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STRUCTURAL SEGMENTS AND THE ANALYSIS OF FLOW PATHS
IN
THE NORTH CANYON OF SNEDEGAR CAVE,
FRIARS HOLE CAVE SYSTEM, WEST VIRGINIA

THESIS
Submitted to the College of Arts and Sciences
of
West Virginia University
In Partial Fulfillment of the Requirements for
The Degree of Master of Science

Roy A. Jameson, B. A.

Morgantown, West Virginia
1985
In general, the larger the problem, the more many-sided it is, the more complicated by secondary and tertiary feedback couples, and the more difficult it is to obtain the evidence, the more essential it is to the efficient prosecution of the study that the system first be understood in qualitative terms; only this can make it possible to design the most significant experiments, or otherwise to direct the search for the critical data, on which to base an eventual understanding in quantitative terms.

J. H. Mackin (1963)

To achieve its potential, karst research must make use of the full complement of sciences and mathematics. It is clear from the above discussion that intuition alone can sometimes lead to false conclusions, and that one’s observations should not be extrapolated blindly into the unknown. However, it is important that equations and computer analyses play only a secondary role to field work. Detailed observations and mapping of geomorphic features provide the only anchor that holds a conceptual model to reality.

Arthur N. Palmer (1984a)
ACKNOWLEDGMENTS

I have incurred an inordinate number of intellectual, social, and financial debts during the preparation of this thesis. R. C. Solomon provided perspective and ideas. Dr. Henry Rauch, Dr. Richard Smosna, and Dr. William Dunne allowed me free intellectual reign to pursue this unsponsored research in a manner that I (perhaps alone) best saw fit. Dr. Rauch went beyond the call of duty in reading and criticising several early versions of the thesis. Dr. Russell Wheeler, Dr. William Dunne, and Dr. Byron Kulander each provided useful criticisms of my ideas on geologic structures in the Greenbrier carbonates. Dr. Smosna and Dr. Milton Heald arranged for the use of the department equipment used in the lithologic analyses. Hobart King provided X-ray diffraction analyses of several rock samples.

The thesis began as an analysis of the role of faults on groundwater flow and cavern development. Hazel and Susan Medville are responsible for having set it in motion, for they showed me the North Canyon in the summer of 1978. Hazel, Susan, and Doug Medville prepared the first map of the North Canyon, and must have listened (Hazel and Doug, at least) with amazement to my initial enthusiastic reports about thrust faults and about the complex geology of what seemed to some but an ordinary canyon. Yet the thesis became something rather different
than an analysis of the role of faults in speleogenesis. As my wife Patty and I began to study the cave, and others in Monroe, Greenbrier, and Pocahontas Counties, we constantly found features that belied my preconceptions about cavern development. I found myself forced to pursue detailed morphologic interpretations of cavern development. I also found myself forced to evaluate and then re-evaluate current ideas on structural controls. In this latter task I have been aided by several researchers, none of whom would agree with all of the ideas advanced here. These workers include Will and Bette White, Art and Peggy Palmer, Stephan Kempe, and Steve Worthington. Scarcely a word of this study would have been possible without the pioneering studies of structural controls on Mendip (England) caves by Derek Ford. Art and Peggy Palmer, Stephan Kempe, and Dr. Henry Rauch accompanied me in the field and offered comments with little or no previous preparation. Will White has also been gracious enough to allow me to intrude myself into several of his annual field trips into Snedegar Cave and elsewhere in the Greenbrier karst.

Without the financial support of Gordon and Aida Mothes, founders of Friars Hole Cave Preserve, and my parents, Dr. David L. Jameson and Dr. Marianne M. Jameson, I would not have had the opportunity to pursue the exhaustive field work or extensive leisure for thinking that I needed to complete the study. Gordon and Aida provided me and Patty with accommodations, food, and jobs as caretakers of Friars Hole Cave Preserve during several years.
A very special thanks must be made to Patty. Without her help, none of this would have been possible. Patty accompanied me in the field as fellow caver. She patiently put up with my compulsive but essential demands for accuracy in both the Suunto and tape survey and the U-tube leveling survey. She read instruments, took notes, assisted in the photography, and waited patiently (most of the time) while I crawled in tiny holes and inspected ceiling half tubes. She chided me (perhaps not enough) when I was too slow, and criticised my theories. She helped resurvey the entire North Canyon when I decided that our first survey did not have sufficient vertical control to interpret speleogenesis. She put up with my initial confusions as we figured out a way to do a U-tube leveling survey in high gradient passages. She maintained a mobile living environment when it was necessary. Finally, Patty offered love and solace with encouragement when I despaired, and maintained, somehow, a cheerful disposition.

Douglas Medville provided working maps of Friars Hole Cave system. Robert Thrun provided computer-generated line plots. Bill Storage provided maps of several caves used in deciphering structural relationships. Charles Williams provided a working map of Friars Hole Cave. William Jones showed Patty and me around the karst in Greenbrier County and posed his usual sarcastic, but always useful questions. Sara Heller provided advance information about the hydrology and geology of her dissertation area in Greenbrier County. Eb Werner put up with endless monologues about speleogenesis. Eb accompanied me in several caves, taught me lab and field procedures for analyzing water
chemistry when I thought I was going to do a thesis in karst hydrology in Mexico, and with his wife Judy, put up with more monologues on caves when I visited them in Morgantown.

Numerous other cavers accompanied me underground or contributed to surveys in Friars Hole Cave system and other caves. Though a full list of contributors to the study of the system is not possible here, I would like to acknowledge the help of Chuck Hempel, Bill Jones, Charles Williams, Doug and Hazel Medville, Ron Simmons, Bill Storage, Andrea Dakowski, Gary Storick, Paul Hadfield, Steve Worthington, Chas and Pam Yonge, Alf Latham, Bill Skinner, Sandy Margo, Sara Heller, Eb Werner, Bob Gulden, Linda Baker, Bob Anderson, Bill Stone, Mike Doerr, Tim Walker, Ed Strausser, Barry Baumgardner, Alan Fincham, Dick Graham, Carol Veseley, Dave Bunnell, Bob Liebman, and Ward Fuller. Bill Mixon located several obscure references from the karst literature. Each of the above cavers has helped make karst research one of the more enjoyable activities worth pursuing in a perpetually unsatisfactory world that confuses satisfaction with mere possession and shallow entertainment. Even Faust knew better:

So taum'l' ich von Begierde zu Genuss,
Und im Genuss verschmacht ich nach Begierde.

From desire I rush to satisfaction,
But from satisfaction I leap to desire.

Faust I
Goethe
Finally, I would like to thank my parents, both for fostering a home atmosphere where life could be more stimulating than just family, and for forcing me into getting out into the world. If I may quote Faust once more:

Was du ererbt von deinem Vaetern hast,
Ewirb es, um es zu besitzen!

That which you have inherited from your forefathers,
Earn it in order to possess it.

Faust I
Goethe
ABSTRACT

Fractures influence cavern development by promoting bedrock collapse. Fractures also localize solution, thus guiding flow paths and promoting the growth of blind fissures or the in situ fragmentation of bedrock. Observations in branchwork caves in West Virginia suggest a method of inferring the locations of the early flow paths along fractures (structural segments) and of analyzing their subsequent enlargement. Detailed mapping and morphologic analyses of structural segments in the Union Limestone (Mississippian Greenbrier Group) in the North Canyon of Snedegar Cave, indicate stage I phreatic growth as ungraded tubes. Flow was guided mostly by bed partings (37%), systematic joints (29%), or bed-joint intercepts (20%). Thrust faults and their intercepts with joints guided 11% of the 1382 feet of inferred tubes. The stage I tubes lay on two levels separated by joint conduits. At the end of stage I, flow paths formed a complex network with several closed loops.

Stage II began with the earliest onset of vadose conditions. Low-discharge streams incised the apices of the ungraded tubes, forming narrow trenches. Lower parts of the ungraded conduits grew under closed-conduit flow in pressure loops. Where stage I flow paths
branched in a downstream direction, the higher downstream paths were abandoned, because stream depth was insufficient for flow to continue past high points. This process reorganized the flow system into three active conduits and three abandoned tubes. The active conduits became canyons (the North Canyon, the Headwall Passage, and the Saltpetre Maze Passage) as the streams cut down, removing pressure loops and grading the floors of the narrow trenches. The joint conduits between the two levels enlarged as shafts.

Stage III began with the introduction of clastic sediments. The sediments promoted undercutting, leading to the development of wide undercut surfaces. Wide trenches formed beneath these surfaces. A partial grading of the floor between the two levels was effected in the North Canyon by headward incision and lowering of the lip of the shaft, combined with a flow-path diversion. Collapse produced wedge-shaped breakdown where undercutting was extensive below bedrock bounded by faults, joints, and the narrow trenches.
CHAPTER 1
INTRODUCTION

The Roles of Fractures in Cavern Development

A fracture is "a surface along which loss of cohesion has taken place" (Dennis, 1967, p. 78). So defined, fractures include joints, faults, and bedding plane partings. The classification of bedding plane partings as fractures is a natural one for speleologists.* Like joints and faults, bedding plane partings are narrow spaces usefully described as surfaces that form planes of weakness and as openings that transmit water.

Tectonic joints, faults, and bedding plane partings usually form before the onset of cavern development. Tectonic activity such as glacial unloading (Palmer, 1975) or near-surface stress release (Renault, 1968) may widen or otherwise modify them during conduit enlargement. The roles of these fractures in guiding ground-water flow and controlling the development of passages in karst caves has long

* To help non-specialists, some standard karst terms are defined in the glossary. However, this study also introduces a number of new terms. These are underlined at their first appearance. If a formal definition is immediately helpful it is given in the text. Otherwise, definitions are relegated to the glossary, which often has an expanded discussion of the relationships between terms.
been recognized (Martel, 1921; Davis, 1930; Swinnerton, 1932; Bretz, 1942). Most importantly, the fractures provide openings along which aggressive ground water may flow (or be injected), thus leading to solution of bedrock. In this capacity the fractures may (1) guide initial or other early flow of ground water along flow paths; (2) promote the development of blind solution pockets, joint spurs, fissures, or anastomoses along the perimeters of existing conduits; and (3) promote in situ disaggregation of bedrock. In addition, the bedding plane partings, joints, and faults provide zones of structural weakness. In this capacity they may (4) promote cavern collapse. Collapse modifies passage morphology and leads to enlargement of conduits if breakdown is removed. Examples of such controls on cavern development are in reviews by Jennings (1971); Sweeting (1973), and Boegli (1981) and in papers by Ford, D. C. (1965b, 1968, 1971); Ford and Ewers (1978); Ford, T. D. (1971); Davis (1966); Atkinson (1968); Ewers (1966, 1972); Palmer (1972, 1974, 1975, 1977); Deike (1969); Kastning (1977); and Waltham (1971).

As caves enlarge, other fractures may form in bedrock exposed on the perimeters of passages, or on breakdown on cave floors. Such fractures include those generated by the following processes: collapse into undercut voids; pressure release of previously confined bedrock; crystal wedging by frost action or by growth of gypsum; exfoliation; and chemical and physical weathering (Davies, 1949, 1951; Pohl and White, 1965; Renault, 1968; White and White, 1969; Powell, 1977; Jagnow, 1978; C. W. Davies, 1977; and Jameson, 1983). These
later-forming fractures play two main roles in speleogenesis. They promote the fragmentation of bedrock, which can lead to increased rates of erosion and conduit enlargement. They also promote the modification of passage morphology.

Tracing the Growth of Cave Passages

This study is concerned with three main topics: (1) the directional guiding by fractures of the early flow of ground water along flow paths; (2) the physical character of the early flow; and (3) the nature of the changes in flow and conduit characteristics that arise as conduits evolve from small fractures into cave passages. These topics are linked by a single purpose—-that of tracing the growth of cave passages throughout their histories.

To trace the growth of cave passages in such detail, it is first necessary to identify and map the fractures that guided the early flows of ground water. This task is sufficiently difficult that it has rarely been attempted. Only a few attempts have been made to specify which fractures guided early flows for lengthy sections of cave in complex structural settings, and to study influences of those fractures on subsequent passage development (for examples, see Ford, 1965b; Jameson, 1981). The paucity of such studies is unfortunate, for it is precisely in complex structural settings that detailed studies of conduit evolution should be most fruitful. Moreover, the generalized nature of many otherwise excellent analyses of structural controls has meant that much potentially useful information has been ignored.
In this study an attempt is made to retrieve some of that information. The attempt begins as a method of inferring which fractures guided early flows of ground water in certain kinds of caves.

**Structural Segments**

In most carbonate aquifers with caves, the earliest dissolution effected by ground water is along fractures. Dissolution of bedrock on the walls of the fractures enlarges the fractures into rudimentary fracture conduits. Fracture conduits are small conduits that (1) transmit ground water along integrated flow paths and (2) are aligned along fractures.

In any large parcel of soluble bedrock exposed to recharge, some of the fracture conduits will capture sufficient, discharge for a sufficient period of time to grow to cavernous size. During this growth, processes of dissolution, abrasion, and collapse obscure or destroy evidence indicating which fractures guided early flows of ground water. Nonetheless, the extensions of the transmissive fractures are often retained as fracture traces that are visible on the perimeters of passages. In some passages these traces may be used along with appropriate morphologic and hydrologic evidence to infer structural segments.

Briefly stated, a structural segment is an inferred fracture conduit. More technically, a structural segment consists of a conduit developed along one or more fractures, such that the fracture(s) can be inferred to have guided the flow of ground water during the early
fracture-conduit stage of the development of the particular flow path. (However, for practical reasons, a structural segment may consist of more than one conduit on a single fracture; for examples, see pp. 23-27.) "Fracture-conduit stage" refers to that stage at which integrated flow from specifiable inputs to different specifiable outputs has been established, such that the bulk of the flow within a given parcel of bedrock is through discrete fracture conduits. Usually the fracture conduits will have sizes considerably larger than nearby less altered fractures that may contribute small diffuse flows. Recent arguments (based on diverse and still controversial models of the chemistry of dissolution and the physics of flow) would require a minimum diameter for fracture conduits on the order of 0.01 to 0.08 feet, assuming flow paths that are phreatic (White and Longyear, 1962; Howard, 1964; White, 1977b, 1978; Dreybrodt, 1981a, 1981b; Palmer, 1981a, 1984b).

