

# THE NSS BULLETIN

*Quarterly Journal of  
The National Speleological Society*

Mapping and Measuring Caves

CLAUDE CHABERT AND RICHARD A. WATSON

Groundwater Pollution

ARTHUR D. BOSNAK AND ERIC L. MORGAN

Color in Speleothems

WILLIAM B. WHITE

VOLUME 43

January, 1981

NUMBER 1

# CONTENTS

Mapping and Measuring Caves, A Conceptual Analysis  
 Claude Chabert and Richard A. Watson ..... 3

Acute Toxicity of Cadmium, Zinc, and Total Residual Chlorine to  
 Epigeal and Hypogean Isopods (Asellidae)  
 Arthur D. Bosnak and Eric L. Morgan ..... 12

Reflectance Spectra and Color in Speleothems  
 William B. White ..... 20

## BOARD OF EDITORS

*Life Sciences*—FRANCIS G. HOWARTH, Bernice P. Bishop Museum, Box 19,000-A, Honolulu, Hawaii 96819; *Social Sciences*—GEORGE HUPPERT and BETTY WHEELER, Geography Department, University of Wisconsin at LaCrosse, LaCrosse, Wisconsin 54601; *Exploration*—JOHN MYLROIE, Department of Geosciences, Murray State University, Murray, Kentucky 42071; *Earth Sciences*—WILLIAM B. WHITE, Materials Research Laboratory, 210 Engineering Science Building, The Pennsylvania State University, University Park, Pennsylvania 16802; *Anthropology*—PATTY Jo WATSON, Anthropology Department, Washington University, St. Louis, Missouri 63130; *Conservation*—THOMAS LERA, P.O. Box 1051, Desoto, Texas 75115; *Computer Applications*—ROBERT B. HOKE, 8727 Hay Shed Lane #12, Columbia, Maryland 21045.

### EDITOR

JAMES HEDGES

Big Cove Tannery, Pennsylvania 17212

### Business Office

NATIONAL SPELEOLOGICAL SOCIETY

Cave Avenue, Huntsville, Alabama 35810

*The NSS Bulletin* is published quarterly, in January, April, July, and October. Material to be included in a given number must be received at least 90 days prior to the first of the month in which publication is desired. The subscription rate in effect 1 August 1975: \$10.00 per year.

Discussion of papers published in *The Bulletin* is invited. Discussions should be 2000 words or less in length, with not more than 3 illustrations; they should be forwarded to the appropriate editor within 3 months of publication of the original paper.

A voluntary contribution of \$25.00 per page is solicited from authors after their manuscripts have reached page-proof stage. This represents about one-quarter of the cost of publication.

All issues through Volume 40 (1978) are copyrighted © by The National Speleological Society; the photocopying or reproduction, or recording by any electrical or mechanical process of any issue still in print is a violation of copyright, unless prior permission has been granted. However, abstracts, figures, and tables may be freely copied by anyone so long as proper credit is given.

Beginning with Volume 41 (1979), the complete issues are still copyrighted © by The National Speleological Society. Individual papers, however, may be in the public domain, copyrighted by the NSS, or copyrighted by the authors, personally (but with the right to grant permissions for non-profit use delegated to the NSS). The copyright status of each paper is given on

its first page. No copyrighted paper still in print may be photocopied or reproduced, or recorded by any electrical or mechanical process without prior permission; permissions for the commercial use of papers copyrighted by their authors *must* be obtained from the authors. As previously, abstracts, figures, and tables may be freely copied by anyone so long as proper credit is given.

A catalog of issues still in print and their cost can be obtained from our Business Office at no charge; facsimile copies of out-of-print issues can be supplied for a nominal fee.

The "fair use doctrine" permits free copying for scholarly or educational purposes, the above conditions notwithstanding.

Copyright © 1981 by the National Speleological Society, Inc.

Entered as second-class matter at Huntsville, Alabama and at additional mailing offices.

Graphic Publishing Co., Inc.  
Lake Mills, Ia. 50450

# MAPPING AND MEASURING CAVES

## A Conceptual Analysis

CLAUDE CHABERT\*

47 rue de Sablière, 75014 Paris, France

RICHARD A. WATSON\*

Departments of Philosophy and of Earth and Planetary Sciences  
Washington University, Saint Louis, Missouri USA 63130

**SPELEOLOGY** is a sportsman's science, the science of exploring caves to discover their geologic and geographic settings, the processes that form them and their features, and the flora and fauna that occupy them. To study these things a scientist must go into caves, and there he must crawl and climb, activities that cavers do for sport. In a cave, scientists must make maps and measurements, for maps are the grids on which scientists locate their discoveries and communicate them to others. Thus, cartography is the basic science, essential to all of speleology.

The father of modern speleology was both a sportsman and a scientist. Between 1888 and 1913, E.-A. Martel mapped many caves while he explored them, for scientific study, and to record their lengths and depths. His maps are the essential foundation and the model for speleology in Europe, as well as for the rest of the world. The key to his success was his immense enthusiasm for caves and his devotion to work, but the most important message he had for all cave explorers is: *Map while you explore.*

In 1948, James Dyer, William T. Austin, and Luther Miller started the modern era of cave exploration in the United States by exploring and mapping in Floyd Collins' Crystal Cave, Flint Ridge, Kentucky. With the encouragement of E. R. Pohl, Philip M. Smith established the Cave Research Foundation in 1957 with a primary goal of mapping the caves of Mammoth Cave National Park and the Central Kentucky Karst. With Dyer and Austin, Smith developed a system of team mapping and documentation so that hundreds of people—everyone who explored in the caves—could contribute to surveying and mapmaking.

Explorers connected the Flint Ridge Cave System to Mammoth Cave in 1972, and they mapped the connection during the discovery trip. At that point more than 232 km of interconnected cave passages had been mapped, making the newly established "Flint Mammoth Cave System" nearly twice as long as any other mapped cave in the world. Today (1981), over 350 km have been mapped in the system, and there is potential for at least 150 km more. But the essential point here is that

when John Wilcox and his team of explorers mapped the connection on the first exploration trip through it, they were following the tradition of the originator of modern speleology.

Also starting in the 1940's, Alfred Bögli in Switzerland initiated a system of integrated exploration and mapping in Hölloch, for many years the longest surveyed cave in the world.

In 1965, at the Fourth Congress (Ljubljana, Yugoslavia) of the International Union of Speleology, Hubert Trimmel formed the Commission for the Largest Caves. Ever since Martel there has been interest in the longest and deepest caves. Particular attention was paid in 1965 to how the length of the then-longest surveyed cave in the world, Hölloch, was mapped under Bögli's direction, and to how the depth of the deepest surveyed cave in the world, Pierre St. Martin in the Pyrenees on the border between France and Spain, was measured by the many people who had worked there.

Trimmel began setting international standards for mapping and measuring caves. And most cavers today do measure the depth of caves in the same way. However, there are at least three distinct methods used for determining the length of caves, with the greatest gap existing between the two systems of *linear development* used by most Europeans and the system of projected *map length* used by North Americans and some Europeans.

The result is that figures given for the lengths of caves in different parts of the world are calculated by diverse systems, making comparisons difficult

### SUMMARY

A cave is an enclosed space in three dimensions. *Cartography* is the basic science essential to all of speleology. *Caves should be mapped* during their exploration. *International standards* of mapping and measurement should be established. Scientists should choose *systems of mapping and measurement* that best facilitate answering the questions and solving the problems they set themselves; sport cavers should choose systems of mapping and measurement that best show the distances they must travel to set the records they are interested in.

*Map length* is distance measured along the projection onto a horizontal plane of all the horizontal components of all cave passages and shafts. *Depth* is distance from highest to lowest points inside a cave measured along the projection onto a vertical plane of only the vertical components of all cave passages and shafts. A *genetically continuous* passage or shaft is one whose origin was temporally and processually the same throughout its length. *Linear development* is distance measured along axes oriented parallel to the trends or longitudinal directions of all genetically continuous passages and shafts whatever their inclinations. For *continuous linear development*, the longitudinal axis of each passage or shaft is extended until it reaches a bedrock or debris termination or connects with the longitudinal axis of another shaft or passage. For *discontinuous linear development*, the longitudinal axis of each passage or shaft is extended until it intersects another genetically continuous shaft or passage. *Volume* is the cubic measure of the enclosed space of a cave.

and sometimes impossible. The problems that arise from using different systems, and problems specific to each system, were discussed in 1977 at the Seventh Congress (Sheffield, England) of the International Union of Speleology. It was decided there that international standards for cave mapping and measurement should be set at the Eighth Congress (Bowling Green, USA).

In this paper, we outline problems that must be solved at the 1981 Congress. We state principles, clarify primary concepts, offer definitions and rules, and suggest how to solve some of the problems. In particular, we show that the ambiguity of such terms as 'length' derives from the different senses given to these terms by sport cavers and cave scientists. By focusing on the measure of vol-

\*Président, Commission des Grandes Cavités, Union Internationale de Spéléologie.

†Past-President, Cave Research Foundation.

§See: *The Longest Cave*, by Roger W. Brucker and Richard A. Watson (NYC, Knopf, 1976).

ume as the ultimate goal of cave scientists and on the measures of *depth* and of greatest *linear development* as the ultimate goal of sport cavers, we show how to eliminate much of the confusion and conflict that has been apparent in previous discussions. It is our hope that the present discussion will facilitate the establishment of international standards of cave mapping and measurement in 1981.

other two axes then extend horizontally.

Although caves are in three dimensions, they are usually represented in two dimensions. That is, their dimensions and locations are shown on maps, longitudinal sections, and cross sections, which are planes. Thus, if a cave is mapped by taking measurements along the three axes oriented in the conventional way, then a longitudinal section in a vertical plane such as Figure 1a

$A'F' = XY$ .

Usually, longitudinal sections do not show width, but sometimes, as in Figure 1a, the other horizontal dimension is sketched in to show the width, as at location B'B where the width is EE'.

The length of the cave on this scheme is  $AB' + BC' + CD'$ . Note that as height or depth is measured on a vertical line, length and width are measured on horizontal lines. If the cave is not

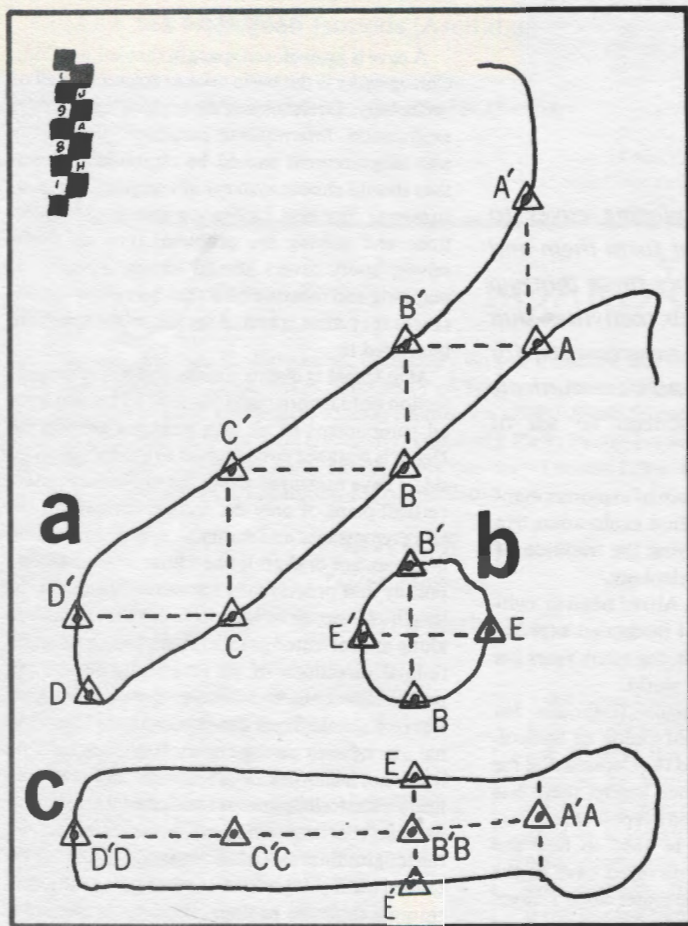


Figure 1. (a) Longitudinal section (vertical plane), (b) cross section (vertical plane), (c) map (horizontal plane).

**A CAVE IS AN ENCLOSED SPACE IN THREE DIMENSIONS**

*The Map Length and Depth of a Cave*

One goal of speleologists is to provide an exact description of the three-dimensional space enclosed by each cave's boundaries, and another is to map each cave with relation to the surface of the Earth. These goals are attained using measurements made in the cave in three dimensions, conventionally: depth (height), width, and length.

In ordinary topographic mapping on or with relation to the surface of the earth, these three dimensions are measured along three axes set at right angles to one another, i.e., the standard three-dimensional Cartesian coordinates of solid geometry. One axis is extended vertically along a line from the center of the Earth to the zenith. The

can be drawn to show the location of the cave in the rock and with relation to the surface. In Figure 1a, AA', BB', CC', and DD' show the height of the cave at various places, and  $AA' + BB' + CC' + DD'$  is the total depth of the cave. Note that the height of the cave at any point inside the cave is a component of its total depth.

The absolute depth of a cave without consideration of horizontal components is also shown on longitudinal sections such as in figures 1a and 2a. That is, the *depth* of a cave is the absolute distance between the highest point inside the cave and its lowest point, measured by projecting the vertical components onto a vertical plane without consideration of the horizontal components, as in Figure 2a. Note that the depth of Figure 2b is exactly the same as that of Figure 2a, i.e.,  $AB + CD + EF =$

straight, additional longitudinal sections may be required.

Figure 1b is a cross section in a vertical plane showing the height BB' and the width EE' at location B'B. When the dimensions of a cave change often, many such cross sections are necessary to show the shape of cave passages. To show the shape of vertical shafts, cross sections can be taken in the horizontal plane. Thus, a cross section such as in Figure 1b could be of a shaft. Cross sections of horizontal passages do not show length, and cross sections of shafts do not show height or depth.

Figure 1c is a map in a horizontal plane which shows the relation of the cave to the surface. Here,  $AB' + BC' + CD'$  is projected onto the horizontal plane of the map, and thus this measure is

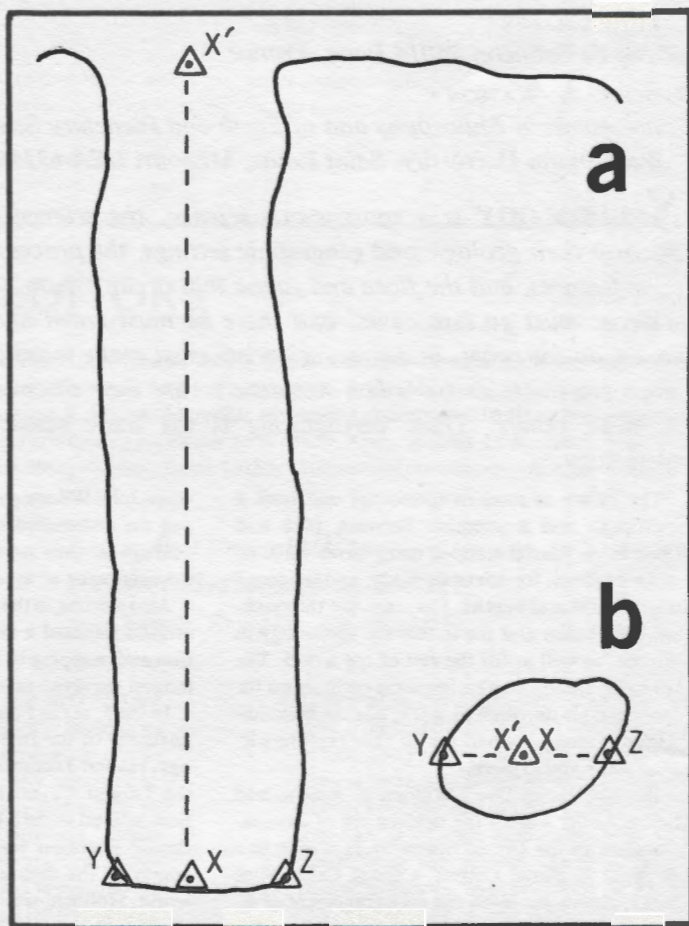


Figure 3. (a) Longitudinal section, (b) map.

known as the projected *map length*. Simple maps such as Figure 1c do not show height or depth.

Clearly there is an analogy between the measurement of *depth* and the measurement of *map length* as here defined. Both are projected onto a plane. However, map length is projected onto a horizontal plane without consideration of vertical components, and distances are measured along all horizontal components, whatever their compass orientations. On the other hand, depth components are projected onto a vertical plane without consideration of horizontal components, but distance is measured only along one line, the vertical. So map length gives the horizontal distance along all passages projected onto the horizontal plane, while depth is a measure only of their vertical components projected onto the vertical plane.

Occasionally a winding passage is projected onto a longitudinal section in a vertical plane in analogy to projection onto a horizontal map plane, and sometimes a winding passage with many horizontal bends is "stretched out" in representation on a vertical plane as though it were straight, and

along an axis oriented parallel to the trend or longitudinal direction of any genetically continuous passage or shaft. (A passage or shaft is *genetically continuous* if its origin was temporally and processually the same throughout its length; this definition is probably adequate for the present purposes, but see our further comment on p. 10 col. 1.) The linear development shown in Figure 1a is thus AD.

Linear development is a concept quite different from that of projected map distance. Both are one-dimensional (linear) concepts, but map length is on a line confined to the horizontal plane, whereas linear development is on a line that follows the actual orientation of cave passages or shafts in three-dimensional space. Both map length and linear development can be determined from a longitudinal section such as Figure 1a, but only map length can be determined from a simple map such as Figure 1c.

Thus, in the case of a vertical shaft of uniform dimensions, say 100 m deep and 10 m wide, the *linear development* (distance along the longest

coordinates along the three axes.

Whatever the orientation of the passage or shaft, the *width* axis is by definition whichever of the two shorter axes is closer to horizontal orientation, and the *height* axis whichever of the two shorter axes is closer to vertical orientation. If one rotates Figure 4 in various directions, then one can see the infinite number of possible orientations of the three-axis framework. Obviously these concepts of height and width are equivalent to the conventional notions of height and width (represented when one axis—the height axis—is oriented vertically so that the width axis is exactly horizontal) only when the orientation of the passages and shafts are exactly horizontal and vertical, and when the dimensions are uniform, or the two shorter axes are extended exactly horizontally and vertically.

Volume can be determined if the three axes are oriented conventionally (one always vertical and the other two always horizontal), but the number of measurements that would be required in inclined passages, shafts, and horizontal passages of greatly varying width and height would be greatly increased, and the calculations would be more complicated, than are required if the axes are oriented parallel to the trends of passages and shafts as described in the present section.

Finally, to determine volume, linear development is measured according to a scheme which excludes counting any space more than once. This measure is called *discontinuous linear development* (DLD) because it results in gaps in the line of development throughout a cave. This can best be shown by means of diagrams. In Figure 5, taken either as a longitudinal section or a map, the discontinuous linear development is  $AB + CF + GH$ . *Continuous linear development* (CLD) is  $AD + CF + EH$ , that is, continuous linear development includes the distances BD and EG, whereas discontinuous linear development does not. It is obvious that if continuous linear development were taken as a base for calculating volume, some parts of the central space would be counted twice, thus giving an incorrectly large figure for the volume.

It is worth illustrating this difference with several more simple diagrams (figs. 5 to 10), all of which can be taken either as maps or as longitudinal sections:

In Figure 6, DLD is  $AC + DE$ ;  
CLD is  $AB + BE$ .

In Figure 7, DLD is  $AB + DE$ ;  
CLD is  $AC + DE$ .

In Figure 8, DLD is *either*  
 $AC + DE$  or  $AB + CE$ ; CLD is  $AC + CE$ .

In each case it is obvious that only discontinuous linear development provides a proper base for calculating correct volume. It is also obvious that discontinuous linear development is always less than continuous linear development except when a cave consists of a single shaft or passage, as in Figure 9. In Figure 9,  $DLD = AB$ ;  $CLD = AB$ ;  $DLD = CLD$ .

