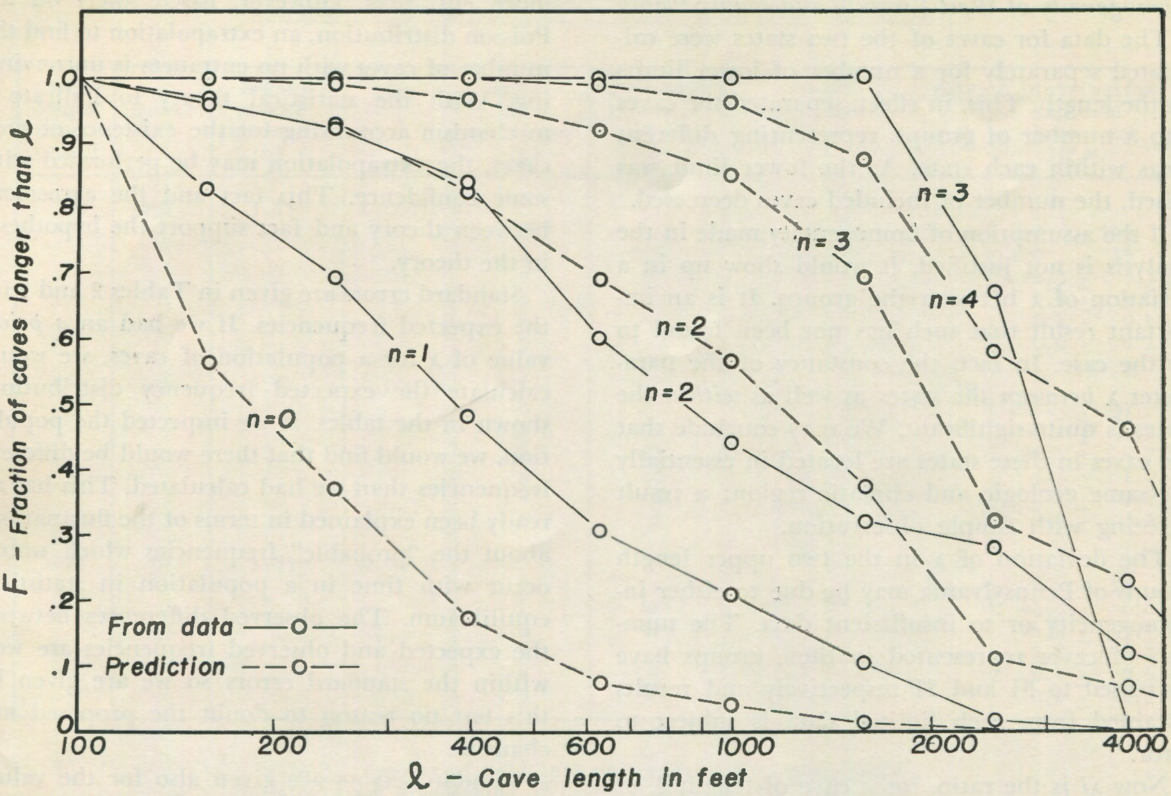


Figure 1
Distribution functions of length for caves of West Virginia over 100 feet long, according to number of entrances. Comparisons of observed and predicted distributions. The lines are shown only to connect related points.

concern about the existence or non-existence of sealed caves, the calculated ratio of 10 unknown caves to every known cave is comparable to the estimates which have been made by those familiar with caves and cave regions (Folsom, 1956).

Distribution of Cave Lengths

A mathematical result of the statistical theory is that it is possible to calculate, starting with the observed fraction of caves with one entrance whose lengths are greater than any given value, the same fraction for caves with zero, two or more entrances. This is a very useful result. Not only can we estimate the number of caves without an entrance, but we can also estimate their lengths. Figures 1 and 2 present the results of these calculations. In Figures 1 and 2 the fraction of caves longer than 100 feet, with lengths greater than some given length, is plotted versus cave length. This relation is called a *distribution function of lengths.* The logarithmic abscissa is used to contract the extent of the graph in the region of great length.

Because of the method of computation, the curves are not smooth. In order to simplify the calculations, only eleven values of length were used to find these distribution functions. Little would have been gained by a finer division.

The observed distribution functions for caves with one entrance in West Virginia and Pennsylvania are quite similar. The median length of caves over 100 feet long with one entrance is about 380 feet, and the average length about 680 feet. Using the single entrance distribution functions for caves of both states, the distribution functions were computed for caves with two entrances. In Figure 1 is shown the result for the caves of West Virginia. Quite good agreement is found between the observed and predicted length distributions for caves with two entrances. This result gives additional confirmation to the hypotheses in the statistical theory, since the prediction is based only on the data for caves with one entrance and is independent of λ, and hence of a. The length predictions, furthermore, did not require that a "fit" be made to data.

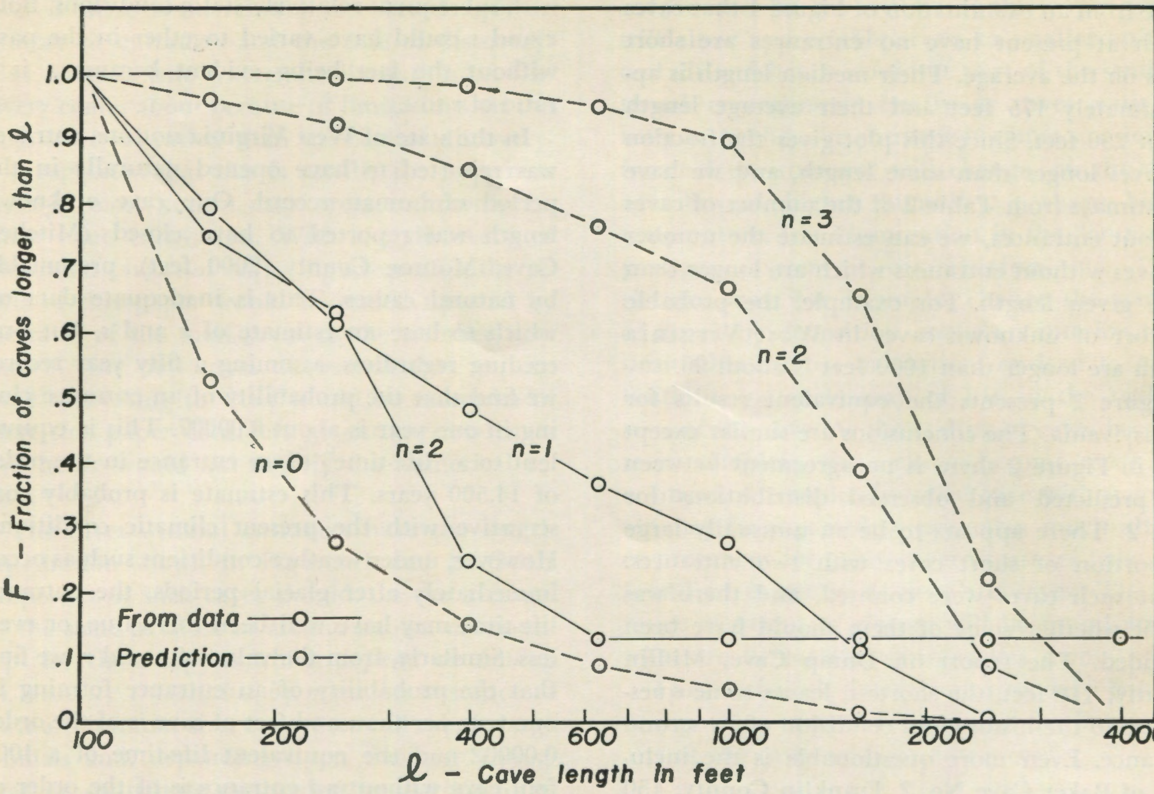


Figure 2
Distribution functions of lengths for caves of Pennsylvania over 100 feet long, according to number of entrances. Comparisons of observed and predicted distributions. The lines are shown only to connect related points.

The agreement between theory and observation for caves with three entrances in West Virginia is poorer. Only three caves in West Virginia are reported to have three natural entrances (Steeles Cave, Monroe County, 1700 feet; Mystic Cave, Pendleton County, 3700 feet; and Snedegars Cave, Pocahontas County, 3100 feet). It would be extremely fortuitous for their lengths to be just right to be correlated by the theoretical predictions. As it is there *is* agreement in the fact that the theory predicts that caves with three entrances should be long caves on the average, which is what is observed. The predicted average length of 2500 feet agrees well with the observed 2800 foot average length.

The predicted distribution function for caves with four entrances is included in Figure 1. Since there is only one such cave reported in West Virginia (Greenville Saltpeter Cave, Monroe County: over 13,000 feet), it is not possible to make a valid comparison except to note that the one four-entrance cave is also an exceptionally long cave.

The major source of error in extrapolating to n larger than one is the emphasis on the longer caves in forming these distribution functions. As n increases, the calculated function depends upon fewer and fewer caves and acquires the ills associated with working with limited data.

In West Virginia the longest cave with one entrance was reported to be Patton Cave, Monroe County, 5500 feet. Since the distribution function from which numerical calculations were made thus became zero at 5500 feet, so did all derived distribution functions. It would have been possible to fit some best equation to the observed distribution before performing the mathematical operations, but it was thought that this would distort the significance of the results. Instead it is concluded that the predictions at great length are probably in error.

The prediction of the length distribution function for caves with $n = 0$, depending most strongly on a large number of shorter caves having lengths known with greater accuracy, may be expected to be more accurate. We can conclude from an examination of Figure 1 that caves which at present have no entrances are short caves on the average. Their median length is approximately 175 feet and their average length about 290 feet. Since this plot gives the fraction of caves longer than some length, and we have an estimate from Table 2 of the number of caves without entrances, we can estimate the number of caves without entrances which are longer than some given length. For example, the probable number of unknown caves in West Virginia which are longer than 1000 feet is about 96.

Figure 2 presents the equivalent results for Pennsylvania. The conclusions are similar except that in Figure 2 there is no agreement between the predicted and observed distributions for $n = 2$. There appears to be an unusually large proportion of short caves with two entrances. Eight such caves were counted, and there was doubt whether some of them should have been included. The report on Dump Cave, Mifflin County; 110 feet, the shortest, leaves some question as to the history and condition of its second entrance. Even more questionable is the inclusion of Baker Cave No. 2, Franklin County; 150 feet. Excluding some of the doubtful cases from the two-entrance tabulation would improve the agreement between observation and prediction, but to do so would contribute no new knowledge — therefore the results are presented as originally obtained.

The Pennsylvania caves with three entrances are too few in number — Auchenbaugh Cave, Franklin County; 300 feet; and Bear Cave, Westmoreland County; 4000 feet — to allow comparison except to note that the average length of these caves is 2100 feet and the predicted average length is 2200 feet. This is fortuitous but agreeable.

The probable number of unknown caves over 1000 feet long in Pennsylvania is about 35.

Rate of Entrance Development

No information is available from this analysis to suggest the magnitude of the parameters r or s. These parameters depend on the time process and can be obtained only from records of the rate of entrance formation or closure. There may be some reason to believe that the present rate of these processes is different from that in the near past. There is the possibility of a very rapid rate having established statistical equilibrium with subsequent relatively static conditions. Both r and s could have varied together in the past, without the fact being evident because λ is a ratio of r to s.

In the state of West Virginia not one entrance was reported to have opened naturally in the period of human record. One cave of known length was reported to have closed (Mitchell Cave, Monroe County, 2000 feet), presumably by natural causes. This is inadequate data on which to base an estimate of r and s, but proceeding regardless, assuming a fifty year record, we find that the probability of an entrance closing in one year is about 0.00007. This is equivalent to a "life-time" of an entrance in the order of 14,500 years. This estimate is probably conservative with the present climatic conditions. However, under weather conditions such as occur immediately after glacial periods, the entrance life-time may have well been this value, or even less. Similarly, from the value of λ and r, we find that the probability of an entrance forming in one year per thousand feet of cave is of the order 0.00002 and the equivalent life-time of a 1000 foot cave without an entrance is of the order of 45,000 years. A hundred foot cave would have a life-time ten times as great. As implied at the beginning of this set of estimates, caution is required when stating values for r and s, based on the single available datum. However, the values estimated are not unreasonable and they suggest that entrance development is relatively more rapid than the development of the caves themselves; a hypothesis which was basic to the statistical theory.

Properties of Caves Without Entrances

It has been suggested here that undiscovered caves are, in general, caves without entrances. This would only be exactly true in an area which has been thoroughly explored. Although it is probable that the reporting of what we consider as caves with entrances is incomplete, it is not believed that further scouting and discovery will find anywhere near as many caves as, for example, the 2400 in West Virginia which are predicted to have no entrances. Furthermore, the discovery of new caves *with* entrances would only change the relative results. If further caves are found *without excavating* they should have much the same distribution of number of entrances, lengths, etc., as the presently known caves if there is no relation between length or number of entrances and the ease of discovery. This latter is true where the limitation on discovery comes about because of limitations on the areas searched rather than the ease of discovery. It is suggested that this is usually the case; new caves in most known cave areas commonly require some excavation. With the discovery of additional caves *not requiring excavation* the results of this paper would be scaled upward by the ratio of the total caves to the number now known. Any new caves discovered that require some excavating to enter would be examples of what this paper considers as *entranceless caves* and hence would not modify the numerical results.*

The caves without entrances have the length distribution shown in Figures 1 and 2. Other properties of such caves should, on the average, be the same as those of all the known caves, except for those aspects which *depend on having an entrance traversable by man.* An entrance of such a minimum size, or larger, will admit large animals and, depending upon the cave configuration, contribute some effect to the humidity, temperature, etc., of the cave interior. These in turn affect the environment for cave fauna and flora. Many of the caves which are considered *entranceless* by the criteria of this paper would still allow appreciable access to smaller animals and air and hence would be part of the same internal environment family as caves with entrances. As the cave entrance becomes smaller the internal environment will change, on the average, toward higher humidity, perhaps higher temperature, less illumination in the "entrance" passages, poorer air circulation, etc. These changes may, for example, change the pattern of flowstone deposition, make an interior room unsuitable for bat habitation, or lead to modifications (or exclusion) of life in the twilight zone of the cave. As the sealing of caves becomes more complete, these effects become more pronounced. A completely sealed cave with stagnant air may be expected to present a much altered environment for many cavern features from that found in presently accessible caves. The full range of extent of closure will be found among what are here called entranceless caves.

*The addenda to Davies (1949) in Bulletin 19 of the National Speleological Society (December 1957) reports 119 new caves in West Virginia. 21 meet the selection rules of this paper. The length distribution of the 20 of these caves with one entrance agrees very closely with the previous data up to 630 feet. For greater length the new caves exhibit a somewhat greater average length. This trend agrees with the correction required for the previous results to account for the additional length reported for some previously described caves, and especially for the introduction of a new very long cave (Culverson Creek Cave, 10,800 feet, one entrance) The length distribution functions should now become zero at 10,800 feet rather than 5,500 feet.

From a population of 21 new caves about 2 ± 1.4 should have 2 entrances. One is reported, the Carpenter's Pit-Swago Pit system, with a length of 8,850 feet.

A recent addition to Pennsylvania data is by Bernard L. Smeltzer and Ralph W. Stone in the Bulletin of the Pennsylvania Department of Internal Affairs, vol. 24, no. 5, April 1956. Seventeen new caves are described, nine being in quarries and cuts. Those over 100 feet long with natural entrances have lengths in rough agreement with Figure 2, $n = 1$ (112′, 600′, 880′ and 1620′). None have more than one entrance.

It is concluded that the newly reported caves in both states probably come from the same populations of "open" caves as the previously reported sets, and hence do not themselves represent any of the entranceless caves (except of course for the new quarry caves). Therefore the predictions of the number of zero entrance caves in each state should be scaled upward proportionately. These changes, + 215 and + 81 in West Virginia and Pennsylvania respectively for caves over 100 feet long, are less than the standard errors of the original estimates.

The statistical theory unfortunately contributes nothing toward determining the location of any of the caves without entrances.

Conclusion

A more complex model would be justified only if some important phenomena are found to be omitted from the present analysis. Just as we might have said that the Poisson distribution was adequate if we did not realize that length was an important variable and that λ should be constant for all caves in an area, we may say that the present model is adequate because we do not yet perceive the relations which still require explanation. The completeness of the theory has been tested by its ability to correlate the frequencies of caves with different numbers of entrances, and by its ability to predict with reasonable accuracy the length distribution of cave with more than one entrance using only the lengths of caves with one entrance. The ultimate test is to *count* the number of caves without entrances and determine their lengths, but this procedure is unavailable to us.

References

Folsom, Franklin, (1956) Exploring American caves: New York, Crown Publishers, pp 3, 18, 187.

Davies, William E., (1949) Caverns of West Virginia: West Virginia Geological Survey, Vol. XIX.

Stone, Ralph W., (1953) Caves of Pennsylvania: National Speleological Society, Bulletin 15, December.

Cramer, Harold (1955) The elements of probability theory: New York, John Wiley.

APPENDIX

The stochastic process

Figure 3 is a schematic representation of the stochastic model of cave entrance genesis. The joint probability, $p(\ell,n,t+\Delta t)$, is the sum of the three mutually exclusive joint probabilities, $p(\ell,n-1,t,A)$, $p(\ell,n,t,C)$, and $p(\ell,n+1,t,B)$. In addition

$$(1) \qquad p(A/\ell,n-1,t) = r\ell\Delta t \ ,$$

$$(2) \qquad p(B/\ell,n+1,t) = s(n+1)\Delta t \ ,$$

and

$$(3) \qquad p(C/\ell,n,t) = 1 - r\ell\Delta t - sn\Delta t$$

from the section Statistical Theory. Only terms first order in Δt have been retained.

The stochastic process may be written

$$(4) \qquad p(\ell,n,t+\Delta t) = p(\ell,n-1,t,A) + p(\ell,n,t,C) + p(\ell,n+1,t,B)$$

or, using (1), (2) and (3),

$$(5) \qquad p(\ell,n,t+\Delta t) = p(\ell,n-1,t)(r\ell\Delta t) + p(\ell,n,t)(1-r\ell\Delta t-sn\Delta t) + p(\ell,n+1,t)(s(n+1)\Delta t)$$

which, after rearranging and dividing through by $s\Delta t$, becomes

$$(6) \qquad \frac{p(\ell,n,t+\Delta t) - p(\ell,n,t)}{s\Delta t} = (n+1)p(\ell,n+1,t) - (n+\lambda\ell)p(\ell,n,t) + \lambda\ell p(\ell,n-1,t) \ ,$$

where $\lambda = r/s$.

In the limit $\Delta t \rightarrow 0$ the left hand term in (6) becomes the partial derivative of $p(\ell,n,t)$ with respect to t. We know from physical reasoning that the solution to (6) in the differential-difference form reaches an asymptotic value for large t which is independent of its initial value. The left hand term of (6) becomes zero when this asymptotic condition of statistical equilibrium is reached. Since we are interested here only in the case of statistical equilibrium, setting the right hand term of (6) equal to zero and rearranging, we obtain

$$(7) \qquad \Big[(n+1)p(\ell,n+1) - \lambda\ell p(\ell,n)\Big] - \Big[np(\ell,n) - \lambda\ell p(\ell,n-1)\Big] = 0$$

which is satisfied by the condition

$$(8) \qquad (n+1)p(\ell,n+1) - \lambda\ell p(\ell,n) = c_1 g(\ell) \ ,$$

where g is an undefined function of ℓ. The sum

$$(9) \qquad \sum_{n=0}^{\infty} p(n) = 1$$

by definition so p(n) must approach zero at least as fast as $1/n^2$ as $n \rightarrow \infty$. Hence the left hand terms of (8) must approach zero as $n \rightarrow \infty$, hence $c_1 = 0$. Equation (8) becomes

$$(10) \qquad (n+1)p(\ell,n+1) - \lambda\ell p(\ell,n) = 0$$

which has the solution

$$(11) \qquad p(\ell,n) = \frac{(\lambda\ell)^n}{n!} p(\ell,0)$$

Probability distribution of n

Equation (11) states that the joint probability $p(\ell,n)$ is a Poisson probability distribution in the variable $\lambda\ell$. The probability p(n) is one marginal distribution of (11) and may be obtained by integrating (11) over all ℓ.

$$(12) \qquad p(n) = \int_0^{\infty} \frac{(\lambda\ell)^n}{n!} p(\ell,0)d\ell$$

Now, $p(\ell,0)$ is not available since we can directly observe nothing about the case n = 0. However, from the available conditional probability $p(\ell/1)$, $p(\ell,0)$ may be obtained and hence (12) evaluated. From (11),

$$(13) \qquad p(\ell,0) = \frac{p(\ell,1)}{\lambda\ell}$$

and also

$$(14) \qquad p(\ell,1) = p(\ell/1)p(1)$$

so therefore, together with (12), we obtain the formula

$$(15) \qquad p(n) = p(1)\int_0^{\infty} \frac{(\lambda\ell)^{n-1}}{n!} p(\ell/1)d\ell$$

The condition (9) suffices for the evaluation of p(1) from (15). The complete expression for p(n) is then

$$(16) \qquad p(n) = \frac{\int_0^{\infty} \frac{(\lambda\ell)^{n-1}}{n!} p(\ell/1)d\ell}{\int_0^{\infty} \frac{e^{\lambda\ell}}{\lambda\ell} p(\ell/1)d\ell}$$

The value of λ may be determined from data by obtaining the best fit of (16) to the empirical probability distribution. However, since data are only available for $n \neq 0$, a truncated probability distribution must be formed from (16) using the condition

$$(17) \qquad \sum_{n=1}^{\infty} p'(n) = 1$$

From (15) and (17) we obtain the truncated probability distribution, analogous to (16),

$$(18) \qquad p'(n) = \frac{\int_0^{\infty} \frac{(\lambda\ell)^{n-1}}{n!} p(\ell/1)d\ell}{\int_0^{\infty} \frac{e^{\lambda\ell} - 1}{\lambda\ell} p(\ell/1)d\ell}$$

This is the relation which may be used to find λ from data by "fitting" to the observed frequencies f_n.