Figure 1 illustrates the concept of a structural segment. The figure shows a single continuous tube aligned along several types of fractures. The tube is aligned successively along a bed parting, the intercept of a bed parting and a joint, and a zone of fractures that are closely spaced. Each part of the tube illustrates one of the three classes of structural segments. A class of structural segment is distinguished on the basis of the number of fractures that guided early flow, or on the basis of the way in which that early flow was guided. Single-fracture segments are conduits developed on individual fractures. Intercept segments are conduits developed on
Figure 1. Oblique-view midline diagram illustrating the concept of a structural segment. B = bedding plane parting. J = joint. From 1 to 2 is a single-fracture segment formed on the parting. From 2 to 3 is an intercept segment formed on the intersection of the bed parting and a joint. From 3 to 4 is a zone segment formed within a zone of joints and a bed parting.
the intersection of two or more fractures; there can be only one intersection. This means that most intercept segments use only two fractures. **Zone segments** are conduits developed along closely spaced fractures. For zone segments it is not generally possible to specify which fracture or fractures of a fracture zone guided early flows; instead one specifies a zone of fractured bedrock that is inferred to have been transmissive.

The concept of a structural segment is not likely to be applicable to more than a small percentage of caves. In fact, the concept is applicable only where ground water flowed during relatively early stages (for each flow path of interest) from discrete, identifiable inputs to similar outputs. This means that the concept is applicable primarily to caves exhibiting branchwork patterns (see White, 1960, pp. 45-49; also, see glossary). The above definitions eliminate the application of the concept to network mazes formed by diffuse infiltration, and to spongework mazes, for in such mazes it is essentially impossible to follow early flow paths from discrete inputs to discrete outputs. However, the concept of a structural segment may be useful in analyzing flow paths in floodwater mazes, particularly those local mazes that bypass constrictions in branchwork caves. The dynamics and origins of maze caves are discussed by Palmer (1975).

It is important to emphasize that structural segments *per se* are not generally observable. The reason is that they are in fact inferred paleo-fracture conduits, for the majority of these conduits have been destroyed by processes of cavern enlargement. In most cases it is, at
best, possible to see only "enlargements" or "remnants" of structural segments. (For example, in branchwork caves of the eastern United States, the enlargements of the structural segments that can be observed are typically small ceiling half tubes or fissures.) However, there are occasional exceptions in which structural segments can be directly observed. For example, some recently formed tubes and fissures transmitting ground water into modern cave passages are small, having only recently been integrated as vadose or floodwater flow paths. These may well be reckoned to be still in a fracture-conduit stage.

Even though structural segments are not generally observable, where their morphologic remnants (i.e., slightly modified remnants such as half tubes) are present, or other evidence is sufficient to identify them, it can be instructive to divide cave passages into structural segments and to attempt to follow flow paths from fracture to fracture. This is true for several reasons. First, the attempt to follow (or more importantly, map) flow paths in such detail forces one to observe cavern features that might otherwise be missed in more generalized studies. Second, in many caves an accurate account of speleogenesis can be obtained only if early flow paths are properly distinguished from later flow paths formed by floodwaters or formed as a result of diversion of ground water to lower levels (Palmer, 1972). (Often, these tasks can be done only if each flow path can be followed continuously over the area of interest. Such a situation is common in complex structural settings in which numerous flow paths formed in
small parcels of bedrock. As will be shown below, detailed knowledge
of fractures [and their influences on the geometries and the shapes of
small conduits enlarged from structural segments] can simplify the
tasks involved in distinguishing types and relative ages of flow
paths.) Third, the geometries of the early flow paths can exert
considerable influence on the modes of enlargement and on the
morphologies of the passages that develop from them (Ford, 1965, 1968,
1971; Ford and Ewers, 1978; Jameson, 1981). In cases where such
influences are suspected, it is essential to be able to identify the
precise positions and characteristics of the early flow paths.

The types of evidence useful in inferring structural segments
varies with the type of cavern development and the extent of passage
enlargement. Unfortunately, in most cavern settings evidence is
insufficient to identify more than scattered structural segments. Yet
in some caves it is possible, due to extraordinary geological condi-
tions and developmental sequences, to follow paleo-flow paths from
segment to segment through long sections of cave. Whole collections of
segments may then be distinguished as initial flow paths, diversion
routes to lower levels, or superimposed floodwater routes.

Some geologic conditions conducive to detailed segment analyses in
caves include: prominent but widely spaced joints, faults, or other
fractures; massive bedding; minimal collapse of passages; and limited
sedimentation, either by transported clastics or by chemical precip-
itates. It is also paramount that enlargement of passages not be
so great or so directed as to have totally removed the traces of the
fractures that were transmissive during early stages of flow. A cavern setting in which these latter conditions are often fulfilled is in canyons in branchwork caves. In such canyons the remnants of the early conduits can be seen on ceilings as small half tubes or fissures whose former floors have been entrenched by free-surface streams. These latter conditions are also often fulfilled in tubes and shafts accompanying the canyons.

Purpose and Design

Many branchwork caves, including some caves formed in complex structural settings in the carbonates of the Mississippian Greenbrier Group of West Virginia, have canyons which fulfill the above geologic conditions. A study was therefore undertaken to develop a method of inferring structural segments and of analyzing the history of development of passages enlarged from them. That method is presented in Part 1 of this thesis. In Part 2 the method is illustrated and further developed through a detailed interpretation of the growth of the North Canyon and several associated passages in Snedegar Cave. Snedegar Cave is in Friars Hole Cave system, a complex multi-level branchwork cave located north of Renick in east-central West Virginia.
PART 1
STRUCTURAL SEGMENTS AND SEGMENT ANALYSIS

CHAPTER 2
SEGMENT ANALYSIS: A PROCEDURE
AND ITS PRINCIPLES

Introduction

The method of segment analysis is based on study of passages in over 40 caves in Pocahontas, Greenbrier, and Monroe Counties, West Virginia. Some of the larger caves investigated are listed in Table 1. The caves marked with asterisks contain passages suitable for segment analysis. Such passages are typically in the purer carbonates of the Greenbrier Group. Passages in the more argillaceous units often contain abundant exfoliation (Jameson, 1983) and are seldom suitable for segment analysis. Canyons particularly suitable for segment analysis are in Friars Hole Cave system, Bone-Norman Cave system, the Portal, and Culverson Creek Cave system. In general, the canyons of the "contact caves," which are developed in the lower members of the Greenbrier Group and in the top of the underlying Macrady Shale, are not suitable for segment analysis. Accounts of speleogenesis in the
TABLE 1
INVESTIGATED MAJOR CAVES

<table>
<thead>
<tr>
<th>Pocahontas County</th>
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<tr>
<td>Martha’s Cave</td>
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<tr>
<td>Beard’s Blue Hole</td>
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<td>Cutlip Cave</td>
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<td>Hills-Bruffey Cave</td>
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<td>Clyde Cochrane Cave</td>
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<tr>
<td>Martens Cave</td>
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<tr>
<td>* Friars Hole Cave system</td>
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<tr>
<td>* Canadian Hole</td>
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<td>* Snedegar Cave</td>
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<table>
<thead>
<tr>
<th>Greenbrier County</th>
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</thead>
<tbody>
<tr>
<td>* Friars Hole Cave system</td>
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<tr>
<td>* Toothpick Cave</td>
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<tr>
<td>* Crookshank Cave</td>
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<tr>
<td>* Rubber Chicken Cave</td>
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<td>* Friars Hole Cave</td>
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<td>Robbins Run Hole</td>
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<tr>
<td>Fox Cave</td>
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<td>Browns Cave</td>
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<td>* The Portal</td>
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<td>Buckeye Creek Cave</td>
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<td>* Bone-Norman Cave system</td>
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<td>* Culverson Creek Cave</td>
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<td>Higginbothams No. 1 Cave</td>
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<td>- Luddington Cave</td>
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<tr>
<td>- McClung Cave</td>
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<td>* Herns Mill Cave</td>
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<td>- Organ Cave</td>
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<tr>
<th>Monroe County</th>
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<tr>
<td>Laurel Creek Cave</td>
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<tr>
<td>Greenville Saltpetre Cave</td>
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<tr>
<td># Patton Cave</td>
</tr>
</tbody>
</table>

* = Cave with passages suitable for segment analysis
- = Contact cave in the lower Greenbrier Group and in the Maccrady Shale (Jones, 1973)
# = Cave in Ordovician limestone (Davies, 1958)
contact caves are given by Balfour (1973), Palmer (1974), Rutherford and Handley (1976), and Wigal (1978).

The method of segment analysis is complex. It is tedious, because it requires detailed observation and interpretation of morphologic features preserved on passage walls and ceilings. The method is also extremely time-consuming as a field technique.

The exposition of the method begins with some additional terms and concepts that are needed for the description and mapping of structural segments. The exposition continues with a set of rules that are used to divide conduits into structural segments and that are used to describe and designate flow paths. (The rules may at first seem arbitrary. However, they are in fact practical necessities. Without them it would be difficult to study paleo-flow paths in complex branching flow systems in which there have been several stages of development using a variety of types of fractures.) Next, criteria for inferring structural segments are presented. In the final part of the chapter, the field procedures used to identify, map, and study structural segments are described. Also, the method of segment analysis is summarized in an outline. The field procedures, the inference criteria, and the outline of the method are further illustrated with the analysis of a hypothetical canyon. It should be stated that the analysis of the hypothetical canyon is worth deciphering with some care. Although that canyon is hypothetical, the analysis has been constructed so as to accurately illustrate the kinds of geomorphic reasoning needed to infer structural segments and
interpret conduit growth from structural segments into canyons. The
geomorphic and structural features that are used in the hypothetical
canyon are common in the caves listed in Table 1, particularly in
Friars Hole Cave system.

Some Segment Terminology

Each class of structural segments (p. 5) can be exemplified by a
variety of types of structural segments, or segment types. Segment
types are designated according to the type or types of host fractures.
A conduit developed on a bedding plane parting is a bed segment
(abbreviated B). Similarly, a conduit on a joint is a joint segment
(J); one on a fault is a fault segment (F); one on the intersection of
a bed parting and a joint is a bed-joint segment (BJ); one on the
intersection of a fault and a joint is a fault-joint segment (FJ); and
one on the intersection of a bed parting and a fault is a bed-fault
segment (BF). (A segment on a fault that is within the plane of a bed
parting is a fault segment.) To designate zone segments it is best to
list the host fractures. Thus Figure 1 has a zone segment containing
joints and a bed parting. Additions and modifications to these terms
(used to identify particular segments, for example) are introduced as
needed below.
Rules for the Division of Conduits
into
Segments, Sections, and Flow Paths

Midline Diagrams

Figure 2 is a midline diagram, a schematic view of a flow path. The diagram is drawn from an oblique view that allows a schematic representation of a bed parting and two joints. The location of the flow path on the fractures is indicated by midlines. Midlines are symbols—usually lines—that show the inferred positions of early flow of ground water along the transmissive fractures. In Figure 2 the flow path consists of two bed segments, a bed-joint segment, and two joint segments. It is continuous from position 1, the input, to position 6, the output. The method of segment analysis requires frequent reference to such passage locations. The passage locations are indicated by position names on plans, profiles, and cross sections of maps, as well as on midline diagrams. Position names are usually numbers. To distinguish position names from measured quantities, position names are underlined in the text. The word "position" is then often omitted. Position names are not underlined where they appear on maps or diagrams.

Endpoint Rules and the Branching Rule

An endpoint is the beginning or end of a segment. An endpoint is designated by a position name. To specify a segment with a segment,
Figure 2. Oblique-view midline diagram of a simple flow path. Flow is from an input at position 1 to an output at position 6. In segment terminology, we have bed segment 1-2, bed-joint segment 2-3, joint segment 3-4, joint segment 4-5, and bed segment 5-6. This is abbreviated as 1-2 = B, 2-3 = BJ, 3-4 = J, 4-5 = J, and 5-6 = B. This flow path is hypothetical. For actual passages the flow lines are usually drawn near the middle of the inferred early conduits from segment to segment, hence the name midline diagram. Midlines may show plan, profile, or oblique views.
name, the name of the segment type (e.g., bed segment) is combined with the names of the segment endpoints (e.g., 1 and 2 in Figure 2) and the underlining is omitted. Thus the farthest upstream bed segment of Figure 2 is bed segment 1-2.

Endpoints of structural segments are designated according to endpoint rules. While endpoint rules specify endpoints, they are simultaneously a set of conventions for dividing paleo-conduits into segments and sections (see below, p. 19) of flow paths. In Chapter 1, structural segments are divided into three classes: single-fracture segments, intercept segments, and zone segments. This division suggests that it would be useful to designate endpoints of structural segments wherever flow changed from:

(1) one class of segments to another class (e.g., from single-fracture bed segment 1-2 to intercept bed-joint segment 2-3 of Figure 2); or

(2) one fracture or fracture zone to another fracture or fracture zone (e.g., from joint segment 3-4 to joint segment 4-5 in Figure 2).

These rules are not sufficient for designating individual structural segments. The main reason is that conduits sometimes branch, and such branching may occur in what otherwise would be a single continuous structural segment. The problem can be visualized with the aid of Figure 3.

Figure 3A depicts what might be labeled "one conduit" branching into "two conduits" on a bedding plane parting. Without further information it is not clear how this should be dealt with. It might be
Figure 3. Oblique-view midline diagrams illustrating the need for a branching rule. (A) One conduit branching in a downstream direction into two conduits on a bedding plane parting. (B) Sequence of development of the conduits of (A) in which bed segment 1-2 forms first, followed by the development of bed segment 3-4. (C) Sequence of development of the conduits of (A) in which bed segment 1-4 forms first, followed by the development of bed segment 3-2. (D) Simultaneous development of the conduits of (A), resulting in the designation of bed segment 1-3, bed segment 3-2, and bed segment 3-4. With the branching rule the conduits of (A) are divided such that a new segment is designated wherever conduits branch. Thus, bed segments 1-3, 3-2, and 3-4 are designated.
decided (e.g., on the basis of morphologic evidence) that there was first a bed segment 1-2, followed by the development of a bed segment 3-4, as shown in Figure 3B. Alternately, it might be decided that there was first a bed segment 1-4, followed by the development of a bed segment 3-2 (Figure 3C). Another possibility would be that the branching conduits grew at the same time as distributaries. In the latter case it might be useful to designate three segments—namely bed segments 1-3, 3-2, and 3-4 (Figure 3D). Such differing (and mutually exclusive) interpretations of the sequence of the development of the conduits clearly result in the designation of segments with different endpoints, depending on the interpretation of the flow-path history, which would have to come first. Yet this procedure would not be helpful at all. Insofar as possible, it is desirable to have conventions for designating structural segments that do not first require an interpretation of the site-specific flow-path history. Instead, it is more appropriate to use the structural segments and the morphologic features of the conduits enlarged from them, to interpret the history of linkage and enlargement of the flow paths.