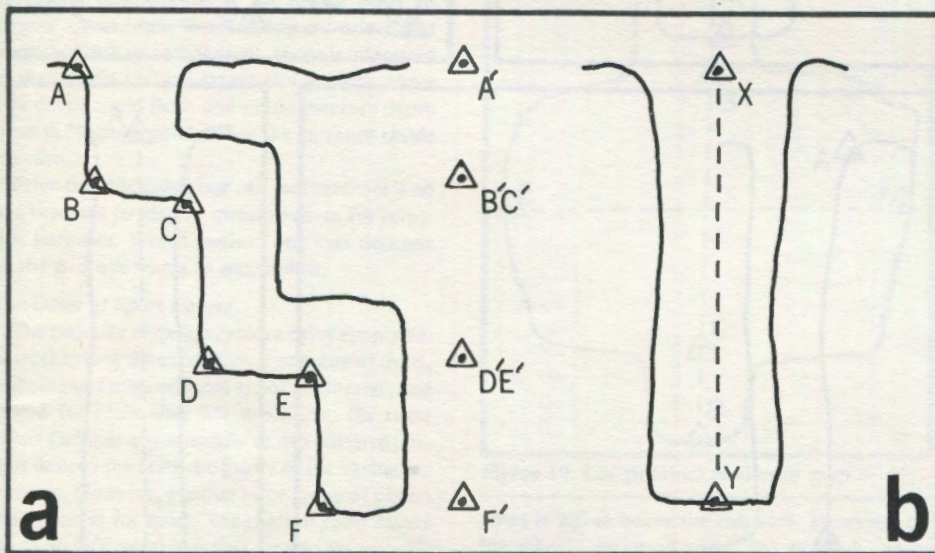


Figure 2. (a) Longitudinal section, (b) longitudinal section.

(similarly) sometimes a passage with many vertical ups and downs is "stretched out" in representation on a horizontal plane as though it were horizontal. It is not necessary for us to go into detail about these specialized forms of representation here.

**The Linear Development and Volume of a Cave**

Most passages and shafts are not exactly horizontal or vertical, but are inclined. The projected map length of a cave, then, is always less than the distance along the inclination of passages and shafts except for horizontal passages. Thus, in Figure 1c, the map length of the cave shown in longitudinal section in Figure 1a is  $AB' + BC' + CD'$ , which is less than the distance along the slope of the passage, which is AD. The measure along a slope or inclination, or, in technical terms, *linear development*, by definition is the distance

axis oriented parallel to the trend of the shaft) is 100 m, whereas the *map length* projected onto a plane is only 10 m. In Figure 3a, the linear development is X'X, and the map length is YZ, as shown in Figure 3b. Note that for a shaft of uniform dimensions, Figure 3b could also serve as a cross section of the shaft.

The *volume* of a cave is the cubic measure of the space enclosed. The best way to measure the coordinates for determining volume is to orient one of the three Cartesian axes parallel to the trend or longitudinal direction of a passage or shaft, *i.e.*, extended along the trend of linear development. The other two axes are then at right angles to this. One of the latter two axes should be extended parallel to the longer of the two cross section dimensions, and the other along the shorter. Volume is then calculated by multiplying the distance

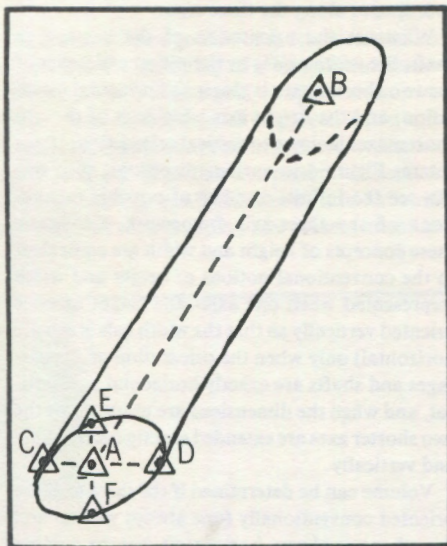


Figure 4. Three-dimensional representation.

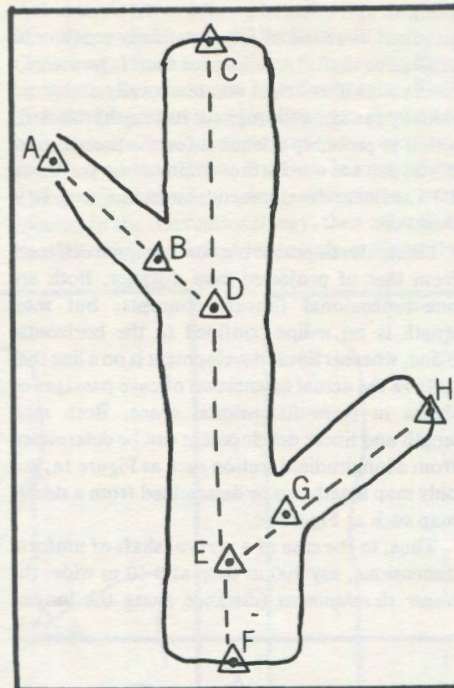


Figure 5. (right) Longitudinal section.

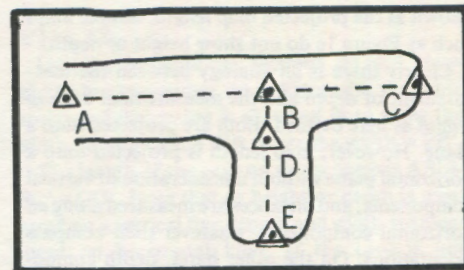
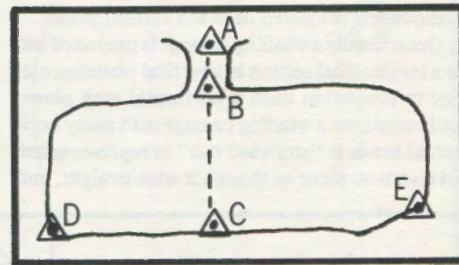


Figure 6. (above) Longitudinal section or map.

Figure 7. (below) Longitudinal section or map.



Some cavers argue that when the dimensions of a passage or shaft such as shown in Figure 9 are above a certain large size, continuous linear development should be  $AB + CD$ . However, this is to forget that linear development (whether continuous or discontinuous) is a measure along only one dimension or axis of any genetically continuous shaft or passage (or room). *Linear development is a one-dimensional concept*, just as volume is a three-dimensional concept. Either  $AB$  or  $CD$  can be counted, but not both.

Some cavers also raise questions about whether or not the width or height of a very large room should be included in linear development. Obviously they should not be if the room is genetically continuous with the passage or shaft that leads to it. This is particularly obvious when *discontinuous* linear development is being measured for the purpose of calculating volume, for then the height and width of large rooms are measured as height and width. It is also wrong to measure as part of *continuous* linear development, the width of rooms (no matter how large) that are genetically continuous with the passages and shafts that lead into them. Remember, only one dimension—distance along only one line—that along the longest axis or along the trend or inclination—can be measured as a part of either continuous or discontinuous linear development in any genetically continuous passage, shaft, or room.

Thus, in a situation like that shown in Figure 9,  $CD$  is never a part of linear development. And in a situation like that shown in Figure 10, if the passage or shaft is genetically continuous, linear development is  $AD$ , not  $AD + EF$ .

However, if the big room in Figure 10 is genetically separate from the smaller passage or shaft,

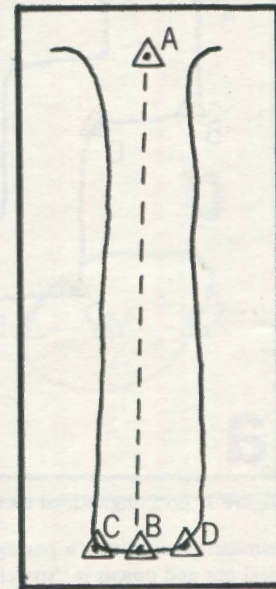
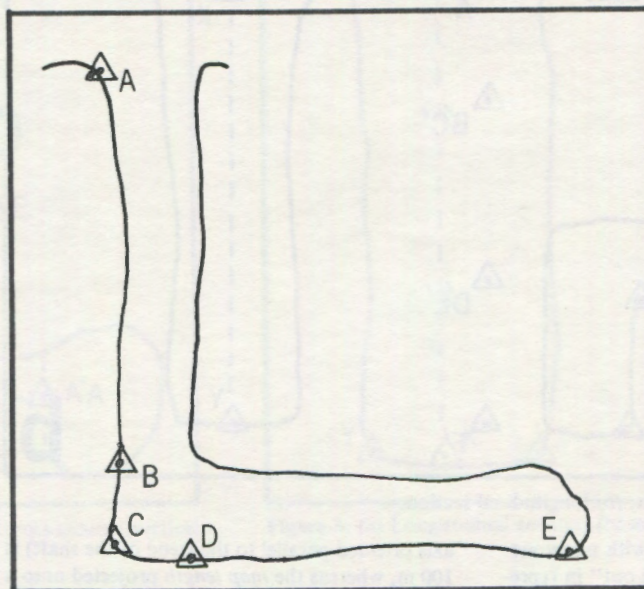


Figure 8. (left) Longitudinal section or map. Figure 9. (right) Longitudinal section or map.

*e.g.*, is formed by a diacase at right angles to it, then discontinuous linear development is  $AB + EF + CD$ . And in this case, continuous linear development is  $AD + EF$ . Note that both continuous and discontinuous linear development may vary depending on whether or not the room is measured as genetically continuous with the passage or shaft that leads into it. But even if the discontinuous linear development on the one measure is different from that on the other, *i.e.*, if  $AD \neq AB + EF + CD$ , the volume calculated from  $AD$  will still be the same as that calculated from  $AB + EF + CD$  as base.

### WHAT SHOULD BE MEASURED?

#### The Goals of Cave Scientists

In the mapping and measurement of caves, an underlying goal of scientists is accuracy in description and representation. For this, different schemes serve different purposes. Thus, if the purpose is to show exactly where underground voids exist with relation to surface features, map projections are best. Longitudinal sections best show the distances of underground voids below the surface, and also the lines along which water flows. Cross sections show the contours of cave passages and shafts.

If a scientist is interested in the volume of a cave, the mapping of discontinuous linear development provides the best base for calculation. Also, orientation of the three Cartesian axes along the trends of the passages and shafts for the measurement of *width* and *height* as described above is better than measures along axes oriented vertically and horizontally as in conventional topographic mapping.

If a scientist is interested in maximum distances of possible water flow, then the best measure is continuous linear development. The use of projected map distance would be misleading here, for it does not show vertical flow lines at all, and gives shorter distances than are actually traversed in all cases except for caves consisting only of horizontal passages.

On the other hand, the depth of a cave taken as the absolute distance between the entrance or the highest point inside a cave and the lowest point—something hydrologists need to know—is measured by projecting the vertical components onto a vertical plane without consideration of the horizontal components. If the lowest point of present water input is the entrance, one might measure depth from that point. If one is interested in the longest vertical extent along which water ever did or could flow, one would measure depth from the highest point above the entrance inside the cave.

From this discussion one can see that there is no one best way to map or measure caves for scientific purposes. Which method one uses depends on the goal one wants to accomplish.

#### The Goals of Sport Cavers

The majority of cavers explore caves simply because they love the experience. For many of them, mapping and measurement are of no interest, and indeed for some they are anathema, for these cavers feel that any scientific or quantitative pursuits destroy the aesthetic purity of the caving experience. However, another large group of cavers explore caves for sport. The goals of sport cavers are to do difficult things well, and to set records. The records sport cavers are most interested in setting have to do with length and depth. Can a certain cave be pushed longer or deeper? What is the longest cave? And the deepest?

If one is to keep—and set—records of length and depth, caves must be measured and mapped. What are the best systems for these purposes?

**Depth.** There seems to be little question about the measurement of depth. It is measured by projecting the vertical components of cave passages and shafts onto a vertical plane with no consideration of the horizontal components as shown in figures 1a and 2a. This is the same measure of depth that scientists use. The main question that arises is about whether depth is from the entrance to the lowest point, or from the highest point inside the cave above the entrance to the lowest point. The most reasonable answer to this question derives from the fact that, by definition, sport records are set only through actual explora-

tion by cavers. For a depth or length measure to count, a caver must have traversed it. Thus, it seems reasonable to conclude that if explorers have reached points inside a cave higher than the entrance, the depth of the cave should be measured from the highest point inside the cave. This is in analogy to how the lowest point for the measurement is set, that is, by actually being reached by explorers. A further argument for this conclusion is that most cave entrances are accidental in the sense that they are established by the vagaries of erosion and tectonics.

Even so, some cavers are interested in how much of the vertical extent is above, and how much below, the actual entrance. To record such information, they establish the entrance as a zero datum, then record vertical distance above the entrance as + and vertical distance below the entrance as -. Thus, in Figure 11, the highest point in the cave is 65 m above the entrance, and the lowest

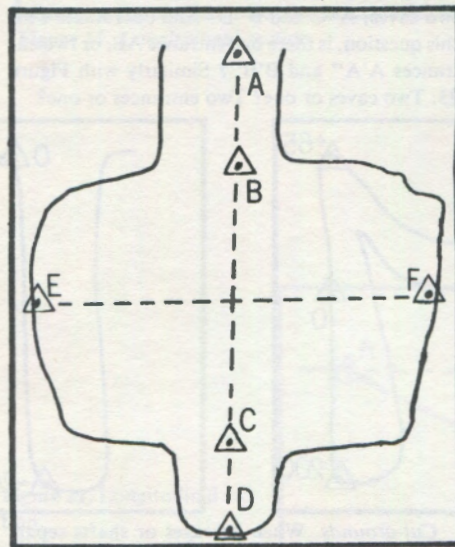


Figure 10. Longitudinal section or map.

point is 200 m below the entrance. However, on the scheme we recommend, the caves shown in figures 12 and 13 are the same depth as the cave shown in Figure 11, even though this depth is represented in one instance as (+65, -200), in another as (-265), and lastly as (+265). The crucial point is that to explore (and thus to record) the vertical extent in each of these three caves, cavers must go downward 265m. That one must first go up 65 m in the cave of Figure 11, and up 265 m in the cave of Figure 13, is incidental to the primary feat of descending 265 m at some time in each cave.

**Length.** There is some contention among sport cavers about how to measure the length of caves. Is it the distance shown by map projection, or by linear development? And if by linear development, is it discontinuous linear development, or the longer continuous linear development? We believe the key to answering these questions again lies in considering just how cavers go about establishing length. That is, just as depth is established

by the actual descent of explorers, so also is length set by explorers actually traversing the passages being measured. And the lines along which they travel are those of continuous linear development. Thus, we believe that the length of caves for sport records should be measured by the scheme of continuous linear development—along the actual pathways that cavers explore. (This is also the line that interests hydrologists, *i.e.*, along which water does or could flow.) This includes the actual distances travelled along inclined passages and up and down shafts (and not merely *depth* as defined above, which is derived from, but which is almost always shorter than, actual distances traveled downward in caves).

Now we can solve a problem that has long bedeviled cavers. Should one count as part of the length and depth of a cave, passages and shafts which can be observed and measured in some way, but which have not actually been visited by cavers? The answer is that for scientific purposes, it would be absurd not to include these *known* distances. In hydrology, *e.g.*, the important thing is to give measures of length, depth, and volume that are as close to the known dimensions of the cave as possible. And in the gathering of this data—so long as it is accurate—it is incidental whether or not a caver has actually traversed the lines measured.

For sport caving, however, the whole point of depth and length measures is that they show the records of where cavers have actually been. So if one can see and measure a shaft, *e.g.*, that no one has gone down, that distance does not count in sport cave depth. One may know that a cave is 100 m deep, but only if someone *visits* the bottom can a sport caver say that—for the record—it is 100 m deep.

Thus, *scientific lengths and depths* are figures that we can *know* without visiting all of the cave known. *Sport cave lengths and depths* are figures recording only those parts of the cave actually visited by explorers. Most lists of long and deep caves give sport cave figures that in some cases are less than the scientifically known lengths and depths of the described caves.\*

## BOUNDARIES

### Entrances, Open Voids, and Cut-Arounds

A cave is an enclosed space in three dimensions, but there must be an opening into it if we are to explore it. Thus, questions are raised as to exactly where a cave begins. Where is the cave entrance? The answer to this question is important to the determination of all the measures discussed herein: depth, map length, linear development, and volume.

We offer here some definitions for discussion. They need discussion because of certain problems, some of which we describe below.

\*On the other hand, Tony Waltham, *e.g.*, thinks length should not be down the long axis of a passage containing huge boulders, but the distance cavers travel to get up and over and down the boulders. We believe this would allow too many arbitrary additions.

**Horizontal entrances.** For measuring map length and linear development, an entrance surface at the terminus of a basically horizontal passage is established in a vertical plane at right angles to where the roof begins.\* Figure 14 illustrates a simple case. The entrance is at AA'. Figure 15 presents a similar case with the entrance beginning at AA'. Some might argue, however, that it is at BB'. The problem is more obvious in Figure 16. Is the entrance at AA' or at B'B''? According to the definition, it is at AA', but there is clearly ground for argument.

Now what about depth? Considering depth to be measured from the highest to the lowest point inside the cave, in Figure 14 (if the entrance is the highest point inside the cave), depth would be measured from A. Figure 15 also presents no problem, for A and B are at the same elevation. In Figure 16, however, the choice makes a big difference, for if AA' is taken as the entrance, the cave is much deeper than if B'B'' is taken as the entrance.

Figure 16 gives rise to another problem. Suppose the cave is on a cliff and the distance B'B'' is

considered to be horizontal, at CC' or perhaps at AA'? If the entrance is at CC', note that the depth of the cave is CC', which is greater than either B'B'' or BB''.

Note also that some people measure depth from the entrance zero datum. But this would make, e.g., Figure 11 only 200 m deep, and figures 14 and 15 0 m deep. This goes against the principle that depth is a measure from highest to lowest point inside a cave.

**Open voids.** Both figures 16 and 19 present problems of open voids. Now consider Figure 20 which (as is also true for figures 14 through 19) can be rotated to represent either a horizontal or a vertical cave. Is the entrance in the plane of AC or in the plane of A'B'? Or in Figure 21, where AD is either 100 m or 1000 m, and BC is 10 m; is the entrance at AD or at BC?

Figure 22 is similar to Figure 21, but now there are several questions: Is CD one cave, or are there two caves, A'C and B'D? And coordinate with this question, is there one entrance AB, or two entrances A'A'' and B'B''? Similarly with Figure 23: Two caves or one? Two entrances or one?

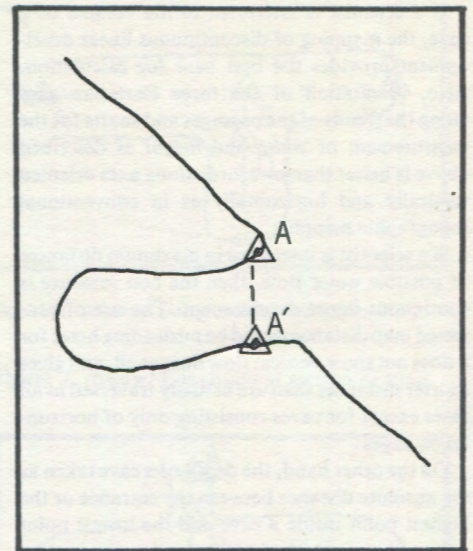
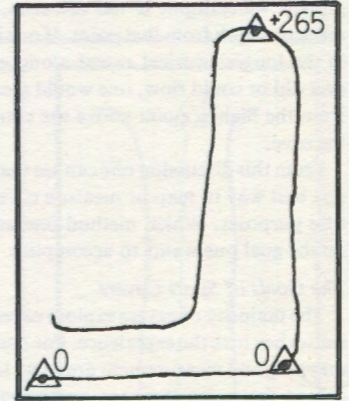
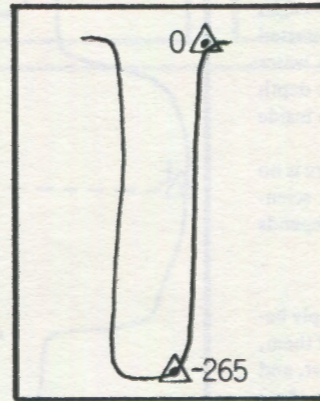
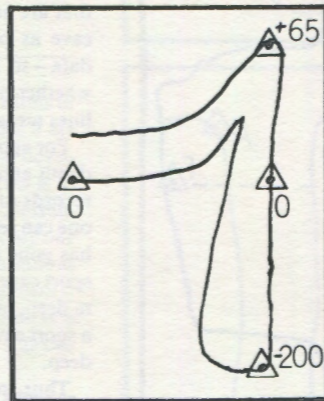


Figure 14. Longitudinal section.

Figure 11. (left) Longitudinal section.

Figure 12. (center) Longitudinal section.

Figure 13. (right) Longitudinal section.



10 m, and the distance AA' is 1000 m. The depth of the cave from highest to lowest point inside the cave is either 10 m or 1000 m, depending on choice of entrance. Clearly there is room for refinement of the definition here.