The technique used here to find the best estimate of λ for an observed cave population is known as the maximum likelihood method (4). In this method the derivative with respect to λ is taken of the logarithm of the likelihood function, and equated to zero, viz.:

$$(19) \qquad \frac{d}{d\lambda} \ln \prod_{n=1}^{\infty} p'(n)^{f_n} = 0$$

This derivation will not be continued here but the result is that the best estimate of λ is obtained by calculating from (18) the average number of entrances for caves with one or more entrances and setting this equal to the observed value. From (18) and the definition of an average value we find

$$(20) \qquad \bar{n} = \sum_{n=1}^{\infty} np'(n) = \frac{\int_0^{\infty} e^{\lambda\ell} p(\ell/1)d\ell}{\int_0^{\infty} \frac{e^{\lambda\ell} - 1}{\lambda\ell} p(\ell/1)d\ell} \ ,$$

while the value from data is

$$(21) \qquad \alpha = \frac{1}{M} \sum_i n_i \quad \text{(i over all caves in M)} \ ,$$

where M is the total number of known caves.

Equating (20) and (21) we obtain the integral equation which determines λ from the observed value of α and the probability distribution of ℓ for n = 1.

$$(22) \qquad \alpha = \frac{\int_0^{\infty} e^{\lambda\ell} p(\ell/1)d\ell}{\int_0^{\infty} \frac{e^{\lambda\ell} - 1}{\lambda\ell} p(\ell/1)d\ell}$$

The method used to solve this equation will be described in the subsequent section on Numerical Procedure.

When λ is obtained, equation (18) yields $p'(n)$ and the predicted values of the number of caves with n entrances, m_n, may be found from

$$m_n = Mp'(n) \tag{23}$$

Frequency distribution of lengths

Inserting $p(\ell,0)$ from (13) into (11), and writing the joint probabilities as the product of the conditional and marginal probability distributions, we obtain

$$p(\ell/n)p(n) = \frac{(\lambda\ell)^{n-1}}{n!} p(\ell/1)p(1) \tag{24}$$

Recognizing that equation (15) is equivalent to

$$p(n) = p(1) \frac{(\lambda)^{n-1}}{n!} \overline{\ell_1^{n-1}} \tag{25}$$

the bar indicating the average value over all caves with one entrance of ℓ^{n-1} we may divide (24) by (25) to obtain

$$p(\ell/n) = \frac{\ell_1^{n-1}}{\overline{\ell_1^{n-1}}} p(\ell/1) \tag{26}$$

or, from the definition of a distribution function,

$$dF(\ell/n) = \frac{\ell_1^{n-1}}{\overline{\ell_1^{n-1}}} dF(\ell/1) \tag{27}$$

$F(\ell/n)$ is the frequency distribution function of lengths for caves with n entrances.

The average length of caves with n entrances may be obtained from (26) in the form

$$\overline{\ell_n} = \frac{\overline{\ell_1^{n}}}{\overline{\ell_1^{n-1}}} \tag{28}$$

The averages are again over all caves with one entrance in the term on the right. Similar expressions arise for averages of higher powers of length.

Numerical procedure

Only basic aspects of the computational procedure will be described below. Details of the computer program and various arithmetical manipulations to obtain results in the desired forms are not presented.

The data used in this study consisted of length and entrance information on individual caves.

(a) Evaluation of α.

$$\alpha = \frac{1}{M} \sum_n nf_n = \frac{1}{M} \sum_i n_i \quad \text{(i over all caves in M)} \tag{29}$$

(b) Evaluation of λ.

Equation (22) may be written, using the identity $p(\ell/1)d\ell = dF(\ell/1)$,

$$\alpha = \frac{\int_0^\infty e^{\lambda\ell}\, dF(\ell/1)}{\int_0^\infty \frac{e^{\lambda\ell}-1}{\lambda\ell}\, dF(\ell/1)} \tag{30}$$

Now, $F(\ell/1)$ is not available as a continuous function, but rather as a series of steps as a function of ℓ. If plotted, each step would correspond to a single cave and would be of size $1/f_1$. At some lengths possessed by more than one cave, a number of such steps would add up to a larger step. Since the numerator and denominator of (30) represent the areas under curves of the arguments versus $F(\ell/1)$, equation (30) may be approximated, using the actual data, by the expression

$$\frac{\frac{1}{f_1}\sum_i e^{\lambda\ell_{i,1}}}{\frac{1}{f_1}\sum_i \frac{e^{\lambda\ell_{i,1}}-1}{\lambda\ell_{i,1}}} \quad \text{(i over all caves in } f_1\text{).} \tag{31}$$

Equation (31) becomes, after expanding the exponentials in their Taylor series (noting that the summations over each term, divided by f_1, are the average values),

$$\frac{1 + \lambda\overline{\ell_1} + \frac{1}{2!}\lambda^2\overline{\ell_1^2} + \frac{\lambda^3}{3!}\overline{\ell_1^3} + \ldots + \frac{\lambda^\nu}{\nu!}\overline{\ell_1^\nu} + \ldots}{1 + \frac{\lambda}{2!}\overline{\ell_1} + \frac{\lambda^2}{3!}\overline{\ell_1^2} + \frac{\lambda^3}{4!}\overline{\ell_1^3} + \ldots + \frac{\lambda^\nu}{(\nu+1)!}\overline{\ell_1^\nu} + \ldots} \tag{32}$$

This may be rewritten as the polynomial expression in λ

$$0 = (1-\alpha) + (1-\tfrac{\alpha}{2})\lambda\overline{\ell_1} + (1-\tfrac{\alpha}{3})\frac{\overline{\ell_1^2}}{2}\lambda^2 + (1-\tfrac{\alpha}{4})\frac{\overline{\ell_1^3}}{6}\lambda^3 + \ldots + (1-\frac{\alpha}{\nu+1})\frac{\overline{\ell^\nu}\lambda^\nu}{\nu!} + \ldots \tag{33}$$

In an actual numerical computation a choice must be made at this point as to how many terms of the infinite series will be used. This depends upon the rapidity of convergence of the series. In the present computation there is another consideration. The higher powers of ℓ depend essentially on the data for only one cave and are strongly influenced by small errors in the length. If the series has not converged before this happens, the resulting value of λ may be strongly in error. Therefore the series was terminated at the term which represented the data of essentially only one cave. In the machine computation, equation (33) was solved by means of Newton's method, keeping all terms up to the sixth power of λ. It was subsequently found that the last term became negligibly small with respect to the others.

Newton's method is an iterative procedure which converges very rapidly if an initial close value of λ is used. Since we hope that the calculated $p'(n)$ will fit the observed distribution, a good starting value should be that which makes the calculated curve fit the data exactly at n = 1 and n = 2. The ratio

$$\frac{p'(1)}{p'(2)} = \frac{1}{\frac{1}{2}\lambda\overline{\ell_1}} \tag{34}$$

therefore

$$\lambda = \frac{2p'(2)}{\overline{\ell_1}p'(1)} \tag{35}$$

which may be approximated by using the ratio of the observed frequencies f_1 and f_2.

$$\lambda \cong \frac{2f_2}{\overline{\ell_1}\, f_1} \tag{36}$$

Using this initial value, Newton's method converged in about four iterations to 0.01%.

Using the notation of equation (31), equation (18) may be put into the form

$$p'(n) = \frac{\frac{1}{f_1}\sum_i \frac{(\lambda\ell_{i,1})^{n-1}}{n!}}{\frac{1}{f_1}\sum_i \frac{e^{\lambda\ell_{i,1}}-1}{\lambda\ell_{i,1}}}, \tag{37}$$

or

$$p'(n) = \frac{\frac{1}{n!}\lambda^{n-1}\overline{\ell_1^{n-1}}}{1 + \frac{\lambda}{2!}\overline{\ell_1} + \frac{\lambda^2}{3!}\overline{\ell_1^2} + \ldots + \frac{\lambda^\nu}{\nu!}\overline{\ell^\nu} + \ldots}, \tag{38}$$

from which $p'(n)$ was obtained numerically. With the formula (23) m_n was computed.

The distribution function for lengths was obtained from

(39) $$F(\ell/n) = \frac{1}{f_1 \ell_1^{n-1}} \sum_{i(\text{longest cave})}^{\text{cave of length } \ell} \ell_{i,1}^{n-1}$$

the summation being carried out with the caves arranged in order of decreasing length.

Poisson distribution

The Poisson distribution, mentioned in the INTRODUCTION and used for comparison purposes in RESULTS, is derived in detail in many books (4). The expression equivalent to (16) for the Poisson distribution is

(40) $$p^*(n) = \frac{e^{-\lambda^*} \lambda^{*n}}{n!}$$

and, equivalent to the truncated distribution of (18),

(41) $$p'^*(n) = \frac{\lambda^{*n}}{n!(e^{\lambda^*} - 1)}$$

Standard errors of predictions

The frequencies f_n would be found to be distributed according to the Poisson distribution

(42) $$p(f/n) = \frac{e^{-Mp'(n)} (Mp'(n))^{f_n}}{f_n!}$$

if an original population of M known caves and the associated ones with zero entrances could be observed over a very long time. The mean f_n is the expected frequency $Mp'(n)$. The standard deviation is

(43) $$\sigma_n = \sqrt{Mp'(n)} \cdot n \neq 0.$$

The standard error of the predicted values of m_o may be shown to be given, to a first approximation, by

(44) $$\Delta m_o \cong \frac{\Delta\alpha}{\alpha - 1} m_o ,$$

in which $\Delta\alpha$ is the standard error of the sample estimate of α, and is equal to

(45) $$\Delta\alpha = \frac{\sigma}{M^{1/2}}$$

where σ, the standard deviation of $p'(n)$, may be approximated by using the Poisson distribution representation for $p'(n)$ and the sample value of α. For this case it is found that

(46) $$\sigma = \sqrt{(\alpha(1 + \lambda^* - \alpha))} ,$$

where λ^* is the transcendental function of α,

(47) $$\frac{\lambda^*}{1 - e^{-\lambda^*}} = \alpha$$

SYMBOLS

A	The event of a cave of length ℓ and n-1 entrances at time t gaining an entrance in the time interval Δt
B	The event of a cave of length ℓ and n+1 entrances at time t losing an entrance in the time interval Δt
C	The event of a cave of length ℓ and n entrances at time t neither losing or gaining an entrance in the time interval Δt
f	Observed frequency (number) of caves
F	Distribution function of cave lengths
ℓ	Cave length, feet
m	Predicted frequency (number) of caves
M	Total number of observed caves with one or more entrances
n	Number of entrances
p	Probability function
r	Probability per foot per year of a cave gaining an entrance
s	Probability per entrance per year of a cave losing an entrance
t	Time
α	Average number of entrances for caves with one or more entrances
Δ	Increment of ....
λ	Ratio of probability of a cave gaining an entrance per foot to probability of a cave losing an entrance per entrance; r/s

Subscripts

i	Summing index for individual caves
n	Number of entrances

Others

*	Poisson-distribution function
$\overline{(\ )}$	Average value
( )'	Truncated probability distributions

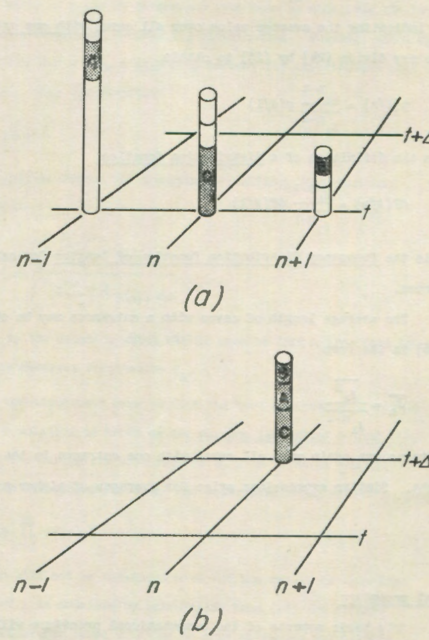


Figure 3. Schematic representation of the stochastic model of cave entrance genesis. The heights of the columns represent the number of caves with each number of entrances or, equivalently, the probabilities of caves having each number of entrances (p(ℓ,n,t), etc...). (a) The situation at time t. The shaded portions A, B, and C represent respectively the fraction of caves of length ℓ and n-1 entrances which will gain an entrance in the time interval Δt; the fraction of caves of length ℓ and n+1 entrances which will lose an entrance in the time interval Δt; and the fraction of caves of length ℓ and n entrances which will neither gain nor lose an entrance in the time interval Δt. The unshaded portions represent the fractions of the number of caves with each number of entrances which will not appear with n entrances at time t+Δt, i.e. caves with n+1 entrances gaining an entrance, etc... (b) The situation at time t+Δt. The number (or probability) of caves with n entrances at time t+Δt is composed of the contributions from the states of n-1, n, and n+1 entrances at time t. Of course there also exist values at n-1 and n+1 but these have been omitted from the drawing.

A similar development may be used to find the probability of there being exactly f_n caves at time t with n entrances. The result of such an analysis is given in Equation (42).

Brooding Slimy Salamanders, Plethodon glutinosus glutinosus (Green)

By PATRICK H. WELLS and WILLIS GORDON

Although the slimy salamander is widely distributed in the eastern United States little is known concerning its reproduction. The recent finds by Patrick Wells and Willis Gordon in Moonshine Cave, Missouri of brooding slimy salamanders is the second observation of that nature. Patrick H. Wells, an Assistant Professor of Biology at Occidental College, Los Angeles, California and Willis Gordon, a zoology major at the University of Missouri are well known to many speleologists. At the time the observations on the slimy salamanders were made Dr. Wells was an Assistant Professor of Zoology at the University of Missouri where he also was faculty sponsor to the student cave club of the University. Willis Gordon was an active member of the cave club.

The slimy salamander, *Plethodon glutinosus glutinosus,* is widely distributed in the eastern half of the United States. It may be found under logs or stones, or under moist humus in wooded areas. On the Ozark Plateau this species often inhabits caves. A general description and discussion of natural history of the slimy salamander is included in Bishop's (1943) *Handbook of Salamanders* and its habit of entering caves is mentioned in Mittleman's (1950) account of Ozark cave salamanders. The following report concerns a significant find of brooding female slimy salamanders in a cave.

In spite of its abundance, little information is available about the eggs, hatchling young, or brooding habits of the slimy salamander. In 1929 two clutches of *P. g. glutinosus* eggs were found in Arkansas caves by Noble and Marshall (1929). One was attended by a female. These two clutches contained 18 and 10 eggs respectively. They were found in August and September, at which time the encapsulated larvae were in an early stage of development. A third group of 15 eggs, attended by a female, was reported by Fowler (1940) from West Virginia. They were found beneath a stump in June, 1938. The eggs contained developing embryos which were not ready to hatch.

Although no other reports of *P. g. glutinosus* broods appear in the literature, Highton (1956) recently has made an intensive study of the Florida form, *P. g. grobmani.* He reports finding five clutches of eggs. These were discovered under logs during the months of September and October. There were 7 to 11 eggs per clutch. The eggs were not ready to hatch when discovered but some were brought into the laboratory where they hatched in late October. From these specimens Highton was able to measure and describe the hatchling young. *P. g. grobmani* is smaller than *P. g. glutinosus* and differs from it in other respects.

Our observation of brooding *P. g. glutinosus* took place in Moonshine Cave (the picturesque name has historical significance), about 4 miles south of Leasburg, Missouri*. This cave has a narrow opening, but progressively enlarges and is of considerable length. Approximately 40 feet from the cave entrance and 4 feet up from the cave floor is a horizontal crevice. This is 4 inches wide at its outer edge and 8 to 12 inches deep. The cave is dry at this level but humidity is high and temperature moderate. Two brooding female slimy salamanders were observed in this crevice on October 27, 1956. The clutches were about 1 foot apart. Each female lay partly coiled about her clutch of eggs. There were 8 and 11 eggs in the egg masses. One egg mass was removed, with intent to take it to the laboratory for study. Large encapsulated larvae were visible within a common gelatinous envelope (fig. 1).

On the morning of October 28, before measurements had been taken on the encapsulated larvae, it was found that all of this group of 11 eggs had hatched. The larvae were examined

* Moonshine Cave is located on the Onondaga Cave property. We wish to thank the owner, Mr. Lyman Riley, for encouraging and assisting speleological research in the caves under his control.

Figure 1
PLETHODON GLUTINOSUS GLUTINOSUS from Moonshine Cave. Top to bottom: Newly hatched larvae and encapsulated larvae of brood No. 2, adult female attendant to brood No. 2, 1-day-old larvae of brood No. 1.

but not measured at that time. The cave was reentered and the second clutch of eggs with attendant female was taken for study. The first female, whose eggs had been removed, had not moved from the nesting site. She was not collected. The two broods and one adult female were transported to the laboratory. On the morning of October 29, when measurements were taken, two of the second clutch had hatched.

Hatchlings of *P. g. glutinosus* are provided with large amounts of yolk. The yolk mass distends the abdomen to the extent that locomotion is difficult in newly hatched larvae. By the end of their first day, however, the yolk mass is somewhat reduced and the larvae are quite active. Pigmentation of the dorsal surface is uniformly black, except that small pigment-free spots are visible upon close examination. The sides are pigmented, except in the costal grooves, and the ventral surface is free of pigment. The rudimentary gills are 1 mm. to 2 mm. in length. Measurements of the newly hatched larvae, 1-day-old larvae, and the adult female are given in Table I. The six unhatched eggs (encapsulated larvae) measured 6 mm. to 7 mm. in diameter.

TABLE I

Measurements (in mm.) of the 1-day-old larvae (brood No. 1), newly hatched larvae and attendant adult female (brood No. 2) slimy salamanders taken from Moonshine Cave.

	Snout-vent length	Total length
Brood No. 1	19	32
1-day-old	18	31
11 larvae	18	30
	18	31
	17	31
	18	31
	18	31
	18	32
	18	32
	18	31
	17	31
Brood No. 2	18	30
Newly hatched	17	30
2 larvae		
Attendant female	68	149

The observation of brooding *P. g. glutinosus* in Moonshine Cave supports the hypothesis that females of this species seek deep rock crevices, caves and similar sites for egg laying and brooding activities. The late October hatching date is in general agreement with the observations of Noble and Marshall (1929) and of Highton (1956). The hatchling larvae from Moonshine Cave averaged 17.8 mm. snout to vent length and 31.0 mm. total length while Highton's (1956) hatchlings from Florida averaged only 13.8 mm. snout to vent and 24.0 mm. total length. The size difference in larvae is consistent with the size difference in adults of *P. g. glutinosus* and *P. g. grobmani*.

References

Bishop, Sherman C. (1943) *Handbook of Salamanders:* Comstock Publishing Company, Inc., New York.

Mittleman, M. B. (1950) Cavern-dwelling salamanders of the Ozark plateau: Bull. National Speleological Society, no. 12, pp. 12-15.

Noble, G. K. and Byron C. Marshall (1929), The breeding habits of two salamanders: Amer. Mus. Nov. 347, pp. 1-12.

Fowler, James A. (1940) A note on the eggs of *Plethodon glutinosus:* Copeia (2), pg. 133.

Highton, Richard (1956) The life history of the slimy salamander, *Plethodon glutinosus,* in Florida: Copeia (2), pp. 75-93.

A Peculiar Type of Cave Gypsum*

By RICHARD V. DIETRICH and JOHN W. MURRAY

Extremely fine-grained platelets (parallel to 001) of gypsum have been found to occur in Dunford Cave, Wythe County and Pig Hole Cave, Montgomery County, Virginia. X-ray patterns obtained by any method except the sphere mount method present d values equal to those of "typical" gypsum but with notable differences in intensities of many reflections — especially noteworthy are the intensity reversals for d = 3.08Å and d = 2.89Å. Differential thermal analyses are significantly different from those of "typical" gypsum — this may be dependent upon the inability to prepare "typical" gypsum with the same size and crystallographic versus shape orientation as that of the peculiar form. Optically the peculiar type has a smaller 2V than most gypsum. Solution and reprecipitation promotes conversion of the 001 platelets to gypsum with the common fishtail twin habit. Association of these gypsum platelets with guano may indicate that the type is formed through reactions involving organisms.

Richard V. Dietrich and John W. Murray are old team mates when it comes to cave minerals. Their previous cooperation was on a paper about Brushite and Taranakite from Pig Hole Cave, Virginia. Both men are professors at Virginia Polytechnic Institute, the former in geology, the latter in chemistry. John W. Murray is also well known to speleologists as faculty advisor to the VPI Grotto of the National Speleological Society and as chairman of the Committee on Chemistry of the National Speleological Society.

Introduction

In conjunction with the investigation by the writers (Murray and Dietrich, 1956) of brushite and taranakite that occur in Pig Hole Cave in Johns Creek Mountain, Giles County, Virginia, numerous specimens of a flour-like white material previously believed to be typical gypsum by speleologists who visited the cave were collected to see if they had been identified correctly. Chemical analyses showed the material to be essentially equal to gypsum in composition. Optical studies of the specimens suggested, however, that it possibly was not gypsum, at least not typical gypsum. Therefore, the material, hereinafter referred to as "peculiar gypsum" or "001 gypsum", and many samples of "typical" gypsum were submitted to optical, *x*-ray, and differential thermal analyses.

Localities and Occurrences

General statements concerning Pig Hole Cave, which is located in Johns Creek Mountain in southeastern Giles County, southwestern Virginia, have been given in another paper by the writers (op.cit.). The material described herein was discovered first as thin (up to one inch thick) coatings on a ledge on the wall of one of the rooms of this cave. It also has been found to occur locally on the floor of one of the passageways of the cave and intermingled with bat hair in the brushite- and taranakite-bearing pit in the cave.

The peculiar gypsum also has been found to occur in layers associated with Allegheny Cave Rat (*Neotoma magister*) guano within Dunford Cave, Wythe County, Virginia. This cave is located within a syncline in the middle Cambrian Elbrook dolomite on the northwest side of New River, approximately seven miles E.S.E. of Max Meadows, Virginia.

Properties

The peculiar gypsum differs from "typical" gypsum in habit, some optical properties, *x*-ray analyses obtained by generally utilized methods, and differential thermal analyses.

The material is extremely fine grained. Most of it passes through a 300-mesh sieve without crushing. The individual grains typically are plate-like and exhibit either polysynthetic "grid" twinning or two well developed cleavages (fig. 1). The facts that all of the plates appear to go to extinction simultaneously between crossed nicols and that they show no noticeable differences in

* This paper was presented by Dr. Murray at the 14th Annual Convention of the National Speleological Society held at Natural Bridge, Virginia, April 8-14, 1957.