The problem is solved with the branching rule. By this rule, the cave is first divided into passage sections wherever branching occurs within the zone of early flow for each flow path. The sections are then divided into their constituent structural segments using the previous endpoint rules, with the following addition: endpoints are designated wherever branching occurs even if this arbitrarily truncates what once was a single continuous fracture conduit. (However, for
practical reasons there are several exceptions as described below on pp. 23-27 and 32-33).

Examples of this procedure are given in Figure 4 and Figure 5. These figures illustrate downstream and upstream branching, respectively. **Downstream branching** is the division of flow or of a conduit into several routes in a downstream direction. **Upstream branching** is the joining of two upstream flow paths or conduits to form a third flow path or conduit farther downstream. In branchwork caves, downstream branching (Figure 4) is typically due to the superposition of later stages of cavern development. An example is the case in which a flow path is abandoned as flow is diverted to a lower level when a water table drops (Palmer, 1975). Downstream branching may also occur as contemporaneous distributaries (Ewers, 1972, 1982). Upstream branching (Figure 5) is typically due to the input of tributaries, which may have formed simultaneously, or one before another.

In either form of branching, the division occurs at a branch-point. A **branchpoint** is a position common to at least three structural segments on three sections. The branchpoint may be specified by naming the position or by designating a **junction** of the sections. Sections are named with numbers or letters, such as section 1 (S1) or section M (SM). In Figure 4, position 2 is the branchpoint. Position 2 is also junction 1,2,3. The latter name is created by combining the word junction with the names of the sections. **Junction names** are abbreviated by placing the capital letter "J" in front of the names of the
Figure 4. Midline diagrams illustrating section and segment conventions for downstream branching. Here downstream branching is caused by diversion of flow to a lower level of the same bedding plane parting. (A) First, the conduits are divided into sections 1, 2, and 3 (S1, S2, S3). Then each section is divided into segments. (B) The section and segment descriptions and the midline diagram are used to describe and illustrate the initial flow path (Path 1) and the later flow path (Path 2).
Section 1: 1-3 = B
Section 2: 2-3 = B
Section 3: 3-4 = B

Initial Path:
Path 1: Section 1: 1-3 = B
Path 2: Section 2: 2-3 = B
Path 3: Section 3: 3-4 = B

Later Path:
Path 2: Section 2: 2-3 = B
Path 3: Section 3: 3-4 = B

Figure 5. Midline diagrams illustrating section and segment conventions for upstream branching. Here upstream branching is caused by the input of a tributary on the same bed parting by which the original flow path was guided. (A) First, the conduits are divided into sections 1, 2, and 3 (S1, S2, S3). Then each section is divided into segments. (B) The section and segment descriptions are used to describe and illustrate the history of development of the flow paths, which consist of the initial Path 1 and the later-developing Path 2.
sections, e.g., junction 1,2,3 is J1,2,3.

The branching rule and other segment conventions help provide a data base of sections and segments which can be further studied in conjunction with field evidence in order to interpret the history of development and enlargement of flow paths. To illustrate the potential results of this part of the method of segment analysis, the data bases of Figure 4A and Figure 5A are interpreted as flow paths in Figure 4B and Figure 5B, respectively.

For simple structural settings and simple flow paths, the entire procedure may seem unnecessarily cumbersome. However, flow paths are often more complex. They may be longer, contain more and different types of structural segments, or have closed loops due to combinations of upstream and downstream branching. An example of a slightly more complex flow system than those of the previous examples is shown in Figure 6. For this and more complex flow systems, it is essential to first have a method of describing structural segments that does not bias the interpretation of flow-path history, before undertaking further steps in the analysis of the flow paths.

Some Exceptions to the Branching Rule

There are several circumstances in which the branching rule is best not used. One is the case of blind fracture-guided fissures, joint spurs, bell holes, or other solution pockets that intersect fracture conduits and that have bedrock terminations. These may be elaborate, irregular fissures of considerable size. Alternately, they
Section 1 (S1):
1-2 = B
Section 2 (S2):
2-3 = B
3-4 = BJ
4-5-6 = J
6-7 = B
Section 3 (S3):
7-8 = B
Section 4 (S4):
2-7 = B
B = bed segment
J = joint segment
BJ = bed-joint segment

Figure 6. Oblique-view midline diagram of a hypothetical flow system with a closed loop. Although there are only two fractures (a bed parting and a joint) that guide flow, there are three types of segments and four sections containing seven segments. Such a flow system is more complex than those previously illustrated. Yet it is simple compared to many flow systems in caves with complex structural settings. To interpret this flow system, one would seek field data to answer these questions: (1) Did section 4 develop as a short cut after an early flow path used section 1, section 2, and section 3? (2) Did section 2 develop as an alternative route to a shorter route that used section 1, section 4, and then section 3? Or (3) did sections 2 and 4 form at the same time as competitive routes?
may be little more than joint spurs barely jutting into the bedrock. Yet whatever their form, and however much they may seem to branch, as long as they are truly blind (forming dead ends that are not merely conduits choked by sediments) they are not to be considered structural segments. Instead, they are fractures (or blind openings enlarged from fractures) into which water has been injected, only to return to the same flow path.

Another circumstance in which the branching rule is best not used is the case of fracture conduits that form short, often irregular closed loops on a single fracture. These are usually high-dipping joints that form fissures. An example is given in Figure 7A. The reasoning behind the exception is threefold: first, designating short sections (on the order of a few inches to a few feet) is cumbersome, and easily trivializes the concept of a section. Second, it is seldom possible to obtain evidence that would allow one to distinguish temporal or other relations between such closely spaced conduits. Third, it is likely that such short closed loops occurred occasionally on a very short spacing on fractures early in the development of fracture conduits, it taking but little enlargement to destroy the intervening bedrock bridges (and short closed loops in the flow paths) that were once present.

A final common circumstance in which the branching rule is best not used is the case of small anastomoses on a single fracture (Figure 7B). In most caves these are confined to bedding plane partings, but they may form on any low- to medium-dipping fractures. Anastomoses tend
Figure 7. Some exceptions to the branching rule. (A) Short closed loops on a single fracture, here a high-dipping joint, may often be treated as a single structural segment. For reasons, see text. (B) Anastomoses that are confined to a single fracture and that do not intersect other flow paths may be treated as a single structural segment as long as there is a principal conduit that transported ground water from a discrete, identifiable input to a similar output.
to branch off larger principal tubes during early stages of development. Usually they die out as tapering distributary tubes into the host fractures. They may also rejoin the main tube, closing loops only a short distance away, thereby creating a distinctive braided or anastomotic pattern (Ewers, 1966, 1972). Generally it is most useful to treat the entire set of anastomoses as a single structural segment. This assumes that none of the branching tubes connects to separate flow paths. It also assumes that there is a distinct, usually central principal tube that discharged its ground water to discrete and identifiable conduits downstream.

Mined Segments and Another Exception to the Branching Rule

Ground water flows from one structural segment to another in a region of transfer. Most such regions are initially small regions where fractures intersect. In fact, the small regions are usually sufficiently small that they are adequately described as the endpoints that they have been called. However, some regions of transfer of ground water to or from structural segments are not small regions of fracture intersection. Instead, they are regions in which short segments of conduits have formed by a process of dissolutional mining. In dissolutional mining, bedrock that lacks fractures is intersected, or a pre-existing conduit is bored into. Dissolutional mining may also link intergranular pores in highly porous rocks to form mined
segments. Such a process has been proposed by Ford and Ewers (1978, p. 1791) to account for bypass tubes ("groundwater shortcuts developed above the downward apices of phreatic loops") that lack associated guiding fractures. Dissolutional mining of intergranular pores to form mined segments is likely to have been important in the development of flow paths in some tropical caves formed in Tertiary or younger limestones that were uplifted before diagenesis could reduce primary porosity to low values (see Ford and Ewers, 1978, p. 1796). There is little doubt that dissolutional mining was also important in the linking of flow paths in the highly burrowed honeycomb zones of the Cretaceous limestones of the Edwards aquifer in central Texas (see Abbott, 1975).

Mined segments tend to be short. Some mined segments form during early stages of flow, before fracture conduits have developed integrated through-flow. That is, some mined segments form while blind fissures are enlarging, before the fissures have integrated to form fracture conduits. This may occur when ground water is carving an initial route through a given parcel of limestone. At such times, ground water confined within fractures may be forced to dissolve non-fractured bedrock bridges between fractures in order to continue the development and linkage of an early flow system. Other mined segments form later, after the development of cavernous porosity, when flow of ground water within conduits in massive rocks is no longer highly concordant to fractures due to the enlargement of the conduits. For example, some canyons have mined segments. The mined segments form
where vadose streams have removed unfractured bedrock floors and then intersected joints that were enlarged to pirate ground water to lower levels (Figure 8).

Figure 8 requires some discussion because it illustrates several theoretical and practical problems that arise when using the concept of mined segments in segment analysis. The figure, and the analysis of it, are hypothetical, but they are based on common sequences of growth for canyons in caves in the eastern United States, particularly West Virginia.

Figure 8A shows the profile of a passage consisting of an upper canyon, a headwardly eroding shaft, and a lower canyon. There are three segments. Bed segment 1-2 is developed on bed parting B1; joint segment 2-3 is developed on a vertical joint; and bed segment 3-4 is guided by bed parting B2. In the bedrock surrounding this passage there is only one other fracture, a joint labeled J. The joint extends from bed parting B2 vertically upward toward the upper canyon, but does not connect into the upper canyon. The passage is assumed to be enlarging in the vadose zone by entrenchment effected by a free-surface stream.

As the stream erodes the floor of the upper canyon, it eventually encounters the joint. Although most of the flow continues past the joint, further lowering the floor of the upper canyon and contributing to headward erosion, some of the water enlarges the joint. This process eventually leads to the abandonment of the shaft as a new smaller shaft forms along the upstream joint. Thus a new joint segment,
Figure 8. Profile midline diagrams illustrating the development of mined segments (MS) and the problems that arise in designating them. For explanation, see text.
joint segment 5-6 (Figure 8B), is formed. At the base of the new shaft, flow is then along bed parting B2 as bed segment 6-7. Continuing downstream, the water flows into the passage below the first, formerly active shaft, between positions 2 and 3. This process leaves two regions of dissolutionally removed bedrock where no fractures exist. One is above joint segment 5-6; the other is immediately downstream of bed segment 6-7. These two regions of dissolutionally removed bedrock clearly contain the mined segments. However, we must now decide how mined segments are to be designated, and how the branching rule is to be applied.

At this point it should be remembered that structural segments are characterized in terms of integrated flow from specifiable inputs to specifiable outputs as guided by fractures. It should also be remembered that the branching rule divides the cave into sections wherever branching occurs within the zone of early flow for each flow path. Of course, a few exceptions are made to the branching rule for anastomoses, other small early looping conduits, and blind pockets and fissures. This procedure keeps the number of sections small, and helps simplify field procedures. Yet mined segments are characterized in terms of dissolutional removal of bedrock lacking fractures. This presents a problem. The dissolutional mining by entrenchment enlarges the passage so that the passage branching no longer occurs within the zone of early flow of the original flow path. Instead, the branching occurs some (usually short) distance away. This leaves a gap along which no ground water actually passes as through-flow from the original
conduit into the new conduit (for the case of downstream branching) or from the new conduit into the original conduit (for the case of upstream branching) at the time of integration of the new conduit into the flow system.

This can be seen in Figure 8B, where there are two gaps and two mined segments. The gap for the case of downstream branching is between position 1a and position 2; the gap for the case of upstream branching is between 2 and 3. For the sake of continuity of conduits (but not flow) the upstream gap should be designated as mined segment 1a-5, and the downstream gap as mined segment 7-3. In the case of mined segment 1a-5, ground water flowing along the canyon removed "x" feet of bedrock by dissolitional mining, thus forming a mined region extending from position 1a at bed parting B1 downward to position 5. In the case of mined segment 7-3, ground water splashing down the shaft and effecting headward retreat of the shaft removed "y" feet of bedrock by dissolitional mining, thus forming a mined region extending from position 3 to position 7.

The theoretical significance of the problem lies in the fact that the manner of branching does not fall strictly under the wording of the branching rule. That rule was stated so as to be applicable to integrated fracture conduits. Nonetheless, it is necessary to apply some version of the principle of branching, which states that separate flow paths need to be designated separately. The practical significance of the problem is as follows. If one designates a position 1a, adds an extra bed segment by dividing bed segment 1-2 into bed segments
l-1a and l-2, and then applies the branching rule, one is then committed to designating four sections as well. With such a procedure, the four sections (A, B, C, and D) shown in Figure 8C would be designated. However, to simplify descriptions, it is best to minimize the number of sections designated, if at all possible. There is a way to do this, as shown in Figure 8D. It is to designate only two sections: section A as the original flow path, and section B as the diversion flow path. The rule can be stated this way: where mined segments begin or begin and end a flow path because of a diversion of flow, the original flow path is not divided into separate sections by the branching rule.

While this procedure may seem an unnecessary complication, it actually makes the description of flow paths and the explication of flow path history much less complicated than they otherwise would be, particularly when discussing the evidence involved. It might be objected that this procedure violates the spirit of the previous requirement that segments and sections first be designated before interpreting flow path history. It should be remembered, however, that the designation of such mined segments as those of Figure 8A is already an interpretation of flow path history, and one presumably based on careful evaluation of the evidence. Thus it does not seem too out of place to simplify matters by designating fewer sections along the original flow path where mined segments begin a section of structural segments that developed due to a flow path diversion.
Nonetheless, one must exercise caution in inferring mined segments. The evidence for their origin is easily destroyed. Only where remnants of mined segments retain a small size, lack fracture traces on bedrock perimeters, display orientations discordant to local fracture attitudes, and fit well into the interpretation of flow path history, can one infer their presence with much confidence.