**Vertical entrances.** For measuring the depth, an entrance surface at the terminus of a basically vertical passage is established in the horizontal plane circumscribed by the highest closed contour describing the depression surrounding the terminus. Thus, in Figure 17, the entrance of a vertical cave of uniform dimensions on a flat surface is in a horizontal plane defined by AB. On a slope as in Figure 18, the entrance is at AB, not at A'B', although some people argue for A'B' on the grounds that the cave should be viewed as going down not from the horizontal plane of AB or A'B', but from the slope plane of AB', making B' the high point of the cave. We do not believe that this reasoning is cogent, and argue for AB.

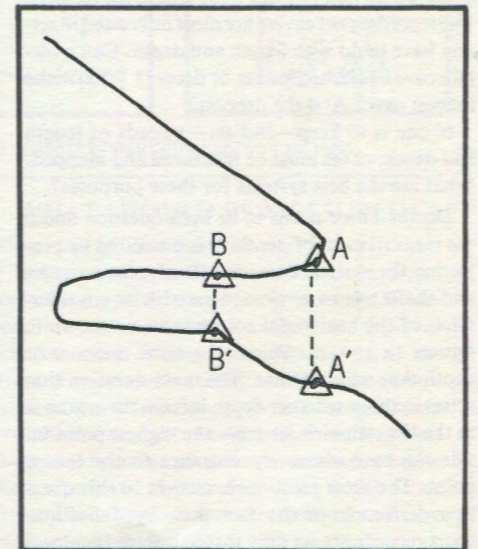
A problem arises with Figure 19. Is the entrance at A'B' or AB, or should the entrance be con-

**Cut-arounds.** When passages or shafts separated by bedrock (cut-arounds) are very close together, do they constitute only one line of linear development, or two? Consider Figure 24, which can be viewed either as a map, or as a longitudinal section (which can be rotated 90° to represent also a vertical cave). Is this one passage or shaft, along line A'B', or is it a cave with ten lines of linear development: A'C + C'D + CD + DE + E'F' + EF + FF' + F'H' + FH + HB?

Jacques Choppy suggests that a bedrock pillar should be taken to separate two different passages or shafts only when its largest dimension is greater than the combined width of the two passages separated. Thus in Figure 24, pillar E'F'FE would be taken to separate two passages, but pillars C'D'CD and G'H'GH would not. On Choppy's scheme, the linear development would be A'E + E'F' + EF + FB'. This seems very reasonable. The same principle can be applied to bedrock bridges in vertical shafts.

Choppy's rule may offer a guide for establishing a rule to determine whether or not open voids should be considered parts of caves. For figures 15, 16, and 19 through 23, one might propose that the large void be considered to establish the en-

Figure 15. Longitudinal section.



\*This plane coincides with the "drip line" only along the innermost segment of the dripline; a dripline is an irregular vertical surface projected downward from the margin of the roof rock at the cave entrance.

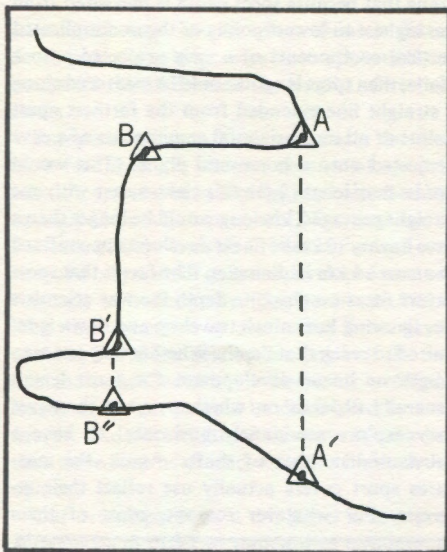


Figure 16. Longitudinal section.

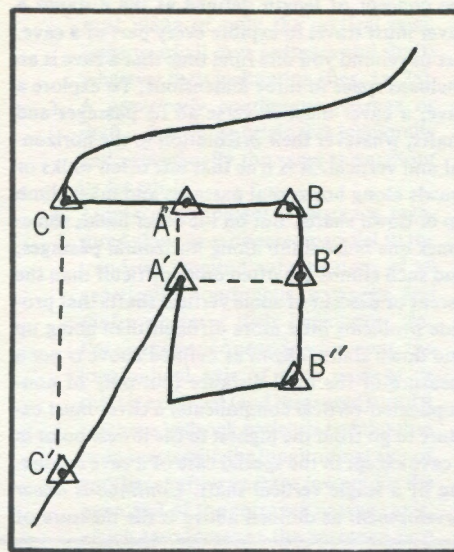


Figure 19. Longitudinal section.

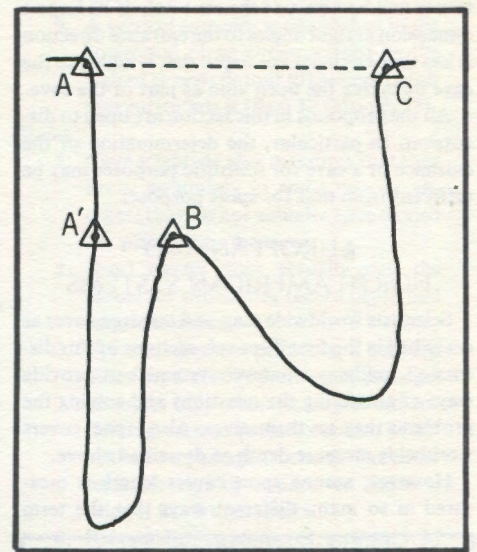


Figure 20. Longitudinal section.

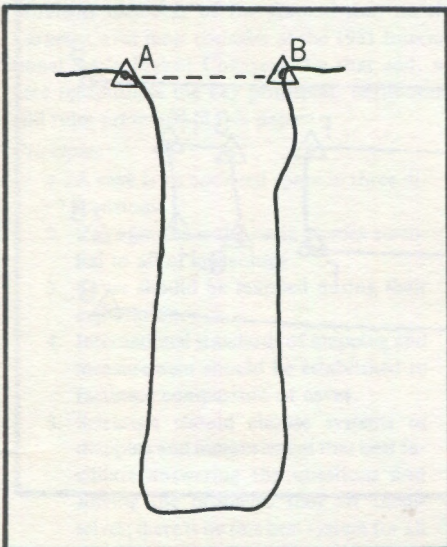


Figure 17. Longitudinal section.

Figure 18. Longitudinal section.

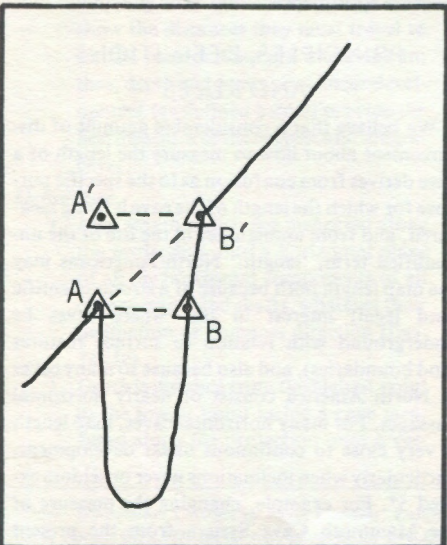


Figure 21. Longitudinal section.

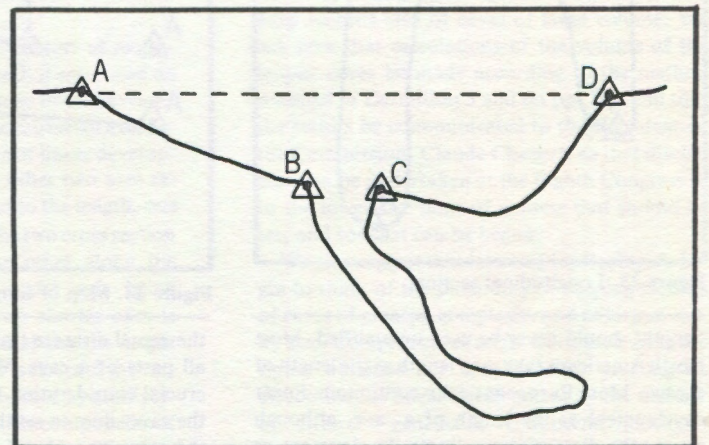
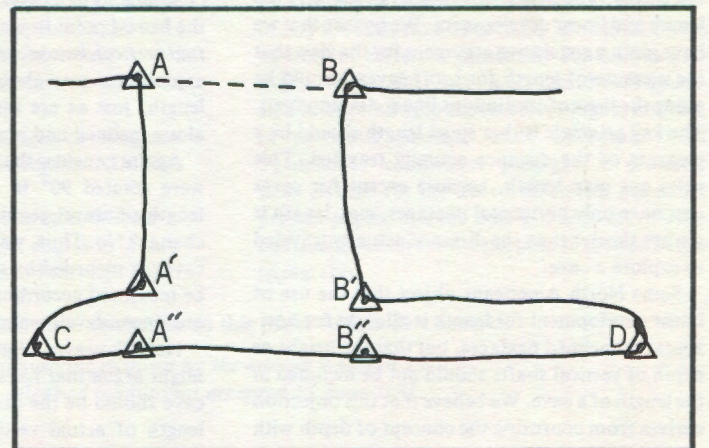


Figure 22. Longitudinal section.



trance and be a part of the cave only if its largest dimension at right angles to the entrance direction is less than the length or depth that is added to the cave by taking the open void as part of the cave.

All the proposals in this section are open to discussion. In particular, the determination of the entrance of a cave for scientific purposes may be different from that for sport purposes.

### EUROPEAN AND NORTH AMERICAN SYSTEMS

Scientists worldwide map and measure caves as described in the first three sub-sections of this discussion, utilizing whatever systems best provide ways of answering the questions and solving the problems they set themselves. Also, sport cavers worldwide measure depth as described above.

However, among sport cavers length is measured in so many different ways that the term

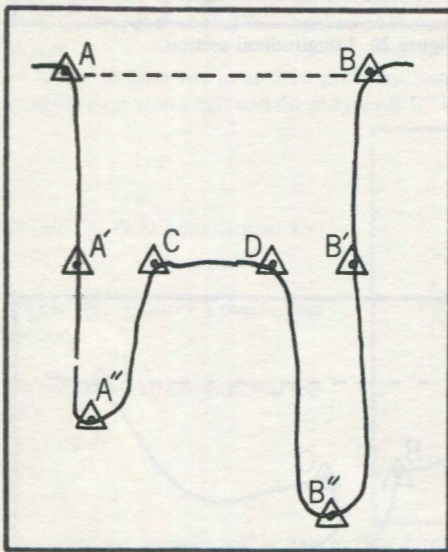


Figure 23. Longitudinal section.

'length' should never be used unqualified. Most North Americans take map length as the length of a cave. Most Europeans take continuous linear development as the length of a cave, although some take discontinuous linear development as the length. The major difference is between map length and linear development. We believe that we have given a conclusive argument for the view that the measure of length for sport cavers should be along the lines of continuous linear development. The key principle is that sport length should be a measure of the distance actually traveled. This rules out map length, because except for caves that have only horizontal passages, map length is always shorter than the distance actually traveled to explore a cave.

Some North Americans object that the use of linear development for length is all right for horizontal or inclined passages, but that the height or depth of vertical shafts should not be included in the length of a cave. We believe that this objection derives from confusing the concept of depth with

the concept of length defined as the distance a caver must travel to explore every part of a cave. Let us remind you one final time that a cave is an enclosed space in three dimensions. To explore a cave, a caver must traverse all its passages and shafts, whatever their orientation to the horizontal and vertical. It is true that one often walks or crawls along horizontal passages and must climb up or down shafts. But on the other hand, sometimes one must climb along horizontal passages, and such climbs are often more difficult than the ascent or descent of some vertical shafts that provide problems little more difficult than going up and down stairs. *Depth* as defined above is *not* a measure of the total distance (but only of non-duplicated vertical components) a caver must explore to go from the highest to the lowest point in a cave except in the special case of a cave consisting of a single vertical shaft. *Continuous linear development* as defined above is the measure of

argue that because sport depth is measured from the highest to lowest points of the nonduplicated vertical components of a cave projected onto a plane, then sport length should be measured along a straight line extended from the farthest apart points of all the horizontal components of a cave projected onto a horizontal plane. (This would *not* be map length.) On this view, a cave with one straight passage 2 km long would be longer than a cave having 10 km of linear development confined in an area 1 km in diameter. The fact is that sport cavers measure absolute depth the way scientists do, ignoring how much travel up and down is required to reach that depth. Whether they use map length or linear development for sport length generally depends on whether or not the caves they explore are mostly horizontal or have a substantial number of shafts. Again, the measures sport cavers actually use reflect their interests. For whatever reasons, most of them

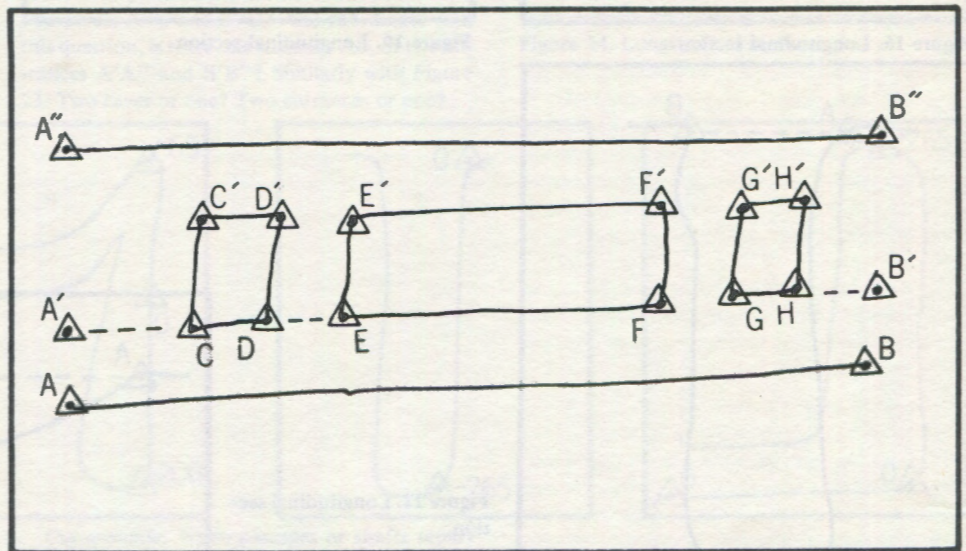


Figure 24. Map or longitudinal section.

the actual distance traveled by a caver to explore all parts of a cave. We believe, again, that the crucial consideration for sport measures is what the caver does to set the record. Because depth is the measure *only of the nonduplicated vertical components* of a caver's travel from the highest to the lowest point in a cave, we believe that the *actual vertical distance traveled* up or down shafts in exploring a cave should be included in its sport length, just as are the actual distances traveled along inclined and horizontal passages.

Again, consider the result if a given cave system were rotated 90° in any direction. Would the length of travel required to explore all its parts change? No. Thus, we conclude that the length of caves as recorded by and for sport cavers should be measured according to the scheme of continuous linear development.

Note, however, that by similar reasoning, one might argue that for sport purposes, the deepest cave should be the one that requires the greatest length of actual vertical travel. Or, one might

would surely find it ridiculous to use the same principles to measure sport length that they use to measure sport depth.

### PRINCIPLES, DEFINITIONS AND RULES

We believe that a considerable amount of disagreement about how to measure the length of a cave derives from confusion as to the specific purpose for which the length of the cave is being measured, and from ambiguities in the use of the unqualified term, 'length.' North Americans may use map length both because of a strong scientific (and legal) interest in just where caves lie underground with relation to surface features (and boundaries), and also because so many caves in North America consist of nearly horizontal passages. For many horizontal caves, map length is very close to continuous linear development, particularly when inclinations never or seldom exceed 5°. For example, changing the measure of the Mammoth Cave System from the present

scheme of map length to continuous linear development would increase its length very little, except for the addition of the lengths of vertical shafts.

Europeans may use continuous linear development for the length of caves because of a strong scientific interest in hydrology, and also because so many caves in Europe consist of vertical shafts. For example, the Dent de Crolles in France\* consists of a labyrinth of galleries developed as much vertically as horizontally. This cave is 36.31 km long when measured by continuous linear development, but if one deleted the length of the vertical shafts that had to be climbed to explore it, the length of the cave would be diminished by one-fourth. The map length of this cave is even less than three-fourths of its continuous linear development.

Our overall purpose in this paper is to expose ambiguities in order to standardize terminology and to clarify and offer solutions to many of the problems members of the Commission on the Largest Caves must consider at the 1981 International Speleological Congress. To that end, we here recapitulate the key principles, definitions, and rules presented in this paper:

#### Principles

1. A cave is an enclosed space in three dimensions.
2. Cartography is the basic science essential to all of speleology.
3. Caves should be mapped during their exploration.
4. International standards of mapping and measurement should be established to facilitate comparison of caves.
5. Scientists should choose systems of mapping and measurement that best facilitate answering the questions and solving the problems they set themselves; there is no one best system for all scientific purposes.
6. Sport cavers should choose systems of mapping and measurement that best show the distances they must travel to set the records they are interested in; thus, depth and continuous linear development (as defined below) provide the best measures of the deepest and longest caves.

#### Definitions

1. *Map length* is distance measured along the projection onto a horizontal plane of all the horizontal components of all cave passages and shafts, whatever their inclination or compass direction (figs. 1a, 1c)
2. *Depth* is distance from the highest point to the lowest point inside a cave measured along the projection onto a ver-

tical plane of only the vertical components of all cave passages and shafts whatever their inclination (figs. 1a, 2a).

3. A *genetically continuous* passage or shaft is one whose origin was temporally and processually the same throughout its length.
4. *Linear development* is distance measured along axes oriented parallel to the trends or longitudinal directions of all genetically continuous passages and shafts whatever their inclination. **4a.** For *continuous linear development*, the longitudinal axis of each passage or shaft is extended (and measured) until it reaches a bedrock or debris termination or connects with the longitudinal axis of another shaft or passage (except for the open end of the entrance passage axis, which terminates at the entrance zero datum) (figs. 5 through 10). **4b.** For *discontinuous linear development*, the longitudinal axis of each passage or shaft is extended (and measured) until it reaches the boundary between its genetically continuous extent and the genetically continuous space of another shaft or passage (except for the open end of the entrance passage axis, which terminates at the entrance zero datum) (figs. 5 through 10).
5. *Volume* is the cubic measure of the enclosed space of a cave; it is calculated on a base of discontinuous linear development, with one of the Cartesian axes extended along the line of linear development as *length*, the other two axes extended at right angles to the length, one along the longer of the two cross section dimensions and the other along the shorter, with the *width* axis being whichever of the two shorter axes is closer to the horizontal and the *height* axis being whichever is closer to the vertical. Volume is calculated by multiplying together the distance components of *length*, *width*, and *height* along the three axes (Fig. 4). The number of measurements required will depend on the variety of dimensions in the cave.
6. *Sport depth* of the deepest caves equals *depth* (Definition 2).
7. *Sport length* of the longest caves equals *continuous linear development* (Definition 4a).
8. A *horizontal entrance* is established in a vertical plane at right angles to where the roof begins (figs. 14 through 16).
9. A *vertical entrance* is established in the horizontal plane circumscribed by the highest closed contour in the depression that surrounds it (figs. 17 through 23).

#### Rules

1. Cave scientists give measures that they know accurately in some way or another; they do not actually have to visit the places they measure.
2. Sport cavers must actually visit the places for which they record depth and length measures.
3. For measurement purposes, a bedrock pillar separates two different passages or shafts only when its largest dimension is greater than the combined width of the two passages formed. The same principle can be applied to bedrock bridges in vertical shafts.
4. For establishing entrances, an open void is considered to be part of a cave only if its largest dimension at right angles to the entrance direction is less than the length or depth that is added by taking it to be part of the cave.

So far the Committee on the Largest Caves has set standards for and kept records of only the longest and deepest caves. At the Seventh International Speleological Congress, it was decided to keep records also of caves of large volume. We ask now that calculations of the volume of the largest caves be made according to the method outlined in Definition 5 and on pp. 5-6, and that the results be communicated to the President of the Commission, Claude Chabert, so that discussion can be undertaken at the Eighth Congress as to the lower size limit of volume that should be set, and so a list can be begun.

We also suggest that interested speleologists begin to think of the possibility of keeping records of caves of greatest complexity and of largest cavity size. Complex caves might be ranked using the figure obtained for each cave by dividing its discontinuous linear development by the number of different genetically continuous passages, shafts, and rooms it contains. Caves of large cavity size might be ranked by using the figure obtained for each cave by dividing its volume by the number of different genetically continuous passages, shafts, and rooms it contain. Much discussion is required as to the viability of these notions, in particular because while Definition 3 of "genetically continuous passage" is probably clear enough for the use to which it is put in the present paper, it is too ambiguous to serve without qualification for the purpose suggested in this paragraph.