TABLE I

X-ray data covering the scan 10° to 40° 2θ for CoK_α radiation for peculiar gypsum and "typical" gypsum.

Peculiar Gypsum		hkl*	"Typical" Gypsum	
d, Å	I, counts		*d*, Å	I, Counts
7.69	525	020	7.69	8300
4.31	260	$12\bar{1}$	4.31	950
3.82	85	031, 040	3.81	1030
3.20	25	$11\bar{2}$	3.20	25
3.08	160	$14\bar{1}$	3.08	1050
2.89	2350	002	2.89	290
2.80	55	$21\bar{1}$	2.80	50
2.69	550	022, 051	2.69	250

* hkl values from Gillery (1955).

interference color between adjacent parts when not at extinction would appear to support the cleavage possibility and not the twinning possibility. However, the choice is not this clearcut because of the extremely small grain size and low birefringence involved.

The grain size and the "gridwork" render completely satisfactory optical study of the peculiar gypsum nearly impossible. The material is colorless in transmitted light. The mean index of refraction is 1.522. The birefringence is low. Most of the grains are biaxial positive but a few appear negative. The size of 2V appears to be variable and to range between 5° and 35°. These optical properties, except for the value of 2V, are all similar to those of "typical" gypsum. The 2V is in all observed grains less than the 55-60° value for "typical" gypsum. The pieces found to be optically negative do not appear to be impurities in the specimens; perhaps this anomaly can be explained by some interference set up as the result of the "gridwork".

X-ray data for the peculiar gypsum and for "typical" gypsum as obtained by numerous methods other than the sphere method (Hildebrand, 1953) are presented (table I and figure 2). Identical procedures so far as sample preparation and the same equipment were used for analyses of both types. All samples were -300 mesh. Both a General Electric XRD-3 diffraction unit with a No. 1 SPG spectrogoniometer and a 114.6mm. Phillips camera setup were used. Cu K α radiation with a Ni filter and Co K α radiation with an Fe filter were used with the XRD-3 unit; Cu K α radiation with a Ni foil filter was used with the Phillips setup. Five forms

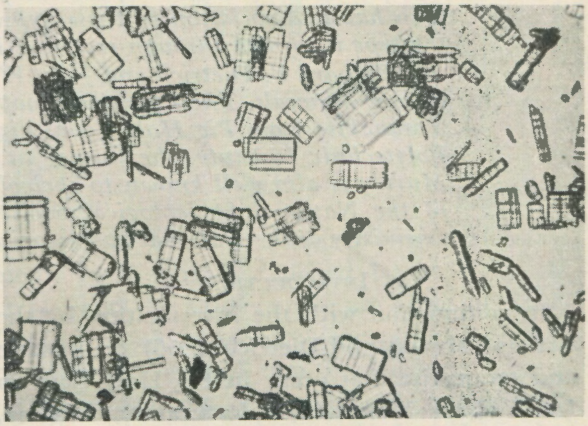


Figure 1
Photomicrograph of the peculiar type of gypsum described in this paper.

of "typical" gypsum, other than the peculiar type described here, were investigated by *x*-ray diffraction: 1) crystals (selenite) from Plasterco, Virginia, 2) aggregates of crystals (selenite) from Pig Hole Cave, 3) alabaster from Pomaia, Italy, 4) satin spar from Plasterco, and 5) a composite sample consisting of these four materials. The *d* values and relative intensities derived from analyses of the patterns are all substantially identical. The set of figures obtained from the -300 mesh Pig Hole selenite are presented (table 1; fig. 2, b and d). The peculiar type of gypsum from the Pig Hole Cave (-300 mesh) was packed in four different ways for investigation with the XRD-3 unit. The packing methods employed were: 1) the powder was flattened into the cavity of a plastic slide with a spatula with the packing force being applied perpendicular to the surface of the slide; 2) the powder was packed onto a

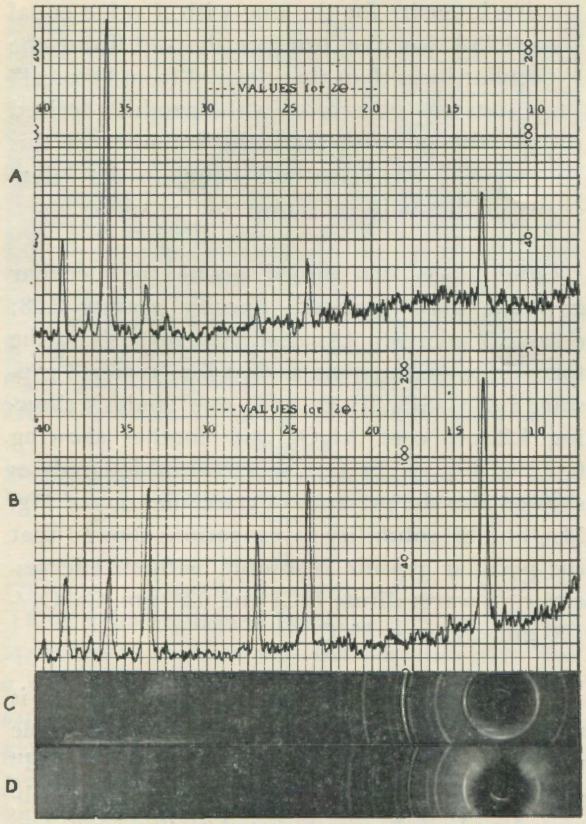


Figure 2
a) X-ray pattern of the peculiar gypsum (XRD3, CoK_α)
b) X-ray pattern of the "typical" gypsum (XRD3, CoK_α)
c) X-ray pattern of the peculiar gypsum (114.6mm camera, CuK_α)
d) X-ray pattern of the "typical" gypsum (114.6mm camera, CuK_α)

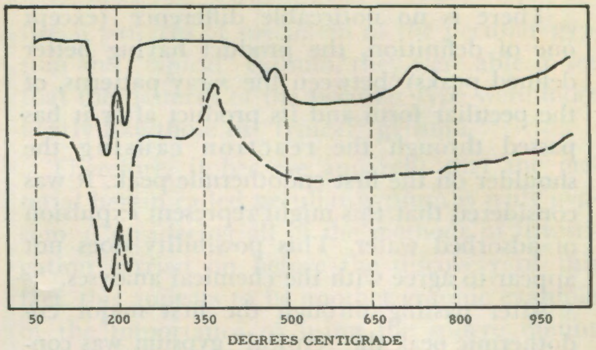


Figure 3
Differential thermal analysis curves obtained from the peculiar gypsum and from "typical" gypsum (dashed line). Scale sensitivity for 50° to 250°C, 1/10th that for 250°C to end.

similar type of slide with the packing force being applied parallel to the surface of the slide; 3) the powder was made into a water-base slurry which was poured onto an etched glass slide and allowed to dry there; and 4) the powder was sifted onto a slide covered with a thin film of tacky *Duco* cement. All samples of the material gave essentially equivalent patterns. Only method "1" was used on the Dunford Cave material. The *d* values and relative intensities of the patterns obtained from Pig Hole material are presented (table I; fig. 2 a and c). It is apparent that with the methods thus far noted that the reflections from the peculiar gypsum have their counterparts, at least so far as *d* values, in patterns given by the "typical" form. It is equally as apparent, however, that the intensities of many of the reflections with equal (or essentially equal) *d* values are not of even the same magnitude.

For the differential thermal analyses all samples were -300 mesh. The differential thermal setup used was an FH305 furnace in vertical position with an x-y recorder attached to a three point Pt-Pt-10Rh wire thermocouple system. Scale multiplications of 2 and 10 were used as is indicated on the curves (fig. 3). The five samples of "typical" gypsum (see above) gave essentially identical curves and all samples of the peculiar form also gave curves that were essentially equal to each other. As is evident from examination of the curves, they are similar in many respects but differ markedly from each other in three ways: 1) A shoulder exists on the first endothermic peak on all curves obtained from the peculiar gypsum. 2) The two endothermic peaks for "typical" gypsum were in all cases of more nearly equal magnitude than those for the peculiar form. 3) All samples of "typical" gypsum gave an exothermic reaction at approximately 375°C, whereas samples of the peculiar form gave no notable exothermic reaction.

The products derived from both the peculiar form and from the "typical" gypsums, *i.e.,* those materials that existed before and after each of the reactions indicated by the thermal curves, were submitted to *x*-ray diffraction. The data for the products derived from "typical" gypsum agree essentially with those given by previous workers (Hill and Hendricks, 1936; Posnjak, 1938). The data for β anhydrite, which were not given by Posnjak (op.cit.), were obtained in this investigation. The data obtained from the products derived from the peculiar form differ from those obtained from gypsum as follows:

There is no noticeable difference (except one of definition, the product having better defined peaks) between the *x*-ray patterns, of the peculiar form and its product after it has passed through the reaction causing the shoulder on the first endothermic peak. It was considered that this might represent expulsion of adsorbed water. This possibility does not appear to agree with the chemical analyses.

After passing through the first major endothermic peak the "typical" gypsum was converted to hemihydrate whereas the peculiar form was converted to a material which has essentially equivalent *d* spacings as those of hemihydrate but different intensities, *e.g.*, the product of the peculiar form gives lower intensities for $d = 3.49Å$ and $d = 3.02Å$ and a higher intensity for $d = 2.81Å$. Further, in the doublet with $d = 2.13Å$ and 2.11Å, the intensity of the second listed member is in all cases much greater than that of the first in *x*-ray patterns of the product of the peculiar form whereas both members of the pair in the product derived from "typical" gypsum have essentially equal intensities.

After passing through the second endothermic peak the "typical" gypsum was converted to typical γ $CaSO_4$. The peculiar form yielded a material, again with *d* spacings essentially equivalent to those of the true γ $CaSO_4$ but with markedly different intensities for some of the major lines, *e.g.*, the peak with *d* value of 2.81Å has a much higher intensity and the peak with *d* value of 3.00Å has a much lower intensity for the product derived from the peculiar form than that derived from "typical" gypsum. In this case, there has been a reversal in relative intensities.

By the end of the differential thermal analysis runs the "typical" gypsum was converted to β anhydrite and the peculiar form to a material essentially indistinguishable optically from β anhydrite. The only marked differences between the *x*-ray patterns were the presence of a line with *d*-value of 3.13Å in the product derived from the peculiar form and no counterpart in the pattern obtained from the true β anhydrite. In addition a much higher relative intensity for the line with *d* value equal to 2.85Å for the product derived from the peculiar form than that derived from "typical" gypsum was observed. In the product derived from the peculiar form the intensity of this latter line was essentially equal to the intensity of the main reflection ($d = 3.50Å$).

Other facts determined about the peculiar gypsum may be listed: Specific gravity 2.28; chemical analyses (Analyst, Murray) show the formula to be the same as that for "typical" gypsum, *i.e.*, $CaSO_4.2H_2O$, with one analysis showing 1.2 per cent Al_2O_3 and another showing 0.61 $Al_2O_3 + Fe_2O_3$; spectrographic analyses showed also the presence of trace amounts of Mg, Mn, and Si; solubility investigations showed that the peculiar gypsum is soluble, without effervescence, in warm dilute HCl and 0.20 gm. $CaSO_4$/-100 gm. water at 25°C.

It is also interesting that the peculiar form is apparently metastable and is definitely less stable under many "normal" conditions than "typical" gypsum. Some of the peculiar type has been observed to have been converted to "typical" gypsum upon merely standing in the laboratory. Although this change has been noted to occur within three months after removal of the material from the cave atmosphere (the temperature of the air within the cave has been found to range between 8.0°C and 10.0°C), other samples have remained unchanged for over a year after removal from the cave atmosphere. What controls the conversion has not been determined. Solution and reprecipitation affects the change from the peculiar type to typical fishtail twinned gypsum. In no case has the peculiar form been reprecipitated by evaporation of solutions of it. The gypsum formed from the peculiar form upon merely standing in the laboratory atmosphere is "typical" except it has an abnormally low 2V (<10°). The gypsum formed by evaporation of a solution of the peculiar form appears to be wholly "typical" (fig. 4).

Discussion

It appeared from the data thus far presented that the peculiar form might be a previously un-

Figure 4
Photomicrograph of gypsum which was derived by evaporation of a saturated aqueous solution of the peculiar type.

reported polymorphic form of $CaSO_4.2H_2O$. The *d* values obtained from the powder patterns appeared to indicate that the peculiar form had a unit cell with the same, or essentially the same, shape and dimensions as those of "typical" gypsum. However, the notable differences of intensity also appeared to suggest that the atoms, ions, and molecules within the unit cell of the peculiar type might have an arrangement different from that within the unit cell of "typical" gypsum. The differences in optical properties and in response to heating between the two materials appeared also possibly to reflect such a basic difference.

Further Data

X-ray patterns obtained with a Buerger Precession Camera setup were made and proved the equality of the unit cell dimensions. Hildebrand (personal communication) found that by using normal and thin spindle mounts plus a mount consisting of a sample of the material packed in a capillary tube that he also obtained patterns marked by the reversal of intensities of lines $d =$ 3.08Å and 2.89Å. He also found, however, that by using small and large sphere mounts that the resulting patterns do not show the intensity reversals, in fact ". . .the patterns show even less preferred orientation than patterns of normal gypsums taken with normal spindles. . ."

The writers subsequently used the sphere mount method and, although they were unable in numerous attempts to get complete accord between patterns of specimens of the peculiar gypsum and "typical" gypsum, they were able to see that the patterns of the peculiar type were more nearly like those of "typical" gypsum.

Therefore, it became apparent that the material herein called peculiar gypsum is truly gypsum (Considering all of the methods of investigation carried on before the discovery of this fact, this appears to be another graphic example of the importance of using the sphere mount method for minerals with habit (s) such as the platy habit exhibited by this gypsum).

Determination of the fact that the peculiar type is true gypsum meant that it could be determined what crystallographic orientation the platelets have (From investigations of minerals of similar habit it is known that the most prominent reflection would likely represent the plane of the platelets). Using the indexing of Gillery (1955), based on the unit cell outlined by Bragg (1937), and making the above assumption, it is apparent that the grains are (probably) basal (001) plates. Correlation of the orientation as determined by the optics of the plates with angular relationships between the plates and reciprocal lattice constants as determined by using the Buerger Precession Camera appear to substantiate this.

Origin

No features other than the association of the 001 gypsum with bat guano in Pig Hole Cave and with rat guano in Dunford Cave suggest a possible origin for the material. The fact that some of it changed to a low 2V gypsum in the laboratory plus the fact that similar low 2V gypsum occurs associated with bat hair and guano in Pig Hole Cave suggest that the form may represent a step in the conversion of certain fractions of guano into "typical" gypsum. Perhaps the 001 gypsum is derived directly from organic processes of digestion. Perhaps it is derived through action of the phosphate- (and/or other cation- and/or anion-) charged cave water on sulfate and/or calcium of the excreta of the bats and rats. Many other modifications of this general hypothesis can, of course, be developed. In any case, it certainly would appear that the direct association of the 001 gypsum with organic derivatives must be considered in any future investigation of its origin.

Summary and Conclusions

Optical, thermal, and *x*-ray investigations of a type that are usually accepted as much more than preliminary suggested that the material described in this paper might be a new polymorphic form of $CaSO_4.2H_2O$. Further *x*-ray investigations—namely those utilizing the sphere method—showed that the material is not a new form but true gypsum. Apparently because of its morphology this peculiar gypsum has a strong tendency to gain a preferred orientation when prepared by the commonly employed methods for *x*-ray diffraction. This would account for the differences between these patterns and those of "typical" gypsum.

The differences between the thermal data obtained from the material and those obtained from "typical" gypsum remains unexplained. Despite the fact that utmost care was taken to use identical procedures in analyses of the peculiar gypsum and the "typical" gypsum that were compared and despite the fact that all analyses of each gave patterns that are equivalent in all essentials, it appears that possibly some variable was overlooked. It may be that the heating curves for the peculiar form also reflect the strong tendency of the material to gain a preferred orientation upon being packed into a restricted space. Perhaps the inability to prepare "typical" gypsum in a way that its grains are of the same shape and with like crystallographic versus size orientation as the grains of the peculiar type may account for the differences.

The origin of the extremely fine 001 gypsum plates is not known. It is suggested that perhaps it is of direct or indirect organic derivation because of its association with mammalian guano. Atmospheric conditions prevalent in the caves may account for its relative abundance there.

Acknowledgements

Mr. A. B. Porterfield, owner of the land under which Pig Hole Cave is located, allowed the writers to enter the cave and permitted them to collect minerals from the cave. E. J. Lowry called the writers' attention to the guano deposit in Dunford Cave. C. L. Rich and Webster Richardson, who are, respectively, in charge of the Agronomy X-ray and Differential Thermal Laboratory and the Physics Department X-ray Laboratory at Virginia Polytechnic Institute, aided in their laboratories. As noted, F. A. Hildebrand of the U. S. Geological Survey made some *x*-ray analyses of the material. J. J. Glass, W. D. Lowry, and C. E. Sears, Jr. checked some of the optical data. The writers gratefully acknowledge these contributions.

References

Bragg, W. L. (1937) Atomic structure of minerals: Cornell Univ. Press, Ithaca, N. Y., pp. 129-131.

Gillery, F. H. (1955) Gypsum: Am. Soc. for Testing Mtls., X-ray Diffraction Card 6-0046, Philadelphia, Pa.

Hildebrand, F. A. (1953) Minimizing the effects of preferred orientation in *x*-ray powder diffraction patterns: *Am. Min.*, vol. 38, pp. 1051-1056.

Hill, W. L. and Hendricks, S. B. (1936) Composition and properties of superphosphate: *Ind. and Eng. Chem.*, vol. 28, pp. 440-447.

Murray, J. W. and Dietrich, R. V. (1956) Brushite and taranakite from Pig Hole Cave, Giles County, Virginia: *Am. Min.*, vol. 41, pp. 616-626.

Posnjak, E. (1938) The system $CaSO_4$-H_2O: *Am. Jour. Sci.*, vol. 35, pp. 247-272.

America's Deepest Cave

By DALE J. GREEN and WILLIAM R. HALLIDAY

Neff Canyon Cave, Utah is believed to be the deepest cave in the United States. Its bottom is 1186 feet below the entrance. The cave is in steeply dipping Cambrian limestone which it follows down dip for a length of 1700 feet. Dr. Halliday is the Director of the Western Speleological Survey and has been instrumental in developing speleology in the western U. S. Dale J. Green is the Director of the Utah Speleological Survey, Chairman of the Salt Lake Grotto of the Society, and a Director of the National Speleological Society.

The name of Neff Canyon is not wholly new to members of the National Speleological Society. After only ten hours in its depths, the Salt Lake Grotto of the N.S.S. nominated it for the list of the most difficult caves in America (Halliday 1953a). 11 months later, after a trip lasting more than 33 hours, the Grotto concluded that "It is entirely possible that this will prove to be the deepest cave west of the Continental Divide." (Halliday 1953b). More recently, the cave has received considerable newspaper publicity as the deepest cave in the United States, surpassing Carlsbad Cavern possibly by more than 110 feet. Much of the newspaper accounts of the explorations and survey of the cave were pure fantasy. The determination of its depth, and the difficulties of its exploration, however, are accurate.

The detailed survey of Neff Canyon Cave was the culmination of a series of exploratory parties by members of the Salt Lake Grotto, extending over a period of 4 years. In addition, we were assisted by the efforts and information received from many others who were also interested in this cave.

The history of Neff Canyon Cave is as interesting as it is short. Cavers' reactions to the story vary from indignation at attempts to close the cave permanently to amusement at wild claims made by unskilled explorers. Also included is sheer horror at the unnecessary risks taken by some of the novices who have entered this cave.

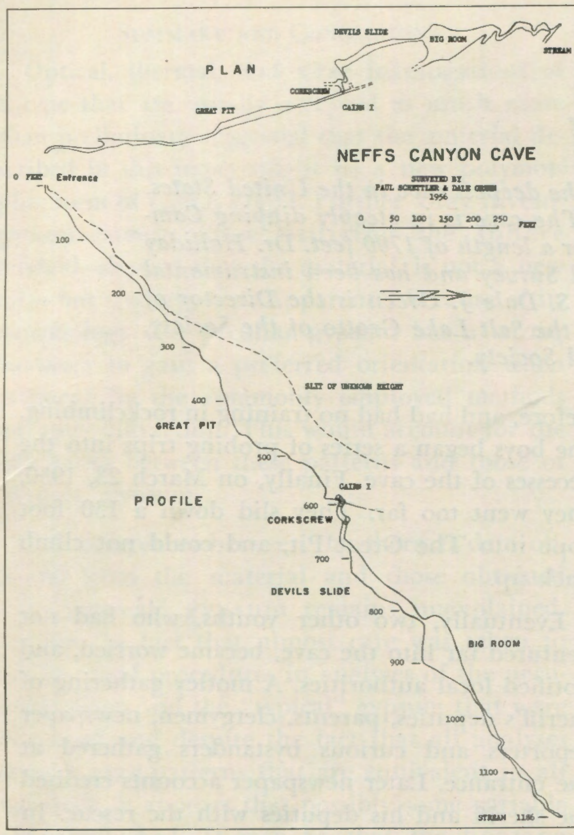
In 1949, the entrance of Neff Canyon Cave was rediscovered by a group of high school students. Rotting remnants of an old ladder in one of the upper pits showed that they were not the original discoverers.

Although they had never been in a wild cave before, and had had no training in rockclimbing, the boys began a series of probing trips into the recesses of the cave. Finally, on March 23, 1950, they went too far. They slid down a 130 foot rope into The Great Pit, and could not climb back up.

Eventually, two other youths, who had not ventured far into the cave, became worried, and notified local authorities. A motley gathering of sheriff's deputies, parents, clergymen, newspaper reporters and curious bystanders gathered at the entrance. Later newspaper accounts credited the sheriff and his deputies with the rescue. In fact, the foolish young explorers were rescued by D. B. (Pete) McDonald, who later became chairman of the Salt Lake Grotto, a friend of Pete, Allen W. Kesler; and James Lyon, brother of one of the trapped boys. As a result of this episode, the cave received some bad publicity (Salt Lake Tribune 1950a, b; Deseret News 1950).