Criteria for Inferring Structural Segments

Primary Conditions

In massive bedrock with low fracture frequencies, prominent fracture traces on the bedrock perimeters of tubes, canyons, or shafts are likely to represent the continuations of the fractures that guided early flow paths. This statement should be true if the following primary conditions hold:

(1) enlargement has not created, through unloading, exfoliation, or other processes, new fractures that could be mistaken for the initially transmissive ones; and

(2) enlargement is neither so extensive nor so directed as to have (a) totally destroyed the initially transmissive fractures, or (b) removed them from view.

To ascertain whether these conditions have been met, it is necessary to assess the structural setting. The most important characteristics of the fractures for interpreting speleogenesis are fracture geometry, size, spacing, and the relations of fractures to
bedrock. It is also necessary to evaluate the types of cavern development that have occurred and the processes contributing to that development.

Figures 9-11 illustrate three ways problems can arise when the primary conditions are violated, and prominent fracture traces do not represent the transmissive fractures. Figure 9 illustrates a case in which processes of enlargement create new fractures that could be mistaken for the one that was initially transmissive. Here, the original structural setting has been modified locally by exfoliation during conduit growth. Figure 9A shows the (correctly) inferred early cross section of a tectonic joint-guided segment on a hypothetical reach. Figure 9B shows the same reach after exfoliation has created pressure-release joints. Processes of dissolution, abrasion, and sediment transport have removed most of the breakdown. Figure 9C shows the same reach at a later stage, when a geologist enters to identify structural segments. He knows (from his assessment of the structural setting) that tectonic joints as well as pressure-release joints are to be expected. Locally, the tectonic joints are closely spaced, and may be confused with pressure-release joints. It takes careful observations of fracture characteristics (orientation, geometry), and breakdown characteristics (shape and size) to determine whether tectonic joints or pressure-release joints or both are (or were) present, and to infer the correct structural segments. Here the geologist finds exfoliation fractures and at least one tectonic joint. Thus, the problem reduces to an assessment of the geologic
Figure 9. Violation, by the creation of new fractures, of a primary condition for inferring structural segments. (A) through (C) are hypothetical cross sections of a conduit that enlarged partly by exfoliation. (C) is the modern passage that grew through an intermediate stage (B) from the original tectonic joint segment (A). In (C) the pressure-release fractures could be used mistakenly to designate a zone segment of closely-spaced tectonic joints if the structural setting were incorrectly interpreted.
Figure 10. Violation of a primary condition for inferring structural segments in a hypothetical canyon. Here enlargement has been so extensive as to totally destroy the initially transmissive joint. Consequently, neither of the prominently exposed bedding plane partings (B1, B2) of the modern canyon of (F) represent the structural segment. (A) shows the joint (J) and the bed partings before any flow. (B) shows the joint segment. (C), (D), and (E) show intermediate stages in the development of the canyon.
Figure 11. Violation, by removal of the initially transmissive fracture from view, of a primary condition for inferring structural segments. (A) shows the cross section of a bed segment that enlarged by paragenesis in stages (B), (C), (D), and (E) to form a (hypothetical) canyon filled with sediments. (F) shows the cross section of the canyon when entered by the geologist. See text.
evidence favoring an attribution of early flow to (1) a (single-fracture) joint segment, or (2) a zone segment consisting of (now missing) closely-spaced tectonic joints. Were the geologist unaware of the correct identification of most of the joints as exfoliation joints, he might erroneously cite them as evidence for a zone segment consisting of tectonic joints that were closely spaced.

Figure 10 illustrates a case in which enlargement has been so extensive as to totally destroy the initially transmissive fracture. Figure 10F shows the hypothetical cross section of a large canyon. Bedding is massive, and only two bedding plane partings are exposed. No joints are present. However, a joint was initially present (Figure 10A), and the earliest conduit was a joint segment (Figure 10B). The joint segment enlarged gradually in all directions (intermediate stages, Figure 10C-10E). Based on the modern cross section (Figure 10F), it would be easy to mistakenly infer a bed segment along B1 or B2. The geologist searching for structural segments in the canyon of Figure 10F therefore would have to rely upon additional information in order to infer a joint segment. He might note (see criteria below) that the reach represented by the cross section was oriented subparallel to a prominent joint set, and that evidence on nearby reaches favored growth in all directions from initially transmissive fractures, rather than growth upward (by paragenesis) or downward (by entrenchment).

Figure 11 illustrates a case in which enlargement has been so directed as to remove the initially transmissive fracture from view
(without actually destroying it). Figure 11 shows the hypothetical cross section of several stages in the growth of a canyon formed by paragenesis. Paragenesis (Renault, 1968; Ford and Ewers, 1978; Ewers, 1985) is the upward growth of a canyon or a tube. Figure 11A shows the initial tube on a bedding plane parting. Figure 11B-11E depicts the gradual growth, which is directed upward by an accumulating column of clastic sediments. Figure 11F shows the canyon after a drop in base level has allowed a free-surface stream to remove much of the sediment. The geologist sees a canyon with a prominent bedding plane parting on the ceiling, and extensive sediment banks. He must use available evidence (such as hydrologic setting, sediment characteristics, dissolutional features on walls or along fractures) to determine whether the canyon originally formed by entrenchment, paragenesis, or by some other process. If he incorrectly interprets the type of cavern development as one of entrenchment, he might incorrectly designate the upper bed parting of Figure 11 as the initially transmissive fracture.

Figures 9-11 suggest that one should be careful in inferring structural segments. Structural segments should not be inferred unless the structural setting is itself appropriate. (For example, fractures should not be so closely spaced [compared to the size of the conduits] that one mostly designates zone segments by default, rather than actually infers which of the fractures guided early flows.) Nor should structural segments be inferred without an adequate understanding of the processes that enlarged the passages of a given
geohydrologic setting.

The passages chosen for segment analysis in Snedegar Cave are in massive beds of the Union Limestone of the Mississippian Greenbrier Group. The structural setting, though complex (see Chapter 3), is generally conducive to segment analysis. The passages consist of a few small tubes, several shafts, and over 1000 feet of canyons whose history renders them suitable for segment analysis. This development is characterized by a long history of vadose entrenchment. The canyons are relatively small. There has been minimal collapse. There are few speleothems or other chemical sediments, and clastic sediments are not so extensive as to unduly complicate geomorphic interpretations. Similar histories and geologic conditions occur in many of the passages suitable for segment analysis that are in the other caves listed in Table 1. To simplify the analysis and to prepare for later analyses of development in Snedegar Cave, the remaining statements of the criteria for inferring structural segments are explained in terms most applicable to Snedegar Cave. However, it will readily be seen that the criteria are applicable in other caves as well.

The Elevations of Features of Entrenchment: Their Significance

The canyons of Snedegar Cave initially grew as tubes or fissures to maximum sizes of about 10 ft² cross-sectional area before the onset of entrenchment. Small enlargements of the early conduits appear as half tubes or fissures on canyon ceilings (Figures 12, 13). The half
Figure 12. Typical cross section of a canyon enlarged from a tube in the investigated passages in Snedegar Cave. The early structural segments were tubes or fissures (see Figure 13) developed on a variety of fractures. This example shows the ceiling remnants of a bed segment formed on bed parting X (BX). The remnants include a half tube, anastomoses, and a dissolitional re-entrant. The early tubes and fissures were enlarged under conditions of closed-conduit flow. Later enlargement was by free-surface streams. The streams cut downward, or laterally and downward, producing features of entrenchment such as notches (N), undercut, sinuous cross sections, and potholes. In many places there are also surfaces of widening (large, laterally extensive undercut) below which passage width greatly increases. Many reaches thus consist of an upper half tube or fissure, a middle narrow region (narrow trench), and a lower wide region (wide trench).
Figure 13. Typical cross section of a canyon enlarged below an early fissure in Snedegar Cave. Joint J1 is exposed in the ceiling of the fissure. A vadose notch is at the base of the fissure, forming the top of the narrow trench. Bed parting BZ and joint J2 lack dissolitional re-entrants or anastomoses and lie at lower elevations in the walls of the narrow trench. These features indicate that joint J1 guided the structural segment.
tubes and fissures were preserved because almost all of the dissolution following the early tubular stage was directed downward, or laterally and downward, by free-surface streams. Such enlargement produced canyons that are narrow in their upper parts, but which are wider lower down. In many places there are abrupt changes in conduit width along surfaces of widening that separate the upper narrow regions from the lower wider regions. In such circumstances it is useful to label the upper narrow regions narrow trenches and the lower regions wide trenches, even though the narrow trenches now lack floors. In both narrow and wide trenches there are often undercuts and notches. Undercuts and notches are produced by a combination of lateral undercutting and downcutting of trench walls. These features are illustrated in Figures 12-14, and in Chapter 5. They contribute to the development of bedrock channel meanders that translate laterally and downstream, producing sinuous cross sections (Figure 14).

No attempt will be made to provide a complete account of entrenchment here; for those unfamiliar with the processes and features characteristic of entrenchment in limestone caves, a more complete account is given in Chapter 5. It is sufficient here to indicate the manner in which features of entrenchment can be used as criteria for inferring structural segments.

Because entrenchment operates downward, the highest elevation of any features of entrenchment at a point along the length of a passage indicates the lowest position possible for initiation of flow at that point (assuming the simplest case of a single phase of entrenchment).
Figure 14. Entrenched canyon in Snedegar Cave. The upper narrow trench (NT) is slightly sinuous.
Some features of entrenchment that form early in downcutting may be destroyed during later enlargement. Therefore, in practice, the features begin at slightly lower elevations on passage walls than the elevations of the midlines of the original structural segments.

To infer structural segments using features of entrenchment, the following procedure is employed. First, features of entrenchment are located and their distributions are recorded on profiles of passages. Second, the highest features of entrenchment are identified for each reach of passage. Finally, the nearest higher appropriate fractures or fracture intercepts are located, surveyed, and considered as candidates for structural segments. In Figure 12, a canyon cross section, the nearest fracture above the highest shown feature of entrenchment (a notch at N) is bed parting X. Bed parting X thus becomes the most appropriate candidate for a structural segment, subject, of course, to other criteria. In Figure 13 the nearest fracture above the highest shown feature of entrenchment (a notch) is joint J1. Joint J1 thus becomes the most appropriate candidate for the structural segment. Examples showing the distribution of notches and other features of entrenchment on profiles of passages are deferred until Chapter 5.

Appropriate Concordance

The narrow trenches in Snedegar Cave are readily accessible from the wider trenches below. In most places the narrow trenches are only 1 to 2 feet wide, so it is generally possible to climb through them to inspect the remnants of the early conduits on passage ceilings. The
remnants of the early conduits closely follow the changing orientations of fractures exposed on their walls or ceilings. Such alignment represents the single most important criterion for inferring structural segments, that of appropriate concordance.

Appropriate concordance is the requirement that the passage—or appropriate parts of it as determined from evaluation of the types of enlargement that have occurred—be concordant to the appropriate fracture, line of fracture intercepts, or zone of fractures. Concordance here means "aligned along." It does not mean "parallel to" and it is not equivalent to "having the same orientation as," even if parallelism and similarity in orientation are at times useful empirical measures of concordance. Of course, it is true that many transmissive fractures are roughly planar, and are adequately described by a single attitude by specifying strike and dip. Yet many transmissive fractures are not adequately so described. In any case, fracture conduits can have any attitudes along their lengths that are allowed by the changing attitudes of their host fractures. Consequently, concordance is a property most readily evaluated where conduits (or appropriate parts of conduits) remain small, as do the half tubes and fissures preserved on the ceilings of the study passages. In such cases it is usually sufficient to seek visual confirmation of the concordance of fracture traces (or their projections into space) with the changing orientations of the half tubes and fissures.

The remnants of the early conduits are not only concordant to fractures exposed on their walls or ceilings, they also exhibit great
continuity in form and size for each type of guiding fracture or fractures. Such features have simplified the task of inferring structural segments, which may be followed as slightly enlarged and nearly continuous ceiling paleo-channels through many passages with little difficulty. However, in some cases more than one fracture trace appears on the ceiling or walls of the early conduits, and it is not immediately clear which fracture trace represents a structural segment. Moreover, in some places processes of dissolitional enlargement, collapse, or sedimentation have disrupted the continuity of the ceiling half tubes or fissures. Consequently, additional criteria are needed that (1) tell us, where possible, which of the prominent fractures or fracture intercepts were transmissive, and (2) allow us to reliably infer structural segments across apparent gaps. Three more such criteria are presented below.

The Significance of the Direction of Tube Growth for Inferring Structural Segments

Anastomoses, and other small tubular conduits associated with low-dipping fractures, grow upward during enlargement from the earliest fracture conduits. This upward growth is due to the protection afforded by insoluble residues, which coat conduit floors and lower walls and protect them from solution (Ewers, 1966). Therefore, the initial flows through anastomoses or their remnants (half tubes, pendants) in canyons are to be sought at the bases of the anastomoses on the nearest appropriate fractures. In Figure 12, the fracture
nearest to the bases of the anastomoses and tubular remnants is bed parting X. Bed parting X thus becomes the most probable candidate for a structural segment, subject again, to other criteria.