Please send your comments on this paper to Claude Chabert!

Manuscript received by the editors 9 March 1979.

Revised manuscript accepted 17 June 1981.

\*See: *Subterranean Climbers* by Pierre Chevalier, Zephyrus Press, Teaneck (NJ), 1975 for the story of one of the most difficult caves ever explored.

# ACUTE TOXICITY OF CADMIUM, ZINC, AND TOTAL RESIDUAL CHLORINE TO EPIGEAN AND HYPOGEAN ISOPODS (ASELLIDAE)

## SUMMARY

*Aquatic toxicological assays are typically employed to evaluate the influence of pollutants upon epigean organisms. Little attention has been given to the fate of pollutants in waters which flow through subterranean karst conduits and to their impact upon hypogean communities. This study tests the hypothesis that hypogean organisms would be more sensitive to selected toxic substances than would ecologically similar epigean forms.*

*During late summer and early fall of 1978, *Caecidotea bicrenata*, a blind hypogean cave isopod, and *Lirceus alabamiae*, an epigean isopod, were collected from similar hydrological systems and tested under laboratory conditions employing ambient spring water to establish 96-hour LC 50 values for cadmium, zinc, and total residual chlorine in flow-through toxicological assays. *C. bicrenata* were taken from Merrybranch Cave, White County, Tennessee, and *L. alabamiae* were taken from a spring-fed stream in DeKalb County, Tennessee.*

*The resulting 96-hour LC 50 values and their 95% confidence levels for each toxicant were derived by Log-Probbit and 10% Spearman-Kärber analyses. Evaluation of heavy metal treatments revealed that epigean *L. alabamiae* were more sensitive to toxicants than were hypogean *C. bicrenata*. In the total residual chlorine treatment, no significant differences between the two species were found in the LC 50 values observed at the 95% confidence level.*

ARTHUR D. BOSNAK  
1247 Pleasant View  
Cookeville, Tennessee 38501  
and

ERIC L. MORGAN  
Department of Biology  
Tennessee Tech. University  
Cookeville, Tennessee 38501

**I**N A NATURAL STREAM, the aquatic community maintains a resilience to numerous seasonal fluctuations, including temperature changes, dissolved oxygen variations, flooding, and sedimentation. Man-induced stresses, such as the introduction of toxic heavy metals and organic substances, may alter the community of aquatic organisms. When the abiotic and biotic components of an aquatic ecological system are extensively altered by pollution, the community may be termed "stressed" (Cairns, 1977).

Within the southeastern region of the United States, studies of karst-aquifer pollution have been seriously neglected. Yet, the occurrence of cadmium and zinc in surface- and groundwater has been shown to be increasing (Hem, 1972). Cadmium is closely related to zinc in nature, as a sulfide salt. Among anthropogenic sources of these metals are wastes from electroplating plants, paint pigment works, textile mills, and other chemical industries (USEPA, 1976).

Free available chlorine ( $\text{HOCl}$  and  $\text{OCl}^-$ ) and combined available chlorine (mono-, di-, and trichloramines) may appear for short periods in surface- or groundwater as a result of disinfection of domestic sewage or from industrial processes that use chlorine for bleaching operations or for controlling organisms that tend to accumulate in and foul cooling-water systems (USEPA, 1976; Brungs, 1973, 1976).

Although not as dramatic and apparent as surface water pollution, degradation of the quality of groundwater in karst aquifers has become widespread (Aley, 1972; George, 1973; Smithson, 1975; Barr, 1976). Studies by Smithson (1975) revealed that effluent from the Cookeville, Tennessee sewage plant flowed 299 m over the surface, then sank into Ament Cave. Resurging 572 m from the sewage plant, the effluent damaged the benthic macro-invertebrate communities of Pigeon Roost Creek for approximately 8 km downstream. Though no data are available from the Ament Cave stream, which becomes Pigeon Roost Creek upon resurging, the loss is readily apparent.

Karst hydrologic systems are of increasing concern to the biospeleologist. Theoretically, the simpler an ecosystem, the more vulnerable it is to change (Roberts, 1974; Odum, 1971). Aquatic cave communities are similar in composition to aquatic epigean communities, but are typically simplified and often contain a lower number of species (Barr, 1968).

Our primary objective in carrying out this research was to generate evidence crucial to the protection of cave ecological systems subjected to toxic substances. Since water quality criteria and stream standards are intended to protect aquatic life, we used standard aquatic toxicological tests and 2 species of isopods common to karst drain-

ages of southeastern United States to establish levels of cadmium, zinc, and total residual chlorine that would be lethal to 50% of the test population exposed for a 96-hour period (96-hour LC 50). Our specific intent was to test the hypothesis that cave dwellers are more sensitive to toxic substances than are epigean forms.

A major problem encountered was the large number of specimens (at least 60) needed to perform a single toxicity test. Of particular importance was that selecting specimens of approximately equal size could alter the cave ecosystem (Barr, 1976; Roberts, 1974; Odum, 1971). We decided that a randomly heterogeneous group of isopods in the size range 3 to 7 mm should be selected. While recognizing the experimental limitations inherent in using mixed sizes of isopods, we were hopeful that the test results would better represent the effects of a toxicant on the cave population as a whole rather than on a single element of the animals' life history.

## STUDY AREA

*Caecidotea bicrenata* (Stafford), hypogean isopods used in this study, were collected from Merrybranch Cave, White County, Tennessee (Fig. 1). This natural cavern is formed in Bangor limestone (Mississippian) between overlying Pennington sandstone and the underlying Hartselle formation (Wilson, 1962). The mean elevation of

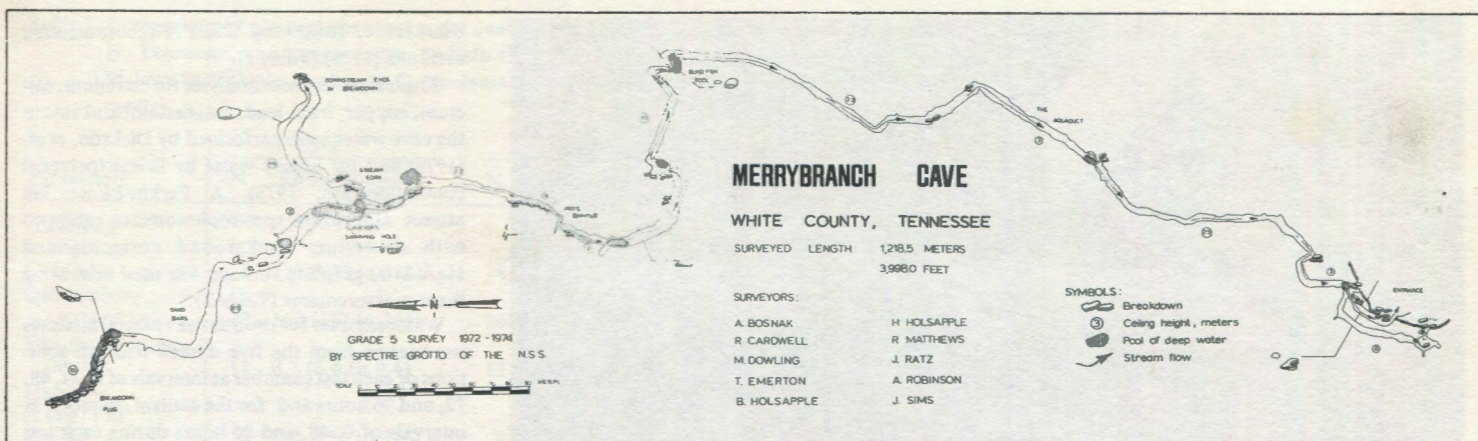


Figure 1. Map of Merrybranch Cave, White County, Tennessee, where *C. bicrenata* were collected in 1978.

the cave is 354 m ASL. Merrybranch Cave contains large pools of water with gravel or smooth bedrock bottoms connected by a slow, meandering stream. The undersides of loose rocks within these pools served as shelters and feeding sites for many of the isopods.

The epigean isopod selected for this study, *Lirceus alabamiae* (Hubricht and Mackin), was taken from an abandoned rock quarry adjacent to Center Hill in DeKalb County, Tennessee. The quarry is opened in Bigby-Cannon limestone (Ordovician) at an elevation of 153 m ASL (Wilson, 1962). At the upper end of the quarry, a fastflowing spring emerges. Its stream traverses a dense mass of aquatic plants and empties into a large pool at the lower end of the quarry. Root mats along the stream sheltered large numbers of isopods.

Habitats of *L. alabamiae* are subject to numerous seasonal fluctuations; whereas, *C. bicrenata* enjoy relative constancy in their physical environment. This physical constancy has led to major morphological, physiological, and behavioral accommodations restricting these cavernicoles to hypogean habitats or to habitats similar to and continuous with the deep-cave zone (Ginet, 1960).

## MATERIALS AND METHODS

### Collecting Organisms and Water

*C. bicrenata* were collected from Merrybranch Cave the same day that each test was initiated, by removing rocks from the pools and retrieving attached isopods with the aid of a small paint brush. In order to limit sampling stress on the isopod community, only the 60 organisms 3 to 7 mm long required for each test were removed, and only a single test was performed for each of the three separate toxicants. Organisms were placed in 5 l plastic containers covered with black plastic for transport to the laboratory. The elapsed time between collection and the initiation of testing was about 6 hours.

To better represent the effects of the 3 toxicants on the cave isopods, and to eliminate acclimation to Cookeville City tap water, dilution water was collected from the same hydrological system, at a

spring 0.9 km NNE of the cave entrance. Dilution water was collected in 100 l plastic containers and transported to the laboratory prior to each test and after 48 hours of testing.

*L. alabamiae* were also collected each day that tests were to be initiated; about 5 hours elapsed between the time of collection and the initiation of testing. Dilution water was taken from the quarry at the beginning of the test and after 48 hours.

### Test Methods

Our procedures for acute toxicological testing were those recommended by the USEPA (1975) and by Sprague (1973). All tests were carried out in the fall of the year, beginning in September and ending in November, 1978. A gravity-flow-modified-proportional-diluter (Mount and Warner, 1965) was constructed for administering treatment solutions to test organisms (Fig. 2). This device utilized a metering system to deliver five different concentrations of the toxicant in the dilution water and a control of dilution water, only —each at a half-cycle interval of 15 minutes ( $\pm 3$  min). In the laboratory, 900 l of dilution water were placed in a constant-temperature fiberglass stock tank equipped with an agitator. A submersible pump delivered dilution water to the proportional diluter.

Each test chamber consisted of 10 subunits constructed from 10 by 2.5 cm glass cylinders. Nitex (280 micron) mesh was cemented to one end of each subunit with silicon sealant. One organism was placed in each subunit, the subunit was capped with a 2-hole rubber stopper (one hole for treatment solution and the second hole for an air vent), and all 10 subunits were placed in a plexiglass holding chamber (24 by 6.5 by 7.5 cm) (Fig. 3).

Six holding chambers were constructed, one for each of the five treatment solutions and one for the control. Prior to testing, the holding chambers were partially submerged in a water bath. Water bath temperatures were controlled to ambient cave ( $13 \pm 0.5^\circ\text{C}$ ) and quarry ( $18 \pm 0.5^\circ\text{C}$ ) temperatures. "Quarry temperature" was varied to better represent the natural diurnal temperature

variations observed.

Because cave isopods are not normally subjected to natural light unless accidentally displaced into surface waters (Minckley, 1966), they were maintained in darkness during all phases of collecting, transporting, and testing, except when exposed to cool-white fluorescent lights with plastic screens during transfer to test chambers and while making mortality observations. The photoperiods selected for tests employing surface isopods were automatically controlled and simulated the natural diurnal cycle at the time of each test. Fluorescent bulbs provided the light.

Prior to each test, the toxicant delivery system and the test chambers were emptied, rinsed with tap water, cleaned with dilute  $\text{HNO}_3$ , rinsed with tap water for 24 hours, and flushed with toxicant and control treatment solutions.

Mortality observations were made at intervals of 3, 6, 12, 24, 36, 48, 60, 72, 84, and 96 hours in the acute metals and total residual chlorine tests, and additional checks were taken at 108, 120, 132, 144, 156, and 168 hours during a supplemental pH test. Death was recorded when prodding the organism with blunt glass rod failed to elicit movement.

### Chemical Measurements

Temperature ( $^\circ\text{C}$ ) and dissolved oxygen (mg/l) values were measured by a YSI Oxygen Meter (Model 51A), hydrogen ion concentration (as pH) was measured by a Turtox/Cambosco Digital Mini pH Meter, and conductivity ( $\mu\text{MHOS}/\text{cm}$ ) was measured by a YSI S-C-T Meter (Model 33) on-site at the time collections were made. Water samples for determining alkalinity and hardness (both expressed as equivalent mg/l as  $\text{CaCO}_3$ ) were collected in one-liter plastic bottles cleaned with  $\text{HNO}_3$ , placed on ice, and transported to the laboratory for measurement by titrimetric analysis (American Public Health Association, 1975) Table 1).

Suspended solids (mg/l), biochemical oxygen demand (mg/l,  $20^\circ\text{C}$ , 5d), sulfate (mg/l), and chloride (mg/l) in each water sample were measured once during the entire experiment by personnel in the Department of Civil Engineering, Tennessee Technological University, Cookeville,

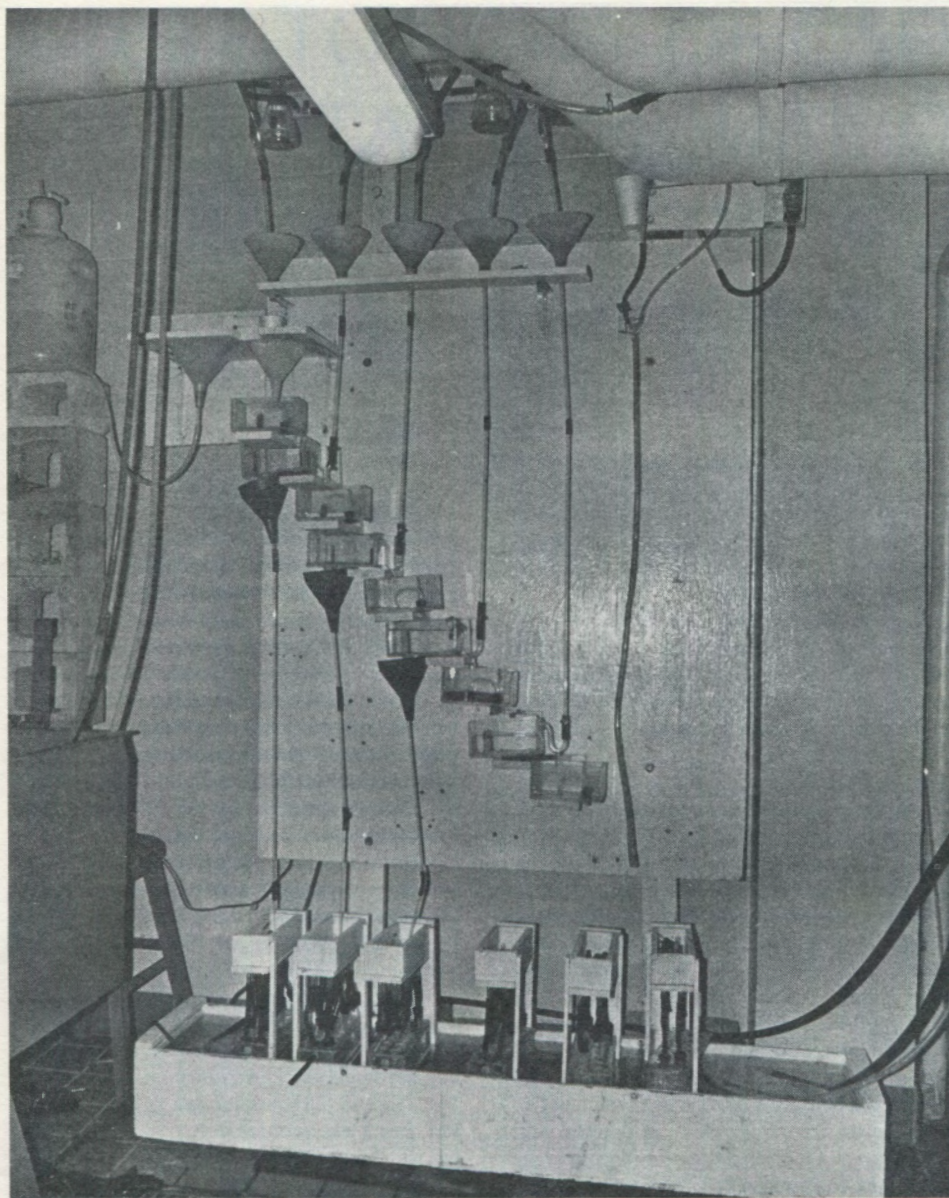
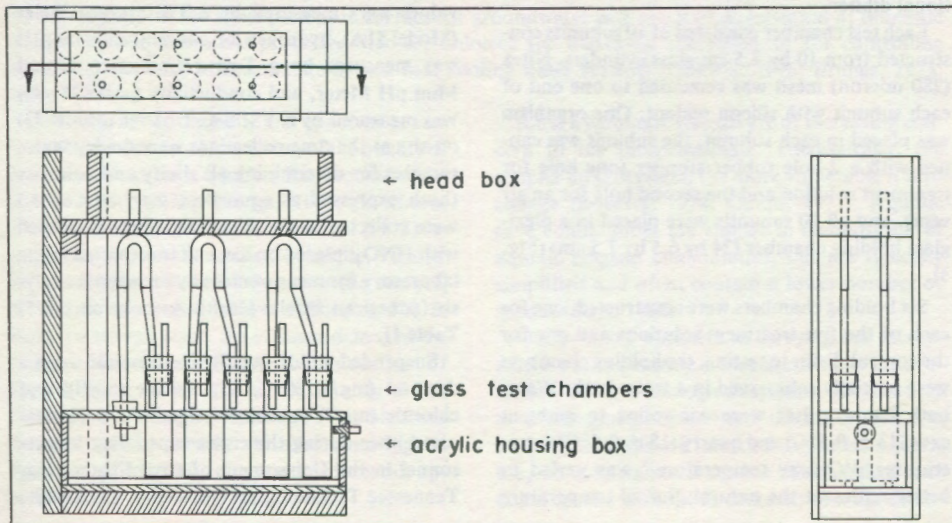


Figure 2. The Mount and Warner proportional diluter used in 96-hour toxicological tests.



Tennessee, following USEPA-recommended methods (1973) (Table 2).

Single trace-element analyses for cadmium, calcium, copper, iron, lead, magnesium, and zinc in the cave water were performed by Dickson, *et al.* (1979) and for quarry water by Briese (personal communication, 1978). A Perkin-Elmer 396 atomic absorption spectrophotometer equipped with deuterium background corrector and HgA-2100 graphite furnace was used in making these measurements (Table 3).

Water samples for routine heavy metal analyses were taken from the five diluted toxicant solutions of each test chamber at intervals of 0, 24, 48, 72, and 96 hours and, for the control chamber, at intervals of 0, 48, and 96 hours during each test (Table 4). These samples were run through 0.45-micron membrane filters and placed in 105 ml bottles cleaned with HNO<sub>3</sub> and containing 5 ml of distilled HNO<sub>3</sub>, following USEPA recommendations. Determination of heavy-metal concentrations was made with a Perkin-Elmer 372 atomic absorption spectrophotometer.

Concentrations of total residual chlorine were measured by amperometric titration using a Wallace and Tiernan titrator (Table 4). All chlorine samples were taken at the "transfer cells" of the dilutor, in order to measure the direct total residual chlorine levels to which the organisms were subjected. The electrodes were cleaned with a mild soap solution, rinsed with distilled water, and wiped dry prior to each analysis.

Hydrogen ion concentration (as pH) was measured at intervals of 0, 24, 48, and 96 hours during the zinc toxicological test; additional measurements were taken at intervals of 120, 144, and 168 hours during the pH toxicity test.

Reagent-grade chemicals were used for all toxicity tests. They were: sodium hypochlorite (NaOCl), cadmium chloride (CdCl<sub>2</sub>•2½H<sub>2</sub>O), zinc sulfate (ZnSO<sub>4</sub>•7H<sub>2</sub>O), and concentrated nitric acid (HNO<sub>3</sub>). Toxicant treatment solutions of each chemical were prepared with spring or quarry dilution water in an 18 l Mariotte bottle. The Mariotte bottle was then connected to the metering apparatus. In the toxicity tests with zinc, 15 ml of concentrated HNO<sub>3</sub> were added in the field to every 75 l of dilution water destined for the zinc toxicity test with *C. bicrenata*, in order to reduce the high pH of the cave water. This further increased zinc solubility and facilitated preparation of the toxic zinc solutions.