A few weeks later, a group of adults decided to explore the cave to determine whether it was of any potential value as a tourist attraction. After they visited the cave, they filed a report with the staff of the Wasatch National Forest, and the Forest Service forwarded a copy of this report to the National Speleological Society. It read in part:

". . . The men of our party crawled down the twisted, tortuous passage for an estimated distance of 1500 to 2000 feet (actually about 500 feet); part of this was climbing vertical drops of 10 to 40 feet hand over hand on a rope. When they arrived at the place where the other boys had been trapped they found a sheer drop of over 100 feet. . . . Our advice is 'Keep Out!' " (Malmberg 1950).



In a recent book on the caves of the United States, this expedition was erroneously reported to have been made by members of the National Speleological Society (Folsom 1956). At the time, there were no members of the Society in Utah.

In turn, the young explorers filed their own indignant report:

". . . Undoubtedly Mr. Malmborg's party never reached the place where the boys were stranded if they were only 2000 feet in the cave. . . . we estimated our maximum distance in to be about 2 miles (actually 1005 feet)" (Ehlers n.d.).

Pressure by a local politician caused the regional office of the National Park Service to make an investigation of the cave in the Summer of 1951. The party consisted of seven men occupying staff positions in the National Park Service. Excerpts from their report stated:

"It is dangerous, and continued exploration by persons small enough to negotiate the opening is inviting eventual tragedy. Further explorations should be discouraged . . . a distance of 550 to 600 feet underground (actually about 300) we reached a point where the passage narrowed. . ." At this point, only one member of the group could continue, and the party wisely returned to the surface. The report concluded:

". . . It is my candid opinion this cave has no scenic value, will not by any stretch of the imagination meet National Park Service standards, and is without a doubt the most hazardous cave I have ever seen. The inscription above the entrance 'Fool's Cave' is a justifiable description" (Kell 1951).

The cave was first visited by experienced cavers on October 26, 1952. On that date, four members of the newly-organized Salt Lake Grotto of the National Speleological Society, William Halliday, Richard Kennedy, Marvin Mellville and Richard Woodford, spent ten hours in the cave. Below the Great Pit, the four cavers located a small room where there was space, it seemed, for four sleeping bags, thus permitting establishment of an advance camp on a return trip. To their surprise, the explorers found that the cave was no more dangerous than any other steep cave they had visited. Despite some difficulties encountered while ascending the Great Pit, the Grotto members looked forward to additional trips into the cave.

Six months later, a bizarre problem developed. Publicity releases by the president of a local mountain climbing club appeared in Salt Lake City newspapers. It was proposed to blast the cave shut because he and some other climbers had entered the cave for "2000 feet" (actually about 1200 feet), and found the cave extremely dangerous (Salt Lake Tribune 1953; Deseret News 1953a). The editorial columns of a local newspaper took up the cry, and advised closing the cave permanently (Deseret News 1953b). Only some logical public statements presented by the Salt Lake Grotto, and by Roy Bailey, chairman of the former Utah's Dixie Grotto of the National Speleological Society (Deseret News 1953c, Bailey 1953), saved the cave.

In October, 1953, one year after the first reconnaissance, the Salt Lake Grotto essayed a full-scale assault on the cave. Equipped with 250 feet of ladder, 500 feet of rope, sleeping bags and field telephones, Halliday, Melville, Woodford and A. Y. Owen of Oklahoma City spent more than 33 hours underground. Despite the assistance of a support team this party found itself much overburdened, and was unable to advance more than a hundred feet lower than previous exploration.

Although important studies of the upper part of the cave were accomplished, this 33 hour expedition was considered a failure. It taught a valuable lesson, however, for it showed that a few hours' fitful sleep in cold, cramped quarters was no recompense for the excessive fatigue resulting from the struggle with bulky packs and unmanageable gear in the narrow, jagged passages of this cave. All members of the advance party emerged completely exhausted, and one member of the support team was hospitalized for a week because of utter fatigue. It was evident that future expeditions would have to be equipped lightly but thoroughly so that they could be fast-moving without sacrificing safety precautions.

Not to be outdone by cavers, the local mountaineers again gathered their ropes for an expedition on October 24, 1953. Lightly burdened and moving rapidly, three of them reached the bottom of the cave and returned to the surface in 14 hours (White, 1953). It is apparent, however, that their techniques were questionable as far as safety goes. The last man down each descent and the first up each ascent was not belayed. The ladder climb out of the Big Room was described in the Salt Lake Tribune:

"The entrance to this cavern is in the center of the ceiling, making it necessary to climb hand-over-hand up a rope without any contact on the rock. 'Nearly 110 feet of rope climbing on half-inch wet nylon rope near the bottom of a long cave was almost more than I could do,' Mr. Goodro said" (White 1953).

Actually, one member of this trio has since related that Goodro had to climb several feet on an almost sheer wall, grasp the climbing rope, swing into free space and climb up the rest of the rope, hand over hand to a 20 foot section of ladder, all without a safety rope. Twice, he attempted the climb, and was unable to make his way onto the ladder, sliding back to the floor of the chamber. On the third attempt, he was successful, but so great was his exertion that he nearly fainted when he got his foot into the bottom rung. The three climbers achieved their goal, but at the expense of risks which any caver would consider prohibitive and wholly unnecessary.

The trio's newspaper claim that the cave was 2000 feet deep and 4000 feet long was ignored by the local cavers. The open invitation which they issued, however, raised a problem. No longer did these climbers advocate blasting the cave shut. Instead, they invited "any doubting Thomases" to follow and see their names at the end of the cave (White 1953). Neither the Forest Service nor the Salt Lake Grotto believed this wise. Within a few weekends, these two groups had installed a chain across the tight entrance of the cave.

In the years that followed, the public forgot about Neff Canyon Cave, but the Grotto did not. The question of its exact depth haunted everyone, and it was decided to try to determine it. The Selective Service System had removed from Utah every local member of the 33 hour advance party, but Caine Alder, who had been one of the mountain club trio in 1953, volunteered to act as guide since he wanted some photographs of the cave. Paul Schettler, the owner of a new Brunton compass was eager to do some mapping. The rest of the Grotto was eager to follow them, and teams were chosen. Other qualified climbers from the Ute Alpine Club of the University of Utah besides Alder, Schettler, and Dale Green, and from the Wasatch Mountain Club, were invited to join the expedition. Yves Erikkson, a geologist, and Bob Wright, a civil engineer, took the bait.

From previous experience, it was apparent that it would be impossible for one party to install the ropes, descend to the bottom, and return to the surface, bringing the ropes with them. The explorers aligned themselves into two groups. The first party, led by Bill Clark, included Jim Edwards, Dave Rideout and Larry

Coates. Their assignment was to install the ropes. The second party, consisting of Alexis Kelners, Caine Alder, Paul Schettler, Yves Erikkson, Bob Wright and Dale Green, was to follow the next day, and retrieve the ropes as they returned. Initially, it was planned that the second group should begin mapping when they reached the bottom as it was felt that two could map while the others retrieved ropes and ladders, but this plan was changed at the entrance.

At 6 A.M. on Saturday, October 20, 1956, the first party entered the cave. They carried more than 250 feet of rope ladder, 350 feet of 3/4 inch manila rope, 240 feet of 5/8 inch nylon rope, and 250 feet of 1/2 inch manila rope. At 9 P.M., they had not yet reported. The others began to worry. A rescue party was hastily organized. It met at the mouth of the canyon just in time to miss seeing the others leave. When it was found that the vehicles were gone, a few telephone calls revealed the situation.

The would-be rescuers swarmed after Bill Clark. They found him soaking bruises in the bathtub. A few questions elicited the information that the advance party had run out of ladders at the top of the Big Room, now known to be 823 feet lower than the entrance. It would be possible, Bill said, to take a ladder from the bottom of the Great Pit and use it to enter the Big Room, but this was beyond the capability of his exhausted party. Dozing off in the tub, he mumbled something about how hard he thought it was going to be to get the ropes out of the cave. The others took his remark too lightly.

Carrying an additional 240 feet of rope, the attack party met at the canyon mouth at 4:30 A.M. 90 minutes later, they entered the cave. Caine Alder and Alexis Kelners took the lead, checking the rigging as they advanced. Paul Schettler and Dale Green followed, mapping. Bob Wright and Yves Erikkson formed the rear-guard.

Progress was slow. The upper part of the cave consists mostly of a series of vertical pitches, often in extremely rotten shale. In many places, the passage is less than two feet wide, and only one man can descend a pitch at a time.

Physically, the descent was relatively easy. Except for the tedium of mapping, Dale recalls, it might have been fun. All the pits were securely rigged with rappel ropes, and the more extensive pitches had rope ladders in place. Furthermore, the very narrowness of the cave makes chimneying possible in many places without need of ropes. This technique, however, plays havoc with clothing of climbers, since the innumerable impurities in the limestone which weather to provide good handholds and footholds form a very jagged surface.

Little difficulty was encountered above The Great Pit. Contrary to its appearance on the map, this part of the cave is far from an even slope. Most of the pitches are too short to be visible on the map, but all delay the caver.

At the Great Pit, the ceiling slot, which is present in most of the cave, reaches a tremendous height. At the ledge overlooking the pit, the top of the slot is not visible even though it is possible to look upward for more than 50 feet. Within a horizontal distance of 30 feet from the ledge, the floor is 150 feet lower, so that the ceiling height of the Pit Room is more than 200 feet. The worst problem at the pit is the shale which underlies the limestone in which most of the cave is developed. Fifty feet of wet, slick, crumbling shale is encountered in this pitch. Shale fragments are dislodged with each movement, creating a hazard to anyone below.

Beyond the Pit Room, a narrow squeezeway and a succession of vertical pitches lead to the most interesting part of the cave. Above and to the west of this section is a small complex of side passages, dubbed the Bedroom Area, where the 1953 party slept during their 33 hour trip. Near the Bedroom are the only fine speleothems in the cave. They consist of a few candle-white stalactites, stalagmites and columns, and a small shelfstone pool thickly coated with tiny white crystals. This area has not been completely explored. It is exactly halfway to the bottom of the cave.

Several pitches and an offset in the passage lead to the top of the drop leading to the Devil's Slide. While the group was engaged in changing carbide at this point, an ominous rumble sent them scurrying for shelter. Two hundred pounds of shale crashed down around them. One large fragment struck Paul on the helmet, almost stunning him, and another demolished Dale's lunch. Paul, incidentally, is now a fervent advocate of hard hats.

After inspecting the peculiar rigging of the ladder the cavers descended to the Devil's Slide. The Slide is the site of the most ticklish climbing in the cave. A climbing rope probably should be used here, but the party's supply was low and they did not employ one. The slide is composed of shale which dips 50 degrees. The slope is smooth, wet and slippery. Most of the few finger- and toe- holds are loose and treacherous. It required 30 minutes to find a spot suitable for the tripod of the Brunton compass.

Below the Devil's Slide is the Big Room, the only sizeable chamber in the cave. It is entered through a small hole in the ceiling. Below is a drop of 78 feet, mostly free of the wall. In order to save time, the party secured a rope, and employed a free rappel to descend. At least one member of the party was not equipped with rappel pads, and was very uncomfortable before he reached the floor of the chamber below. Adding insult to injury, he was asked to stop in midair for an action photograph. His reply was distinctly unkind.

Bob and Yves were left at the top of this pit so that the others could be safetied on their return. The others continued into the cave.

The Big Room appears to be about 70 feet in diameter, but its margins have not been examined in detail. Only two parties have gone this far into the cave. Its floor consists of loose, sliding slabs of shale. Beyond this room, the nature of the passage differs considerably from that of the upper part of the cave. The high, narrow slit is gone. The passage is much wider and contains large blocks of breakdown. There are a number of possible routes in this breakdown, but only the one mapped was followed. In this part of the cave are flowstone-coated walls which show re-solution, and a few small helictites and tubular stalactites are present. On the floor are a few small boulders of quartzite and some stream-worn travertine boulders about a foot in diameter.

About 100 feet from the end of the cave, the trickle of a stream becomes audible. At the sound, the members of the party suddenly realized that they were very tired. The mapping team, realizing that its job was almost over, was greatly relieved. Its members had made 45 measurements in 13½ hours.

Entering the cave as a small waterfall, this stream runs along a cross passage for about 50 feet, then sinks into gravel. At the point where the stream disappears, the ceiling is about 1 foot high. A few feet beyond this point, the passage is completely filled with gravel. When seen in October, the stream was only about one inch deep and two feet wide. A pine cone was found alongside the stream, but other debris is found throughout the cave as Spring floods enter the main entrance of the cave. When the map was completed, it was found that this rivulet is 800 feet directly beneath the main stream of the canyon overhead.

When Caine and Alexis reached the end of the cave, they returned to the Big Room and exchanged places with Bob and Yves. A few minutes later, Dale and Paul heard a loud rumble as they completed their last measurement. They pocketed their gear, and started back. Within 200 feet, they learned the reason for the rumble. They met Bob and Yves, who looked pale and shaken. While descending a short pitch, Bob had tested a large rock and found it stable. He descended without incident, but when Yves followed, the rock began to slide on top of him. Shouting a warning to Bob, Yves managed to push himself aside, but the rock came close enough to knock the eyeglasses from his face. The frame broke, and one lens could not be found. Yves is extremely nearsighted, and it would not be easy for a one-eyed man to climb out of Neff Canyon Cave.

Miraculously, Dale spotted the missing lens 15 feet lower than the point of the accident. It was lying on a rock, unbroken. The spectacle frame was taped together, and the party was ready to go again.

Reassembling at the top of the Big Room at 8 P.M., everyone voiced optimism about the time required to get back to the entrance. Dale Green recalls:

"We figured that it took about 1 hour per 1000 feet to climb on the outside, and since the cave was just a little harder, we should be out by 10 P.M. Twelve hours later, we staggered from the cave with all our equipment still somewhere inside."

Trouble began with coiling the ladders and ropes. It was 9 P.M. before the cavers left the Big Room. At the Devils Slide hauling the ladders became a major problem. The sacks were ripped, and the ladders continually oozed out. Getting the gear up each pitch became a major task. "In fact", Dale relates, "getting *anything* up a pitch, including ourselves, was a major undertaking."

The ascent proved far more difficult than the descent. The chimney climbs were exhausting, and the cavers became so chilled during the long, inevitable periods of waiting in the damp coldness that their teeth chattered audibly. Such are delights of Neff Canyon Cave!

At 6:30 A.M., 24½ hours after entering the cave, the group was struggling to haul the equipment up a pit about 275 feet below the entrance when it became obvious that they were in no condition to continue. They had found it necessary to belay one caver out over the edge of the pit to keep the ropes clear. Unfortunately, the belayer went to sleep. No damage resulted, but the experience foreboded impending disaster. Furthermore, a prearranged rescue party would soon be starting for the cave.

The sextet abandoned the ropes and ladders, and headed for the entrance at the best speed they could muster. At 8 A.M., the green pines and the grey of the dawn sky were truly welcome sights. After a few minutes' rest, the party headed down the canyon to intercept the rescue party.

A day's rest and a good sleep did much to revive the cavers. Inevitable curiosity caused Dale Green to plot the survey data within 24 hours. The slope length of the cave was found to be only 1700 feet, but its depth proved to be 1186 feet. Before this measurement, America's deepest cave was said to be Carlsbad Cavern, listed by former Park Naturalist T. Homer Black at 1076 feet (Black 1955). A survey made by a tripod-held Brunton compass is very accurate. Its inherent error is only a small fraction of the 110 feet, and Neff Canyon Cave is therefore believed to be the deepest cave known in the United States.

Since so few persons have visited the depths of this cave, its geology and speleogenesis are only partially known. The cave lies within the middle and lower members of the Mid-Cambrian Ophir formation. On the north slopes of Mt. Olympus, a prominent landmark on the western margin of the Wasatch Range just east of the southern end of Salt Lake City, the Ophir formation rests comformably on the Tintic quartzite, and is overlain by a Mississippian series. At the cave entrance, the beds dip north about 50 degrees, with the strike almost precisely east-west.

In this area, the middle members of the Ophir formation consists of a moderately thin-bedded grey limestone about 80 feet thick. It contains prominent serpentine impurties. The lower member is about 240 feet thick (Marsell 1952). It consists largely of flaky shale which is reddish-brown to dark brown in color. Beneath 28 feet of this shale, and not previously recorded in the Wasatch Mountains, is another limestone bed which is exposed at the base of The Great Pit. Its thickness has not been determined.

The main passage of Neff Canyon Cave, from the entrance to the offset, is developed along a fault paralleling the dip of the formation with a vertical throw of about four feet. The side-passages of the upper part of the cave appear to be joint-determined, but the possibility that some follow parallel faults has not been excluded (Halliday 1954a). In the deeper parts of the cave, preliminary observations indicate that the passages plunging down dip follow a series of parallel faults.

The speleogenesis of the upper part of cave has received brief study (Halliday 1954b). There is evidence that the basic origin of the cave is the result of phreatic solution. It has been subject to cyclic vadose modifications in the form of deposition of fills of different types, speleogens of stream origin, perched false floors and gravels, speleothems with subsequent re-solution, and stream channels. The cave was covered at least once by a Pleistocene glacier, and moraine of a second glaciation surrounds its entrance. It is possible that glacial and inter-glacial periods have been responsible for the cyclic nature of the vadose features of the cave (Halliday 1954b). The relation of the origin of the cave to Tertiary peneplanation and uplift is not yet clear.

There is still a possibility that the cave may go even deeper than 1186 feet. The cave is not fully explored, and a deeper passage may be found. The cave stream does not represent the water table. To dig out the gravel blocking the stream passage would be a major undertaking. Attempts will probably be made to bypass this obstacle instead. If a side passage exists in this area, it will probably be encountered at or below the Big Room. The side passages above the Devil's Slide do not appear to be properly aligned to bypass the main passage below the offset. These passages were partially explored in September, 1958 by a party led by Dale Green and were found to be very extensive.

The exploration of Neff Canyon Cave is not an undertaking to be considered lightly. The writers believe that certain steps are essential for future exploration in this cave:

1. Contact the Wasatch National Forest in Salt Lake City for permission to enter, and to obtain the key to the cave.

2. Any party passing the Great Pit should have not less than four and not more than six members.

3. Successive parties should be employed to install ropes and ladders, to explore and study the cave, and to bring out the gear.

4. Only experienced cavers should enter the cave.

References

Bailey, L. J. 1953 Says speleologist should inspect cave: Deseret News, Apr. 27, pg. 16-A.

Black, T. Homer 1955 Carlsbad Caverns: in Mohr, Charles E. and Sloane, Howard (ed.) Celebrated American caverns: Rutgers Univ. Press, New Brunswick, N. J., pg. 142.

Deseret News 1950 Student trio pulled from icy Utah cave. Mar. 23, pg. B-1.

Deseret News 1953a Sealing of cave near Holladay urged by group: April 20, pg. B-9.

Deseret News 1953b Ounce of prevention: April 24, pg. 16-A.

Deseret News 1953c Salt Lake group flays proposal to close cave: April 30, pg. 11-A .

Ehlers, Jack n.d. Report on Mt. Olympus (Neff's Canyon) Cave with comments on Malmborg Report. Unpublished ms.

Folsom, Franklin 1956 Exploring American caves: Crown Publ. Co., New York, pg. 152.

Halliday, William R. 1953a Salt Lake Grotto visits Neff Canyon Cave: N.S.S. News, vol. 11, no. 1, January, pg. 2.

Halliday, William R. 1953b Salt Lake Grotto spends 33 hours underground: N.S.S. News, vol. 11, no. 12, December, pg. 7.

Halliday, William R. 1954a The basic geology of Neff Canyon Cave, Utah: Tech. Note #4, Salt Lake Grotto, Nat. Speleol. Soc., January.

Halliday, William R. 1954b The speleogenesis of Neff Canyon Cave, Utah: Tech. Note #5, Salt Lake Grotto, Nat. Speleol. Soc., January.

Kell, John E. 1951 Field Investigation Report: Neff's Canyon Cave: National Park Service, Region 3, September.

(Malmborg, Charles) 1950 Conservation Committee receives report on Utah cave: N.S.S. News, vol. 8, no. 12, December, pg. 6.

Marsell, R. E. (ed) 1952 Geology of the central Wasatch Mountains, Utah: Guidebook to the geology of Utah #8, Utah Geol. Soc.

Salt Lake Tribune 1950a U student trio lost in Canyon Cave: March 23, pg. 1.

Salt Lake Tribune 1950b Rescuers save U freshmen trapped in cave near S. L. March 24, pg. 21.

Salt Lake Tribune 1953 Climber urges sealing of Canyon Cave: Apr. 20, pg. 32.

White, Jack 1953 Climbers conquer depths of hazardous Neff Cave: Salt Lake Tribune, Oct. 25, pg. C-11.

Caves of Kwangsi

By ROBERT E. SCHWORM

Here in pictures is an introduction to caves in Kwangsi, China. China's karst and cavern areas are extensive and large, yet they are little known. Robert Schworm, as an airman stationed in China, made the most of his opportunity and recorded photographically many of the caves in Kwangsi.

Aerial view of the Kweilin exploration area. River in background issues from underground, possibly from pool found in one of the caves examined.

The strange and beautiful conical mountains that bisect the South China Province of Kwangsi offer a fascinating field for speleological exploration. Arising sharply from the rice paddies, these sparsely vegetated, monolithic peaks are honeycombed with caves that are little known and unexplored.