The Significance of Secondary Tubes or Other Dissolutional Features for Inferring Structural Segments

Where the principal tube of a flow path has enlarged sufficiently to intersect a higher bed parting or other fracture, there arise several interpretative possibilities. The first is that the principal tube grew and intersected a transmissive fracture that was part of a different flow path, or perhaps of a transmissive zone (Figure 15A1-15A3). The second is that the intersection was fortuitous, and that there was no transmissivity along the intersected fracture (Figure 15B1-15B3). If anastomoses appear on the higher fracture, then there may well have been several flow paths that merged through growth, as in Figure 15A. If, however, the higher fracture lacks anastomoses, solution pockets, or other signs of dissolutional enlargement, as shown in Figure 15B, then no matter how prominent the fracture, it is unlikely that it served as a flow path. Probably it has merely been intersected during conduit growth. A similar argument can be made for almost any fracture intersected by other conduit types during their growth if that fracture lacks appropriate features of dissolution. What counts as appropriate features of dissolution must be determined for the specific geohydrologic setting by studying such features as dissolutional re-entrants, blind pockets, joint spurs, and anastomoses.
Figure 15. Cross sections illustrating the significance of secondary tubes or other dissolitional features in inferring structural segments. (A) depicts the growth of a principal tube from an early stage (1) to a final stage (3) before the onset of entrenchment. In (3) the principal tube has secondary dissolitional features (anastomoses and re-entrants) associated with it; these occur on both the upper and lower bed parting. They, and the general shape of the cross section, suggest that independent flow paths (on separate bed partings) merged through growth. In contrast, (B) depicts the growth of a principal tube that developed from the lower bed parting (1) and only randomly intersected the upper bed parting as it grew through an intermediate stage (2) to the final stage (3). In (B, 3) the principal tube has anastomoses and a re-entrant, but these appear on the lower bed parting only,
Inferring Across Gaps: Target Segments and Their Orientations

Where dissoluitional processes or collapse of breakdown have enlarged the passage surrounding the remnants of the early conduits, there may be apparent gaps in the record of structural segments. Commonly there will be an unmistakable upstream structural segment, an unmistakable downstream structural segment, and an area in between where it is not at first clear how development occurred. Yet in the absence of dissoluitional mining, some fracture or fractures must have been used to cross that gap. To solve the problem it helps to first make sure that there are no hidden branching conduits (resulting, for example, from collapse or clastic sedimentation). Next, it helps to make sure that one has identified the correct downstream structural segment---the target segment---by checking for morphologic indicators of flow direction (such as scallop asymmetry; see Curl, 1972; Lauritzen, 1981). One then carefully searches for any trace of an appropriate intervening fracture. The intervening fracture may be easier to find than one may at first think. It may, for example, be readily located as a fracture trace on a block of breakdown that was not at first suspected to contain useful information. Alternately, if the previously transmissive fracture has been totally destroyed or is otherwise impossible to locate, then the orientation of the presumed gap should be compared with known fracture attitudes.
The Criteria Applied: A Hypothetical Example Illustrating
the Method of Segment Analysis

The method of segment analysis is outlined in Table 2. The
remainder of this chapter analyzes a hypothetical canyon. The purposes
of the analysis are to: (1) aid interpretation of the criteria
for inferring structural segments; (2) illustrate the procedure by
which segments are inferred and flow-path history is analyzed; and (3)
introduce some additional concepts that are useful in studying flow
paths. Although the analysis is rather complex, it actually is
abbreviated, and represents a simplification of the problems liable to
be encountered in studying real caves. It is worth noting that the
outline of the method in Table 2 is a minimal outline. Any application
of the method will require the use of additional standard geologic
techniques---for example, techniques used to study structural features
or lithology.

Geologic Reconnaissance

Assuming that a favorable passage has already been chosen for
analysis, step 1 is one of geologic reconnaissance. Its purpose is to
determine the lithologic, structural, hydrologic, and general passage
settings, as well as to get a rough idea of the characteristics and
locations of structural segments and the conduits enlarged from them.
In fact, much time and effort can be saved in later steps by first
constructing a lithologic column and by becoming familiar with the
TABLE 2
AN OUTLINE OF THE METHOD OF SEGMENT ANALYSIS

<table>
<thead>
<tr>
<th>Step</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Geologic reconnaissance.</td>
</tr>
<tr>
<td>2</td>
<td>Preparation of a detailed base map. The map should have a plan, a profile, and cross sections.</td>
</tr>
<tr>
<td>3</td>
<td>Mapping of relevant lithologic and structural features.</td>
</tr>
<tr>
<td>4</td>
<td>Inference of structural segments.</td>
</tr>
<tr>
<td></td>
<td>Task 1. Designation of branching conduits and sections of passages and segments.</td>
</tr>
<tr>
<td></td>
<td>Task 2. Inference of structural segments using detailed observations of morphologic features, fractures, and the inference criteria.</td>
</tr>
<tr>
<td>5</td>
<td>Interpretation of the history of development of the flow paths.</td>
</tr>
<tr>
<td></td>
<td>Task 1. Preparation of the midline diagrams.</td>
</tr>
<tr>
<td></td>
<td>Task 2. Identification of the earliest flow paths.</td>
</tr>
<tr>
<td></td>
<td>Task 3. Determination of the sequence of development and integration of later flow paths.</td>
</tr>
<tr>
<td></td>
<td>Task 4. Evaluation of all available morphologic, hydrologic, lithologic, structural, sedimentologic, and other evidence. The evidence is used to prepare maps (with plans, profiles, and cross sections) and block diagrams that illustrate and help explain the evolution of the passages.</td>
</tr>
</tbody>
</table>
fractures exposed on conduit perimeters.

Preparation of a Detailed Base Map

**Step 2** is the preparation of a detailed base map. The base map consists of a plan with numerous cross sections and an extended profile. The extended profile is usually drawn down the middle of the passage. Survey stations must be closely spaced, no farther apart than the midline lengths of structural segments. In most cases it is necessary to place stations directly on or underneath segment endpoints. This increases the accuracy of later structural maps and flow-path maps that are needed to interpret the development of the passages. In practice, such placement of stations is tedious. Because that placement is not always possible, stations are best placed on bedrock projections on walls or floors as near as possible to segment endpoints. It is best to place permanent, but conservation-minded stations, and to draw only a rough line plot of the survey at the beginning of the study. The survey data are then reduced and line plots are constructed at a suitable scale on graph paper before returning to the cave to prepare accurate plans, profiles, and cross sections. If, as in the investigated passages of Snedegar Cave, extreme accuracy is required for the vertical component of the survey, then a leveling survey using a U-tube manometer or other device (Palmer, 1970) should be carried out before drawing the profile. Again, it is helpful to place permanent stations for later use, because interpretation of the development of the passages may require careful
measurements of the elevations of lithologic contacts, geologic structures, and passage morphologic features, as well as ceiling, floor, and sediment elevations. Step 2 results in a base map showing passage outlines to which further information easily may be added. A sample base map for the hypothetical canyon appears in Figure 16.

Mapping of Relevant Lithologic and Structural Features

In step 3 the base map is used to plot relevant lithologic and structural features. Traces of lithologic contacts, fractures, and other features are drawn on the plans, cross sections, and profiles. The result of step 3 is a geologic base map similar to the one drawn for the hypothetical canyon in Figure 17. (For present purposes, bedrock is assumed to be uniformly soluble and sedimentologic information is not needed, so only fractures are plotted.)

Inference of Structural Segments

The geologic base map is next used in the inference of structural segments (step 4). The inference procedure has several parts. Task 1 is to locate any branching conduits or branching paleo-conduits and to designate sections of flow paths.

In the hypothetical canyon (Figure 18), branching occurs in two places. There is an upstream branchpoint (BP1 in Figure 18) and a downstream branchpoint (BP2). The reach of passage upstream of branchpoint 1 contains the structural segments that will be designated as belonging to section A. For convenience, the term "section A" can
Figure 16. Base map of the hypothetical canyon. The survey base line is shown with solid lines drawn between triangles; the triangles represent survey stations. The base line is shown on both the plan and the profile. Several stations exactly overlying one another are shown on the profile, but not the plan. Base lines from a leveling survey are shown on the profile with dashed lines drawn between circles; the circles represent permanent stations. Changes in the elevation of the base lines are shown by vertical dashed lines. The leveling base lines are shown only on the profile, but station locations are shown on both the profile and the plan.
Figure 17. Geologic map of the hypothetical canyon. Traces of relevant bed partings and joints have been plotted on the plan, profile, and the cross sections. B1 = bed parting 1. B2 = bed parting 2. J = joint.
Figure 18. Branchpoints and the sections of the hypothetical canyon.
be applied either to the structural segments, or to the reach of passage containing them. At branchpoint 1 the passage divides into two conduits on two levels. The upper conduit contains the segments of section B. The lower conduit contains the segments of section C. Downstream of branchpoint 2 are the segments of section D.

**Task 2** of the inference procedure is to take detailed notes on the morphologic features of the reach enlarged from each suspected structural segment and to attempt to follow paleo-flow paths from fracture to fracture using the inference criteria. As segments are identified, their endpoints are plotted as position names on the map. A table of structural segments is constructed. A sample table for the hypothetical canyon appears in Table 3; Figure 19 shows the resulting map of structural segments. The kind of reasoning used in inferring structural segments from the passage features (Table 3) may be appreciated by reasoning through the following explanations with the aid of Table 3 and Figures 17 and 19.

Between positions 1 and 2 there is a sinuous half tube accompanied by numerous minor anastomoses near the ceiling. The half tube has smooth, rounded walls, as do the anastomoses. The cross section shows that entrenchment was also sinuous, and vadose notches begin near the tops of the meanders. A prominent bed parting, labeled B2 in Figure 19, is exposed near the ceiling. The half tube and anastomoses are concordant to B2. No other fracture traces are present near the ceiling or the half tube. However, an inclined joint is exposed in the lower part of the canyon. The inclined joint appears to have been
### TABLE 3

**STRUCTURAL SEGMENTS AND THE MAIN MORPHOLOGIC FEATURES OF THE HYPOTHETICAL CANYON (SEE FIGURE 19)**

<table>
<thead>
<tr>
<th>Segment</th>
<th>Features</th>
</tr>
</thead>
</table>
| B 1-2   | (1) At the ceiling is a smooth-walled, sinuous half tube. The half tube is concordant to B2.  
(2) Anastomoses are present along B2, and are absent from other fractures.  
(3) Vadose notches are present only below B2, and dip gently downstream, to the left in Figure 19.  
(4) Sinuous meanders propagate laterally and downstream in the narrow trench (see Chapter 5).  
(5) The inclined joint is discordant to the ceiling half tube and to the reach of passage in which it is exposed. The inclined joint lacks dissolitional features such as re-entrant spurs, and is exposed only within the narrow trench. |
| J 2-3   | (1) The ceiling is a smooth-walled joint fissure. The fissure descends below B2, then rises back to B2 at position 3.  
(2) The ceiling and walls of the half tube of segment 1-2 are continuous into the ceiling and walls of the joint fissure.  
(3) The joint fissure and the passage as a whole are roughly parallel on the plan.  
(4) Vadose notches from segment 1-2 die out against the descending ceiling fissure. (This is not depicted in Figure 19; for examples, see Chapter 5.)  
(5) Vadose notches from segment 2-3 on the rising part of the joint segment descend gently downstream. They pass continuously across the passage of segments 3-4, 4-5, 5-6, 6-9, and 9-10. |
| B 3-4   | (1) Features are similar to those of bed segment 1-2. However, there is no joint in the narrow trench. |
| BJ 4-5  | (1) The trend of the plan of the passage changes abruptly to parallel that of a vertical joint.  
(3) There are no anastomoses or prominent half tubes on B2. |
**TABLE 3**
(CONTINUED)

<table>
<thead>
<tr>
<th>Segment</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>B 5-6</strong></td>
<td>(1) Features are similar to those of bed segment 1-2. However, there is no joint in the narrow trench.</td>
</tr>
</tbody>
</table>
| **J 5-6** | (1) This conduit begins section B. The conduit begins upstream at 6 as a tube, but rapidly becomes a half tube as it rises along a joint fissure. Both the tube and the half tube have smooth walls.  
  (2) The cross-sectional area of the half tube between 6 and 7 is about the same as that of the half tube of bed segment 5-6, but is greater than the area of the half tube of segment 6-9.  
  (3) The tube/half tube combination rises to bed parting B1 at the ceiling. There the walls and ceiling of the half tube pass continuously and smoothly into the smooth-walled ceiling half tube of bed-joint segment 7-8. |
| **BJ 7-8** | (1) A smooth-walled joint fissure extends a few inches above the half tube; the half tube is concordant to B1 between 7 and 8.  
  (2) The cross-sectional area of the half tube plus the area of the joint fissure sum to about the same area as that of the half tube of joint segment 6-7.  
  (3) B1 has anastomoses on it. The anastomoses are not shown on the plan, which is of the lower part of the main canyon.  
  (4) Below B1 the walls have notches that extend continuously across the passage of segment 7-8, descending gently from joint segment 6-7 to joint segment 8-9. (See Chapter 5.) |
| **J 8-9** | (1) A smooth-walled joint fissure descends from 8 to 9. At its top is a half tube that is concordant to the joint, but lower down the fissure becomes a tube near 9.  
  (2) The cross-sectional area of the half tube of joint segment 8-9 is about the same as that of joint segment 6-7 and that of bed-joint segment 7-8. |
<p>| <strong>B 9-10</strong> | (1) Features are similar to those of bed segment 1-2. However, there is no joint in the narrow lower trench. |</p>
<table>
<thead>
<tr>
<th>Segment</th>
<th>Features</th>
</tr>
</thead>
</table>
| BJ 6-9   | (1) There is a half tube concordant to the intersection of B2 and a joint.  
(2) No anastomoses are present on B2.  
(3) The cross sectional area of the half tube is slightly smaller than that of the half tube of bed segment 5-6, or that of bed segment 9-10.  
(4) Notches begin just below the bed-joint intersection. They extend continuously across to the narrow trench of the passage of segments 3-4, 4-5, and 5-6 of section A in an upstream direction; and extend across to the narrow trench of the passage of segment 9-10 of section D. |
Figure 19. Structural segments of the hypothetical canyon. See text. The following segments are indicated: Section A: 1-2 = B; 2-3 = J; 3-4 = B; 4-5 = BJ; 5-6 = B; Section B: 6-7 = J; 7-8 = BJ; 8-9 = J; Section C: 6-9 = BJ; Section D: 9-10 = B.
exposed only as a result of vadose entrenchment, has an orientation discordant to the orientations of the appropriate parts of the passage, and lacks dissolitional pockets or re-entrants. It is therefore unlikely that the inclined joint transmitted ground water during early stages of flow. The only remaining candidate (bed parting B2) is thus chosen, and segment 1-2 is inferred to have been a bed segment developed on B2.

Assuming continuity of flow, segment 1-2 must have discharged its ground water to an intersecting fracture in a downstream direction. At position 2, bed parting B2 intersects a prominent joint exposed in the ceiling. The ceiling drops along this joint to a low point, then rises back to bed parting B2 at position 3. The cross section along this reach shows the remains of a fissure-like ceiling re-entrant. By standing in the canyon and looking upstream at position 2, it is possible to see that the bed-guided half tube of segment 1-2 has walls whose surfaces pass smoothly and continuously into those of the joint fissure. By standing below position 3 or position 4 and looking up at the ceiling, it is possible to see that the same types of morphologic features occur from 3 to 4 at the ceiling and just below it on the upper walls, as occur along bed segment 1-2. This leads to the conclusion that there is a bed segment 3-4. It also means that position 2 must be a target position for a segment from position 2 to position 3. The only likely candidate for the guiding fracture is the ceiling joint, given the above morphologic information. Also, the passage as a whole (as well as the relevant remnants of paleo-conduits
on the ceiling) has an orientation roughly concordant to that of the joint. Hence joint segment 2-3 is inferred.