**Statistical Evaluations**

The results were statistically evaluated by both the Litchfield and Wilcoxon (1949) and the 10% Trimmed Spearman-Kärber (Hamilton, *et al.*, 1977) methods, due to growing concern among aquatic toxicologists about which statistical method should be accepted as the standard (Stephan, 1977).

Figure 3. Schematic diagram of a test chamber used in the *C. bicrenata* and *L. alabamiae* 96-hour toxicological tests. Scale 1:7.

**Table 1. Comparison of physical-chemical water quality values of cave and spring waters, White County, Tennessee, and quarry water, DeKalb County, Tennessee, employed as dilution water in 96-hour toxicological tests with *C. bicrenata* and *L. alabamiae*, 1978 (N = number of measurements).**

Parameters	Cave		Spring		Quarry	
	N	Mean (Range)	N	Mean (Range)	N	Mean (Range)
Alkalinity (mg/l as CaCO <sub>3</sub> )	8	136 (132 to 138)	8	128 (123 to 132)	5	102 (90 to 120)
Conductivity (μMHOS/cm)	20	169 (122 to 215)	20	134 (120 to 150)	12	140 (122 to 170)
Dissolved Oxygen (mg/l)	12	8.7 (6.6 to 9.6)	12	7.7 (7.1 to 7.8)	10	5.9 (5.7 to 6.2)
Hardness (mg/l as CaCO <sub>3</sub> )	8	284 (281 to 316)	8	220 (172 to 224)	5	152 (134 to 182)
pH	20	7.9 (7.3 to 8.3)	20	7.0 (6.8 to 7.6)	12	7.5 (7.3 to 7.6)
Temperature (°C)	20	13.0 (12.5 to 13.5)	20	13.0 (13.0 to 13.5)	12	20.5 (18.0 to 21.5)

**Table 2. Comparison of physical-chemical water quality values of cave and spring waters, White County, Tennessee, and quarry water, DeKalb County, Tennessee, employed as dilution water in 96-hour toxicological tests with *C. bicrenata* and *L. alabamiae*, performed by personnel of the Civil Engineering Department, Tennessee Technological University, Cookeville, Tennessee 1978 (N = number of measurements; N.D. = no detection).**

Parameters	N	Water Sources		
		Cave	Spring	Quarry
Biochemical Oxygen Demand (mg/l, 20°C, 5d)	1	1.0	1.0	5.2
Chemical Oxygen Demand (mg/l)	1	1.6	4.4	5.2
Chloride (mg/l)	1	0.42	0.95	2.3
Stream Velocity (m/sec)	1	N.D.	0.11	0.41
Sulfate (mg/l)	1	1.8	2.0	10.2
Suspended Solids (mg/l)	1	1.0	1.5	1.0
Total Organic Carbon (mg/l)	1	2.7	2.8	3.4

The Litchfield and Wilcoxon method of log-probit transformation of dose-effect mortality curves was recommended by Sprague (1969), who stressed the need for a uniform method of testing and statistically evaluating measurements of pollutant toxicity. The method has two disadvantages: (1) it is somewhat subjective, because it is partly graphical, and (2) zero and total mortalities must be "adjusted" to a chi-square curve-fitting technique (Stephan, 1977).

The main advantages of the Litchfield and Wilcoxon method of log-probit are that it (1) provides a rapid and simple means of computing the "lethal concentration causing 50 percent mortality" (LC 50), when at least one but less than half of the sample organisms perish, and (2) provides a rapid test for parallelism by calculating a function known as the "slope function ratio" (SR). Once the test for parallelism is completed and the curves are found to be parallel, a second value, known as the "potency ratio" (PR), is computed to find

whether or not the LC 50 values being compared are significantly different.

Stephan (1977) recommended that the 10% Trimmed Spearman-Kärber method be used when the data include both zero and total sample mortalities. Hamilton, *et al.*, (1977) programmed this method in FORTRAN and found that it was not subject to the problems of probit and logit models, having good statistical properties and ease of use. They recommended this method for developing accurate calculations of aquatic toxicological LC 50 values and associated 95 percent confidence intervals.

## RESULTS AND DISCUSSION

### Cadmium Toxicity Tests

Epigeal *L. alabamiae* were more sensitive to cadmium than were hypogean *C. bicrenata*. In estimating the 96-hour LC 50 values and associated 95 percent confidence levels using the Litchfield-

Wilcoxon method, we found that *C. bicrenata* responded to 2.20 (1.40 to 3.45) mg/l Cd compared to 0.15 (0.12 to 0.18) mg/l Cd for *L. alabamiae* (Fig. 4). With the 10% Trimmed Spearman-Kärber method, we observed that *C. bicrenata* had 50 percent mortality at 2.06 (1.32 to 3.22) mg/l Cd, while *L. alabamiae* again showed a considerably lower LC 50 value of 0.15 (0.13 to 0.17) mg/l Cd (Table 5). The calculated slope function ratio and associated 95 percent confidence level for the two species according to the Litchfield-Wilcoxon method was 1.94 (1.14 to 3.30) and the potency ratio with its accompanying 95 percent confidence level was 14.66 (8.96 to 24.11). The ratios deviated significantly at the 95 percent confidence level during the 96-hour interval tested (Table 6). Thus, it appears either that different sets of factors were important in controlling toxic response, or that different modes of response were operating in the two species tested.

Briese (personal communication, 1978) recently found relatively low levels of Cd (0.00005 mg/l) in a grab sample of water taken from the abandoned rock quarry where our *L. alabamiae* were collected. However, whole-body analyses of *L. alabamiae* revealed concentrations of 0.035 mg/l Cd. Kneip and Laver (1973) reported that aquatic organisms tend to concentrate cadmium in their tissues.

**Table 3. Comparison of heavy metal analyses of cave water, White County, Tennessee (Dickson, *et al.*, 1979)<sup>a</sup>, and quarry water, DeKalb County, Tennessee (Briese; unpublished data, 1978)<sup>b</sup>.**

Parameters	N	Water Sources	
		Cave <sup>a</sup>	Quarry <sup>b</sup>
Cadmium (mg/l)	1	0.00021	0.00005
Calcium (mg/l)	1	37.3	33.1
Copper (mg/l)	1	0.008	0.0003
Iron (mg/l)	1	0.129	0.0312
Lead (mg/l)	1	0.0023	0.0013
Magnesium (mg/l)	1	6.1	3.6
Zinc (mg/l)	1	0.0016	0.001

In additional analyses by Dickson, *et al.* (1979), the aquatic environment of Merrybranch Cave was found to contain a relatively higher sub-lethal concentration of 0.00021 mg/l Cd. Whole-body analyses of *C. bicrenata* from this water source revealed only 0.002 mg/l Cd. In a comparison of possible synergistic reactions between dissolved oxygen and cadmium toxicity, Clubb, *et al.* (1975) found that cadmium uptake may be coupled to aerobic metabolism in certain aquatic insects. The metabolic rates of cave-dwelling organisms are lower than those of epigeal species (Poulson, 1964), which may account for some of the differences found between the two isopod species compared in this study.

### Zinc Toxicity Tests

Epigeal *L. alabamiae* were more sensitive to zinc in toxicity tests than were hypogean *C. bicrenata*. In estimating the 96-hour LC 50 and as-

**Table 4. Cadmium, zinc, and total residual chlorine concentrations (mg/l) employed in 96-hour acute toxicological assays for *C. bicrenata* and *L. alabamiae*, 1978.**

Test Treatments	N <sup>a</sup>	<i>C. bicrenata</i>	<i>L. alabamiae</i>
Cadmium	5	7.2 (6.8 to 7.4) <sup>b</sup>	0.28 (0.26 to 0.34)
	5	5.6 (4.9 to 6.3)	0.22 (0.20 to 0.26)
	5	3.9 (2.8 to 4.7)	0.15 (0.12 to 0.18)
	5	1.9 (1.5 to 2.3)	0.12 (0.10 to 0.12)
	5	0.5 (0.4 to 0.6)	0.06 (0.04 to 0.09)
	Control	3	0.3 (0.3 to 0.3)
Zinc	5	106.0 (104.0 to 110.0)	12.2 (11.8 to 12.5)
	5	87.0 ( 75.0 to 95.0)	11.4 (11.0 to 11.7)
	5	68.0 ( 60.0 to 75.0)	10.8 (10.7 to 11.0)
	5	12.0 ( 11.7 to 12.8)	8.5 ( 8.3 to 8.6)
	5	9.0 ( 8.6 to 9.5)	4.7 ( 4.2 to 5.4)
	Control	3	2.0 ( 2.0 to 2.0)
Chlorine (TRC)	5	0.593 (0.567 to 0.635)	0.504 (0.460 to 0.540)
	5	0.292 (0.270 to 0.320)	0.270 (0.260 to 0.280)
	5	0.179 (0.129 to 0.199)	0.180 (0.148 to 0.198)
	5	0.052 (0.048 to 0.059)	0.060 (0.056 to 0.062)
	5	0.016 (0.014 to 0.018)	0.009 (0.008 to 0.009)
	Control	3	N.D.

<sup>a</sup>number of measurements; <sup>b</sup>mean and range values (mg/l); N.D. not detectable

**Table 5. Comparison of median lethal concentration (LC 50), 95% confidence intervals, and slope function (S) of the mortality curves tested by Log-Probit analysis, and median lethal concentration (LC 50), and 95% confidence intervals for the 10% Trimmed Spearman-Kärber analysis in 96-hour toxicological tests with *C. bicrenata* and *L. alabamiae*.**

Treatment	LC 50 and 95% Confidence Intervals for Log-Probit (mg/l)	S	LC 50 and 95% Confidence Intervals for Spearman-Kärber (mg/l)
Cadmium			
<i>C. bicrenata</i>	2.20 ( 1.40 to 3.45)	2.45	2.06 ( 1.32 to 3.22)
<i>L. alabamiae</i>	0.15 ( 0.12 to 0.18)	1.26	0.15 ( 0.13 to 0.17)
Zinc			
<i>C. bicrenata</i>	20.00 ( 9.11 to 44.00)	4.88	20.22 (12.14 to 33.66)
<i>L. alabamiae</i>	8.45 ( 6.81 to 10.32)	1.25	8.30 ( 7.20 to 9.57)
Total Residual Chlorine			
<i>C. bicrenata</i>	0.110 (0.042 to 0.286)	2.76	0.185 (0.131 to 0.261)
<i>L. alabamiae</i>	0.155 (0.082 to 0.295)	2.81	0.145 (0.108 to 0.210)

**Table 6. Comparison of mortality curves: slope function ratios (S. R.), potency ratios (P. R.), and 95% confidence intervals<sup>a</sup> for *C. bicrenata* and *L. alabamiae* tested in 96-hour toxicological bioassays, 1978.**

Curves Comparison	S. R. (mg/l)	P. R. (mg/l)
Cd, <i>C. bicrenata</i> versus <i>L. alabamiae</i>	1.94 (1.14 to 3.30) <sup>a</sup> P > 0.95	14.66 (8.96 to 24.11) P > 0.95
Zn, <i>C. bicrenata</i> versus <i>L. alabamiae</i>	3.92 (2.14 to 7.17) P > 0.95	2.38 (1.05 to 5.40) P > 0.95
Cl, <i>C. bicrenata</i> versus <i>L. alabamiae</i>	1.02 (0.36 to 2.86) P < 0.95	1.41 (0.47 to 4.20) P < 0.95

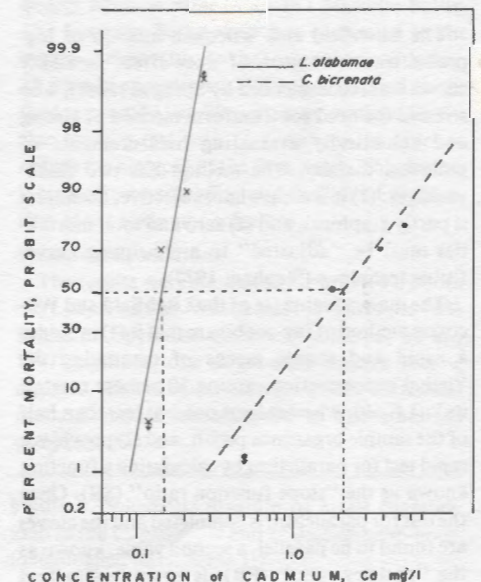
sociated 95 percent confidence level using the Litchfield-Wilcoxon method, we found that *C. bicrenata* responded to 20.00(9.11 to 44.00) mg/l Zn, compared to 8.45(6.81 to 10.32) mg/l Zn for *L. alabamiae* (Fig. 5). Similar results were obtained using the 10% Trimmed Spearman-Kärber method, where a 96-hour LC 50 value of 20.22 (12.14 to 33.66) mg/l Zn for *C. bicrenata* and an LC 50 value of 8.30(7.20 to 9.57) mg/l Zn for *L. alabamiae* were calculated (Table 5).

Using the Litchfield-Wilcoxon method, the slope function ratio and associated 95 percent confidence level was 3.92(2.14 to 7.17). A 2.38 (1.05 to 5.40) value was found for the potency ratio at the 95 percent confidence level. The ratios deviated significantly between the two species at the 95 percent confidence level (Table 6). It is reasonable to assume that different modes of toxic response were involved, or that factors other than zinc treatments have contributed to the different 96-hour LC 50 values.

Zinc toxicity is known to be modified by several water quality factors, including alkalinity, hardness, temperature, pH, and dissolved oxygen (Doudoroff and Katz, 1953). The toxicity of zinc is particularly modified by the presence of other heavy metals. The resistance of aquatic animals to a given toxic component in the environment varies at both the species and individual levels and in relation to prior exposure to the tested substance and to other toxicants (Skidmore, 1964).

Initially, attempts were made to do this research on the hypogean isopods within Merrybranch Cave. One test was completed before the experiment was flooded out. A calculated concentration of 50 mg/l Zn (ZnSO<sub>4</sub>•7H<sub>2</sub>O) was prepared at 13°C, pH 7.6, and CaCO<sub>3</sub> hardness 210 mg/l, and no mortalities were observed after a 96-hour exposure. An unfiltered sample may contain zinc attached to colloidal particles and sus-

**Figure 4. Estimation of 96-hour median lethal concentration (LC 50) of cadmium for *C. bicrenata* and *L. alabamiae*.**



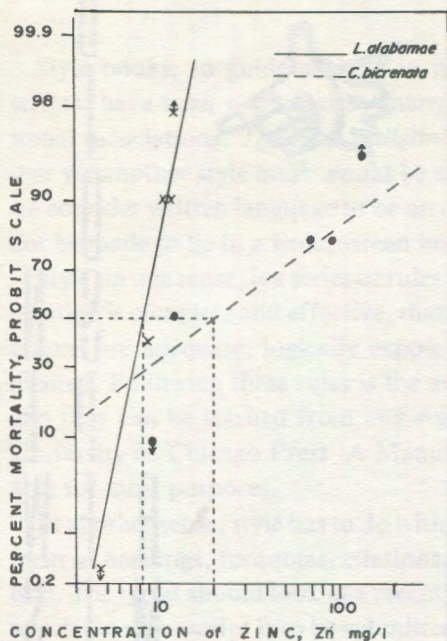
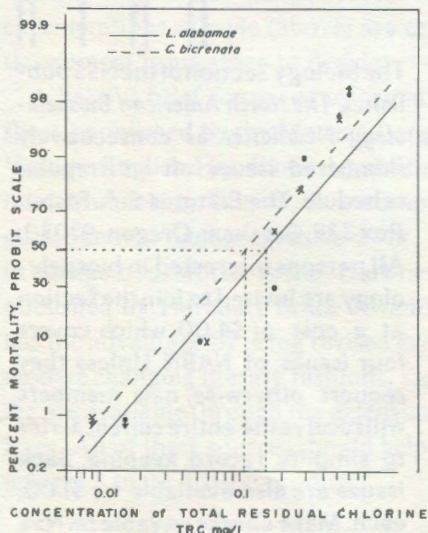


Figure 5. Estimation of 96-hour median lethal concentration (LC 50) of zinc for *C. bicrenata* and *L. alabamiae*.

pended sediment; whereas, a filtered sample contains only the ionic zinc portion of the total zinc present in a water sample. This may partly account for the lack of mortalities in the Merrybranch Cave toxicity test.

Subsequently, concentrated  $\text{HNO}_3$  was used in the laboratory experiments to lower the pH of the dilution water and stock toxicant solution in order to increase zinc solubility. The resulting ranges of pH were 6.3 to 6.5 for *C. bicrenata* tests and 6.5 to 6.8 for *L. alabamiae* tests. In earlier studies at similar pH values, Cairns, et al. (1972) found that, when using bluegill sunfish (*Lepomis macrochirus*) Rafinesque at pH 6.0 to 7.3,  $\text{Zn}^{++}$  readily

Figure 6. Estimation of 96-hour median lethal concentration (LC 50) of total residual chlorine for *C. bicrenata* and *L. alabamiae*.



dissociated and was believed to be the principal factor causing mortalities. Dissociation of  $\text{Zn}^{++}$  was much less at pH 8.0 and above and did not cause zinc-induced mortalities. Additionally, at such high pH values, total alkalinity and hardness of the test solution are known to influence the toxic action of zinc (Skidmore, 1964).

A separate toxicity test was run using solutions of  $\text{HNO}_3$  to separate possible cause/effect relationships between the pH and zinc. No mortalities were observed following the 168-hour exposure to a pH range of 3.9 to 6.5, but isopod losses of 60 percent at pH 3.0 and 20 percent at pH 3.3 were observed in the *C. bicrenata* toxicity test. For *L. alabamiae*, 100 percent survival resulted from 168-hour exposure to a pH range of 3.3 to 6.5, but mortalities of 20 percent were observed at pH 3.0. During the 96-hour zinc toxicity tests with *C. bicrenata* and *L. alabamiae*, no observed pH values fell below 6.2. Therefore, it is reasonable to assume that the pH values which occurred during the zinc toxicity tests did not contribute significantly to the isopod mortality.

Wurtz and Bridges (1960) reported that epigeal *Asellus communis* could tolerate 14.36 mg/l Zn in both hard and soft waters for 72 hours. Rerwold, et al. (1963) observed that an unidentified damselfly responded to a lower concentration with a 96-hour LC 50 of 26.2 mg/l Zn. Epigeal macroinvertebrates may be expected to vary widely in zinc tolerance (Doudoroff and Katz, 1953). However, most organisms studied by other authors were found to be more tolerant of zinc than were *L. alabamiae* in the present study.

#### Total Residual Chlorine Toxicity Tests

*C. bicrenata* were not found to be more sensitive than *L. alabamiae* in the total residual chlorine (TRC) toxicity tests. The estimated 96-hour LC 50 value and associated 95 percent confidence level, using the Litchfield-Wilcoxon method, for *C. bicrenata* was 0.110(0.042 to 0.286) mg/l TRC and for *L. alabamiae* was 0.155(0.082 to 0.295) mg/l TRC (Fig. 6). The 10% Trimmed Spearman-Kärber method gave 96-hour LC 50 values of 0.185(1.131 to 0.261) mg/l TRC for *C. bicrenata* and 0.145(0.108 to 0.210) mg/l TRC for *L. alabamiae* (Table 5). The Litchfield-Wilcoxon method gave a slope function ratio of 1.02(0.36 to 2.86) and a potency ratio of 1.41(0.47 to 4.20) which did not deviate significantly at the 95 percent confidence level (Table 6).

Gregg (1974) found that the majority of 4- to 7-day LC 50 values for continuous exposure to TRC were between 0.01 to 0.10 mg/l TRC in tests using mayflies, stoneflies, sowbugs, amphipods, and caddisflies. Arthur and Eaton (1971), work-

ing with the freshwater crustacean *Gammarus pseudolimnaeus* in dilute wastewater, found that the 96-hour LC 50 was 0.22 mg/l TRC. The LC 50 values for our *C. bicrenata* and *L. alabamiae* toxicity tests compare reasonably well to these other experimental findings.

## CONCLUSIONS

*L. alabamiae* were more sensitive to cadmium and zinc than were *C. bicrenata*; neither species was significantly more sensitive to total residual chlorine at the 95 percent confidence level. Thus, our initial hypothesis, that cavernicoles may be more sensitive than their epigeal relatives to toxicants due to the constancy of their physical environments, was not supported. However, we feel that the hypothesis may still hold merit, for the following reasons: (1) Barr (1976) found the hypogean isopod *Asellus stygius* to be more sensitive than the epigeal isopod *Lirceus fontinalis* to the heavy metals nickel, cadmium, and chromium in static toxicity tests using distilled water at 13°C; (2) *C. bicrenata* from Merrybranch Cave appeared to have been acclimatized to higher ambient sub-lethal levels of heavy metals than were epigeal *L. alabamiae*; (3) possibly, different modes of toxic response to cadmium and zinc were operating between *C. bicrenata* and *L. alabamiae*; and (4) differences in metabolic activity may have influenced both modes and rates of response to toxic metals.