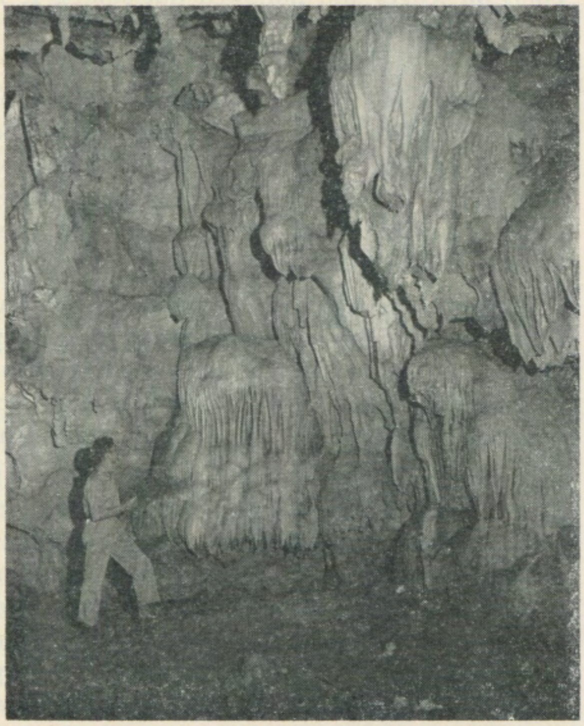
Several of these caves were examined and photographed by the author and a few companions in off-duty hours while serving in the Kweilin area with the 14th Air Force during World War II. It is believed that these visits were the first made in modern times. The local Chinese appear to be uninterested in them, and no sign was found that they were used for any purposes by the natives. One exception was a large, open-mouthed, shallow cave that was walled up and contained an abandoned schoolroom.

We did find undecipherable markings on the low ceiling of one cave near its entrance, but who made them, and what they meant must be decided by others more expert. No artifacts of any kind were found, but since these examinations were regretfully but necessarily brief, who knows what histories of possible former occupants competent investigation might unearth? The only life discovered in our searchings were the companies of bats hanging from the walls and ceilings.

The caves vary in size and extent. Some are small with difficult passageways. Some are large with interconnecting rooms. The largest room found was about two to three hundred feet in length and seventy to eighty feet in width with a ceiling of thirty-five to forty feet high. The floors range from fine clay to gravelly stone to

Entrance hole in one of the first caves explored. Submachine gun was carried by one man as a precautionary measure as Japanese collaborators were in the area.

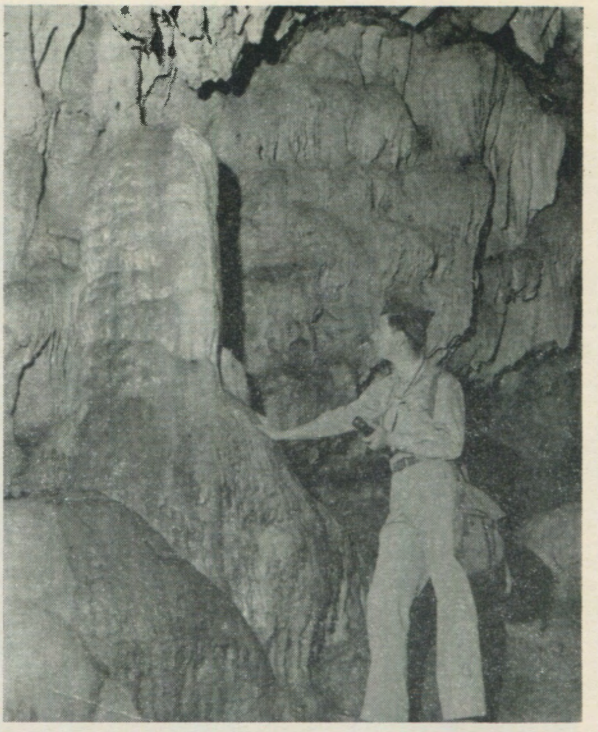
Curtains of stone decorate ledge in China cave. This type of formation is very common in the caves.



"Waterfall" formations in largest cave found. The floor here is muddy and slick.

Passageway that leads to another room in China cave. From here the floor is mostly gravel.

Four of the Air Force men who examined Kwangsi caves investigate a side shaft of the first cave entered.



Large stalagmite in one of the bigger caves.

slick mud. All are relatively free from rubble and are easily traversed.

The caves are a wonderland of rooms and galleries, with connecting aisles and tortuous tunnels all revealing grotesque architecture, both Gothic and baroque, shaped by time and water. Large clusters of stalactites descend from the ceilings. Stalagmites, some of impressive size, are posted throughout the rooms and halls. Great curtains of limestone are strung, sheet upon sheet, across roofs and ledges. Flowstone is freely distributed in falls and cascades. The colors are varied and beautiful—blacks and browns to creams and pinks—the whole spectrum is spanned in a square foot of rock. The dancing shadows produced by small, hand-held flashlights presented a never-to-be-forgotten picture to the explorers.

If these caves were properly lighted, publicized, and as easily reached as some of our well known American caverns they could justly take their places with the best.

The uniformly cool moist interiors are a welcome relief from the sub-tropical heat of South China in summer. Water is in evidence in all the caves, issuing in drops, trickles, and streamlets from fissures and walls, and collects in small pools on ledges and hollowed out stones. It is sweet and palatable.

We came upon one large pool of clear water that disappeared beneath a lowering ceiling of dripping stalactites to the far recesses of the cave. It could be fully examined only by boat or skin diving. It might be the source of an underground river we found later as it emerged from the mountain farther away.

Some enticing holes and crawl spaces that led to guessed-at sights were reluctantly passed by because of time and lack of necessary equipment to examine them effectively. Ropes and protective gear would be needed to carry out extensive exploration.

With even this small entry into the underground mysteries of China revealing such sights of beauty and interest, who can say what other wonders are hidden in the countless unamed and unknown mountains of Kwangsi? Maybe other Mammoths or Carlsbads are waiting, as they have for ages past, for the first light of some inquisitive and adventurous cavern seeker to penetrate their Stygian darkness and unfold their enchantment to the world.

Speleology in Czechoslovakia

By FRANTIŠEK SKŘIVÁNEK

Speleology, like all other forms of human endeavor, has reached a point where it is impossible to keep up with current activities throughout the world. František Skřivánek, Secretary of the Speleological Department of the Natural Scientific Society, National Museum, Praha, presents an introduction to "who is doing what" in speleology in Czechoslovakia that will bring to many American speleologists a much needed insight into the accomplishments of other speleologists in foreign lands. This is the first of a series of "get acquainted" papers to be published in the Bulletin. It is hoped that these papers will bring a broader understanding of the scientific data available in the field of speleology.

This is one of a series of papers by which the Speleological Department of the Natural Scientific Society of the National Museum in Prague hopes to get in touch with colleagues of the speleological world in various countries. We have already established contacts with such societies in Italy, France, Hungary, Östereich and would very much like to extend our relations to the United States as well.

We are interested in the research work you are undertaking, the places in which it is being carried out, and the methods you use, and would be very pleased to receive news about karst regions in your country. You, also, will probably be interested to know how we work in our country which is rich in karstic phenomena.

To begin with we will describe the main karstic regions and the caverns in Czechoslovakia, beginning at the west of the country. The numbers of the caverns correspond to the numbers on the adjoining plan (Fig. 1).

The Czech karst is a region of folded Silurian and Devonian limestones near Prague. The river Berounka, which is bordered by extremely well—developed terraces, runs through the centre of the region. The largest caverns are those known as Koněprusy (1), nearly two kilometres long. They were discovered in 1950 and have three levels. The middle level is the largest and in it some stalactites have been metasomatically replaced by chalcedony. There is a main dome with an alluvial cone in which were found skulls and tools of mankind living in the Würm 1+2 periods, as well as a large quantity of bones belonging to animals of the Pleistocene age.

During the 15th Century, the top level served as a workshop for a gang of counterfeiters. The entrance had been perfectly hidden and blocked so that the remains of the false coins, the waste material from their production, as well as some of the counterfeiters' tools were preserved right up to present times.

A large group of eccentric capilliary stalactites, which are the most perfect in the Czechoslovak Republic, is found in the lower level.

The caverns were formed during the Tertiary period. They are in the summit of a large hill. Extremely ancient sediments have been preserved in these caverns, and with them also is linked a *karstic pocket* C 718 where we discovered a rich fauna of Pleistocene beasts: mammoths, tortoises, machairodus and malakofauna. In many of the quarries found in the Czech karst reigon where limestone is exploited, karstic pockets have been found in which have been conserved remains and sediments carried from the surface of the ground by external geological factors.

Another cavern known in this region is that at Chlum, near the township of Srbsko. It is a little more than 500 metres long. The passages of the cavern are linked to the surface by chimneys where we have found a rich fauna of the early Pleistocene age.

A further cavern named Barrandova (2) is 120 metres long with narrow corridors and a deep chasm but is without stalactites.

The cavern Nad Kačákem (3) is only 30 metres long but it is made very important by Paleolithic archeological discoveries.

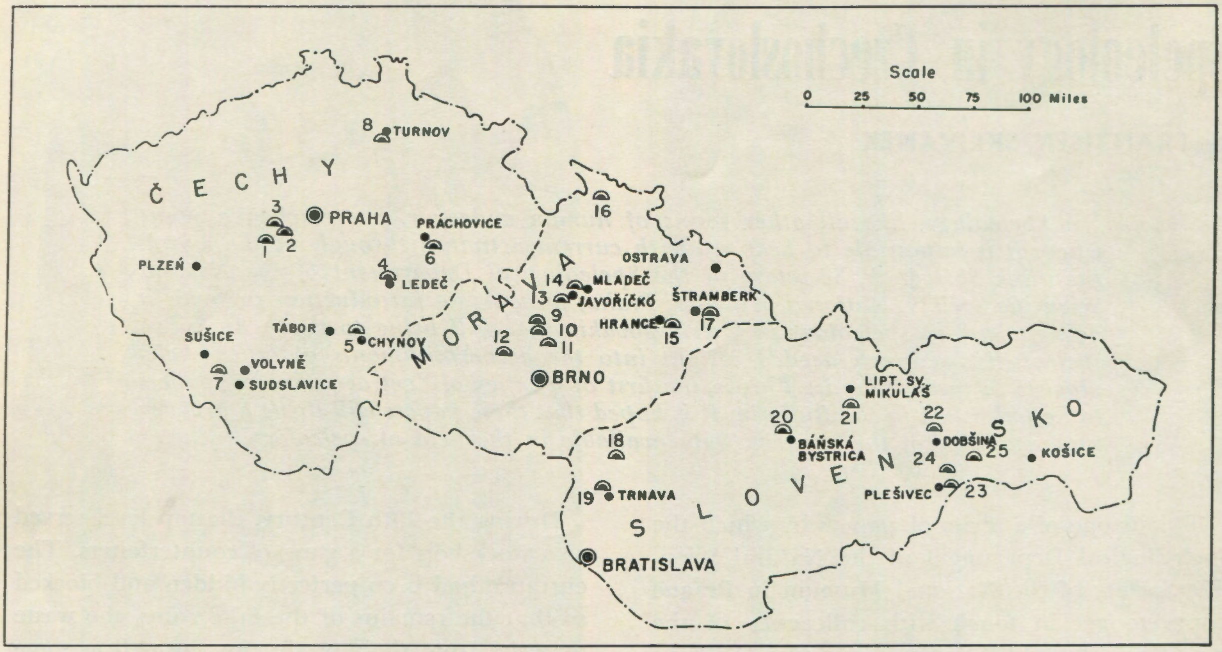


Figure 1

Czechoslovakian cave areas. Numbers refer to cave names cited in the text.

Many caverns border the Berounka River. The caverns follow exactly the contours of the terraces.

Other karstic regions are found in the west of the Republic near the village of Ledeč by the Sázava river (4), where there are two caverns reaching more than 100 metres in length. They have formed in crystalline limestone.

Near the village of Chýnov (5), in the district of the town of Tábor, there is a 400 metre-long cavern without stalactites, through which an underground stream passes.

In the limestone quarries near the village of Práchovice (6) are a few small caves.

Another karstic region is near the towns of Sušice and Volyně. Here is found the Strašínská Cavern (7), only 80 metres long but which is interesting because of the content of the limonite which contains 63.05 percent of iron oxide (Fe_2O_3). Limonite is formed from the corrosion of limestone which contains pyrites and pyrrhotite. The caverns were formed in the Quaternary age.

The pseudo — karstic caverns found in the sandstone in the north and east of Bohemia are interesting because of their origin. They were formed by mechanical erosion and have the same forms as caverns developed in limestone. The largest of these is the Amerika cavern near the town of Turnov (8).

The largest karstic region in Moravia is the Moravian Karst. It is developed in the limestones of the Devonian period and includes several notable caverns. Sloupsko - Sošůvské (9) has two levels of corridors into which the stream named Sloupský disappears and after running five kilometres underground comes out again in the chasm of Macocha, in the same manner as another river, the Punkva. The caverns are nearly four kilometres long and have been known for a long time. They are abundantly decorated with stalactites.

The Punkevní or Macošské Caverns (10) are linked with the bottom of the Macocha chasm which is 138 metres deep. The river Punkva runs through these caverns, which to a large extent were discovered by Dr. Absolon and his col-

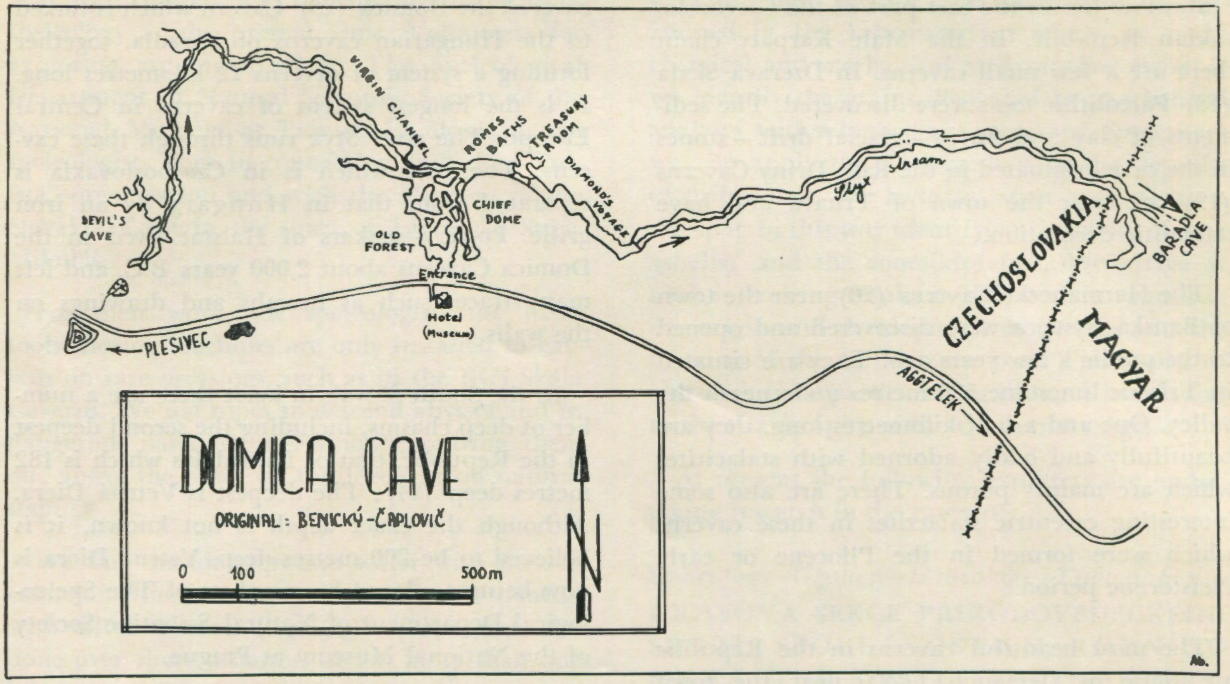


Figure 2

Speleology transcends international boundaries in Domica Cave which extends from Czechoslovakia to Hungary (Magyar).

leagues in the period between the two world wars. They were equipped with modern technical apparatus. To remove the water from syphons they used Nautilus pumps. They also had diving equipment. The Punkevní caverns have a magnificent stalactitic decoration and are nearly two kilometres long.

In Moravia the caverns of Kateřinská are noted for a large dome measuring 96x44x20 metres. The remains of Pleistocene fauna were also discovered in these caverns.

The stream of Jedovnický runs through the Býčí Skála Caverns (11). Of the probable total length of three kilometres, only 700 metres of the passages are known.

Containing a large proportion of phosphates, clay of the Würm period was worked in the Výpustek Caverns (12). During the war the Germans constructed an underground factory there but afterwards destroyed it.

In Northern Moravia, caverns have developed in isolated islands of Devonian limestone and in crystalline limestone. The most beautifully decorated caverns are those of Javoříčské, discovered in 1938 (13). A complicated labyrinth is formed by the Mladečské Caverns (14), in which were discovered the remains of Pleistocene man.

Zbrašovské (15), caverns containing aragonite, discovered in 1912 near the town of Hranice na Moravě, have a particularly interesting origin. They were corroded by carbonic mineral waters which rose and followed faults towards the surface. Invisible reservoirs of carbon dioxide (CO_2) are found in these caverns. On the walls of the caverns you can see patches of aragonite, and less frequently, of wad and limonite. One of the rarities of the caverns is the geyseric stalactites which border the channels through which the thermal water containing calcium bicarbonate mounts.

The Pomezí Ve Slezsku (16) have a system of passages with a particularly fine array of stalactites. The Šipka (17) is a short corridor of 50 metres nearly at the summit of Kotouč hill, near the town of Štramberk. The hill of Kotouč is formed by Jurassic limestone. During the 19th Century, J. Maška made the famous discovery of the jawbone of a Pleistocene man here.

Slovakia lies in the east part of the Czechoslovakian Republic. In the Malé Karpaty chain there are a few small caverns. In Dzerava Skala (18) Paleolithic tools were discovered. The sediments of clay and fluvio – glacial drift – stones in the cave originated in the Riss. Driny Caverns (19) are near the town of Trnava and have stalactitic decoration.

The Harmanecké Caverns (20) near the town of Banská Bystrica were discovered and opened to the public a few years ago. They are situated in Triassic limestone 500 metres underneath the valley. One and a half kilometres long, they are beautifully and oddly adorned with stalacitites which are mainly porous. There are also some interesting eccentric stalactites in these caverns which were formed in the Pliocene or early Pleistocene period.

The most beautiful caverns in the Republic are those of Demänová (21) near the town Lipt. Sv. Mikuláš in the Demänová Valley. They are formed in Triassic limestone and are more than 12 kilometres long with abundant stalactitic decoration coloured in lovely tints by iron and manganese. The Lúčanka river running through the lower level carries to the surface lumps of granite which help to widen the passages. There is a 74 metre – deep chasm in the caverns. This system of caverns was discovered in 1921, and the cavern Demänová Dračí, with its rich decoration of ice stalactites also is a part of it. Here were discovered many bones of bears of the Pleistocene period (*Ursus speleus* BLMB).

The ice cave of Dobšinská (22) is a vast dome filled almost to the roof by a glacier. It is a cave of very complicated static-dynamic ice. The glacier remains from the last Ice Age and it is increasing on the upper side while underneath it is melting. In the lower levels very richly decorated spaces were discovered within recent times.

The greatest karstic region in the Republic is Jihoslovenský Kras (the Karst of Southern Slovakia), with valleys 500 metres deep which, according to the most recent researches, are the remainders of chasms. This region is divided into plateaux. On the Silica plateau J. Majko discovered the Domica (23) Cavern which is linked to the Hungarian caverns of Baradla, together forming a system of caverns 22 kilometres long. It is the longest system of caverns in Central Europe. The river Styx runs through these caverns. The part which is in Czechoslovakia is separated from that in Hungary by an iron grille. Pottery–makers of Halstat lived in the Domica Caverns about 2,000 years B.C. and left many traces such as hearths and drawings on the walls.

In the South Slovak in karst there are a number of deep chasms, including the second deepest in the Republic, that of Barazdalas which is 182 metres deep (24). The deepest is Vetrná Diera. Although the exact depth is not known, it is believed to be 200 metres deep. Vetrná Diera is now being explored by members of The Speleological Department of Natural Scientific Society of the National Museum at Prague.

In this same region there are the Jasovská Caverns (25) forming a vast labyrinth with many levels. The inscriptions made by religious emigrants of the Fifteenth Century have been preserved here.

The Gombasek Caverns, two miles in length and richly adorned by stalactites, connect with the Silica Chasm. A subterranean stream, which forms lakes more than 100 metres long separated by isthmuses, runs through the Brozotínská Caverns.

Most of the caverns mentioned are open to tourists and are lighted by electricity. The most visited caverns are those of Macošské, Demänová, Domica, Harmanecké, Javořičské, Dobšinská and Dračí. The Dobšinská and Dračí caverns are ice caves. The caverns belong to the State and this year were visited by 300,000 tourists. The guiding of tourists who visit the caverns is not organized by private companies but by national societies.

Nearly all these caverns were discovered during the period between the two world wars. Some of them were found only recently, such as the Gombasek Caverns, a part of the Demänová Caverns and the caverns in the Malé Karpathy chain.

Many explorers are working in the field of speleology at the present time. Volunteers for exploring are organized in The Speleological Department of Natural Scientific Society of the National Museum at Prague. In Slovakia, the speleologists work in connection with the "Turista" organization and with the Museum of the Slovakia Karst in the town of Liptovský Svätý Mikuláš.

For their work, the speleologists use hand tools. Boring machines are only installed in caverns on rare occasions, such as in the Býčí Skála Caverns. We use ropes to descend abysses and in dangerous parts we use winches, putting them one above the other on the levels or on natural steps.

We tint the underground water with fluorescein. Sometimes we use sodium chloride (NaCl) with silver nitrate ($AgNO_3$). These tests are done over short distances of not more than one kilometre.

Many speleologists make maps of caverns. All the large caverns opened to tourists and a large number of smaller caverns are plotted in detail at scales of 1:200 or 1:50. We use theodolites, compasses, etc. for surveys.

Before the Second World War, the explorers were above all interested in the morphology and the decorations of the caverns. Many of the published works concern the origin of the stalactites and the speed of their growth.

The speleologists in Slovakia also made a successful experiment in transforming the Belanská Cavern into an ice cave. They walled-up one of the entrances, thus stopping the circulation of air.

There has also been a great deal of interest in, and descriptions of, paleontological and archeological discoveries in the sediments in the caverns.

In the caverns we drill bores, plotting the data on scales of 1:10 and 1:50, and describing the structure and texture; specimens are also examined in the laboratories where we make chemical and mechanical analyses. For example we identify the grains, levigated by mechanical analyses, with a binocular microscope. Sometimes we also apply the Lais method of the deposits of drift-stones. We levigate larger specimens on the spot, in this way identifying the malakofauna (shells) and the zoomikrofauna. We arrive at most interesting results in this work in respect to the origin and development of caverns and the forming of the earth in the past. The results of our work have particular significance in relation to the stratigraphy of the Quaternary Age.