As previously noted, segment 3-4 is a bed segment. Downstream of position 4 the passage changes its plan trend abruptly to parallel a joint. Along this joint the ceiling rises (see profile, Figure 19) but then falls back to the level of B2 at position 5. No notches appear on the sides of the fissure created by this joint. Instead, fissure walls are smooth and lack scallops. However, notches do appear on the walls immediately below bed parting B2. Hence early flow could not have been on the extension of the joint below B2. No anastomoses appear on B2 where it is exposed on the walls a short distance laterally from the central ceiling joint fissure. This observation suggests that it is unlikely that flow was along B2 away from the joint fissure (which would then be interpreted as a blind joint fissure enlarged during later growth). The remaining possible locations for early flow are (a) along the joint above B2, or (b) along the intersection of the joint and bed parting B2. The latter interpretation appears to be the most probable. Had primary flow been along the joint only, somewhat above its intersection with B2, then entrenchment would likely have left notches in the joint fissure, rather than the smooth, rounded walls characteristic of the remnants of segments 1-2, 2-3, and 3-4. This conclusion is strengthened by the morphologic features observed downstream within the closed loop, as explained below.

Immediately upstream of the closed loop is a reach of canyon from position 5 to position 6. This reach has the same relevant morphologic
features (Table 3, Figure 19) as bed segments 1-2 and 3-4. Thus it is inferred that there is a bed segment 5-6. Similar observations and conclusions apply to the reach immediately downstream of the closed loop; that reach has bed segment 9-10. Bed segment 9-10 will now be seen to form a target point at position 2 for both halves of the closed loop, the segments of section B and section C (Figures 18 and 19).

The passage of section B is a small canyon with a tube at each end. Scallops indicate flow from position 6 toward position 2. The passage begins at the upstream end as a tube rising from position 6. The tube rapidly changes into a half tube. The half tube has a smooth ceiling and smooth walls. The half tube is concordant to a joint. The half tube rises along this joint to position 7. Between 7 and 8 there is a smooth-walled half tube concordant to the intersection of B1 and the joint. Anastomoses are present on B1, and a narrow fissure along the joint rises barely above the half tube on B1. The joint fissure lacks vadose notches. However, in the canyon between 7 and 8 there are notches on passage walls below the elevation of B1. From position 8, the passage descends as a half tube that turns into a tube; this tube is concordant to the joint, and has a smooth ceiling and walls. From these observations, it is clear that section B has joint segment 6-7 at its upstream end, and joint segment 8-9 at its downstream end. There also is a bed-joint segment between 7 and 8.

On section C, in the main canyon between position 6 and position 2, there is a half tube concordant to the intersection of bed parting B2 and the same joint used in section B. The half tube is smaller in
cross-sectional area than the half tube of bed segment 5-6 or bed segment 9-10. Immediately below the bed-joint intersection there are notches; the notches extend continuously through the canyon from the passage of section A to section C to section D. From these observations it is clear that section C consists of a bed-joint segment, segment 6-9. It is also clear that some explanation must be devised to account for the presence of a loop in the flow path. This explanation must account for the variations in cross-sectional area of the early conduits, as well as all other morphologic features, particularly the features of entrenchment (vadose notches) within section B in the upper part of the closed loop.

Interpretation of the Development of the Flow Paths

After the structural segments have been inferred, the map of structural segments is used in step 5, the interpretation of the development of the flow paths. The procedures used in this step vary according to the lithologic, structural, and hydrologic settings, and according to the local cavern features. Only a few of the possible procedures useful in interpreting the growth of canyons from the early structural segments can be illustrated here.

Task 1 of step 5 is to prepare midline diagrams of the structural segments. To do this it is necessary to measure the midline lengths of the structural segments. The elevations of most, if not all of the segment endpoints must be accurately determined, preferably from measurements based on the previously set permanent stations along the
leveling base line. These data are then used to construct midline diagrams with both plan and profile views; examples are given for the hypothetical canyon in Figure 20A and 20B. Where flow paths and structural segments form complex patterns, it may also be necessary to construct oblique-view midline diagrams (Figure 20C).

Task 2 of step 5 is to identify the earliest flow paths through the sections. This task is closely related to the third task, and is often carried out at the same time; task 3 is to determine the sequence of development and integration of the later flow paths. Both tasks require careful analysis of the characteristics of remnants or enlargements of early conduits, and of the developmental patterns of entrenched canyons below them. In many settings the most important characteristics to consider are the shapes and sizes of the remnants of early conduits, and the continuity or lack of continuity of the remnants from one section to another.

In the hypothetical canyon (Figure 19), anastomoses are present on bed segments or bed-joint segments in sections A, B, and D, but not in section C (Table 3). The remnant half tube on bed parting B2 (from position 5 to position 6 of section A) is larger than the remnant half tube guided by the bed-joint intersection from 6 to 2 of section C. The remnant half tube on B2 (in section D from 2 to 10) is larger than the one of section C, but not quite as large as the one ending section A from 5 to 6. Finally, the ceiling and upper walls of the half tube ending section A appear to pass continuously upward into the remnant joint conduit 6-7 of section B (Table 3). All of these observations
Figure 20. Midline diagrams of the hypothetical canyon. See Figure 19. These diagrams contain much useful information, for they indicate the three-dimensional pattern of the early conduits. The pattern constrains the ways in which enlargement to cavernous size can occur, depending on the lithologic and hydrologic settings and changes in the latter. The information in the midline diagrams can be used, along with morphologic observations of the remnants of the early conduits and of the trenches, to infer stages in the development of the passages. (A) Plan. (B) Profile. (C) Block diagram.
can be explained with the following interpretation, which assumes that lithologic factors do not differentially affect conduit size in the hypothetical canyon. (There, lithology is assumed to be uniform.) First, there was an early flow path from section A to section B to section D. Second, flow within section B was diverted to a lower level to form the route of section C. In particular, this explains the basic continuity in form and size of the remnant conduits and associated anastomoses from section A to section B to section D. The fact that the section C remnant is smaller makes sense because it should have had less time to grow by upward dissolution before the onset of entrenchment. The lack of anastomoses on bed-joint segment 6-9 is also suggestive of a change in flow conditions, and supports the concept of section C being a diversion route.

The continuity in form and size of remnants of early conduits are not the only important features to consider in interpreting the history of development of passages. The continuity of features of entrenchment, particularly vadose notches, may also provide evidence useful in deciphering which sections transmitted ground water during which stages of cavern development.

For example, in the hypothetical canyon, notches are continuous across (and dip gently from) section A to section C to section D (see Table 3). This indicates that at some time, vadose flow was continuous across these sections. The notches probably formed at floor level or only a few inches above floor level, for that stage of development. Yet these are not the only notches present, for notches are also
present at a higher level in section B, where they are isolated from
the lower notches. The presence of the upper notches in section B is
evidence that entrenchment began relatively early, before flow was
diverted from section B downward to section C.

With these kinds of observations in mind, it is now possible to
turn to task 4 of step 5. In this final task, the midline diagrams and
all available evidence are evaluated and used to prepare plans,
profiles, and block diagrams that illustrate the evolution of the
passages. The explanations that accompany these maps then become the
basic interpretations of the influences of the various geohydrologic
parameters on the early development, integration, and enlargement of
the passages, assuming sufficient evidence is available. The explana-
tions may also guide further research by suggesting empirical measures
that could be used to test the interpretations.

The evolution of the hypothetical canyon is illustrated in Figures
21 and 22 and analyzed below. The analysis concentrates on the
evolution of the passage in profile view; no attempt is made to
illustrate or analyze changes in the plan.

From the previous evidence, the most likely initial flow path is
from section A to section B to section D. This gives an initial
midline profile as drawn in Figure 21A and Figure 22A. The profile
shows that ground water looped in the vertical plane. That is, ground
water descended below the levels of downstream midline positions before
returning to those or higher elevations farther downstream. This
looping created two lower loops. Each consists of a reach of conduit
Figure 21. Evolution of the extended profile of the hypothetical canyon. See Figures 19, 20, 22. For explanation, see text.
Figure 22. Evolution of the hypothetical canyon. (A) Block diagram of initial midline flow path, corresponding to the segments shown in Figure 21A. For explanation of symbols, see Figure 19. (B) The stage I tubes. The exaggerated tapering tubes on bed segments represent anastomoses. This diagram corresponds to Figure 21C, where the presence of ground water is indicated by solid black. The black is omitted here so as to emphasize (by shading) the shapes of the early tubes and fissures as they appeared during stage I, before the onset of entrenchment.
Figure 22 (continued). (C) The conduit at the onset of entrenchment (stage II). A high point at Z is the downstream end of a lengthy pressure loop (PL) that is interrupted by an air bell (AB). Upstream of the pressure loop and downstream of Z are regions of entrenchment (RE). A small waterfall (WF) is near Z. This corresponds to Figure 21D. (D) The conduits after a small amount of entrenchment. Entrenchment has lowered the previous high point below the level of Z. This lowering has resulted in the break up of the original pressure loop into two pressure loops that are separated by a region of entrenchment. Enlargement has begun along a bed-joint intersection on B2 between 6 and 9. This corresponds to Figure 21E.
Figure 22 (continued).  (E) The conduits at a later time of stage II. Piracy from section B (SB) into section C (SC) has removed the downstream pressure loop, and entrenchment has begun in section C. This corresponds to Figure 21F. A pressure loop (PL) remains upstream and below J.  (F) The conduits after the last pressure loop has been eliminated, but before the onset of wider entrenchment. This corresponds to Figure 21G.
determined by a downstream high point, whose elevation is higher than all other points within the lower loop except the farthest point upstream within the lower loop. Each lower loop has a low point at its lowest elevation. The two loops share a common low point, but the high points are at different locations. The lower loop that is farthest upstream (to the right in Figure 21) is nested within the other lower loop, which has a greater length and vertical relief.

For any interval of time in which a lower loop is completely filled with flowing water, it may be described as a pressure loop. The presence of the lower loops within the flow path shows that the flow path is ungraded. A graded flow path is one with a slope that is relatively uniform and that is consistent in a downstream direction. (This definition is modified from the definition of a graded profile given by Palmer, 1972, p. 101.) Most likely the flow path of Figure 21 would have formed under phreatic conditions. However, Palmer (1972, 1975) has shown that floodwater flow paths are also often ungraded. For this reason the use of the term phreatic loop by Ford (1968, 1971) and Ford and Ewers (1978) is here eschewed. Instead, the term pressure loop is used for the general case of looping flow paths.

For the hypothetical canyon it is simplest to specify an initial phreatic flow path. The development of that flow path before the onset of entrenchment is stage I development. During stage I (Figure 21C) the fracture conduits grow into a network of tubes and fissures. Figure 21C uses solid black to represent ground water under conditions of closed-conduit flow. The conduit outlines of Figure 21C represent
the tubes and fissures that were enlarged from the earliest fracture conduits. These tubes and fissures are represented in the fully-developed hypothetical canyon as remnant half tubes and fissures on passage ceilings (see cross sections, Figure 19). Figure 22B also shows stage I development.

For present purposes, it is not necessary to consider the processes by which fractures are selected to become structural segments. Similarly, because there are no independent tributaries to the hypothetical canyon, it is not necessary to consider how, why, or when tributaries developed. However, such considerations are expected to play a role in the analysis of real passages.

In the hypothetical canyon, stage II begins with the onset of vadose conditions. Without further information about the geohydrologic setting and the character of the upstream and downstream continuations of the canyon, it would not be possible to analyze the mechanism(s) which led to this change in flow conditions. Here it is best to assume that discharge decreased to a value at which flow was continuous, but was not sufficient to maintain pipe-full conditions throughout the flow path. It is also assumed that such hydrologic conditions were maintained while the narrow, upper parts of the canyon were entrenched to an approximately constant conduit width, as shown by the cross sections of Figure 19. Following this period, discharge then increased, allowing wider trenches to form.

Figure 21D shows what the flow path would have looked like after the onset of entrenchment in stage II. (In Figure 21D-21G, solid black
represents ponded ground water.) The same stage is also shown in Figure 22C. The downstream high point at position \( z \) is the top of a bedrock dam which creates a lengthy pressure loop. The pressure loop is interrupted by an air bell, a region filled with air at the ceiling of the ponded passage. (The air bell forms because the elevation of the high point at \( z \) is lower than the top of the blind fissure that is enlarged on the joint above bed-joint segment 4-5. The air enters as a vortex of air bubbles, [see Boegli, 1981].) Upstream of the pressure loop the stream entrenches the floor of the bed conduit on bed parting B2. Downstream of the loop, the stream entrenches section B and section D. There is a small waterfall where ground water splashes down from section B to section D. In summary, Figure 21D shows two regions of entrenchment separated by a region of continued "phreatic" conditions. Because any entrenchment on section B lowers the height of the bedrock dam, the system is a dynamic one. Changes in the height of the bedrock dam are reflected immediately in a decrease in the height of the pressure loop.

Figure 21E and Figure 22D show the flow path at a slightly later time. Several features stand out. First, entrenchment on section B has lowered the height of the dam sufficiently so as to pass slightly below the level of the height for the second, previously nested lower loop. This means that vadose entrenchment has now begun there as well, so there are two pressure loops separated by an air bell and a region of entrenchment. Second, dissolution within the downstream pressure loop has begun to enlarge bed parting B2 between positions 6
and 2. Some dissolution along B2 has also occurred near position 2 as a result of splashing of ground water from the waterfall. It is clear that diversion of ground water from section B to section C is imminent. The diversion occurs because section C forms (as bed segment 6-9) and enlarges fast enough to capture the available discharge before entrenchment can cut entirely through the bedrock bridge that separates section B from section C.

Figure 21F and Figure 22E show the canyon shortly after piracy. The piracy has eliminated the downstream pressure loop. Entrenchment is under way between positions 2 and 10. The height of the bedrock floor below position 2 now determines the level of the remaining pressure loop. Entrenchment occurs by downcutting and headward retreat downstream of the pressure loop. The floor is gradually lowered and the pressure loop is eliminated (Figure 21G and Figure 22F). About this time, discharge increases, perhaps due to increased ground-water infiltration brought about by increased size of the drainage basin, or changes in climatic conditions. Widening occurs as the floor is further lowered, leading to the formation of the modern profile (Figures 21H, 19).