The 96-hour LC 50 values for TRC fall within the concentration ranges presently being observed in many discharges from sewage plants and industrial users (Brungs, 1973, 1976).

## ACKNOWLEDGEMENTS

We are grateful to the Save-the-Caves Fund of the National Speleological Society for a grant in partial support of this study. We thank Dr. Frank Bulow of Tennessee Technological University for the use of the Aquatic Research Laboratory; Dr. Charles E. Warren of Oregon State University for the loan of an amperometric titrator; Dr. John R. Holsinger of Old Dominion University for the identification of *Caecidotia bicrenata*; Deedee Kathman of AWARE, Inc. for identification of *Lirceus alabamiae*; Gary Dickson, Linda Briese, and James Orr for analyses of heavy metals; Lou Martino, Mark Mitches, and Lee Grimes for help with the statistical analyses; Ross Cardwell, David Gallagher, David Vaught, Gillen Young, Jim Swigert, Mike Henry, and others for assistance with field studies and collections; and Steve Mead for preparing the schematic diagram of the test chamber.

## LITERATURE CITED

- Aley, Thomas (1972)—Groundwater Contamination from Sinkhole Dumps: *Caves and Karst* 14(3):17-23.
- American Public Health Association (1975)—*Standard Methods for the Examination of Water and Wastewater*, 14th Ed.: Washington, American Public Health Association, 874 pp.
- Arthur, J. W. and J. G. Eaton (1971)—Chloramine Toxicity to the Amphipod *Gammarus pseudolimnaeus* and the Fathead Minnow *Pimephales promelas*: *Fisheries Resource Board of Canada, Journal* 28: 1841-1845.

- Barr, T. C. (1968)—Cave Ecology and the Evolution of Troglobites: *Evolutionary Biology* 2:35-102.
- (1976)—*Ecological Effects of Water Pollutants in Mammoth Cave*: U.S. National Park Service, Final Technical Report, Contract No. CX500050204.
- Briese, Linda—Savannah River Ecology Laboratory, Aiken, South Carolina.
- Brungs, W. A. (1973)—Effect of Residual Chlorine on Aquatic Life: *Water Pollution Control Federation, Journal* 45(10):2180-2193.
- (1976)—*Effects of Wastewater and Cooling Water Chlorination on Aquatic Life*: U.S. Environmental Protection Agency (Duluth, Minnesota), No. EPA-600/3-76-098.
- Cairns, J., Jr. (1977)—Quantification of Biological Integrity, IN: *The Integrity of Water*: U.S. Environmental Protection Agency (Washington, D.C.), pp. 171-187.
- Clubb, R. W.; A. R. Gaufin; and J. L. Lords (1975)—Synergism between Dissolved Oxygen and Cadmium Toxicity in Five Species of Aquatic Insects: *Environmental Research* 9:283-289.
- Dickson, G. W.; Linda Briese; and J. P. Giesy, Jr. (1979)—Tissue Metal Concentrations in Two Crayfish Species Cohabiting a Tennessee Cave Stream: *Oecologia* (Berl) 44:8-12.
- Doudoroff, P. and M. Katz (1953)—Critical Review of Literature on the Toxicity of Industrial Wastes and their Components to Fish. II. The Metals as Salts: *Sewage and Industrial Wastes* 25:802-839.
- George, A. L. (1973)—Pollution of Karst Aquifers: *Water Well Journal* 3(3):27-30.
- Ginet, R. (1960)—Ecologie, Ethologie et Biologie de *Niphargus*: *Annales de Spéléologie* 15:127-177.
- Gregg, B. C. (1974)—*The Effects of Chlorine and Heat on Selected Stream Invertebrates*: Virginia Polytechnic Institute and State University Thesis, 322 pp.
- Hamilton, M. A.; R. C. Russo; and R. V. Thurston (1977)—Trimmed Spearman-Kärber Method for Estimating Median Lethal Concentrations in Toxicity Bioassays: *Environmental Science and Technology* 11(7):714-720.
- Hem, J. D. (1972)—Chemistry and Occurrence of Cadmium and Zinc in Surface Water and Groundwater: *Water Resources Research* 8:661-679.
- Kneip, T. J. and G. J. Laver (1973)—Trace Metal Concentration Factors in Aquatic Ecosystems: *Progress in Analytical Chemistry* 5:42-62.
- Litchfield, J. T. and F. Wilcoxon (1949)—A Simplified Method of Evaluating Dose-Effect Experiments: *Journal of Pharmaceutical and Experimental Therapy* 96:99-113.
- Minckley, W. L. (1966)—Occurrence of Subterranean Isopods in Epigeal Water: *American Midland Naturalist* 66:452-455.
- Mount, D. I. and R. E. Warner (1965)—A Serial-Dilution Apparatus for Continuous Delivery of Various Concentrations of Material in Water: *U.S. Public Health Service Publication* No. 999-WP-23, pp. 1-16.
- Odum, E. P. (1971)—*Fundamentals of Ecology*, 3d Ed.: Philadelphia, Saunders, 574 pp.
- Poulson, T. L. (1964)—Animals in Aquatic Environments: Animals in Caves, IN: D. E. Dill (Ed.), *Handbook of Physiology*, sec. 4, Adaptation to the Environment: Washington, American Physiological Society 47:749-771.
- Roberts, A. (1974)—The Stability of a Feasible Random Ecosystem: *Nature* 251:607-608.
- Skidmore, J. E. (1964)—Toxicity of Zinc Compounds to Aquatic Animals, with Special Reference to Fish: *Quarterly Review of Biology* 39(3):227-248.
- Smithson, K. (1975)—*Some Effects of Sewage Effluent on the Ecology of a Stream Ecosystem*: Tennessee Technological University Thesis, 74 pp.
- Sprague, J. B. (1969)—Measurement of Pollutant Toxicity to Fish. I. Bioassay Methods for Acute Toxicity: *Water Research* 3:793-821.
- (1973)—The ABC's of Pollutant Bioassay using Fish, IN: J. Cairns, Jr. and K. L. Dickson, *Biological Methods for the Assessment of Water Quality*: Philadelphia, American Society for Testing Materials, pp. 6-30.
- Stephan, C. E. (1977)—Methods for Calculating an LC 50, IN: R. L. Mayer and J. L. Hameisnk, *Aquatic Toxicology and Hazard Evaluation*: Philadelphia, American Society for Testing Materials, pp. 65-85.
- U.S. Environmental Protection Agency (1973)—*Manual of Methods for Chemical Analysis of Water and Wastes*: U.S. Environmental Protection Agency (Cincinnati, Ohio), Office of Technical Transfer, No. EPA625/6-74-003A.
- (1975)—*Methods for Acute Toxicity Tests with Fish, Macroinvertebrates, and Amphibians*: U.S. Environmental Protection Agency (Corvallis, Oregon), No. EPA-660/3-75-009.
- (1976)—*Quality Criteria for Water*: U.S. Environmental Protection Agency (Washington, D.C.), 256 pp.
- Wilson, C. W. (1962)—Stratigraphy and Geologic History of Middle Ordovician Rocks of Central Tennessee: *Tennessee Division of Geology, Report of Investigation* 15:481-501.
- Wurtz, C. B. and C. H. Bridges (1960)—Preliminary Results from Macroinvertebrate Bioassays: *Pennsylvania Academy of Science, Proceedings* 35:51-56.

Manuscript received by the editors 8 August 1979.

Revised manuscript accepted 11 May 1981.



B  
I  
O  
S  
P  
E  
L  
E  
O  
L  
O  
G  
Y  
N  
E  
W  
S  
L  
E  
T  
T  
E  
R

The Biology Section of the NSS publishes *The North American Biospeleology Newsletter* as consecutively numbered issues on an irregular schedule. The Editor is S.A. Foster, Box 335, Gresham, Oregon 97030. All persons interested in biospeleology are invited to join the Section at a cost of \$4.00, which covers four issues of NABN. Unless they request otherwise, new members will receive the entire current series to simplify record keeping. Back issues are also available for \$1.00, each. Make checks payable to: NSS BIOLOGY SECTION and mail to the Editor - Treasurer.

## TECHNICAL NOTE

Style books, to guide authors in preparing their manuscripts, have been published by many journals and professional associations. *The NSS Bulletin* has none. We believe that yet another style book would be superfluous; moreover we consider written language to be an art form which should not be made to lie in a Procrustean bed.

Style, in one sense, is a series of rules ensuring that communication is complete and effective, that the data and interpretations are adequate, logically expounded, and fully documented. Following these rules is the author's responsibility, and they can be learned from any style book. We find the University of Chicago Press 'A Manual of Style' to be suitable for most purposes.

In another sense, style has to do with the arbitrary arrangement of headings, footnotes, citations, etc. within a publication. The typist should look at a recent issue of the journal to which the manuscript is to be submitted, in order to learn the correct form of presentation, before commencing the final draft.

Those are the mechanical forms of 'style,' ones which are verified by editors before a manuscript is sent to the printer. All too many writers (and editors!) act as though there were nothing further to do. In fact, the most important part of the author's job remains: That of making his story interesting, compelling, aye (!) irresistible. The most closely reasoned argument will fail if no one pays attention to it. Style, as artistry, must be developed by practice, by reading and emulating the work of good writers.

We realize that many *Bulletin* contributors are inexperienced. The editors are sometimes very heavy handed with poorly done manuscripts; such manuscripts tend to be recast in the mould of the individual editor. Where, however, it is clear that an author has definite ideas about style, we grant him full measure of independence. So long as the first two considerations of style (above) are satisfied, the third, artistic, element is his alone to decide.

A helpful brief source of information is the 'MLA Style-sheet,' published by the Modern Language Association. The 'Instant English Handbook,' published by the Career Institute, Mundelein, Illinois, is a comprehensive grammatical guide; another comprehensive work, one generally available in college bookstores, is the 'Harbrace College Handbook,' published by Harcourt Brace Jovanovich, NYC. The latter has the advantage of being revised every few years to accommodate changing literary fashions. Courses in technical writing are available through the extension divisions of some colleges. All of these sources should help the prospective author achieve a more artistic product.

The relationship between clear writing and sound logic is well stated in articles such as 'Sounder Thinking Through Clearer Writing' by F. P. Woodford (*Science*, ns 156:743-745), 'Freight Trains' by J. A. Peoples (*Science*, ns 153:480), and 'Little Thought Given to Requirements of Good Writing' by Norman Cousins (*Saturday Review*, 8 June 1963).

Writing styles, like clothing fashions, change with time. Thus, one should not spend time cultivating a literary style but try instead to make one's writing as clear as possible. For example, geologists seldom read Hutton; they read Lyell. Hutton used a style of writing which overlaid many of his ideas (however good the ideas were!) and confused rather than enchanted his readers. Lyell took nearly those same ideas, and he made them so simple and clear that 150 years later he is still read.

Authors should remember that written language must communicate through time as well as across space. The more traditional and general the style, the longer your paper will be intelligible to posterity. The editors intentionally discourage the use of hip jargon and the latest fads, although we realize that, should we drag our feet too hard, we won't be understood by our contemporaries, much less by future generations. **JH, Oscar Hawksley (Central Missouri State University), Donald W. Ash (Indiana State University), Karl Barnaby (Indiana State University)**

### ADDITIONAL READINGS

- American Chemical Society (1978)—*Handbook for Authors*. \$7.50
- American Medical Association (1976)—*Stylebook—Editorial Manual*. \$7.50
- Council of Biology Editors, American Institute of Biological Sciences (1978)—*CBE Style Manual*. \$12.00
- Menzel, D. H.; et al. (1961)—*Writing a Technical Paper*: McGraw Hill. \$2.95
- Mitchell, J. H. (1968)—*Writing for Professional and Technical Journals*: Wiley. \$14.95
- U.S. Geological Survey (1978)—*Suggestions to Authors*. \$6.25
- U.S. Government Printing Office (1973)—*Style Manual*. \$10.00
- Zweifel, F. W. (1961)—*A Handbook of Biological Illustration*: University of Chicago Press. \$3.95.

# REFLECTANCE SPECTRA AND COLOR IN SPELEOTHEMS

WILLIAM B. WHITE

*Department of Geosciences and Materials Research Laboratory, The Pennsylvania State University, University Park, Pennsylvania 16802*

CALCITE in its pure form is colorless. Iceland spar, a hydrothermally deposited calcite occurs as water-clear single crystals which have considerable importance as an optical material. Calcite as it occurs in vein fillings in limestone is usually milky white, translucent rather than transparent. Typical limestone vein fillings appear to have formed at some depth, from solutions under pressure, and since they are often associated with euhedral quartz and fluorite, probably crystallized from hot water (hot is not defined here . . . possibly 75 to 200°C).

In contrast, nearly all calcite in speleothems is colored. Various hues of yellow, tan and brown are most common. Pure white speleothems are quite rare although they do occur. Examples seen by the author occur in Lincoln Caverns, Pennsylvania, where there is a white cascade (quite an anomaly in a cave mostly decorated with cream, yellow, orange and brown calcite), in Ohio Caverns, northwest of Columbus, where white stalactites and stalagmites are common, and rarely in the Cueva del Guácharo, Venezuela. In addition to the common yellow to brown colors, there occur occasionally speleothems ranging from deep orange to blood red. When red speleothems occur, there are usually a lot of them in a small area. Some speleothems are deeply pigmented dark brown or black. Very rarely other colors occur, usually blue or green (the latter must not be confused with algal stains that occur in many commercial caves).

A standard liturgy has grown up, based on no evidence at all, concerning the origin of the colors in speleothems: Blue and green colors are due to iron-group ions, usually copper, substituted into the calcite structure. Deep browns and black are due to iron oxide and manganese oxide pigments respectively. The common tans, oranges, browns, etc. are due to hydrated iron oxide stains on calcite grain boundaries. Not only is this the standard lore of commercial cave guides but it has been repeated in the two major reviews of cave minerals (Hill, 1976; White, 1976).

Efforts to document the origin of speleothem colors have mostly consisted of comparing the visible color with a chemical analysis for trace elements. Correlations for the speleothems colored by iron-group elements have given the best results. Thus bright blue-green flowstone occurring in the Grotte Bleue (Pyrenees) was shown to

## SUMMARY

*Calcite in its pure form is colorless. White speleothems are rare; most are colored shades of yellow, tan, gray and brown. Occasionally, blood-red dripstone is found, and still more rarely, green and blue speleothems occur. Possible sources of speleothem color include: iron group ions substituting for  $Ca^{++}$  in the calcite structure; included clay, silt and metal oxides (mostly of iron and manganese) between the calcite crystals; hydrated iron oxide stains along grain boundaries; and organic stains incorporated into the growing crystal. Gascoyne has challenged the long-held (but unsupported) view that the common yellow to brown colors are due to iron oxides and advances organic stains as the dominant colorant. This hypothesis is tested by the use of diffuse reflectance spectroscopy, which permits one to extend his "color vision" into the near-infrared.*

*Pure calcite exhibits a complex spectrum in the 1.4 to 2.5  $\mu m$  region due to incorporated water either as water-filled voids within the calcite crystals or adsorbed on grain boundaries. Characteristic d-electron spectra of the iron-group elements were found in a few cases:  $Ni^{++}$  from yellow Timpanogos Cave calcite,  $Cu^{++}$  from several Arizona caves and from the Grotte Bleue in France, and  $Fe^{++}$  in a vein calcite.*

*The spectra of hematite, goethite, and other iron oxide hydrates all contain a characteristic band in the 850 to 950 nm region. This band also appears in the spectra of iron oxide speleothems from Porter Cave, Pennsylvania and Butler Cave, Virginia, and from the hematite-stained boxwork formations from Wind Cave, South Dakota. The spectra of most yellow and brown speleothems are featureless in the 700 to 1400 nm region. The characteristic 900 nm band of the iron oxides is systematically absent. The conclusion is that the almost universal yellow to brown colors of most speleothems are not due to iron oxides. The spectra suggest that a single colorant is responsible and the leading possibility is humic substances extracted from the overlying soils.*

contain several percent copper (Cabrol, private communication). A lemon-yellow calcite and a green aragonite from Timpanogos Cave, Utah, were shown to both be colored by a few hundred parts per million of nickel incorporated into the calcite structure as  $Ni^{2+}$  to give the yellow color and as a dispersed second nickel-bearing phase intimately mixed with the aragonite (White and Van Gundy, 1974). Attempts to correlate the yellow-to-brown colors with iron concentration have been much less successful. Kral (1971) found several percent iron in a nearly colorless speleothem while there were only hundredths of a percent iron in a deep red speleothem. Beck (1978) found no correlation between the color of "fried egg" stalagmites and iron concentration and concluded that speleothem microstructure rather than trace element concentration was responsible for the color banding. Gascoyne (1977) found no correlation between color and trace element concentration in some 24 speleothem samples collected from many places in North America (Northwest Territories to Bermuda and Jamaica) and proposed the hypothesis that the yellow-tan-brown colors common to most speleothems are due to organic compounds, possibly humic and fulvic acids.

The present paper utilizes diffuse reflectance spectroscopy to quantify the color characteristics of speleothems and extend the range of "color" well into the infrared where interesting features occur that cannot be seen with visible light. The paper supports Gascoyne's hypothesis and gives a test for distinguishing between iron oxide pigmentation and other sources of brown coloration.

## EXPERIMENTAL

### *Sources of Specimens*

The speleothems used for spectroscopic measurements are listed in Table 1. Most of the materials were drawn from a collection of speleothems that has been built up over many years and which provided representative examples of most of the colored materials. Within this collection are specimens sent in by different individuals at various times and for some of which the source documentation is not good. Thus there are several specimens from unknown caves. The specimens of blue copper-bearing speleothems from the Pyrenees in southern France were kindly provided by Patrick Cabrol.

Qualitative spectrographic analyses for minor and trace elements were obtained for some of the

**Table 1. List of Specimens Examined.**

Sample Number	Mineral	Color, Form and [Munsell Color]	Source
<i>White Speleothems</i>			
LAS-10	Calcite	White Flowstone	Grotte Bleue, French Pyrenees
305	Calcite	White Crust On Stalagmite	Butler Cave, Virginia
1078	Aragonite	White Massive Stalactite	Porters Cave, Pennsylvania
—	Gypsum	White Granular Crust	Flint Ridge System, Kentucky
<i>Speleothems Colored by Iron Group Elements</i>			
838	Calcite	Lemon Yellow, Coarsely Crystalline Flowstone [10Y 9/4]	Timpanogos Cave, Utah
—	Calcite	Clear, Coarse-Grained Bacon Rind with Green Streaks —	Unknown
581	Aragonite	Green Fibrous Flowstone [5G 7/6]	Unknown Arizona Cave
LAS-C	Aragonite	Green Flowstone [5B 9/2]	Grotte Bleue, French Pyrenees
LAS-STG	Aragonite	Blue Flowstone [5B 9.5/2.5]	Grotte Bleue, French Pyrenees
—	Aragonite	Blue Massive Flowstone [5B 7/6]	Mine de Dernacueippette, French Pyrenees
—	Calcite	Pink Vein Calcite from Greenbrier Limestone [5R 9/2]	Randolph Co., West Virginia
280	Aragonite	Blue-Stained Stalactite [10B 6/10]	Carlsbad Caverns, New Mexico
114	Mixed Aragonite and other Carbonates	Blue-Stained Crust [7.5 BG 7/8]	Cumberland Caverns, Tennessee

**Table 1. List of Specimens Examined—Continued.**

Sample Number	Mineral	Color, Form and [Munsell Color]	Source
<i>Speleothems Colored by Iron Oxide Pigments</i>			
97	Goethite	"Limonite" Stalactite	Porters Cave, Pennsylvania
76 BC 001	Goethite	Iron Oxide Crust	Butler Cave, Virginia
327	Hematite	Red-Coated Boxwork	Wind Cave, South Dakota
986	Hematite	Bedded Red Sediment	Wind Cave, South Dakota
<i>Speleothems Colored by Organic Compounds</i>			
695	Calcite	Pale Yellow Stalactite [5Y 9/4]	Prah Cave, Pennsylvania
—	Calcite	Clear Yellow Stalactite [5Y 9/1.5]	Boyer Cave, Pennsylvania
1067	Calcite	Cream-to-Tan Stalactite [10 YR 9/2]	Coffee River Cave, Jamaica
673	Calcite	Tan Stalactite [5Y 9/1]	Unknown, Pennsylvania Cave
1122	Calcite	Tan Stalactite [7.5 Y 8/4]	Jones Quarry Cave, West Virginia
1107	Calcite	Yellow-Orange Bacon Strip [7.5 YR 6/6]	Hesston Cave, Pennsylvania
D-28	Calcite	Yellow-Orange Flowstone [7.5 YR 7/8]	Mammoth Cave, Kentucky
1121	Calcite	Light-Brown Stalactite [2.5 Y 7/4]	Jones Quarry Cave, West Virginia
155	Calcite	Caramel-Brown Stalactite [5YR 3/2]	Lawrence Domepit Cave, West Virginia
LAS-7	Calcite	Caramel-Brown Stalactite [5YR 4/4]	Grotte Bleue, French Pyrenees
635	Calcite	Caramel-Brown Stalactite [5YR 3/2]	Tumbling Rock Cave, Alabama
691	Calcite	Orange Stalactite [5YR 6/11]	Prah Cave, Pennsylvania
1014	Calcite	Orange-Red Stalactite [7.5 YR 5/8]	Cueva del Guácharo, Venezuela

specimens that appeared to be colored by iron group ions. Table 2 lists the results.