At present the following explorers are undertaking research in the caverns:

Speleology—Geology—Hydrology—Topography

KRASOVÁ SEKCE PŘÍRODOVĚDECKÉHO SBORU SPOLEČNOSTI NÁRODNÍHO MUSEA. THE SPELEOLOGICAL DEPARTMENT OF NATURAL SCIENTIFIC SOCIETY OF THE NATIONAL MUSEUM in Prague, Czechoslovakia.

Prague—2, Václavaské nám. 1700

MORAVSKÝ SPELEOLOGICKÝ KLUB, Brno, Těsnohlídkova 10.

MUSEUM SLOVENSKÉHO KRASU, Liptovský Mikuláš.

Prof. Dr. J. Kunský, Praha — 2, Albertov 6.

Frant. Skřivnek, Čakovice at Prague, Nerudova 302.

Petrography—Geology—Cavern sediments

Dr. J. Kukla, Praha—15, Podolské nábř. 2.

Malakozoology—Quaternery geology

Dr. V. LOŽEK, ÚÚG, Praha-l, Hradební 9.

Archeology

Frant. Prosek, Arch. institut ČSAV, Praha — 3, Letenská 4.

Paleontology

Dr. O. Fejfar, ÚÚG, Praha-l, Hradební 9.

The Reservoir Theory of Spring Flow

By JERRY VINEYARD

The large springs of Missouri have been a source for speculation as to their origin and supply of water. Based on evidence obtained first hand by actual traverse of portions of the subterranean network feeding the springs, it is apparent that large multi-purpose vadose reservoirs supply and control the flow of water into a network of phreatic conduits connecting with the springs. Jerry Vineyard, now serving as an Ensign in the U. S. Navy, was an active member of the Missouri Speleological Survey.

The large springs of Missouri, second only in size to those of Florida, have long been sources of intense interest due to their clarity and the relatively constant flow of very large volumes of water. Their size is such that a spring is not called "large" unless its flow is measured in millions of gallons per day. The largest, Big Spring in Carter County, has a maximum flow of 1,300 second-feet, or more than 840,000,000 gallons per day. The springs fluctuate with the seasons, as might be expected, but they have far more constant flows than surface streams of comparable size. Generally, their water is exceptionally clear, although not always pure, and has a temperature of about two degrees above the mean annual temperature for the surrounding area. The distribution of these springs is such that many of the rivers in the big spring region are fed almost entirely by springs. In spite of their widespread distribution and unique characteristics, these mighty springs have been little studied from the standpoint of their water sources, the mechanisms by which they maintain their flow through periods of drought, and the characteristics of their supply systems.

Doll (1940) attempted to outline the catchment or drainage areas of many of these springs. He suggested that spring drainage transcends topographic boundaries, and concluded that part of the spring flow is derived from subterranean stream piracy. Bretz (1942) believed that the springs were outlets for phreatic cave networks which were still in the first stage of cavern development. The study of large springs has been hampered by the fact that until now there has been no opportunity to study their supply systems at first hand. Indeed, Bretz believed that the entire spring supply system was phreatic, with no air space, thus ruling out entry into a spring feed system without the use of diving apparatus. The first recognized entry into the supply system of a large spring occurred in March of 1955 (Hawksley and Vineyard 1956). The results of this and subsequent studies of a spring supply system are presented in this paper.

Cave Spring, on the Current River in Shannon County, Missouri, is a medium-sized spring as Missouri springs go. It ranges in flow from 16,000,000 to 47,000,000 gallons per day, according to Missouri Geological Survey records. Bretz, (1956) has described the spring in detail. It issues, at the base of a bluff, from the Potosi-Eminence dolomites of Cambrian age (Figure 1). The spring is at river level and is often flooded during high water. The apparent source of the spring water lies at a depth far below the river valley bottom. The spring basin is 77 feet deep. The water wells up from its deep-seated source through a shaft dissolved from the native dolomite. From all indications at the spring, the only way to examine the supply system would be with skin-diving equipment. However, about 300 feet downstream and in the same bluff there is a small cave, called Wallace Well, which leads back into the ridge as a very small, tubelike crawlway. Near the end of this passage, about 300 feet from the cave entrance, is a hole in the floor which apparently formed as a result of ceiling collapse in a chamber directly beneath. Looking through this hole one can see about 25 feet down to the surface of an underground lake having remarkably clear, green water. Although only 60 feet long and 20 feet wide, the lake is an astounding 58 feet deep!

One mile north of Cave Spring there is a sinkhole called the Devil's Well. The sink is about 40 feet deep. At the bottom, a hole opens into a huge chamber 400 feet long and 85 feet wide, with a vertical extent of 175 feet. This chamber is filled with water to a depth of 76 feet (Figure 2). There is a free drop of 100 feet from the sinkhole bottom to the surface of the underground lake. All outlets, except the sinkhole entrance, are below the lake level.

The location of these three units with respect to the local topography is shown in figure 3. A more detailed description of Cave Spring, Wallace Well and Devil's Well is necessary before conclusions can be drawn concerning their interrelationship.

Speleological investigation reveals a rather complex history. Cave Spring issues from a short, discontinuous section of a cave. Stalactites occur on the cave ceiling and there is a flowstone dome near the spring orifice. Bretz (1956) argues a phreatic origin of this cave. Nearby Wallace Well, except for the large lake chamber, is little more than a small diameter tunnel, yet it bears unmistakable evidence of phreatic development. Parts of it contain spongework; a small natural bridge has been left spanning the passage by waters which receded before they were able to complete their task. The tunnel is sealed off, just past the lake chamber, by a rising red clay fill. There are no speleothems in this part of the cave. On a level about 20 feet below the entrance to the lake chamber is a second passage, also a crawlway for the greater part of its length. This portion of the cave can be reached by descending a rope ladder to the lake, then using a small rubber raft to reach the second passage. Unlike the phreatic entrance tunnel, this corridor seems to have been carved, at least in part, by a vadose stream; a stream which is still very active after heavy rains. It contains no red clay fill and has been appreciably altered by the stormwater stream which now occupies the channel. This channel may be followed for about 200 feet before it becomes too small to allow further penetration. The third level in Wallace Well is far below the surface of the lake and, as we shall see later, links Cave Spring, and probably Devil's Well, with Wallace Well. Thus Wallace Well has at least 3 levels, one containing spongework and red clay fill, one now undergoing vadose enlargement, and one now in the phreatic stage, completely filled with water. This lowest level is now receiving sediment, possibly a clay fill like that which now occupies part of the highest level.

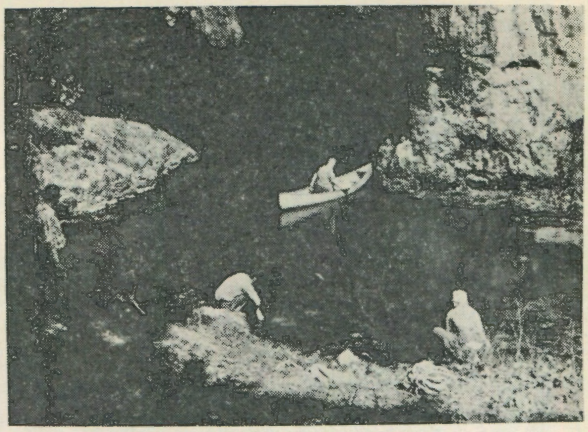


Figure 1
Checking dye tests at entrance to Cave Spring. Maximum flow of spring is 47,000,000 gallons per day.

Figure 2
Oscar Hawksley and Jack Reynolds taking water samples from the deep lake in the Devils Well. The lake, 76 feet deep is more than 125 feet below the surface.

The large lake chamber which integrates the three levels in Wallace Well is apparently excavated along a roughly east-west joint which is also reflected in Cave Spring. The walls of this chamber bell out from the top down, giving a bottle-shaped outline much larger at the bottom than at the top. The exact outline of the chamber can only be inferred. To get a better idea

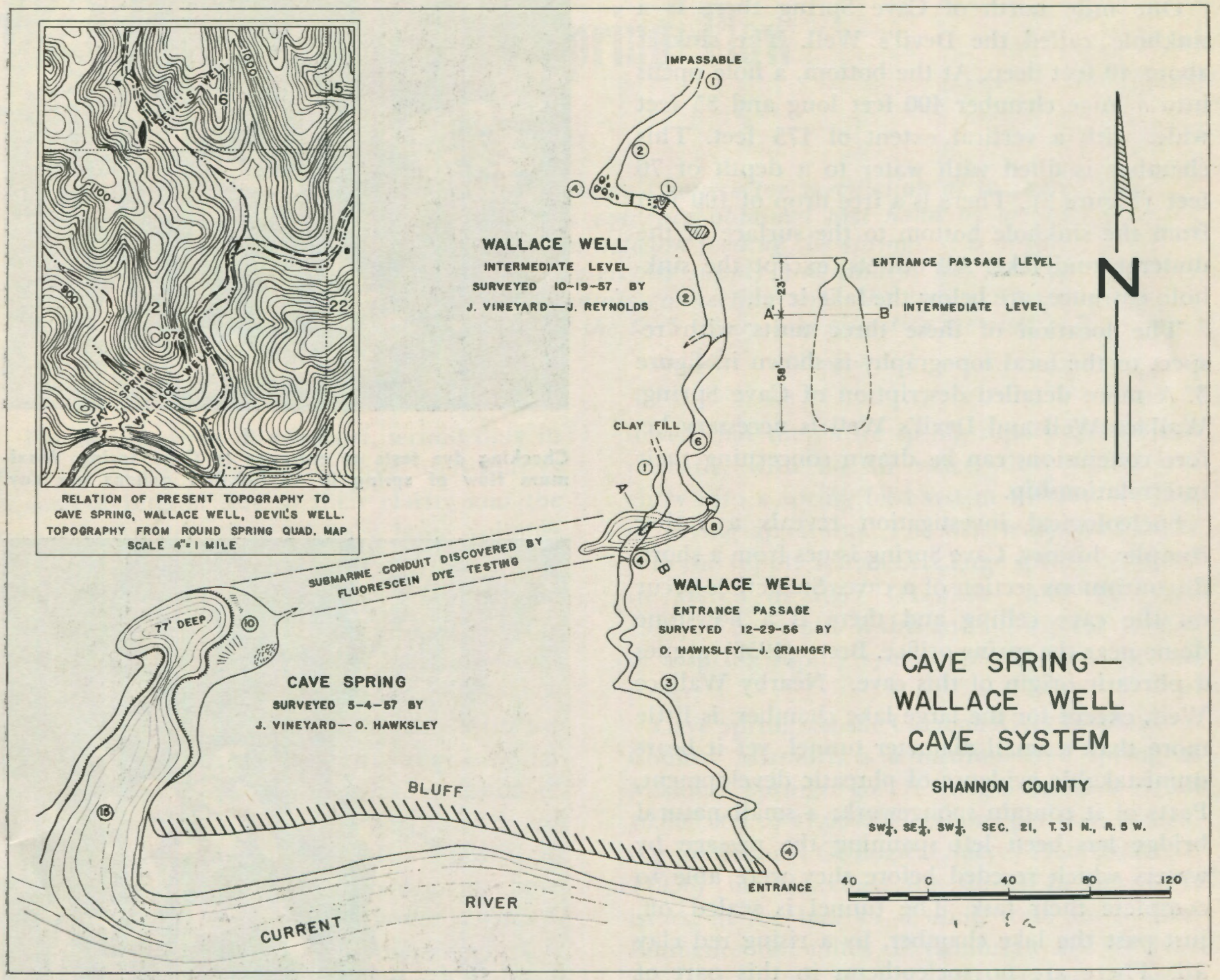


Figure 3
Map of Cave Spring—Wallace Well cave system.

of what this and similar chambers must be like, we turn to the Devil's Well, which is not only a large chamber but also has more of its walls exposed above the water surface.

In order to study the Devil's Well, one must descend via bosun's chair 100 feet to the surface of its huge underground lake. The trip down affords an excellent opportunity to study the walls and roof of the chamber. That collapse has played a major part in the formation of this room is quite apparent. Huge ceiling blocks have broken off in the past and fallen into the lake below to add to the debris accumulating at the bottom of the lake. Large, angular blocks still cling to the walls and ceiling in places, some apparently ready to fall at any moment. This collapse probably resulted from a combination of weakening by solution and by failure of ceiling beams and cantilevers as described by Davies (1951). Although collapse has contributed to the enlargement of the room, another agent must have done the initial excavating. Examination of the chamber walls reveals evidence of an entirely different nature. The walls are deeply eroded and pock marked (Figure 2), attesting to the dissolving power of ground water. Indeed, the enlargement by solution is still going on beneath the surface of the lake, and to some extent above the surface by water running down the walls. A north-south joint determines the trend of the chamber, and, like Wallace Well, Devil's Well in cross section is bottle-shaped; with the aid of spotlights the walls can be seen to bell out beneath the surface of the water.

It becomes apparent that these units must be integrated in some way, inasmuch as we have noted their similarities and their close geographical relationship. In order to definitely establish their integration, fluorescein dye was introduced into both wells. The first tests, however, were inconclusive. In searching for a reason for the failure, we noticed that the water in both wells had no observable current. Since the velocity of a fluid in a conduit varies with the size of the conduit, dye was introduced again, this time at the *bottom* of Wallace Well, where theoretically the spring's main feed conduit is located, and where the greatest velocity should occur. The results were conclusive. The dye came through within two hours, indicating beyond all doubt that Wallace Well is a part of the Cave Spring supply system and that the two are connected by some sort of conduit. The nature of this connection was further defined when a Hog Sucker *(Hypenetelium nigricans)*, a common fish in nearby creeks and rivers, was sighted in the deep waters of Wallace Well. The principle of deep-seated flow has not yet been applied in dyeing Devil's Well because of the difficulty of revisiting it, but it is assumed to be a part of the supply system in view of the other evidence supporting this hypothesis.

Thus is appears that Wallace Well and Devil's Well are huge storage reservoirs in the supply system which feeds Cave Spring. Other authors have suggested the presence of large storage reservoirs, but their work has been based largely on theory rather than on actual field observation. Beckman and Hinchey (1944) state that ". . . the continuance of rather large flows through months of drought indicates a very large storage capacity in the solution channels forming the underground drainage system. This does not mean necessarily that the water is stored in one huge lake or reservoir; it is more probable that the storage is in many small cavities, pools, and streams." Bretz (1953) believes that the springs, if drained dry, would reveal extensive, well integrated networks closely resembling and comparable in size to some of the large caves of the Ozarks. He also attributes the storage capacity to the natural characteristics of the rock and to the size of the spring network itself. He further states that the red clay fill, which he believes was deposited in all caves of phreatic origin during the second, or peneplain epoch of cavern development, is now being removed. However, it is difficult to imagine the removal of extensive clay fills by springs which are noted for their clear water.

In addition to serving as huge underground storage chambers, Devil's and Wallace Wells must also play a large part in producing the very clear, cold water for which Cave Spring, along with the other large springs, is famous. Hamilton (1949) said that "Under many conditions, muddy water pours into a cave and clear water flows out. This may be due to filter action, or more likely results from settling of sediments in areas of low velocity." Velocity is extremely low in these large chambers, so they are well suited to act as settling basins, removing sediment from incoming water. From all indications, this is a very important function. No less than four small springs, including one that issues from a vadose side passage similar to the one described in the intermediate level of Wallace Well, discharge directly into Devil's Well, as well as runoff water and debris funneled in via the sinkhole entrance. At least one vadose stream discharges directly into Wallace Well, carrying gravel, sand and silt. The two wells are in turn fed by submerged conduits bringing in water from widespread collecting points through the spring's supply system. This system must resemble a city water or sewer system, with its mains and laterals collecting and distributing water. Suspended particles remain in suspension as long as water movement and turbulence will support them, but will settle out if given a chance. Therefore it is probable that velocity in the feed system is too great to allow settling out in the conduits, but when the velocity decreases upon reaching a large chamber, part or all of the suspended load must be dropped. Consequently we can assume that sediment is now being deposited in the Devil's and Wallace Wells and in any other areas of extremely low velocity in the system, the criteria for deposition being whether or not the necessary conditions are met, rather than a specific period or epoch in cavern development. The entrance tunnel in Wallace Well received a red clay fill at a time when the lake chamber was completely filled with water, yet there is no evidence of a clay fill either in the portion of Wallace Well's lake chamber that is above water level or in the intermediate-level passage now being altered by vadose work.

Springs are noted for their relatively constant flow, but they actually fluctuate more than is generally supposed. Spring flow increases greatly after heavy rains and the water commonly becomes turbid. There is generally a short time lag between rainfall and rising springs, but in general springs exhibit remarkably good connections with the surface, indicating well developed drainage systems.

As might be expected, the storage-settling basins also serve as flood control agents. Water marks on the walls of Devil's Well indicate that the water level rises in times of heavy rain, and that water which accumulates faster than the spring conduits can carry it off, is stored. As Bretz, (1953) has pointed out, springs at flood stage, and some springs at all times, exhibit a "boiling" effect which occurs as a result of increased velocity of flow through the spring orifice. This phenomenon can be brought about by a series of storage-settling chambers similar to those in the Cave Spring system. When water enters the underground reservoirs faster than it can be removed by the spring conduits, the water level in the reservoir rises, increasing the hydrostatic head and forcing water through the spring network at a higher velocity. This greater velocity is manifested at the spring orifice as a "boil." When the velocity throughout the network increases, some suspended material is not allowed to settle out in the settling basins, so the spring becomes turbid. Increased velocity may also stir up sediment on the chamber floors where it has been previously deposited by settling.

Springs are much slower to return to their normal levels than are surface streams. Their flow may in part be derived from subterranean stream piracy, but most of it comes from water percolating down through the vadose zone. In times of drought the storage reservoirs regulate spring flow by collecting water from a wide area. The basins themselves have a tremendous capacity. The exact volume of the Devil's Well is unknown, since from all indications the water-filled portion is far larger than the air-filled part, but a rough estimate based on the water-level outline of the lake gives a figure of more than 20,000,000 gallons. Given several of these large chambers linked together into a spring network, it is not hard to see where part of the water comes from during dry seasons. However, such reservoirs cannot be completely drained, and cannot be construed as the only water sources during periods of drought. Rather, as the reservoirs are drained, the water table must drop correspondingly, and thus a far greater supply of water is made available for the mains and laterals of the spring supply system to bring into the storage reservoirs for delivery to the spring.

I wish to acknowledge the advice and encouragement given me by Dr. Oscar Hawksley, who also read the manuscript, and personnel of the Missouri Speleological Survey, who helped make possible the large and expensive operations necessary to enter and study the system, and helped in preparing the maps.

Summary

The supply system of a large spring, heretofore thought to be inaccessible, has been entered and studied. The results of this study have shown that the supply system is dominated by at least two, and probably more, very large storage reservoirs which collect water from a wide area and deliver it to the spring by a network of phreatic conduits. The reservoirs are multipurpose, serving as settling basins for removing suspended matter from incoming water, flood control agents, and as storage reservoirs which contribute to spring flow in time of drought.

It is hoped that this paper will provide the impetus for a closer study of the supply systems of large springs, with the consequent strengthening of the theory advanced in this paper.

Literature Cited

Beckman, H. C. and N. S. Hinchey 1944 The large springs of Missouri: *Missouri Geol. Survey and Water Res.*, 2d ser., vol. 29, 141 pp.

Bretz, J Harlen 1942 Vadose and phreatic features of limestone caverns: *Jour. Geology*, vol. 50, pp. 675-811.

——— 1953 Genetic relations of caves to peneplains and big springs in the Ozarks: *Am. Jour. Sci.*, vol. 251, pp. 1-24.

——— 1956 Caves of Missouri: *Missouri Geol. Survey and Water Res.*, 2d ser., vol. 39, 490 pp.

Davies, William E. 1951 Mechanics of cavern breakdown: *National Speleological Soc.*, Bull. 13, pp. 36-43.

Doll, W. L. 1940 Large springs, pirates of the Ozarks: *Missouri Acad. Sci. Proc.*, vol. 5, no. 4 p. 133.

Hawksley, Oscar and Jerry Vineyard 1956 Missouri spelunkers explore Devil's Well: *National Speleological Soc., News*, vol. 14, pp. 56-59.

Hamilton, Dan K. 1949 Hydrologic investigation of caves: *National Speleological Soc.*, Bull. 11, pp. 8-10.

Caves of Yucatan and Guatemala

By ARNOLD MEYERS

Our knowledge of caverns in the tropical regions of the Americas is very limited. What little data are available indicate that in size and number the tropical caves probably exceed those known in the temperate areas. Arnold Meyers of Trenton, Ontario has visited the caverns of Yucatan and Guatemala as a journalist with interests in geography and archeology. In his paper he presents an interesting introduction to the potentials of speleology in Latin America as well as an engaging narrative of his journeys.

Regional Geology

The Peninsula of Yucatan is almost entirely a flat plain of shallow soil. Approaching the central and southern regions, extending into Guatemala, the land rises very gradually and the soil becomes deeper and deeper so as to support the much larger trees of the rain forest. Beyond the rain forest and commencing rather suddenly is the huge mass of the Alto Cuchamatanes Mountains and beyond them the large interior plateau of Guatemala (fig. 1).

The rocks of the Yucatan Peninsula are late Tertiary and Quaternary in age. However, in Guatemala, even in the deep valleys of the mountains, there are no rocks younger than Tertiary limestones. Upon the slopes of the Cuchamatanes are outcroppings of metamorphic rock such as, talc, chlorite, gneiss, micaceous schists and phyllite. Curiously enough, a layer of chalk occurs all along the northern slopes of these mountains extending intermittently throughout the mountains of the Alta Verapez and into the Sierra de Santa Cruz above Lake Izabal. Chalk deposits also are at Tikal in the far north of Guatemala in the Petén jungle, which suggests the probability that the land between may contain a layer of chalk.

The plain which extends northward from Tikal is broken locally by the Sierra de Yucatan, two ranges of limestone hills that are less than 800 feet in height. The limestone in the hills differs from that of the surrounding plain in that it is fine, porous and subcrystalline while the latter is reddish in color and fairly compact. The limestone of the hills overlies semi-crystalline white or gray marble. It is also noteworthy that in the central part of the area between Yucatan Province and the highlands of Guatemala there are Quaternary deposits above the Tertiary, whereas no Quaternary has been found in the northern section.