Conclusion

Segment analysis identifies structural segments using (1) inference criteria and (2) rules that divide conduits into segments, sections, and flow paths. The structural segments are mapped and studied. By applying an understanding of the processes by which the
early conduits are enlarged, and by using morphologic features preserved in the modern passages, it is then possible to interpret the development of canyons, particularly those of branchwork caves in complex structural settings.

The analysis of the hypothetical canyon has made it possible to illustrate the method, which is tedious and time-consuming to effect. That analysis has also allowed the presentation of several concepts that are useful in the study of the growth of entrenched canyons. However, it is now necessary to turn to real passages and present analyses that are grounded in specific settings, which take into account details of the influences of lithology, structure, and changing hydrologic conditions. Such details have not been incorporated, except in the most general way, into the theoretical example above.
PART 2
SEGMENT ANALYSIS IN THE NORTH CANYON
OF
SNEDEGAR CAVE,
FRIARS HOLE CAVE SYSTEM

CHAPTER 3
THE GEOHYDROLOGIC SETTING

Introduction

Sneagar Cave is in Friars Hole Cave system at Friars Hole, West Virginia (Figure 23). The system formed in carbonate rocks of the Mississippian Greenbrier Group, which crops out extensively in the Valley and Ridge and Allegheny Plateau physiographic provinces in eastern West Virginia. Plate 1 (rear pocket) shows the surface geology of the Friars Hole and surrounding regions west of the Greenbrier River and north of Spring Creek. The system lies mostly under the Lobelia and Friars Hole valleys to the west of Droop and Brushy mountains, where streams flowing off Pennsylvanian clastic rocks sink in the upper units of the Greenbrier Group. Major springs that drain the Greenbrier carbonates are east of Droop Mountain on Locust Creek.
Figure 23. Location of the Friars Hole area.
and south of Droop Mountain on Spring Creek.

Snedegar Cave is near the middle of Friars Hole Cave system (Plate 2) on Friars Hole Cave Preserve. A description of Friars Hole Cave Preserve and its caves is given by Jameson and Mothes (1983).

Previous Work at Friars Hole

Friars Hole Cave system has a current (September, 1985) mapped length of over 43 miles and a depth of about 580 feet. A brief description of the geography of the system is in Medville (1981). The system has six separately named caves with nine entrances (Plate 2). Although several of these caves have been known since before the Civil War, when saltpetre was mined in Snedegar Cave (Faust, 1959), serious mapping and exploration did not begin in the Friars Hole region until the late 1940's. The first map of Snedegar Cave appeared in Davies (1949). In the late 1950's and in the 1960's attention was directed to Snedegar, Crookshank, and Friars Hole caves, resulting in several early connections that linked the former two caves into a single system. It was not until the 1970's that large numbers of sinkholes were excavated and the majority of pits open to the surface were entered. With the discovery of Canadian Hole (Coward, 1973) and Rubber Chicken Cave (Medville, 1977) the stage was set for the exploration, mapping, and connection of the caves into the present system. Details of the history of exploration and mapping are in Medville (1979) and Baker et al. (1982). This work has been accomplished by a loose coterie of cavers from several cave clubs in the eastern United
States, Canada, and Great Britain; the group is informally known as the Droop Mountain Cave Club.

The plan and profile of Friars Hole Cave system (Plate 2) show a complex network with numerous interconnecting levels. The speleogenesis of the system is similarly complex. Recent research, in fact, suggests that Friars Hole Cave system has undergone a multi-stage history with shifting ground-water inputs and complex reorganizations of several sets of flow systems (Worthington, 1984).

Early work on the modern flow paths through dye tracing was carried out by Zotter (1963, 1965) and Coward (1975). Wolfe (1964) and White and Schmidt (1966) described and interpreted the hydrologic setting and many of the details of ground-water flow. Their work has been partly dated by the more recent discoveries of passages and interconnections between caves, as well as by more recent dye tracing by Williams and Jones (1983) and Jones (1983). The latter workers have shown that the bulk of the recharge to Friars Hole Cave system flows south to resurge at JJ Spring on Spring Creek (Plate 1).

Medville (1981) gives a generalized description of the modern flow paths of the system. Medville disagrees with early contentions by White and Schmidt (1966) and Coward (1975) that there was once a single master conduit underdraining the Friars Hole region from sinkpoints of Hills and Bruffey creeks (north of the presently mapped parts of the system, in the Lobelia valley; see Plate 1). Instead, Medville (1981, p. 413) states, "No evidence exists for there ever having been a single conduit carrying one master stream through the entire length of the
system. Rather, it appears that numerous streams, sinking over the length of an 11 km long limestone outcrop, have resulted in the development of several separate caves which have subsequently been integrated into a single long system."

Worthington (1983, 1984) resurrects the contentions of the single active flow path of White and Schmidt (1966) and Coward (1975). He uses them in modified form as the major premise for an interpretation of north-to-south flow of ground water and concomitant passage development below a series of progressively lowering piezometric surfaces. Worthington (1984) argues that the oldest flow path is more than 4 million years old, and that most of the cave is more than 730,000 years old, based on radiometric and paleomagnetic dating of speleothems and other evidence.

Other studies in the Friars Hole region include that of Wolfe (1973), who studied effects of clastic sediments on surface and subsurface flow in the Greenbrier karst. Jameson (1979, 1980, 1981, 1983) investigated breakdown in fault zones, exfoliation breakdown, and the growth of passages on fault segments. Parts of these latter studies were carried out in Snedegar Cave. Kempe and Jameson (1983) studied the geochemistry of the Friars Hole Cave trunk stream at low discharge.

The Topographic and Hydrologic Settings of Snedegar Cave

Figure 24 shows the topographic setting of Friars Hole Cave system. Most of the system is immediately west of Brushy and Droop
Figure 24. The topographic setting of Friars Hole Cave system. Elevations are in feet. The contours have been modified from the 1:62,500 Lobelia, West Virginia quadrangle (U.S.G.S, 1935). Dark lines show the main passages in Friars Hole cave system from Medville (1981).
mountains, underneath the Friars Hole and Lobelia valleys. Brushy and Droop mountains form a ridge that trends southwest to northeast and that merges to the north into a major upland of the Allegheny Plateau. Northwest of the middle of the system is Jacox Knob, an erosional outlier of the upland. The southeast flank of Jacox Knob is drained by intermittent streams that flow into Cove Run. Cove Run trends southeast toward Droop Mountain as a perennial stream. Its streambed terminates surficially at the Swallet entrance (one of the two "North entrances") to the North Canyon of Snedegar Cave, thus forming the downstream surface terminus of the Cove Run drainage basin.

The Cove Run basin (Plate 1, Figure 25) has an area of about 1.3 mi². Its relief is about 1435 feet. Shales and sandstones of the Mississippian Mauch Chunk Group form a caprock over the Greenbrier carbonates and cover nearly the entire basin. This limits recharge into the main cavernous units (the Greenbrier Group below the Greenville Shale) to a narrow band of limestone exposed along the bed of Cove Run near Snedegar Cave, and to Snedegar Cave itself via the Swallet entrance. Table 4 gives generalized descriptions of the strata of the Cove Run basin and the Friars Hole and surrounding regions.

Snedegar Cave is beneath a hill south of the sinkpoint of Cove Run. A simplified plan of the cave, showing its position beneath the hill, is given in Figure 26. A slightly more detailed plan of most of the cave is in Figure 27. The plan of Figure 27 is keyed with numbers to descriptions of several of the main passages (see below) and to profiles of several passages in Plate 3.
Figure 25. The Cove Run basin and stream profiles. Cove Run sinks in the Swallet entrance to the North Canyon. DE = Dry entrance to the Saltpetre Maze. SS = Snedegar Saltpetre entrance. SE = Staircase entrance. W = White House col. CP = Crookshank pit. X = top of Cove Run basin.
TABLE 4
STRATA OF THE FRIARS HOLE REGION*

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<tr>
<td>MacCrady Formation</td>
<td>shale</td>
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</table>

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* After Price (1929); Price and Heck (1939); and Wells (1950).
** Exposed on the surface in the Cove Run basin.
Figure 26. The topographic setting of Snedegar Cave. After unpublished surveys by the Droop Mountain Cave Club and the U.S.G.S. (1977) Droop 7 1/2 minutes quadrangle.
Figure 27. Plan of Sne degar Cave. Based on unpublished surveys by the Droop Mountain Cave Club, compiled by Doug Medville, Robert Thrun, and Robert Gulden. Segment analyses were undertaken in those parts of the North Canyon, the Headwall Passage, and the Saltpetre Maze Passage that are shown as unshaded outlines.
The North Canyon is the primary active passage supplying surface water to Snedegar Cave. However, the North Canyon is gradually becoming abandoned as a result of upstream piracy of the Cove Run stream. During floods the stream flows through the entire North Canyon, the Amphitheater Room, and the Downstream Trunk Continuation en route to the Snedegar Sump. The stream then joins an inlet stream from the Snedegar Staircase entrance, and passes into Crookshank Cave en route to a sump in the Drought Way (Medville, 1981; Mothes, 1981). Floods of sufficient discharge to pass through the Snedegar sump occur perhaps three to seven times per year and last one to about five days per flood. At lower stages the stream disappears into occluded fractures in the floor of the North Canyon near the Amphitheater Room, or into occluded fractures and small fissures in the floor at several places near the Swallet entrance. At yet lower stages, usually during the summer or fall, the stream sinks several hundred feet upstream of the cave. Medville (personal communication, 1980) has traced this water during a summer drought to Monster Cavern of Canadian Hole using fluorescein dye. Monster Cavern is underneath the Cove Run valley a few hundred yards upstream of the Swallet entrance. The destinations of the water from the various sinkpoints within the North Canyon are not known. The water probably joins the Monster Cavern water upstream of Monster Falls.

At the Swallet entrance (Figures 25, 26) Cove Run is entrenched about 26 feet below a low saddle; the saddle is barely distinguishable above the floor of a gently sloping blind valley. The valley floor
lies at 2425-2440 feet above sea level. The valley trends southeast toward Droop Mountain, then turns southwest parallel to Droop Mountain. The valley is narrow and has a number of shallow sinkholes along its sides and at its abrupt southern end. At the southern end the valley rises at the saddle to 2509 feet on the White House col (Figure 25), as surveyed by Worthington (1984).

To the northwest of the Swallet entrance is a short blind valley. The valley rises about 22 feet to the top of a surface debris cone. The debris cone is below a surface headwall. Below the debris cone and slightly west of it are the Headwall Room and the Headwall Passage (Figures 26, 27).

Figure 26 shows the relationships of these valleys and the present course of the Cove Run stream to passages in Snedegar Cave. Most of the passages terminate in an upstream direction against the edges of the valleys, either as entrances (Saltpetre entrance, Staircase entrance, Dry entrance to the Saltpetre Maze, Swallet entrance), or in sediment fills. The sediments consist of rounded or flat boulders and cobbles set in matrices of muds and sands. A few passages also contain finer, saltpetre-bearing muds. Most of the cobbles and boulders (some as large as 6 by 6 by 2 feet) are ripple-marked Webster Springs sandstone of the Bluefield Formation of the Mauch Chunk Group (Table 4). Such clasts occur throughout Snedegar Cave, generally as imbricated fluvial deposits.

The above surface and subsurface features suggest a genetic relationship between Cove Run and Snedegar Cave, in which Cove Run has
been diverted underground at a variety of places. The precise nature of this relationship, however, is not clear, and further consideration of the topic must await results of the segment analyses.

The Investigated Passages

The passages chosen for segment analysis are in the North Canyon, the Saltpetre Maze, and the Headwall Passage. These passages are shown in a simplified version in Figure 27. A more detailed map of the studied passages, complete with profiles and cross sections, is given in Plate 4.

The North Canyon, the Headwall Passage, and the Saltpetre Maze Passage were chosen for segment analysis because they are readily accessible passages that fulfill the basic requirements for segment analysis (pp. 9-10, 34-41). The passages are developed in a complex structural setting. They contain remarkably well-preserved morphologic features that can be interpreted to yield a surprising amount of information about the early development, integration, and enlargement of several related flow paths.

It should be stressed that only parts of these passages were analyzed in detail. The selected parts were chosen because preliminary study indicated that their histories were so closely related that no parts could be omitted without serious distortion; however, to have extended the analysis to other parts of these passages would have greatly lengthened and complicated the study. The original intention was to study the entire North Canyon and all important related
passages. Toward this end, a detailed map was made of the North Canyon, the Headwall Passage, parts of the Saltpetre Maze, and several other passages. The map was prepared at a scale of 1:240 with a Suunto compass and clinometer, and a fiberglass tape. Stations were placed no farther apart than 30 feet. A U-tube manometer leveling survey (Palmer, 1970) was also extended through the passages. This gave a data base of several hundred survey stations with elevations determined to the nearest 0.01 feet. The survey data were then used to locate positions and elevations of fractures, contacts between lithologic units, and other features, both in the parts of the passages chosen for segment analysis, and in the other mapped passages.

Figure 28 is a schematic block diagram of the North Canyon, the Headwall Passage, the Saltpetre Maze Passage, and several other associated conduits. Figure 28 shows that the passages consist of a series of canyons, tubes, shafts, paleoshifts, fissures, and rooms. Segment analyses were carried out in the North Canyon from the entrance chamber downstream through Canyon 1 to position 59 in Canyon 2; in Canyon B of the Headwall Passage; in the tubes, fissures, and shafts connecting the North Canyon to the Headwall Passage; and in the Saltpetre Maze Passage. In the following pages, brief descriptions of the passages of Figures 27 and 28 are presented. These descriptions set the stage for lithologic and structural information (pp. 111-135); they also set the stage for the segment analyses and interpretations of flow-path history of Chapters 4-6.
Figure 28. Schematic block diagram of the North Canyon and nearby passages. B6, B15, B18, and B19 are bed partings in the Union Limestone (see Figure 31). C = continues, passage omitted. J, K, and L are passage positions whose names are underlined in the text and in figure captions, but not on diagrams. The drawing is not to scale. Note that a passage trending north from Canyon 5 has been omitted.
Passage Descriptions

(1) **North Canyon.** The North Canyon trunk has a length of about 1200 feet. It begins at the Swallet entrance and ends 100 feet lower at the Amphitheater Room. The trunk consists of passage developed on three levels. The upper level ranges from datum (Plate 4, profile P1) on the ceiling at the Swallet entrance, to about -55 feet. The middle level ranges from roughly -42 feet to -72 feet. The lower level ranges from -72 feet to -100 feet.