**Spectroscopic Measurements**

The data presented in this paper are diffuse reflectance spectra. The charts plot the amount of light absorbed by the speleothem at each wavelength as a function of wavelength. The spectra were measured on a Beckman DK 2-A spectrophotometer equipped with an integrating sphere type diffuse reflectance attachment. The effective wavelength range was 400 to 2500 nm. The reference "pure white" standard was Kodak's BaSO<sub>4</sub> optical paint. This material was also the coating on the integrating sphere.

Diffusion reflectance spectra are closely related to absorption spectra. Light enters a translucent material, is transmitted through some grains and reflected from others until, after following a complex grain-to-grain path, some of the light returns to the surface of the specimen where it can be observed. The diffusely reflected light now has superimposed on it the characteristic absorption spectrum of the specimen.

The speleothem samples were simply taped over the sample port of the integrating sphere; they were not cut, polished, or powdered. The reflectance curve should therefore be a representation of the speleothem color as seen by the human eye.

**Table 2. Qualitative Analyses of Colored Speleothems.**

	Green Aragonitic Flowstone 581	Pale Yellow Stalactite 695	Blue Aragonite 280	Green Calcitic Flowstone	Pink Vein Calcite (Greenbrier)
Major Elements (> 2%)	Ca	Ca	Ca	Ca	Ca, (Si)
Minor Element (0.02-2%)	Zn, Cu, Sr	Mg	Mg, Sr	Zn, Cu	(Si), Mg, (Fe), Sr
Trace Element (< 0.02%)	Mg, Si, Ba	Si, Al, Yb, Sr	Si, Al, Yb, Ba	Mg, Al, Sr	(Fe), Mn, Al, Yb
Not Detected	Mn, Al, Yb	Mn, Ba	Mn	Si, Mn, Al, Yb, Ba	Ba

Not detected in any: B, Be, Mo, Y, Cr, Ni, V, Ti, Co, Zr, La.

The spectrometer measures the ratio of the light reflected from the specimen, *I*, to the intensity of light reflected from the reference material, *I*<sub>0</sub>. The reflectance, *R*, is *I*/*I*<sub>0</sub> which would be unity for a sample of the same whiteness as the reference and zero for a black specimen. The spectra in this paper are presented as plots of absorbance (*A* = log *I*<sub>0</sub>/*I* = -log *R*). The reason is that the peak absorbance of a spectral band is proportional to the concentration of the coloring center responsible for the band whereas the peak reflectance is not.

**Relation of Spectra to Color**

The human eye is sensitive to light spanning the wavelength range from roughly 400 to 650 nm. The perception of color is a complex physiological phenomenon in which the eye and brain integrate the spectral character of light reflected from an object and record it as "color". The color of an object is actually the convolution of three functions: the spectral distribution of illuminating light, the spectral absorption characteristics of the object, and the spectral response of the eye. The spectrophotometer measures only one of these,

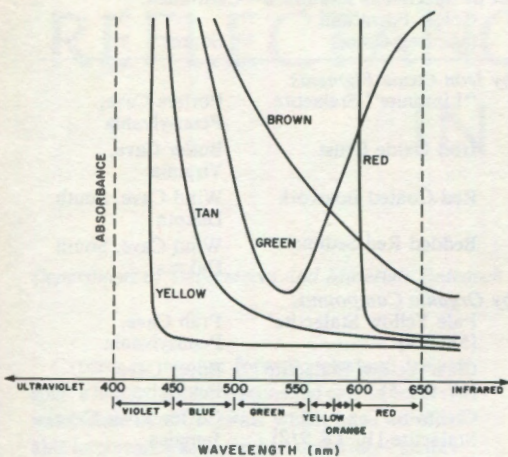


Figure 1. Schematic spectra showing some relations between absorption curves and perceived colors.

the spectral absorption characteristics of the object. The color of an object is not always obvious from its absorption spectrum.

In general, color is complimentary to the absorbance of light. If an object absorbs both blue and red light but not green, the object will appear green. Objects that absorb strongly in the blue often appear yellow. However, objects that absorb some light all across the spectrum but more blue than red, will appear in various shades of tan or brown depending on the distribution of absorption. Some schematic absorption curves and their corresponding colors are illustrated in Figure 1. These are the curves most pertinent to the observed spectra of speleothems but are not the only absorption curves which will produce these colors.

Color is produced by the minima in the absorption curves (as for example the spectrum labeled "green" in Fig. 1.) but it is the maxima in absorption that relate to the color producing processes. The visible spectrum is, in fact, too narrow to record many of the absorption maxima (or absorption bands), and for this reason spectral measurements must be extended into the infrared.

Although it is possible to calculate quantitative color coordinates by integrating the spectral reflectance curve with the spectral emission curve of the light source and the spectral curve of the human eye (see Judd, 1975) a more convenient expression of color is through the Munsell system. (Munsell Color, 1976) Munsell colors are a carefully prepared catalog of standard colors which can be matched against the unknown by direct visual comparison. Munsell colors are also expressed as three coordinates: hue, value, and chroma. *Hue* is color: red, blue, green, etc. *Value* is the depth of color compared with a neutral gray scale, black = 0; white = 10. *Chroma* is a measure of color purity and expresses how much the specimen color deviates from the neutral gray scale of the same value. Munsell color descrip-

tions for the speleothems are listed in Table 1.

SPECTRA OF WHITE SPELEOTHEMS

White speleothems do not absorb in the visible region of the spectrum but have a complex absorption spectrum in the near infrared. Figure 2 shows the spectra of white specimens of calcite, aragonite and for comparison, gypsum. The spectra of the carbonate minerals are quite similar to the spectrum of gypsum although the absorption bands of gypsum are more intense and somewhat better resolved.

The near infrared spectrum of gypsum is due to vibrational motions of the two water molecules that make up the  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  structure. Further, the two bands at 1400 and 1900 nm are known to arise from molecular water in a number of compounds. This and the close agreement be-

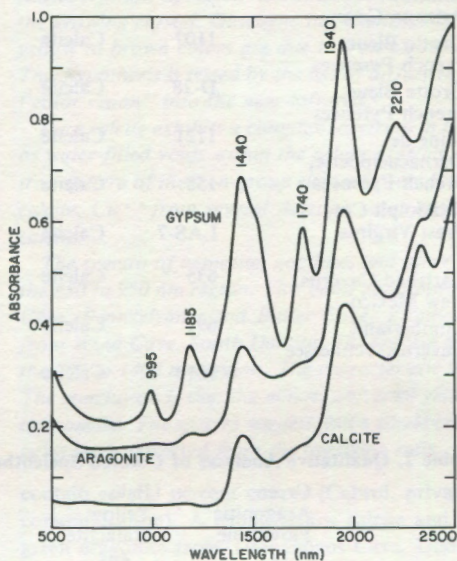


Figure 2. Diffuse reflectance spectra of colorless specimens of calcite, aragonite and gypsum. Note the correspondence between the strong bands in the gypsum spectrum with the peaks in the calcite and aragonite spectra.

tween the main bands in the near infrared spectrum of calcite and aragonite with the gypsum spectrum lead to the conclusion that the absorption bands in the 1400 to 2500 nm region are due to absorbed water in the speleothems. Since there is no essential structural water in either calcite or aragonite, it may be presumed that the water is present either as fluid inclusions within the crystals (which may give calcite and aragonite their characteristic translucent appearance) or is present as adsorbed water on the crystal grain boundaries.

The ubiquitous water bands, however, limit the useful range of the infrared spectrum since they will mask other absorption features. The observation of color source in speleothems is limited to the range of 400 to perhaps 1200 nm.

SPELEOTHEMS COLORED BY IONS OF THE IRON GROUP

The elements that occur on the first long row of the periodic table, sometimes called the transition elements or iron group elements, have in common a partially filled d-electron shell. The ions of these elements,  $\text{Fe}^{2+}$ ,  $\text{Cr}^{3+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Cu}^{2+}$ , etc. also have partially filled electron shells. The energies required to move electrons from their ground state to nearby empty states is relatively low, 1 to 3 electron volts, and these processes can be driven by electromagnetic radiation with frequencies in the visible and near infrared portions of the spectrum. The energy for the internal electron rearrangements is drawn from the electromagnetic wave and results in an absorption band at the corresponding wavelength. These processes are relatively weak and the materials colored by them are still partially transparent.

The details of the absorption process are strongly influenced by the electrostatic field created by the negatively charged anions that surround the positively charged cation in the mineral crystal. The magnitude of this "crystal field" is dictated by the anion charges, their distances from the cation, and their arrangement in space. These are known if the crystal structure is known. Each of the iron group ions has a characteristic spectrum dictated by its particular electronic structure. When salts of these ions are dissolved in water there is formed a regular octahedron of water molecules around the ion,  $\text{Ni}(\text{H}_2\text{O})_6^{2+}$  for example, and it has been customary to use the hexaquo complexes as a sort of reference state. The fact that trivalent chromium salts usually form deep green solutions, copper salts blue solutions, and nickel salts yellow-green solutions is a demonstration of the constancy of the hexaquo complexes regardless of whether the original salt was a nitrate, sulfate, halide or whatever. Using the spectra of the hexaquo complexes as a reference it is then possible to correlate the observed spectra of minerals with known details of their crystal structure.

The crystallographic factors that serve to modify the absorption spectra from the reference spectra are:

- (i) The coordination number of the cation—that is the number of anions that occur as immediate nearest neighbors.
- (ii) Deviations of the cation coordination polyhedron from regular octahedral (or tetrahedral) symmetry.
- (iii) The cation to anion distances.

The quantum mechanical underpinnings of crystal field theory may be found in any of several textbooks on the subject (e.g., Ballhausen, 1961; Cotton, 1971). For a discussion of the applications of crystal field theory to mineralogy, the reader is referred to Burns (1970).

Spectra of a collection of speleothems colored by the iron group elements are given in Figure 3. In each case, there is a characteristic absorption

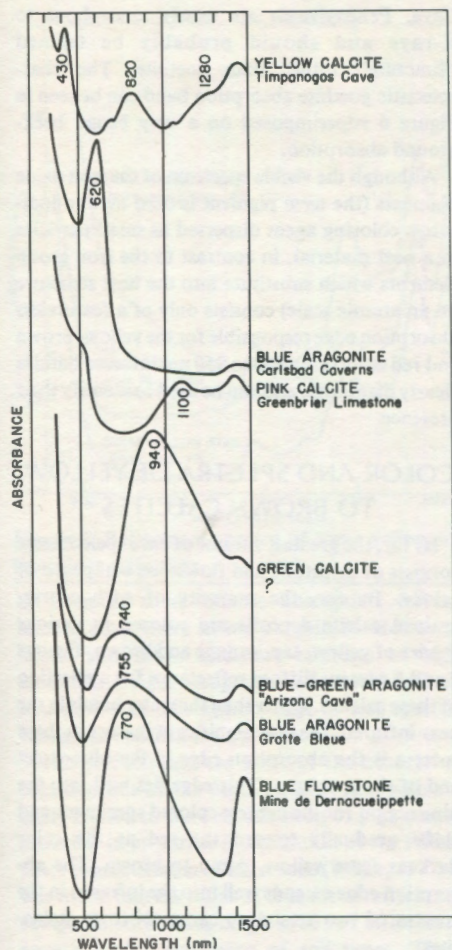


Figure 3. Diffuse reflectance spectra of some speleothems colored by transition metal ions.

band or bands (the maxima in the absorbance curves) and the color is determined by the "window" between this band and a common strong absorption edge in the violet end of the spectrum. The subtlety in the relation between absorption spectrum and color is illustrated by the collection of copper spectra at the bottom of the figure. The absorption minima for the three aragonite specimens is near 500 nm and the colors are distinctly blue or blue green. In copper-substituted calcite the window shifts ever so slightly to about 550 nm and this specimen is a distinct green.

The spectra are not themselves sufficient evidence to determine which iron-group ion is responsible for the color. Except for  $\text{Ni}^{2+}$  which has a characteristic three-band spectrum, both  $\text{Fe}^{2+}$  and  $\text{Cu}^{2+}$  have single broad absorption bands in the same general region of the spectrum. It is helpful, if not necessary, to have a chemical analysis for trace elements to assist in the interpretation of the spectra.

Direct correlation of trace element composition with color, which has been attempted by several investigators in the past, is a dangerous business if one does not have a grasp of the factors responsible for the color. As an example, zinc usually occurs with copper in speleothems and often the zinc

concentration is much higher than the copper concentration. Therefore it has sometimes been inferred that the blue color of some of these speleothems is due to zinc. However, the  $\text{Zn}^{2+}$  ion has a completely filled d-electron shell. There are no empty states to which electrons can be activated by light, and thus  $\text{Zn}^{2+}$  does not serve as a coloring ion. It is necessary that the absorption spectrum be consistent with the assigned ion on the assigned site in the mineral and that chemical analysis shows that the ion is actually present.

It was shown by White and Van Gundy (1974) that the yellow calcites from Timpanogos Cave were due to  $\text{Ni}^{2+}$  substituted for  $\text{Ca}^{++}$  in the calcite structure. The detailed interpretation of the spectrum is given in the earlier paper and is not repeated here.

Although iron is commonly supposed to be responsible for color in speleothems, examples of calcite with  $\text{Fe}^{2+}$  substituted in the crystal structure are not common. The example given here is a pink vein calcite found in the Greenbrier limestone in Randolph County, West Virginia. The reflectance spectrum shows a broad absorption band at 1100 nm (or perhaps at longer wavelength; there is an interference from a water band). Comparison of this spectrum with the spectra of other ferrous iron compounds (Jones, 1967) confirms the assignment. The chemical analysis shows iron to be present but there are no other iron-group elements. The pink color of the vein calcite is due to the broad window between the band due to  $\text{Fe}^{++}$  on the  $\text{Ca}^{++}$  site in the calcite structure and the absorption edge (which also contains a shoulder of unknown origin) in the violet portion of the spectrum.

The optical absorption spectrum for  $\text{Cu}^{2+}$  in  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$  consists of a single broad, rather asymmetric band centered at  $13,000 \text{ cm}^{-1}$  (769 nm) (Holmes and McClure, 1957). The absorption spectrum of  $\text{Cu}^{2+}$  in the reference material is quite similar to the spectra observed for the various blue and blue-green aragonite speleothems given in Figure 3.

The green calcite sample consists of a coarse-grained, nearly white "bacon strip" speleothem with a green color banding instead of the usual brown. The coloring agent appears under microscopic examination to be uniformly distributed in the nearly transparent calcite grains. The absorption maximum of this material occurs at 940 nm ( $10,640 \text{ cm}^{-1}$ ). The copper ion in both calcite and in the reference copper sulfate occurs in 6-fold coordination. However, the average Cu-O bond distance in  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O} = 2.118 \text{ \AA}$  (Baur and Rolin, 1972) whereas the Ca-O distance in calcite is  $2.36 \text{ \AA}$ . The absorption band frequency of the  $\text{Cu}^{2+}$  ion is shifted to longer wavelengths by the weaker crystal field in the larger  $\text{Ca}^{++}$  site. The observed value for the copper-containing calcite is a confirmation that the copper found in this specimen by chemical analysis is actually substituted for  $\text{Ca}^{2+}$  in the calcite structure.

The copper-containing aragonites are a problem. The Ca-O distances in aragonite, mean =

$2.526 \text{ \AA}$  (Dickens and Bowen, 1971), and the 9-fold coordination of aragonite would both act to shift the absorption maximum far out into the infrared. Yet the absorption maximum of  $\text{Cu}^{2+}$  in the aragonite specimens is very similar to the spectrum of the reference material. Microscopic examination of the aragonites suggests an answer; The blue color of these speleothems is due to a dispersed copper-containing second phase, perhaps azurite or a related carbonate. Although the color of these specimens is due to copper, the copper is not substituted for  $\text{Ca}^{2+}$  in the aragonite structure.

A similar situation was found in the Timpanogos Cave green aragonites. The coloring agent was found to be a nickel-containing second phase dispersed among the aragonite grains. The explanation may be found in the relative ionic sizes of the iron group elements compared with  $\text{Ca}^{2+}$ . The ionic radii of  $\text{Ni}^{2+}$ ,  $\text{Fe}^{2+}$ , and  $\text{Cu}^{2+}$  are 0.70, 0.77, and 0.73  $\text{\AA}$  respectively, compared with 1.00  $\text{\AA}$  for  $\text{Ca}^{2+}$  (Shannon and Prewitt, 1969). The calcium ion is at about the upper size limit for stability of the calcite structure, which is why it is found in both a calcitic and aragonitic form. The carbonates of the many of the iron-group elements are isostructural with calcite. The large cation site of the aragonite structure is more accommodating to large ions and the carbonates of  $\text{Sr}^{2+}$ ,  $\text{Ba}^{2+}$ , and  $\text{Pb}^{2+}$  take on the aragonite structure. The iron group ions are simply too small to satisfy the bonding requirements of the aragonite structure and it becomes energetically more favorable for these elements to segregate into separate phases rather than form a solid solution. Aragonite is therefore often colorless even when nearby calcite is colored.

One small mystery remains in Figure 3. The origin of the blue color in a small stalactite from Carlsbad Cavern was not identified. The specimen is a straw stalactite with an outer coating of aragonite needles with daubs of both a blue material and a black material coating the surface. Its absorption spectrum does not resemble any of the other spectra or any known spectra of the iron-group elements. Nothing was found in the chemical analysis to suggest an origin for the blue color. A similar patch of blue-green material was found in a cluster of aragonite crystals (sample 114) from Cumberland Caverns, Tennessee with a similar absorption spectrum.

## SPELEOTHEMS PIGMENTED BY IRON OXIDES

The stable form of iron oxide in the cavern environment is goethite,  $\text{FeOOH}$ . Hematite,  $\text{Fe}_2\text{O}_3$ , is not thermodynamically stable in the presence of water at cavern temperatures but in fact the kinetics of the hydration reaction are so slow that hematite formed in a dry cave or hematite which is protected by encapsulation in calcite or other minerals is likely to remain for long periods of time. Both goethite and hematite are very strongly

colored and both may appear a deep brown or black in thick specimens. In finely powdered form or as very thin layers goethite is yellow whereas hematite is a maroon red. Crushing a mineral until the particles are thin enough to transmit light is the basis of the "streak test" of elementary mineralogy which is often used to distinguish hematite from the hydrated forms of iron oxide.

Diffuse reflectance spectra of hematite, goethite and another polymorph of  $\text{FeOOH}$ , lepidocrocite, are shown in Figure 4. The characteristic features of these spectra are an absorption band at 850 to 950 nm and a steep absorption edge that cuts off most of the visible light. It is the steep absorption edge that gives the iron oxides their deep red or brown colors; the materials are essentially opaque except at the red end of the spectrum. Although the spectra of the iron oxides appear superficially similar to the spectra of the speleothems colored by iron group elements, the

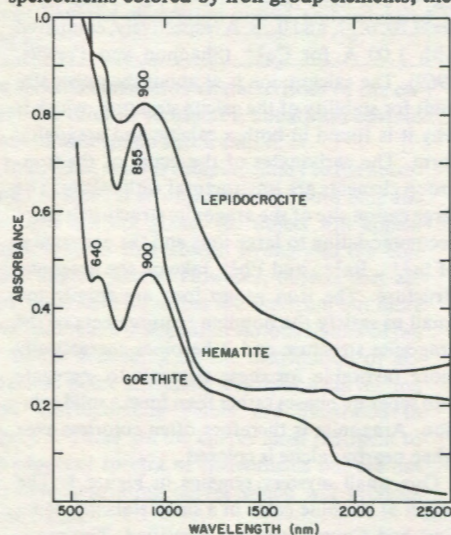


Figure 4. (above) Reference spectra for hematite,  $\text{Fe}_2\text{O}_3$  and two of the polymorphs of  $\text{FeOOH}$ , goethite and lepidocrocite.

absorption features are, in fact, much more intense. The spectra shown for the calcite speleothems were obtained by direct reflectance from the surface of bulk materials and the penetration of light into the specimen was substantial. The spectra of the iron oxides were measured on finely ground powders.