History of Cave Exploration in Yucatan

The entire hill area of Yucatan abounds with caves known as "cenotes", or water caves; in addition the remnants of water caves occur all over Yucatan. Those cenotes occurring in southern Yucatan Province have been uplifted and are substantially dry today although many contain small pools of water known as *haltuns.*

The history of cave exploration in Yucatan goes back to John Lloyd Stephens' journey as ambassador-extraordinary to the newly formed Central American Federation. To him we owe practically the only known account of the remarkable cavern of Bolonchenticúl (Stephens, 1843).

To the superstitious inhabitants of the village of Bolonchenticúl, the annual appearance of water in all the nine wells of the plaza comes as something of a mystery. The wells are simply perforations across the irregular face of the rocks and are such that in the dry season a man can enter one and leave by another located at the greatest extremity of the plaza. The wells fill up during the rainy season from the percolation of surface water; but when this is ended, the waters begin to disappear and, since there is no observed subterranean stream involved at this level, it can be inferred that deep beneath the surface there is probably a large cavern into which the water descends through small openings in the well bottoms.

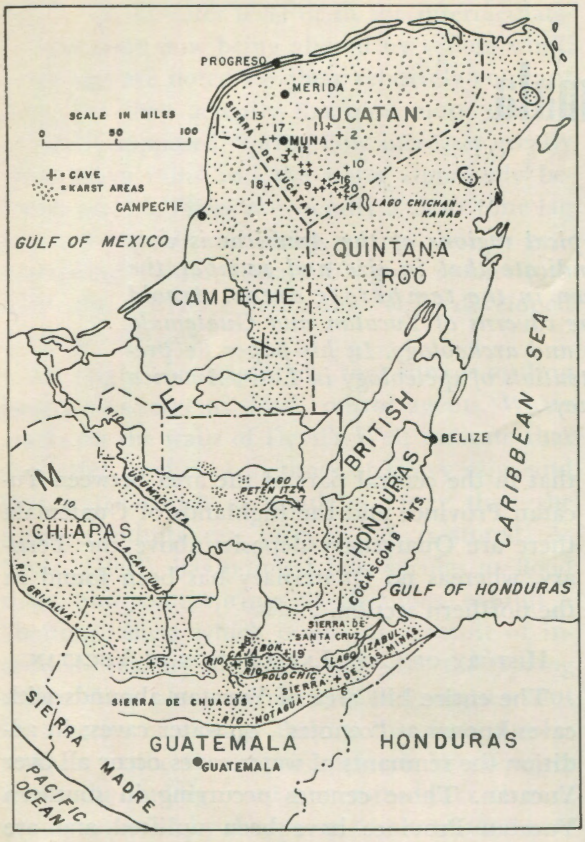


Figure 1
Caves and Karst Areas of Yucatan and Guatemala

1. Bolonchenticul	8. Languin	15. San Juan Chamelco
2. Cabachen	9. Loltun	16. Sitz
3. Chektaleh	10. Mani	17. Spukh
4. Coyok	11. Mayapan	18. Tabi
5. Cunen	12. Muna	19. Tequinco
6. Dona Maria	13. Oxkintok	20. Tuzul
7. Jobitzinaj	14. Sabaca	

The cavern of Bolonchenticúl extends far beneath the village from an opening located about 2 miles south of the village. One and one-half miles south along the paved highway to Campeche lies a wide path of orange-red earth which can be traced through the forest to a large open space. Upon the left is a hut and beside it a path passes to the brink of a wild, rocky depression at the deep end of which is the opening of the cavern.

Looking into the entrance of Bolonchenticúl is like looking into the gullet of some prehistoric monster. Anything more weird would be hard to imagine. The entrance is rough, jagged reddish rock and descends from one rock mass to another until the bottom is reached. All around is a play of colors in the protruding rocks — dark greens, metallic greens like that of weathered copper, red and yellows. A brilliant yellow-green stalactite is typical of this outstanding display. The cave is considered to be a holy place by the natives and inside the entrance to the right stands a cross of bold timber firmly set in the rocks. Here it was, according to legend, that a beautiful Mestiza maiden determined to adopt a hermit existence in the cave after an unfortunate love affair. For this reason the cave is known locally as "Xtucumbi Xunan" (Shtoo-coombee Shoo-nahn), Mayan for "Hidden Maiden".

The most notable feature of this great cave is the chamber containing a 210-foot pit which is bridged by a giant stairway, 78 feet in length and 12 feet in width made of wooden boughs.

Stephens, like myself at Loltún, entered Bolonchenticúl with Indian guides bearing torches of reeds. Stephens mentions specific distances. Seventy paces from the entrance a cut stone stairway 20 feet long takes one past a precipitous incline. A short distance further there is the edge of the chasm mentioned above. An immense roof of rock spreads overhead and all round appear remarkable formations of stone assuming all manner of fantastic shapes which might be likened to animals of a subterranean world.

Stephens reports that the stairs were repaired each year when the wells of the plaza in Bolonchenticúl began to fail. Indeed, they would need to be, for he mentions how one of his Indian guides had a narrow escape from certain death when one of the steps broke. Being placed there in green condition the withes dry, fray and rot.

Upon a designated day a fiesta is held on the platform at the base of the great stairway. The walls are decorated with branches, all is illuminated and the Indians come here with music and refreshment.

To one side of the platform is the beginning of another passage, inclined at a considerable angle at the end of which is another "suspicious" ladder. At the foot of this long ladder is a huge cavernous chamber from which different passageways lead to various pools of water. 75 feet further along two successive stairways are to be climbed, 9 feet and 5 feet, respectively, and on the other side of the latter another descends 18 feet. Two more descents are made, one of 11 feet and another, the seventh, of unknown length, and to use Stephens' own words, "whose length and general appearance induced us to hesitate for a moment and to enter into serious reflection."

This stairway extends over the wide and bulging surface of a rock, protected on one side by a vertical wall, and exposed on the other by an open precipice. Stephens and one companion passed this obstacle, but found themselves cut off from their associates. Advancing across a fissured passage brought them to an eight-foot stairway which led into another long passage. After a 300-foot crawl, they came to a large pool of water where they were about 1420 feet from the entrance and 450 feet below the surface.

After enjoying a bath in the pool, named *Chac-ha,* by the Indians, Stephens and his comrade returned to the broken stair where they waited until the Indians returned with a rope. They made their way back to the divergent passageways, followed one different from the one used coming in the cave and came to a pool 401 paces long. This is called *Puoul-ha* which means that the water has flowed and reflowed, like the sea.

While returning to the surface, Stephens found two more large pools of water and learned that all had been named by the Indians: the third is called *Sayab* which signifies flowing water; the fourth *Akab-ha* by reason of the obsecurity that reigns there; the fifth the *Choco-ha,* owing to the water always being hot; the sixth *Ooil-ha,* by reason of its milky color; and the seventh *Chimez-ha,* because it contains certain insects called "Chimez".

In 1895 the Corwith Expedition from the University of Pennsylvania investigated no less than 27 caves in the Sierra de Yucatan with a view to making excavations to determine whether or not any race preceded the Maya in Yucatan. Significant traces of human habitation were found in six caves: Sabaka, Oxkintok, Coyok, Tiplamas, Loltún and Chekt-a-leh. Of these six, three showed decisive results: Sabaka, Oxkintok and Loltún. Based on the findings in these three caves the following conclusions were reached:

1. The caves were not used as permanent dwellings, but rather as temporary halting places.
2. Human bones scattered about showed that the ancient Maya, at least at times, practiced cannibalism.
3. No people inhabited these caves prior to the Maya.
4. The caves were not used as burying places.

During the summer of 1936 the Carnegie Institution sent an expedition under A. S. Pearse (1938) to investigate the fauna of these caves. In addition, observations on archeology were made and various potsherds were found. Walls which cut off parts of caves and apparently served as defenses against enemies or animals were observed. The expedition also found carvings, bones, excavated holes in rock for catching drip waters, stone blinds for hunting birds, and carved steps.

It is to be noted also in the biological department, that, according to the above author, the caves of Yucatan contain bird ticks which carry the germs of relapsing fever and typhus. Mites are also present and they also transmit typhus.

I had not yet read the above references when I first determined to visit Loltun, but had only seen brief references in Terry's Guide to Mexico together with maps and a photograph in the Museum of Archaeology in Merida. Inquiries told me the cave was located 6 kilometers southwest of Oxkutzcab in the Sierra de Yucatan.

Unfortunately I was alone on this and some subsequent ventures, otherwise, much more might have been acomplished and more easily. In Oxkutzcáb, however, five boys offered to guide me to the cave which we reached after a hard tramp over sharp rocks. We pushed our way through the jungle scrub over several hills until, quite suddenly, we came upon a great jungle-clad depression. On the far side, I could see that the pit face was scarred with numerous dark openings, like a mouse-worried piece of cheese. Creepers dangled down the cliff face. Descending the rough carved steps, my boys cleared the way some distance up along the base of the cliff to disclose an ancient Mayan stone carving which I photographed. The figure depicted bore a ghoulish face surmounted by an ornamental headdress (fig. 2).

The cave entrance yawned before us, some 20 feet wide and 10 feet high. Climbing over and down the pile of talus, we found ourselves in a large room, topped by a wide dome perhaps 40 feet high. Facing us hung a curtain of large stalactites, all of a peculiar bluish-green color. Beyond these was the eternal blackness of the interior. My guides drew my attention to a pool of water on the right hand side of this chamber; its water was crystal clear.

Having ignited torches of wooden boughs, the boys led me past the curtain into a passageway with brownish walls. It was slippery underfoot, largely because of curious ripples crossing the corridor. Soon we climbed down an incline by crude steps carved in the rock into a gallery, its roof literally a forest of fat, bulky stalactites, all quite pointed. The roof was not particularly high, though we could easily stand upright and I remember wondering about the possible effects of an earthquake.

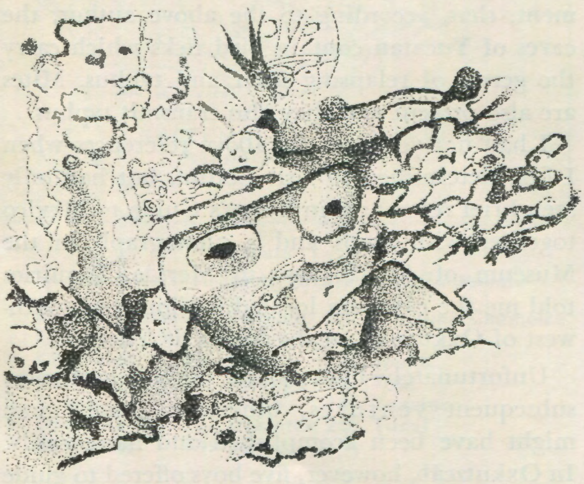


Figure 2
Mayan stone carving on cliff face beside entrance to Loltun Cavern, Yucatan.

We passed directly into a second chamber much larger than the first; here many stalactites had joined their stalagmite counterparts, forming fine columns; here we halted for a few minutes while my companions snuffed their torches by banging them on the floor. The resulting thunder, I was sure, would bring down the edifice about our heads! But they went right on with their banging, though the very floor seemed to shake and all was a bedlam of sound.

When my ears had stopped ringing, I noticed a carved stone basin close to the far wall. It measured 2 1/2 feet in length. I found it hard to understand why there should be a need for drip basins in a cave which already had a good source of water — unless the *haltun* was considered to be too near the entrance in time of danger.

No sooner had we left this gallery than we came to the edge of a great dark void, arising from which were tremendous boulders as far as the eye could see. I was to conclude later that here was part of the chasm that had stopped the H. C. Mercer party in 1895. The floor between the boulders was not particularly deep, probably no more than 15 feet, but one would have needed ample preparations for such a venture.

At this point my boys escorted me back towards the entrance, but going by a different route. And here I met the only part of the entire journey that came anywhere near being dangerous. We each had to jump the space between two huge boulders which was all the more treacherous by reason of the slimy character of the rocks. After handing over all my gear, however, it was managed without too much difficulty.

I wish to point out that whereas I entered Loltún from the north side (there are seven entrances), the Corwith expedition entered from the south via Tabi. Thus it was that they came to several large rotundas known as Alamos, arising out of which were many jungle trees. The centers of these openings were often filled with rock debris. They entered the cave via a carved rock stair and a crude wooden ladder.

Mercer (1895) relates how the Indians used to come daily to this cave for water. His expedition came to a rotunda 320 feet long by 290 feet wide, bearing symbolic rock carvings at four places on its walls. Certain masses of stalagmitic rock had been crudely chiselled into human shapes. The third chamber from the entrance yielded, just under the sky light, two rude statues on top of the central rock pile. Could this cave have been a training place for novice artisans of the ancient Maya?

Mercer and his men continued along a high gallery leading from the right of the rotunda entrance. They passed scattered potsherds, pools of drip water and came into a large vault of unknown height. From here the way was lost in a maze of enormous blocks which covered the floor, but along one side a narrow ledge came into view. Attempting to scale this ledge, Mercer soon found he had to crawl on hands and knees. Because of the danger of slipping, he had to return.

GUATEMALA'S CAVES MORE GRANDIOSE

In the mountains of the province of Alta Verapaz the chalk flanks the mountains. The provincial capital of Cobán is in the midst of a chalk area. Eastward at the village of San Augustin Lanqúin there is an abrupt change to Tertiary rocks and along the junction of these two sediments occurs the cavern of Lanqúin. I suspect the presence of many more caves in the mountains of the Alta Verapaz, but I know of only two more for certain: that of San Juan Chamelco located some nine kilometers southeast of Cobán, the cave being located a half day's march into the mountains. It is purported to be even larger than Lanqúin. The other cavern is below Tequinco and a stream that discharges into the Rio Cajabón issues from it.

Figure 3.
The triangular entrance to Lanquin in the Alta Verapez, Guatemala. Note the angle of incline of rock strata on the right. At a lower level, and about 30 feet to the right, the Rio Lanquin emerges.

The journey to the cave of Lanqúin was a test of gluteal endurance. I made the trip twice, once in a bus of ancient vintage, once in the rear of a half-ton truck with seven Guatemaltecos. The former method took 5 1/2 hours, the latter 3 hours, to cover the distance of about 42 miles from Cobán.

San Augustín Lanqúin village lies upon a plateau of low elevation in the center of a valley surrounded by steep 1500-foot hills. The cave is located about a 20-minute walk along the road which bears northwesterly from the village. A tiny lane, at the end of which is a thatched shelter for parking a car, leads towards the cave.

Following along a stony path which winds steeply, the bluish colored waters of the Rio Langúin are suddenly encountered. This river flowing 37,500 gallons per minute issues from a cave in Cretaceous limestone and flows around a 1000-foot hummock bearing northerly and southeasterly to join the Rio Cajabón.

At the point where we entered the cave it trended north. Streaming lianas fell over the entrance, streaming past the violently upended

Figure 4.
Curious flowstone formation in Languin, Guatemala.

rock strata, apparently part of a synclinal fold. From the roof of the triangular-shaped cave mouth pended dark gray stalactites. Climbing a short flight of wooden steps, we passed into a high chamber, the prevailing color being a very pale gray with a bluish cast (fig. 3). On the right we made our way down a cleated 8-foot plank which bridged a narrow fissure in the rock. Working our way carefully along a passage we

Figure 5.
Pipes and huge column in Lanquin, Guatemala.

observed a tremendous stalagmitic mass of unusual beauty. The lines of the mass flowed into one another with a subtlety quite defying description and resembled a collection of figures, some kneeling, others in the upright position like a composite statue (fig. 4). Various alcoves along our way were filled with bulbous shapes like strange vegetables or animals. Many of our number tried to photograph these wonders, but unfortunately my own flash bulbs were not strong enough to penetrate the distances of 25 and 30 feet. This corridor is called "Salle Blekú".

Climbing down an 8-foot declivity, we came directly into an enormous chamber, the roof of which is said to be 120 feet high. The light of our gasoline lanterns soon disclosed a 30-foot length of wooden stairway in good state of repair which led to the top of a platform known as "La Pelota". From the top there is a fine view of the entire gallery. When our guides turned their torches upon the roof, hundreds of bats took wing and flashed off into the darker recesses of the cavern, chattering with anger.

From this gallery the way led across a 15-foot chasm by means of a heterogeneous pile of mouldy logs. I didn't relish being first, but on the other hand, I didn't want to be last either. Next came another climb up an irregular wall and no sooner had we reached the top than it became obvious that we had to climb down the other side. This is typical of Lanqúin—up one wall, down another, as one passes a succession of chambers separated by partitions.

But the sight which we beheld from the top of this last wall was sufficient to hold us for a time in wonderment. The light of our torches disclosed a tremendously large stalagmite as large as the giant Sequoia of California. The dripstone hung upon it in folds and the modeling was quite as amazing as anything we had yet seen. From a giant base this marvel gradually narrowed as it reached the ceiling. Straight in front, in a niche in the wall, were a series of "pipes" for all the world like a pipe organ (fig. 5). Such was "Salle Cortinas."

After partaking of this scene we scrambled down the wall onto a wide ledge but were still about eight feet or more from the floor of the chamber and the only means of descent was a single pole with wooden cleats nailed at intervals along its length. This would not have been too bad had the cleats been securely nailed, but each had only one nail through it so it would turn when tread on. Once on the floor, we advanced through an area of unusually shaped speleothems.

By this time we had spent three hours in the cave and as Guatemaltecos always seem to start out for a cave in mid-afternoon (I cannot understand the reason for this) it was now 10:30 at night and we had not had supper. An argument ensued as to whether we should go on or return. The guide stood half way up a pile of rubble at the brink of another dark hole. Finally, the more sensible minds among our number prevailed. We would return.

So up the "greased pole" again. But this time our guide turned to the right and soon disappeared into a hole in the wall. One by one we did the disappearing act and when it came my turn, I found myself in a passageway which rapidly tapered to a hole little more than a crawlway. I forced my awkward knapsack around until it hung about my neck like the canteen of a St. Bernard and proceeded to crawl on hands and knees over boulders and treacherous little slipways, my hands invariably plopping down into something that felt like mud and all the while muttering things not too complementary about our guide. A few minutes later, however, I emerged into the first gallery again right near the entrance. Then we climbed out of the place, quite weary.

What a spectacle we must have made to any unseen observer! A long line of glowing torches issuing from the mouth of this great cave, passing gingerly from rock to rock and finally winding its way up the steep, rocky path to the road.

On the morrow my companions had planned to take a hike over the mountain containing the cave, to visit a small lake to the west of Lanqúin which is crossed by a natural bridge. I had previously determined to stay behind and do a painting of the cave entrance because I was disgusted at not being able to see the cave entrance in daylight on either of my two visits to the cave.

At long last we coaxed an Indian woman to prepare a snack for ten hungry spelunkers to which she responded with black coffee, frijoles, tortillas and sweet breads. I suppose I shall never know where I picked up the bug of infectious jaundice which was to lay me low three weeks later.

We slept that night on the cement floor of the Alcalde's office (the mayor), for there is no hotel whatsoever in San Augustín. If you go there, and think of staying awhile, you must be prepared to camp out. All water must be boiled and it is advisable to be inoculated against yellow fever because the altitude is comparatively low. Of course, Aralen tablets will ward off malaria. The weather is the most objectionable single factor in the Alta Verapaz, indeed, there is a popular quip in Guatemala: "It rains 13 months a year in Cobán!"

The Province of Alta Verapaz extends from the Rio Chixoy on the west to the center of the Sierra de Santa Cruz on the east and from the headwaters of the Rio de la Pasión on the north to a point just below the Rio Polochíc on the south.

According to Sapper (1894) the Rio Polochíc flows from its source in the highlands of Alta Verapaz to Lake Izabal. It has two tributaries of importance, the Rio Panima, which follows a simple fault and the Rio Cobán, which crosses Paleozoic, Cretaceous and Tertiary rock, respectively, and, after briefly cutting through a little limestone ridge, emerges as the Rio Cajabón, once more in Paleozoic rock.

Tributaries of the Cajabón are the Okeba and Tyalihux, the latter subterranean, discharging into the Cajabón near Seriquiche in a deep gorge; the Lanqúin, which pours from the Cavern of Lanqúin and of which various underground tributaries are suspected. Others are the Chiacam, the Chisay, and a small river which flows from a cave in early Carboniferous limestone below Tequinco and after a course of scarcely fifty meters, empties into the Cajabón.

The great English archaeologist, Alfred P. Maudslay, visited the cavern of Lanqúin briefly on his expedition bound for Tikal. He tells of seeing a small stream that disappeared in a deep valley as he neared Lanqúin. To the north he described a high range of mountains, apparently Santa Pocolhá. On descending through a gorge, the village comes into view and on the left he saw the lost stream bursting from a cliff. He reasoned that a large tract of land must be drained through subterranean channels to supply all this water.

The cavern of Lanqúin has had one major attempt to explore it completely. But just how much of its was explored the world at large probably will never know. In the days before the last world war a German-Guatemalan, Professor Helmuth Sapper is known to have spent 15 days in the cave and to have penetrated a distance of 75 kilometers. If this is true, it makes the cave a major one, possibly one of the world's largest. But the facts are that in 1943, when Nazi activities were rife in Guatemala, the government seized all German owned lands. The Sapper rancho was among these. The family was dispossessed, and the Professor's manuscript fell into the hands of ignorant Indians who destroyed it. It is a tragic thing that such valuable scientific data is lost after so much hard work. There is a challenge here for some person or persons of initiative to organize an expedition to explore, map and otherwise study Lanqúin as well as other known caves in Guatemala.

References

Mercer, H. C. (1895) Hill Caves of Yucatan: J. B. Lippincott Co., Philadelphia.

Pearse, A. S. (1938) Fauna of the Caves of Yucatan: Carnegie Institution of Washington.

Sapper, Carl (1894) Grundzüge der physikalischen Geographie von Guatemala: Petermanns Mitteilungen Ergänzungsheft nr. 113 (Ergänszungband 24), pp. 110-114.

Stephens, John Lloyd (1843) Incidents of Travel in Central America, Chiapas and Yucatan, Vol. 2.