The electron exchange processes responsible for the colors of the iron oxides are not so well understood as the processes described by crystal field theory. There is a relatively detailed interpretation of the optical absorption spectrum of hematite based on measurements on thin films and single crystals (Marusak, *et al.*, 1980) but there is no equivalent analysis of goethite.

Wind cave, South Dakota, provides examples of speleothems that are pigmented with hematite. Red sediments occur and there are grains of hematite dispersed in the clear calcite crystals that make up the boxwork. The hematite is well-crystallized and can be identified by its X-ray powder pattern

(White and Deike, 1962). Figure 5 shows the reflectance spectra of two such materials. The spectra of the boxwork and of a red clastic sediment found cemented between layers of boxwork are remarkably similar. In both spectra the characteristic hematite band appears at 875 nm.

Speleothems of hydrated iron oxides occur in a few caves. The material is usually carried into the cave dispersed as fine particles in water, not in solution. In a strict sense, such speleothems should be considered clastic sediments rather than speleothems because they are not formed by chemical precipitation in the cavern environment. A wall coating from Butler Cave, Virginia, (Fig. 6) gives a spectrum with a well defined absorption band at 915 nm. The X-ray powder diffraction pattern of this material contains the characteristic goethite reflections although they are weak and there is a considerable background of amorphous material. Iron oxide stalactites from Porter's

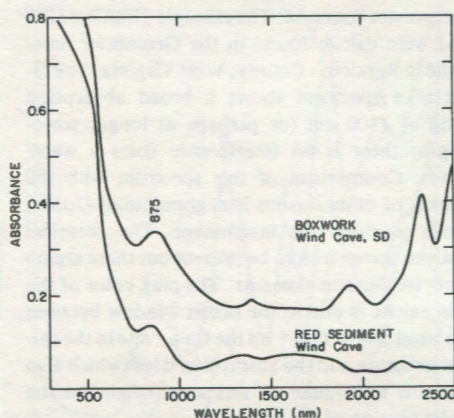
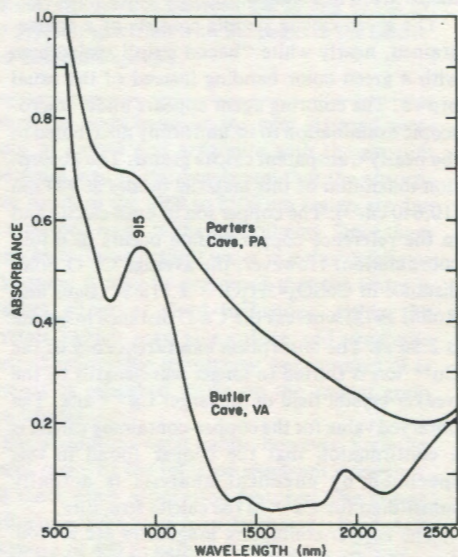


Figure 5. (above) Reflectance spectra for two hematite-pigmented specimens from Wind Cave, South Dakota.

Figure 6. (below) Reflectance spectra for two goethite speleothems.



Cave, Pennsylvania are nearly amorphous to X-rays and should probably be termed "limonite" rather than goethite. The characteristic goethite absorption band can be seen in Figure 6 superimposed on a very broad background absorption.

Although the visible spectrum of the iron oxide pigments (the term pigment is used here to indicate a coloring agent dispersed as small particles in a host material, in contrast to the iron group elements which substitute into the host structure on an atomic scale) consists only of a featureless absorption edge responsible for the yellow, brown and red colors, the 850 to 950 nm infrared band is clearly diagnostic and can be used to identify their presence.

## COLOR AND SPECTRA OF YELLOW TO BROWN CALCITES

By far, the greatest volume of cave speleothems consists of dripstone and flowstone composed of calcite. By far, the majority of such coarse-grained calcite deposits are colored in various shades of yellow, tan, orange and brown. Figures 7 and 8 present diffuse reflectance for a selection of these calcites. Other than the water bands in the near infrared, the only significant feature in these spectra is the absorption edge in the blue-violet end of the spectrum. This edge lies well into the blue region for the lightest colored specimens and shifts gradually toward the red as the color darkens from yellow to tan to brown. The absorption edge extends well into the infrared in the spectra of two very deep caramel-brown stalactites.

Conspicuous by its absence is any indication of an absorption band in the range of 850 to 950 nm. The absence of this feature in any of the calcite speleothems examined seems to be clear proof of at least the first part of Gascoyne's hypothesis: the brown colors of common speleothems are not due to pigmentation by hydrated iron oxides coating grain boundaries or distributed through the growing calcite crystals. Some other origin for the common colors of speleothems must be found.

Gascoyne's hypothesis, that the common speleothems are pigmented by organic stains of humic or fulvic acids is consistent with the spectroscopic evidence but the spectra do not provide a conclusive proof. Organic compounds containing unsaturated bonds usually absorb strongly in the ultraviolet. Discrete compounds of relatively simple molecular structure such as benzene and the aromatic hydrocarbons, compounds containing conjugated series of double bonds, and compounds containing unsaturated nitrogen bonds will produce one or more broad and intense absorption bands. As the number of conjugated aromatic rings increases or as the number of conjugated unsaturated bonds increases, these bands shift from the ultraviolet into the visible region of the spectrum. One may presume that the observed absorption edge is merely the long wavelength tail

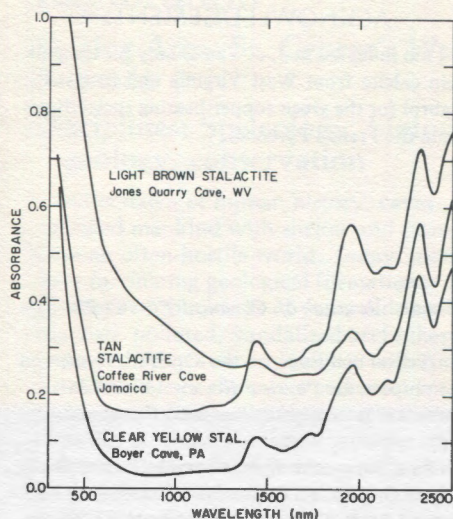


Figure 7. Reflectance spectra of some yellow to tan calcite stalactites.

of a much more intense absorption feature located somewhere in the ultraviolet. However, humic and fulvic acids are mixtures of high molecular weight compounds of poorly defined structure. The absorption edge is not specific enough to confirm their presence.

The position and the slope of the absorption edge depends on the depth of color and both are likely related to the concentration of pigmenting material. In an earlier investigation of the reflectance characteristics of karst soils (White, 1977) it was found that the ratios of blue to red reflectance compared with ratios of green to red reflectance gave a useful separation of soil types. These ratios, in a rough way, measure the curvature of the absorption edge and the fact that red karst soils fell on a different plot from brown soils was taken to mean that these families of soils had different pigmenting materials. Reflectance ratios were constructed for the yellow-to-brown calcite speleothems by first subtracting the background absorption determined from the minimum in the reflectance curves in the near infrared (necessary because the spectra were measured on irregular chunks of material rather than smooth surfaces of powder plaques) and then taking the ratio of the absorbance at 450 nm (blue) and 525 nm (green) to the absorbance at 600 nm (red).

$$B/R = \frac{A_{450} - A_{\text{background}}}{A_{600} - A_{\text{background}}}$$

$$G/R = \frac{A_{525} - A_{\text{background}}}{A_{600} - A_{\text{background}}}$$

Figure 9 shows the plot of B/R against G/R. It can be seen that all specimens fall neatly on a single straight line. The very dark brown speleothems fall near the lower left of the figure because of the overall high absorbances, but there is no apparent separation of the spectral behavior of the calcites into distinct regions of the curve. Very light colored speleothems occur at both ends of the line. From Figure 9, it is deduced that all of the dozen speleothems examined contain a common pig-

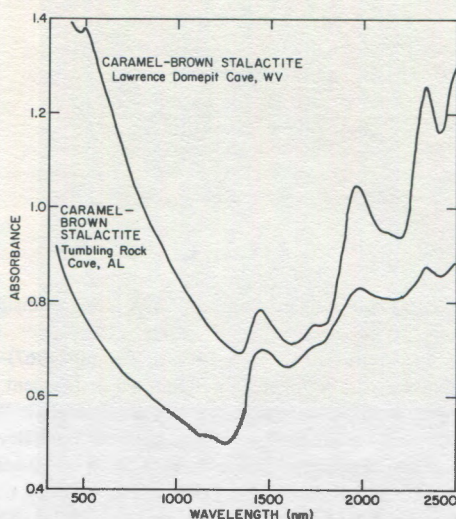


Figure 8. Reflectance spectra of two deep-brown speleothems.

menting material. As can be seen from Table 1, the colors of these speleothems vary from light yellows and tans, through orange to deep brown. The color variation is due to the position and intensity of the absorption edge. What Figure 9 shows is that there is a geometrical similarity to all of the absorption edges, a similarity that would not be expected if some of the specimens were colored by one pigment, perhaps an organic stain while others were colored with a different pigment, perhaps hydrated iron oxides. As shown earlier, however, the absence of an absorption band in the 850 to 950 nm region rules out the iron oxides as candidates for the pigmenting material.

There is one further circumstantial piece of evidence for organic pigments. Sometimes deeply colored calcites are found that have been weathered. Specimen 635 has an outer crust nearly a centimeter thick over a massive, coarsely-crystalline inner core. The calcite of the outer crust is fine grained, very porous, and changes continuously through a transitional region to the massive material of the core. The outer crust is pure white; the brown pigmenting material from the core was completely bleached during the later weathering process, a behavior consistent with organic pigments but not with iron oxides.

## SUMMARY AND CONCLUSIONS

This paper had its initiation in Gascoyne's comments on the absence of a correlation between trace element concentration and speleothem color. The approach in the present work was to use the spectroscopic characteristics of selected speleothems as parameters which could be compared in a more quantitative way with the chemical composition of the materials. Spectra were measured by diffuse reflectance of light from the bulk speleothems, so the optical effects of grain size, fluid inclusions, grain boundary phases and related scattering centers should be similar to those experienced during visual observation. The main conclusions drawn from the

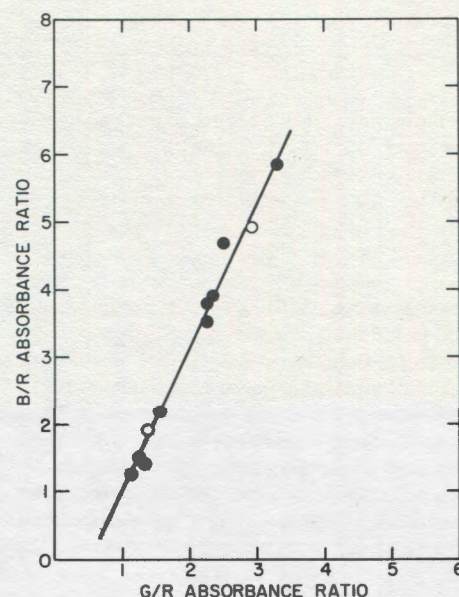


Figure 9. Plot of blue/red absorbance versus green/red absorbance for yellow-to-brown colored calcite speleothems.

spectroscopic study may be summarized as follows:

- \* All speleothems, including colorless ones, exhibit a rich set of absorption bands in the near-infrared which were shown to result from included water either as fluid inclusions in the grains or trapped on grain boundaries.
- \* Ions of the iron group elements, notably  $Fe^{2+}$ ,  $Ni^{2+}$  and  $Cu^{2+}$  act as colorants by replacement of  $Ca^{2+}$  in the calcite structure. Each has a characteristic spectral signature which is dependent on the particular ion and on the detailed geometry of the crystallographic site on which it occurs. Coloration of aragonite by these same ions is usually due to the presence of minor amounts of highly colored second phases rather than to substitution of the colorant ions into the aragonite structure.
- \* The oxides and oxyhydroxides of iron, mainly the minerals hematite and goethite (and limonite) are deeply colored materials that act as pigments. Their spectral signature is a characteristic absorption band in the range of 850 to 950 nm. The observation of this band identifies iron oxide pigments and allows them to be separated from the effects of other yellow-orange-brown pigmenting substances.
- \* The common yellow, tan, orange, and brown colors observed in most calcite speleothems are not due to the oxides and oxyhydroxides of iron. They appear from the behavior of the spectral absorption edge to be all due to a single pigmenting substance which is dispersed

through the calcite grains as well as over grain surfaces. The absence of a correlation between the observed colors and chemical analysis for metals leads indirectly to the conclusion that organic pigments, possibly humic and fulvic acids,

are responsible for the common colors of speleothems. This was Gascoyne's hypothesis, and the present work supports it although neither the chemical or spectroscopic evidence constitutes a proof.

#### ACKNOWLEDGEMENTS

I am indebted to J. J. Van Gundy for the pink vein calcite from West Virginia and to Patrick Cabrol for the green copper-bearing speleothems from the French Pyrenees.

#### LITERATURE CITED

- Ballhausen, C. J. (1961)—*Introduction to Ligand Field Theory*: NYC, McGraw-Hill, 298pp.
- Baur, W. H. and J. L. Rolin (1972)—Salt Hydrates IX. The Comparison of the Crystal Structure of Magnesium Sulfate Pentahydrate with Copper Sulfate Pentahydrate and Magnesium Chromate Pentahydrate: *Acta Crystallographica* **B28**:1448-1455.
- Beck, B. F. (1978)—Color Differentiation in "Fried Egg" Stalagmites: *Journal of Sedimentary Petrology* **48**:821-824.
- Burns, R. G. (1970)—*Mineralogical Applications of Crystal Field Theory*: Cambridge, Cambridge University Press, 224pp.
- Cabrol, Patrick—Centre d'Études et de Recherches Géologiques et Hydrogéologiques, Université des Sciences et Techniques de Languedoc, 34060 Montpellier Cédex, France.
- Cotton, F. A. (1971)—*Chemical Applications of Group Theory*: NYC, Wiley, 386pp.
- Dickens, B. and J. S. Bowen (1971)—Refinement of the Crystal Structure of the Aragonite Phase of  $\text{CaCO}_3$ : *National Bureau of Standards, Journal of Research*, **75A**:27-32.
- Gascoyne, Mel (1977)—Trace Element Geochemistry of Speleothems: *International Congress of Speleology, 7th, Proceedings*, pp. 205-208.
- Hill, C. A. (1976)—*Cave Minerals*: Huntsville, National Speleological Society, 137pp.
- Holmes, O. G. and D. S. McClure (1957)—Optical Spectra of Hydrated Ions of the Transition Metals: *Journal of Chemical Physics* **26**:1686-1694.
- Jones, G. D. (1967)—Jahn-Teller Splittings in the Optical Absorption Spectra of Divalent Iron Compounds: *Physical Review* **155**:259-261.
- Judd, D. B. and G. Wyszecski (1975)—*Color in Business, Science and Industry*: NYC, Wiley, 553pp.
- Kral, Z. (1971)—Studie Vzniku a Barevnosti Krapnikovych Utvaru (Study of the Origin and Coloring of Dripstone): *Ceskoslovensky Kras* **23**:7-15.
- Marusak, L. A.; R. Messier; and W. B. White (1980)—Optical Absorption Spectrum of Hematite,  $\text{Fe}_2\text{O}_3$  Near IR to UV: *Journal of the Physics and Chemistry of Solids* **41**:981-984.
- Munsell Color (1976)—*Munsell Book of Color*: Baltimore, Macbeth Div. of Kollmorgen Corp., 6 pp + 42 pl.
- Shannon, R. D. and C. T. Prewitt (1969)—Effective Ionic Radii in Oxides and Fluorides: *Acta Crystallographica* **B25**:925-946.
- White, W. B. (1976)—Cave Minerals and Speleothems, IN: T. D. Ford and C. H. D. Cullingford (eds.)—*The Science of Speleology*: London, Academic Press, pp. 267-327.
- (1977)—Characterization of Karst Soils by Near Infrared Spectroscopy: *NSS Bulletin* **39**:27-31.
- and G. H. Deike III (1962)—Secondary Mineralization in Wind Cave, South Dakota: *NSS Bulletin* **24**:74-87.
- and J. J. Van Gundy (1974)—Reconnaissance Geology of Timpanogos Cave, Wasatch County, Utah: *NSS Bulletin* **36**:5-17.

Manuscript received by the editors 14 June 1980.

Revised manuscript accepted 1 July 1981.

*"It is of great importance that the general public be given the opportunity to experience, consciously and intelligently, the efforts and results of scientific research. It is not sufficient that each result be taken up, elaborated, and applied by a few specialists in the field. Restricting the body of knowledge to a small group deadens the philosophical spirit of a people and leads to spiritual poverty."*

ALBERT EINSTEIN

# Bermuda Cave Exploration

**Staging Area: St. George's West,  
Bermuda**

**Disciplines: Speleology, biology,  
geology, conservation**

In the dawn of human history, caves provided mankind with shelter and protection from an often-hostile world. Today, many of these fascinating geological formations, some hundreds of thousands of years old, are being quarried, polluted, vandalized and otherwise destroyed. Yet caves and the life within constitute one of the rarest and most fragile environments on earth. Here one encounters icicle-like stalactites — some growing only inches in thousands of years — and tubular "soda straws", so fragile that they sometimes shatter from their own weight. Here too are gravity-defying, twisted helectites and cave pearls. Within the dark cave are rare animals — many lacking eyes and pigment — which have adapted to their dark domain.

The limestone caves of the oceanic islands of Bermuda, which boast one of the highest concentrations of caves in the world, offer a unique opportunity for biological, geological and paleontological studies. Dr. Thomas M. Illiffe, Research Associate at the international research center, the Bermuda Biological Station, plans to investigate and document Bermuda's many caves so that they may be better understood and thereby protected.

EARTHWATCH volunteers will work closely with specialists to explore for new caves in a jungle area not far from the B.B.S. Teams will learn to survey, collect small marine animals, photograph cave features, determine submarine connections (using dye tracing) and other speleological field work. As part of an effort to clean up and restore the caves, which play an important role as tourist attractions in the islands' economy, volunteers will help remove refuse and repair the damaged speleothems.

The result of this expedition, which supplements other cave research ongoing at the B.B.S., is not just to better understand Bermuda's many caves, but also to return them to their state of natural beauty for future generations.

*Field conditions:* Team members will bed and board at the Bermuda Biological Station, an international oceanographic station with cottages, laboratories, research vessels and libraries. Volunteers will have time to collaborate with the many scientists doing research here as well as to explore the island, snorkel, scuba-dive, and photograph the caves. Autumn weather on these tropical islands is usually very pleasant — water and air temperatures typically in the 80s (F).



*Bermuda's caves must be restored to their original beauty.*

**Team I: Sep 28-Oct 11**  
**Team II: Oct 12-25**  
**Team III: Oct 26-Nov 8**  
**Team IV: Nov 9-22**

**Share of costs: \$1360**

## EARTHWATCH

10 Juniper Road  
Box 127  
Belmont, Massachusetts 02178

## AUTHOR'S REPRINTS

Author's reprints of *Bulletin* articles should be ordered from the printer. Reprints will be in two-page increments and will include all material which appears on that increment. An extra charge of \$6.00 per page will be made if deletion of extraneous material is requested. Payment should accompany the order. Send payment and order to Graphic Publishing Co., 204 North 2nd Ave. West, Lake Mills, Iowa 50450.

No. of Reprints	2 page	4 page	6 page	8 page	10 page	12 page	Add'l Pages
50	20.00	22.50	27.50	33.00	38.50	44.00	6.50
100	24.00	27.00	33.00	39.50	46.50	52.50	7.00
150	28.00	31.50	38.50	46.00	54.00	61.50	7.50
200	32.00	36.00	44.00	53.00	61.50	70.00	8.50
300	40.00	45.00	55.00	66.00	77.00	88.00	11.00
400	48.00	54.00	66.00	79.00	92.50	105.50	13.00
500	56.00	63.00	77.00	92.50	108.00	123.00	15.50
Additional 25 copies	1.60	2.25	2.75	3.50	4.00	4.50	.60

**NATIONAL SPELEOLOGICAL SOCIETY**

Cave Avenue  
Huntsville, Alabama 35810

Address Correction Requested  
Forwarding & Return  
Postage Guaranteed

12386 R  
 HORTON H. HOBBS,  
 601 WHITE OAK DR.  
 SPRINGFIELD, OH 45504  
 82-07-1118