An Initial Survey of Caves of the Hawaiian Islands

By WILLIAM R. HALLIDAY

Dr. William R. Halliday, while on duty with the U. S. Navy, traveled extensively in the Pacific. His visits to the little known cavern areas of the Pacific islands have extended our knowledge of speleology to many places of scientific interest. The lava caves of Hawaii have received little attention in the past even though they are in an area that is renown for its volcanoes. This paper outlines the interesting potentials of speleological research on these volcanic islands.

The Hawaiian Islands are almost entirely composed of volcanic rocks, which accounts for the fact that lava tubes and sea caves are predominant. Due to the heavy rainfall, the vesicular basaltic lava — which is rich in calcium, magnesium, and iron but low in silica, — is rapidly decomposed. Lava tubes are to be found, in general, only in the more recent flows. Harold S. Palmer, Professor Emeritus of Geology at the University of Hawaii, points out that entrances of tubes on the older islands, such as Oahu, are commonly found on steep slopes. This is in contrast to lava tube areas in the Western United States, and also to the tubes on some of the young and still growing surfaces of Mauna Loa and Kilauea.

Sea caves of all sizes are widely scattered around the periphery of the islands. A small amount of limestone of emerged coral reef origin is present, and contains evidence of solution. A collapse sink, for example, has been reported at Laie (Stearns, 1939), and Dr. Palmer has seen a three foot stalactite said to come from a cave in the emerged reef of the Ewa coral plain. Stalactites not originating in caves are also found on Oahu, however (Stearns, 1939).

CAVES OF OAHU

The island of Oahu has few caves if sea caves and blow holes are excepted. Sea caves of moderate size are developed in the Honolulu volcanics near Koko Head, and elsewhere. Dr. Palmer reports that in the 1920s a very short lava tube, 20 feet in diameter and about 40 feet long, was found on the slopes east of the east end of Kahaloa Drive in Honolulu which might still be enterable. Submitted to his files was an old sketch map of a Judd Street Cave in Honolulu. The map, however, shows a plan suggesting artificial excavations by children rather than a lava tube. Apparently its exact location is not now known.

Tourist guide books mention Pohukaina Cave in the ridge above Lae o ka oio, north of Kualoa on the northeast side of the island. Despite rumors that this is an immense cavern, Dr. Palmer is skeptical that this is more than a small fissure.

The most important cave on the island appears to be Makua Cave, also known as Dry Cave or Kaneana (Cave of the god Kane). Many legends are attached to this roadside cavern, just as in the case of the cave at Kualoa. It was given cursory study by Stearns (1939), but still presents interesting problems in speleogenesis.

Makua Cave bears south-southeast into the base of a volcanic cliff on the western shore of Oahu, about four miles from the northwest tip of the island. Stearns placed it "in the heart of the Waianae Dike Complex". He deduced that the cave had been formed by wave action along "a fault crack" and the margins of two parallel, cross-jointed, resistant dikes which are prominent at the entrance of the cave. This would have occurred during the period when the sea was rising to and falling from a level 95 feet above present sea level. The floor of the entrance is 55 feet above sea level, but Stearns found the elevation of the main room only about 30 feet above sea level. A large amount of talus has been removed to lower the entrance to the road level.

One dike is two and a half feet wide and forms the northeast side of the cave. The other, Stearns notes, is four feet wide, but pinches out upward along the southwest wall. This wall consists of an eight foot thickness of olivine aa lava, overlain by 25 feet of pahoehoe, which is in turn overlain by additional pahoehoe. On the south side of the northern dike, he postulated the existence of a slight downthrow.

The pattern of the cave is fairly simple, but interesting. The entrance portion is about 40 feet in width, and an estimated 50 feet in height. After about 75 feet, its vault arches downward rather abruptly to a nine foot ceiling height. Beyond that point is a higher Y-shaped chamber.

To the left and a little higher is a low passage, semiovoid in section and thus more like a lava tube than a littoral cave. It terminates in a crawlway and a small, damp, narrow chamber 193 feet from the entrance. In this terminal area are coarse coralloids of both lava and a calcareous substance, together with a minor vein of an opal-like material. A peculiar speleothem tentatively called "melt-cups" by the writer in the apparent absence of a standard term also occurs in this section of the cave. They consist of occasional, very thin horizontal ripple-like ridges on vertical lava surfaces, each ridge about 1 cm in length and protruding 1 mm from the wall. The appearance of cup-like tiny gours that are also present suggests some minor remelting of the surface, causing a small downward flow before resolidifying. Some of these cups, however, are slightly translucent, and may prove instead to be secondary mineral deposits.

The southern half of the main chamber has an upper and a lower division, so that its section approximates a figure 8 with a small lower loop. The upper area is reached by a narrow ledge leading to a low crawlway in a chamber of moderate size, characterized by a level calcareous floor. Near the farthest point reached is a narrow chimney, morphologically similar to a chimney of a limestone cavern.

The main lead descends into the Beer Can Crawl, where a twisting corridor leads to the farthest point of the cave, 364 feet from the entrance. At the end of this crawl is a wide, very high chimney that has obviously been climbed in the past. Cave visitors reported that a chimney in the north lead connects to the surface, but Beer Can chimney is more likely the one. The climb appears to be a ticklish one. "Melt-cups" and coralloids are also apparent in the farthest recesses of this moist passage. Near its end, the floor appears to consist of a tongue of lava, separated from the walls by contraction fissures. At the end, it has the appearance of a permissively intruded flow without alteration by marine erosion. Perhaps the lava tongue was formed subsequent to the littoral development of the cave.

There are thus several features of the cave which suggest the presence of considerable heat after development of the cave. Such a conclusion however, implies relatively recent volcanic activity in the Waianae Range — a conclusion not in concurrence with current geologic opinion. Dr. Palmer points out: "Presumably the Waianae Volcano became extinct long before the Koolau Volcano, which had been deeply eroded before the eruption of Diamond Head. Then there was a long wait until sea level rose enough in the 'climatic optimum' for the formation of the reef rock that is now emerged". He also points out that had there been recent volcanic activity, additional features should be present. It might be mentioned, however, that the writer has observed what appear to be thin dikes of a reddish igneous rock in the emerged coral shelf just northwest of the Nanakuli beach, which, if confirmed, would also fall into the category of recent volcanic activity.

A very interesting feature of this most remote passage is the occurrence of vertical tubes developed in the lower part of this presumed lava tongue and in a large, irregular block in the center of the passage. An inch to more than a foot in diameter, they are round in horizontal section, though some are superimposed upon others causing some irregularity. They possess vertically grooved walls much like those in larger vadose shafts in horizontal limestones (Pohl, 1955), and are probably the result of water action. Each is below a potential drip-point, and some show a small splash cup at the bottom. The development of the splash cup is probably the first step in the evolution of these tubes. Subsequently, decomposition of the walls by the splashed water trickling down produces their enlargement. Stearns noted their occurrence and states that they are found in white coral sand which is coated with black tufa, resembling basalt.

The floor of the cave varies considerably. Calcareous sand predominates just beyond the Beer Can Crawl. Elsewhere, lava cobbles are prominent or exclusive. The floors of the upper passages are far more consolidated and level than that of the lowest passage. Stearns has noted local tufa deposits up to several inches in thickness, which appear to be in addition to minor calcareous speleothems of more usual origin. Their source mineral is readily dissolved out of the basalt and can be precipitated just as in a limestone cavern.

OTHER ISLANDS

No field investigations were carried out by the writer on other islands of the Hawaiian group. Two important sea caves are to be found on the north shore of *Kauai* near Haena. They are called Wet Cave and Dry Cave. Dr. Palmer describes Dry Cave as having an entrance 25 feet high and 120 feet wide. It extends back 250 feet, with an extension to the left about 150 feet long. The smooth floor slopes inward slightly, and is only a few feet above sea level. Wet Cave appears to be smaller; at sea level, it is cut off from the sea by a talus ridge.

On the island of *Hawaii,* especially in the Mauna Loa, Kilauea and Puna flows, there are many major lava tubes. Their locations and natures are best known to the staff of Hawaii National Park. In the center of the rugged eastern half of Molokai, road maps show a Malahini Cave. These maps also show a Holua Cave within Haleakala "Crater" in the *Maui* section of Hawaii National Park. Dr. Palmer thinks that this may be a lava tube formed since development of the huge depression, but has never seen it. Other lava tubes should exist within the flows on the flanks of Haleakala. Sea caves are well developed on the islets of *Kaula* and *Lehua* (Palmer, 1936). Of all the islands, therefore, only Hawaii appears of real speleological promise, though most of the others show isolated features of interest.

ACKNOWLEDGMENT

Material for this report was obtained through two visits to Makua Cave, bibliographic research in Honolulu, surface reconnaissance on Oahu, aerial reconnaissance of major parts of the eastern islands, marine reconnaissance of minor parts of the western islands, and several discussions with Dr. Harold S. Palmer, to whom I am greatly indebted for much of this information as well as for reviewing the first draft of this report.

BIBLIOGRAPHY

Palmer, Harold S. (1936) *Geology of Lehua and Kaula Islands:* Bernice P. Bishop Museum, Occ. Papers, vol. 12, no. 13, pp. 1-36.

Pohl, E. R. (1955) *Vertical shafts in limestone caves:* Nat. Speleological Soc., Occ. Paper No. 2, April.

Stearns, Harold T. (1939) *Geologic map and guide of the island of Oahu, Hawaii:* Div. Hydrography, Terr. Hawaii, Bull. 2.

Use Of Decamired Filters in Cave Photography

By HOWARD N. SLOANE

Filters for color films to fit all conditions of lighting met with in caves and karst areas have always been a problem with speleologists. The Decamired system recently introduced commercially offers the speleologist a system of addative filters that should correct for any condition of light. Howard Sloane presents here the practical aspects of Decamired filter in cavern photography gained from use in caves and based on a background of many years of cave exploration and photography in the Appalachians.

At the outset it should be stated that under all conditions of photography a minimum use of filters should be employed. Nevertheless, no branch of color photography entails more difficulties under unique conditions, than cave photography.

The first major difficulty confronting the cave photographer employing color, is that of attempting to standardize the use of his film and light. Unfortunately, without great expense, this is rarely possible. The photographer wishes to record, if possible on one camera, indoor cave pictures and outdoor cave entrances. He is faced usually with other photographers present, perhaps using blue bulbs when he is using white or strobe, or using daylight film when he is using tungsten. Never, it seems, do all photographers have the same film and the same light source at one time, so that 'riding' the lights of the other photographer is possible.

Recently the manufacturers of filters have devised a system which inexpensively answers all color balancing and conversion filter problems. This system is called the *Decamired* system or principle. Filters for this system are made by most manufacturers of filters and complete sets of filters are available at prices ranging from $8.00 to $16.00.

The advantages of the *Decamired* system are not solely those of price. It is not necessary to be a color balance technician in order to employ the system to advantage. Nevertheless, some explanation of the principles behind the system is in order.

Every photographer knows that different types of film have different Kelvin temperatures. Likewise every source of light has a different Kelvin temperature. Unless these temperatures are in balance, off-color pictures will result. For this reason film manufacturers have different types of film for daylight, tungsten, floodlight, etc. Each film is balanced for a specific color temperature for a specific grade of light. The present 81 and 82 series and other filters commonly used for color balance present an inherent problem: that is, that they cannot be used in combinations because their degree of effect on color temperature varies at different color temperature levels. For example an 82C filter used at 3200 degrees would raise the color temperature 400 degrees. But at 5500 degrees it would raise the temperature 550 degrees.

The *Decamired* (DM) filters employ a new principle based on the reciprocal of the color temperature. For example, the DM value of Daylight Kodachrome (balanced for 5500 degrees Kelvin) is 5500 degrees divided into one million = 181 Mireds. 181 Mireds divided by 10 = 18 DecaMireds. (the fraction is dropped). Likewise the DM value for all films and light sources can be determined and designated by a similar number. These numbers are given below.

The DM filters consist of two sets of filters. One set has three filters in the reddish (R) or warm colors valued at R3, R6 and R12. Three others are the bluish (B) or cool colors and are valued at B3, B6 and B12. The B or the R filters can be used in combination with each group but not together. That is, it is possible to get an R9, an R15, an R18 or an R21, or similar combinations of the B filters, depending on the conditions that prevail or upon the film characteristics of either present film or any new type film that may be made in the future.

It is not necessary to have all this information however in order to properly use the filters. In Table A below appears the Film Type Ratings. In Table B below appears the Light Source Ratings. For the information of the reader the Color Temperature (Degrees Kelvin) is given in both tables but all that is necessary is the DM Value. With this information any type of color film that happens to be in your camera can be used with any type of light source that happens to be available merely by employing the proper filters. The filter adapters are made to hold three filters, all that are necessary under any condition.

To use the filters merely refer to the DM Tables below and determine the DM value of your light source. Subtract this DM value from the DM value of the film. The difference is the required DM Filter value. If the subtraction results in a positive (+) number, you use the R or warming filters. If the subtraction results in a negative (−) number, use the B or cooling series. If the result is such that no combination of filters fits it exactly simply use the next *lowest* filter combination. For example for a − 14, use a B12. For a +10, use R9.

Finally, refer to Table C for the DM Exposure Increase Guide and change the exposure as indicated.

It can be seen that any combination of film and light can be used without changing film or camera. A few examples will illustrate. Assume that you have been using Kodachrome F in an undeveloped cave and you later stop at a commercial cave which has formations lighted by floodlight. The DM value of Kodachrome F is 26. The DM value of the commercial cave lighting system is 29. Subtracting 29 from 26 gives you minus 3 which means that a B3 filter will correct your film for this picture. Another illustration, you have been photographing a cave using Kodachrome F and upon emerging from the cave you wish to take a picture of the cave entrance which at this time is in sunlight at about 2 P.M. in the afternoon. Kodachrome F is rated at DM 26. The sunlight is rated at DM 18. Subtracting 18 from 26 gives a DM value of

TABLE A

FILM TYPE DM VALUES AND KELVIN RATING

Film Type	Color Temperature (Kelvin)	DM Value
Daylight Type	5500	18
Anscochrome, Ektachrome, Kodachrome, Super Anscochrome		
Flash Type	3800	26
Ansco Flash, Ektachrome F, Kodachrome F		
Photoflood Type	3400	29
Anscochrome Tungsten, Kodachrome A		
Tungsten 3200 Type	3200	31
Ektachrome B, Anscochrome Tungsten Sheet, Super Anscochrome Tungsten		

TABLE B

LIGHT SOURCE RATINGS

Light Source (Average Ratings)	Color Temperature (Kelvin)	DM Value
Household Tungsten Lamps (40-60 Watts)	2760	36
Household Tungsten Lamps (100 Watts)	2860	35
Studio 3200 Lamps	3200	31
Photoflood Lamps	3400	29
Clear Flash Lamps	3800	26
Blue Flash Lamps	6000	16
Electronic Flash	6500	15
Sunlight (9 AM to 3 PM)	5500	18
Sunlight (other times)	5000	20
Light Overcast Sky	7500	13
Hazy Blue Sky	9000	11
Blue Skylight (Shadow)	12,000	8
Clear Blue Sky	25,000	4

TABLE C

DM EXPOSURE INCREASE GUIDE

R Series	*F Stop*	*B Series*	*F Stop*
R3	1/3	B3	1/2
R6	1/2	B6	1
R3+R6=R9	5/6	B3+B6=B9	1 1/2
R12	1	B12	2
R12+R3=R15	1 1/3	B12+B3=B15	2 1/2
R12+R6=R18	1 1/2	B12+B6=B18	3

plus 8 so an R6 filter can be used to correct the color. A final illustration is a case in which Kodachrome F was in a camera in use in a cave and it was desired to ride your companions strobe light. The film is rated at DM 26. The Strobe is rated at 15. Subtracting 15 from 26 gives a DM value of +11. In this case R3+R6 filters (= R9) are used. In all instances do not forget to increase the exposure as indicated on the chart C. It should be noted that all filters are clearly marked to indicate their value.

The DM values indicated are accurate for all practical purposes. However, in cases where *extreme* color accuracy is required, a Color Temperature Meter calibrated in DecaMireds can be employed. The need for such a meter in cave photography, or for all ordinary photography, is not great enough to justify the expense, in the opinion of the writer.

The writer recently photographed the same subject 80 times using four rolls of twenty exposures, one each of Kodachrome F, Kodachrome Floodlight, Anscochrome Daylight and Super-Anscochrome Daylight. He took 5 pictures on each roll in daylight, floodlight, clear flash bulbs and blue flash bulbs, using the indicated filters from Tables A and B in each case, with the correct increase in exposure. Seventy five of these pictures cannot be told one from the other, either in color correction or exposure. Five of the Super-Anscochrome slides were over exposed in one series, probably due to an error in the F stop.

The use of *Decamired* filters seems to be the cavers' answer to carrying an assortment of different types of film and light, at a minimum of expense.

IN PRESS FOR FORTHCOMING ISSUES

WILLIAM E. DAVIES	Conservation of surface features in karst areas
G. E. GATES	Earthworms of North American caves
HUNTLEY INGALLS	Cass Cave
DAVID B. JONES	Telephone circuits used in Flint Ridge exploration
RAYMOND G. KNOX	The land of burnt out fires (Lava Beds National Monument)
BRIAN J. O'BRIEN	Caves of Australia (Second in a series of "get acquainted" articles)
LEIGH READDY	Observations on cave pearls in California
T. R. SHAW	Recorditis
PATRICK H. WELLS	Bear bones from a Boone County, Missouri cave

Index of Bulletins One Through Twenty of the National Speleological Society

By GEORGE F. JACKSON

In the preparation of the index, space limitations made general groupings necessary, as for example, all living cave organisms mentioned in the bulletins have been listed under either "flora" or "fauna". In the case of the author's biography the most recent is listed.

In some fields the language of speleology is often ambiguous and vague and the user's indulgence is begged for seeming contradictions in such areas and for any errors or omissions in the index.

The numbers of Bulletins are listed in bold face type, page numbers in regular type.

NATIONAL SPELEOLOGICAL SOCIETY PUBLICATIONS

The following publications are available from the office secretary of the Society and are paper bound unless otherwise noted.

Prices are correct as of November 1958 but are subject to change.

BULLETIN NINETEEN — October 1957 — 48 pages $2.50

Flint Ridge, Kentucky — Earth fills and clay minerals, Carlsbad Caverns — Rillenstein in Greenland — Caverns of West Virginia.

BULLETIN EIGHTEEN — December, 1956 — 56 pages 2.50

The Hell Hole in the Muota Valley — New Caving Techniques — The Leather Man and His Caves — St. Michaels Caves — Blind Fishes — Prospecting for Caves — Discovery at Fontana Christaina — Eagle Lake Lava Caves — Cave Description of the 17th Century — Principals of Effective Organization — After Glow of Calcite.

BULLETIN SEVENTEEN — December 1955 — 48 pages 2.50

Caverns of St. Thomas — Saltpeter Mining Tools used in caves — Magnetic Cave, the Wonderful Hoax — Caverns and Related Features of Michigan — Proposed Classification of Physical Features found in Caves — Recent Explorations in Floyd Collins' Crystal Cave.

BULLETIN SIXTEEN — December 1954 — 96 pages 2.50

The Speleo-barometer — Ice Cages of the United States — Caves of the U. S. S. R. — Origin and Development of Caverns in Indiana — Development of Caves in Middle Tennessee-Mineralogy of New River Cave — Origin of Sea Caves — Pleistocene Ecology of Cumberland Bone Cave — Caves of Indiana.

BULLETIN FIFTEEN — December 1953 — 144 pages 3.00

The Caves of Pennsylania — Contains Special Articles on Geology, Fauna, Fossils, Commercial Caves, and Descriptions of 264 Individual Caves — 83 photographs — 46 maps.

BULLETIN FOURTEEN — September 1952 — 64 pages 2.00

A Survey of Bat Banding in North America — The Guacharo Cave of Venezuela — Hydrologic and Atmospheric Studies in Schofer Cave — Lava Caves in Central Oregon — Origin of the Palettes in Lehman Caves, Nevada.

BULLETIN THIRTEEN — December 1951 — 64 pages 1.50

Techniques for Dating Cave Deposits — Caves and Rockshelters in Southwestern Asia — The Cave Salamanders of California — Mechanics of Cavern Breakdown — Southwestern Caves as Books of History.

BULLETIN TWELVE — November 1950 — 86 pages 1.50

Ozark Cave Animals, Living and Fossil — West Virginia's Schoolhouse Cave, with map and 10 drawings — Ice Caves — Bats — Cave Mineralogy — Cave Mapping — and Other Articles.

BULLETIN ELEVEN — November 1949 — 75 pages 1.50

Formation of Saltpeter in Caves — Saltpeter Mining — Alaskan Burial Cave — Cave Sicknesses — Fluorescein Tests — Safety Procedures — Cave Rescue Organization — Cave Breakdown — Anthodites — A Stormwater Cavern.

BULLETIN TEN — April 1948 — 137 pages 3.00

The Caves of Texas — Location and Description of 175 Caves and Rockshelters — 80 photographs — 12 maps — Archeology — Paleontology — Mineralogy — Geology — Biology — History — Folklore Cloth 3.50

BULLETIN NINE — September 1947 — 84 pages.......... 2.50

Cave Photography — Britain's Biggest Cave — Cave Diving — Breathing Cave — Caves in the Bible — Cave Mapping — Application of Geophysics to Speleology

BULLETIN SEVEN — December 1945 — 84 pages.......... 2.00

Cavern photography — Observation on Cave Life — Cave of the River Styx — Subterranean Adventures — Speleological Equipment — Formation of Stalactites and Gypsum incrustations — Notes on collecting Cave Spiders.

BULLETIN ONE (REPRINT) — June 1940 — 66 pages 2.50

Descriptions of numerous caves in Virginia and West Virginia.

BULLETINS NOT ON THIS LIST ARE OUT OF PRINT

OCCASIONAL PAPERS

Number 2. Vertical Shafts in Limestone Caves — April 1955 — 24 pages .... .40

Number 3. Notes on the Plethodontid Salamanders *Eurycea lucifuga* (Rafinesque) and *Eurycea longicauda longicauda* (Green) — November 1956 — 24 pages .... .40

NOTE: a 50-cent discount on all BULLETINS is Granted to NSS members.