The North Canyon trunk can be divided into five canyons and two tubes (Figure 28). Canyons comprise about 1100 feet of passage length. The typical reach of canyon consists of a ceiling half tube or fissure on top of a narrow, stream-cut trench; below the narrow trench is a wider trench that forms the lowest part of the passage. The two tubes are low, wide conduits that account for only 100 feet of passage length.

The continuity of the trunk is broken at intervals by a number of intersecting ceiling tubes. Some of the tubes rejoin nearby, forming short closed loops. Others lead upstream as tributaries or downstream as connections into other passages. In this study, the most important of the ceiling tubes are the ones that are on the upper passage level and that are along Canyon 1 (Figure 28).

Canyon 1 begins at the Swallet entrance. It lies mostly on the upper passage level. Its downstream terminus is at and below the Second Paleoshift. At the Second Paleoshift, Canyon 1 is transitional
into Canyon 2 on the middle passage level.

Canyon 2 extends a short distance downstream from the Second Paleoshift to an intersection with the Headwall Passage at the First Paleoshift. Canyon 2 then continues downstream underneath the First Paleoshift and ends at the Fault Maze. Within the Fault Maze, Canyon 2 is transitional into Tube 1. Tube 1 is short; it immediately intersects the lower, wide trench of Canyon 3.

Canyon 3 begins in the side passage of the Fault Maze and extends downstream to a thrust fault (Plate 4) where it is transitional into Canyon 4. Canyon 4 is developed along the strike of the thrust and is transitional into Canyon 5 where the North Canyon trunk changes orientation to descend along the dip of the thrust. Canyons 2, 3, and 4, and Tube 1 are on the middle passage level. Canyon 5 is transitional into and partly lies on the lower passage level. Canyon 5 passes into Tube 2 where the trunk changes orientation to become parallel to the strike of the thrust fault. Tube 2 extends only a short distance downstream on the lower passage level to its connection with the Amphitheater Room. Along the east side of Tube 2 is a sediment wall that separates Tube 2 from several muddy crawlyways that are usually plugged but which occasionally are washed open by floods. They connect downstream into the Amphitheater at a slightly higher elevation than does Tube 2. Occluded fractures or tubes within the crawlyways may lead elsewhere.

In the North Canyon there has been little collapse, except in part of Canyon 2 where several large, wedge-shaped breakdown blocks are
associated with thrust faults. The collapse has not been so extensive, however, as to preclude segment analysis.

The floor profile is highly irregular. Irregularities arise because of the patchy nature of sediment fills. In places, particularly on the middle passage level in Canyons 2, 3, 4, and 5, the floor is bedrock. However, most of the trunk floor is formed by clastic sediments. The sediments average 3 to 6 feet in thickness where thickness is measurable without excavation. At two places in Canyon 1 just upstream of the Second Paleoshift there are log jams with sediments trapped on the upstream sides; the one farthest downstream has trapped over 6 feet of sediment (Plate 4, profile P1). The majority of the clasts consist of Webster Springs sandstone.

(2) Headwall Passage. The Headwall Passage extends from the Headwall Room to the First Paleoshift where it connects into the North Canyon (Figure 28). Most of the Headwall Passage is developed within the range of elevations of the upper passage level of the North Canyon. However, parts of the Headwall Passage are transitional into the top of the middle passage level, and parts are entirely within the middle passage level.

Just downstream of the Headwall Room is a canyon filled nearly to the ceiling with clastic sediments. This is canyon A; it branches in several places into small fissures or tubes that reconnect nearby or that lead to side passages (Plate 4). One of the side passages drops to a room at a lower level nearby to the north (Figure 27). Another is Fissure 1, which is plugged with sediments.
The segment analysis of the Headwall Passage begins where Canyon A branches into Fissure 1 and Canyon B. The analysis extends downstream through the rest of the Headwall Passage to the First Paleoshift, and includes all of Canyon B and the nearby conduits labeled Shaft 3, Shaft 4, and Fissure 2 in Figure 28 or Plate 4.

Canyon B gradually increases in height downstream (Plate 4, profile P3). Over most of its length, Canyon B has a ceiling half tube or fissure below which there is a narrow trench. The trench gradually widens downward. The floor is covered by clastic sediments consisting of sands and muds. Several holes in the floor open into the tops of Shaft 3 and Shaft 4. These shafts lead to fissures on the middle passage level; the fissures are considered to be part of the Headwall Passage, as are the shafts. Shaft 4 has been entrenched on its upstream side, where there is a thick deposit of coarse clastic sediments.

Near the downstream end of Canyon B is an abrupt drop in the floor into a room. The room extends about 30 feet downstream to the First Paleoshift and the intersection with the trunk of the North Canyon. At the upstream end of the room, directly below the top of the drop, is Fissure 2. Fissure 2 extends upstream into the base of Shaft 3. It then extends farther upstream into the base of Shaft 4, and into an undercut part of the lower wide trench of Canyon 2.

The Headwall Passage is mostly inactive, for it is perched well above the level of Cove Run at the Swallet entrance. However, major floods may be sufficient to fill part of it by backflooding from
downstream constrictions. A small stream, with a maximum discharge of a liter per minute, flows across part of Canyon A and disappears into a side passage at a lower level to the north (Figure 27).

(3) **Saltpetre Maze, and the Saltpetre Maze Passage.** The Saltpetre Maze is not a true, genetic maze (see Palmer, 1975) but rather consists of a series of branchwork passages. The passages originate from a number of inputs and are characterized by several stages of development. No attempt will be made to describe the Saltpetre Maze in detail. However, it is necessary to describe the general setting before describing the Saltpetre Maze Passage.

Most of the passages of the Saltpetre Maze are canyons. There are also several tubes, shafts, and collapse rooms. The canyons typically have ceiling half tubes or fissures with narrow or gradually widening trenches. Some canyons also have wide trenches. Short diversion routes are common. In places, large blocks have collapsed after lateral undercutting. The most prominent examples of lateral undercutting are in the Block Room. Upper passage levels typically have fine muds that partly fill joint spurs and blind solution pockets. Lower passage levels have floors covered with a variety of clastic sediments, including imbricated fluvial deposits and fine muds bearing saltpetre. In places sediments are more than 15 feet thick. Large logs are reported to have been used for leaching saltpetre during the Civil War (Faust, 1959), but some logs and other organic debris (near the Dry entrance to the maze) were likely transported into the cave during major floods, such as that caused by hurricane Camile in

Preliminary observations in the Saltpetre Maze suggested that some of the ground water that formed the early conduits (as part of the trunk of the North Canyon) came from the Saltpetre Maze Passage. The ground water followed a ceiling tube (the Sound Hole) that is too small to be traversed. The Sound Hole trends north from the Saltpetre Maze Passage toward a similar small tube, the Rat Hole, in the ceiling of Canyon I (Figure 28). Neither of these tubes was entrenched. To study these tubes and relate them to the flow paths of the North Canyon trunk, segment analyses were undertaken in relevant parts of the Saltpetre Maze. The "relevant parts" are collectively labeled "the Saltpetre Maze Passage."

The Saltpetre Maze Passage is a canyon located a short distance from the Dry entrance to the Saltpetre Maze (Figures 27, 28). The canyon has ceiling half tubes and fissures. Most of it has a narrow and a wide trench. Although considerable collapse resulted from lateral undercutting, that collapse was mostly on lower walls. Thus segment analysis has not been impeded by collapse. However, the Saltpetre Maze Passage is within a complex of canyons, tubes, and rooms that formed on several levels. These passages interconnect---in ways too complex and too unrelated to the development of the North Canyon trunk---to be worth fully describing here. Yet they are of direct concern for an understanding of the development of the parts of the Saltpetre Maze Passage that formed following the onset of entrenchment. To study this later development would require an extensive
re-mapping of much of the Saltpetre Maze. It would also require an extension of the segment analysis through several thousand additional feet of passage. Because that is impractical, and would greatly lengthen this study, it is best to be content with a partial analysis of the development of the Saltpetre Maze Passage. Toward that end, all connecting side passages were ignored in studying the relationships between the Saltpetre Maze Passage and the North Canyon. Consequently, the Saltpetre Maze Passage has been depicted in a limited fashion in Plate 4, Figure 28, and elsewhere in this thesis. On Plate 4 the Saltpetre Maze Passage has been left as a hanging survey without any clear indication of the connections to other passages. (However, a rough idea of the complexity of the connections in this region is indicated in Figures 27 and 28.) The plan of Plate 4 shows only the ceiling half tubes and fissures. The plan omits the walls of the lower wide trenches of both the Saltpetre Maze Passage and the connecting side passages. The profile is more complete. It depicts the floor and the ceiling (Plate 4, profile P2).

(4) Saltpetre Trunk. The Saltpetre Trunk consists of several canyons and rooms extending from the Saltpetre entrance to the Amphitheater Room (Figure 27). A profile of the Saltpetre Trunk appears in Plate 3.

Between the Saltpetre entrance and the First Bend is a short canyon; the canyon has an upper narrow trench that gradually widens downward. A much larger canyon with a rectangular cross section intersects the entrance canyon at the First Bend. To the east of the
First Bend is a short canyon that is plugged by terminal breakdown, clastic sediments, and other surface debris. Most likely these sediments plug a former entrance.

To the north of the Second Bend, the large canyon widens into the Saltpetre Room. Several large passages intersect this room. To the east is a large, sediment-filled canyon. This canyon likely led to a former sink point for the Cove Run stream (see Figure 26). At the start of this canyon is a sediment wall that was mined for saltpetre. Several piles of used saltpetre dirt and test pits are near the sediment wall. Elsewhere in the Saltpetre Room, especially near its downstream (northwest) end, there is much large block breakdown. Smaller breakdown covers the floor along the sides of the canyon between the Second Bend and the Saltpetre Room; the smaller breakdown likely fell from heavily fractured parts of the upper walls. These walls appear to have been fractured as a result of stress release unloading or perhaps ice wedging (see pp. 140-147). Fragments of the Webster Springs sandstone line the floor of the Saltpetre Room and much of the Saltpetre Trunk. At the downstream end of the Saltpetre Room is a canyon leading to the Block Room and to other passages of the Saltpetre Maze.

From the Saltpetre Room, the Saltpetre Trunk descends a breakdown slope into the Amphitheater (Plate 3). Along the slope hidden against the walls behind breakdown are several side passages leading to the Saltpetre Maze. Another hole leads into the Druid Passage, a series of canyons and tubes that may lead to Canadian Hole.
(5) **Amphitheater.** The ceiling of the Amphitheater, the largest room in Snedegar Cave, is irregular because of collapse within a zone of thrust faults. Much of the floor is covered with large block breakdown. At the north end of the room is the connection to the North Canyon. During floods, the stream from Cove Run discharges from the North Canyon out Tube 2 and from another, slightly higher tube that is often plugged with sediments. The stream then flows along the west wall of the Amphitheater toward the Trunk Continuation at the southwest end of the Amphitheater. A distinct stream bed has imbricated rock fragments deposited on and between breakdown. The highest part of the Amphitheater in the southern end has several side passages developed along thrust faults. One major tube trends south toward the Quartz Room, paralleling the fault zone.

(6) **Trunk Continuation.** This passage trends south from the Amphitheater, ending at the Cobble Crawls (Figure 27). The Trunk Continuation begins as a wide canyon, becomes a wider room with a low ceiling, but then becomes a canyon farther downstream. It is roughly parallel to the zone of thrust faults that trends south from the Amphitheater. However, the Trunk Continuation lies mostly below and to the west of the faults. The floor is covered with imbricated clastics, and there are several large sediment banks and terraces.

Along the east side of the Trunk Continuation are several side passages. These passages trend up the dips of the faults and lead to the upper-level tubes connecting the Amphitheater with the Quartz Room.
South of the Quartz Room are several other passages that rise east up the dips of the faults. These passages are so filled with sediments that it is difficult to discern their relationships to the faults. Each passage leads to domes or breakdown terminations near but below the wall of the valley that lies to the east of Snedegar Cave.

(7) Quartz Room. This passage is a canyon (Figure 27, Plate 3). It can be followed east up the dip of a thrust fault to several domes near the edge of the valley (Figure 26). The name comes from the quartz crystals lining slickensides of fault surfaces.

Regional Structure

Friars Hole is near the southern margin of the central Appalachian fold and thrust belt. That margin has been placed in central Monroe County at the Covington lineament (Rodgers, 1970; Dean et al, 1979). The major structures in the sedimentary cover of the central Appalachians are the result of thin-skinned tectonics during the Allegheny orogeny. In this region, first order folds, major thrust faults, and many smaller structures trend about N 30° E. In contrast, to the south of the Covington lineament in the southern Appalachians, the major structures trend N 60° E.

Figure 29, a tectonic map of part of the central and southern Appalachians, depicts the Webster Springs, Williamsburg, and Sinks Grove tectonic blocks (Dean et al., 1979). The blocks are bounded to the north and south by lineaments and by major folds to the east and west. The lineaments separate areas which are defined by varying fold
Figure 29. Tectonic map of part of the central and southern Appalachian mountains in West Virginia and Virginia. Modified from Dean et al. (1979). FH = Friars Hole, at the black rectangle.
intensities, fold frequencies, or trends of axial traces of folds.

The Friars Hole area is at the southern margin of the Webster Springs block. This block is characterized by a near absence of intermediate map-scale surface structures. The Webster Springs block is bounded on the east by the Browns Mountain anticline, on the south by the Modoc lineament, and on the west by the Webster Springs anticline (Dean et al., 1979).

The Browns Mountain and Webster Springs anticlines are complex folds created primarily by ramping and splay faulting from deep-seated decollements. Under the Browns Mountain anticline (Figure 30), ramps rise from the middle Cambrian Waynesboro Formation to the middle Ordovician Martinsburg Formation (Kulander and Dean, 1972).

A detachment in the Martinsburg Formation extends west from the Browns Mountain anticline underneath the Webster Springs block to the Webster Springs anticline. The detachment ramps upsection to an upper Silurian or middle-upper Devonian decollement. The detachment is under the Modoc lineament and the Williamsburg block (Kulander and Dean, 1972; Dean et al., 1979).

The Modoc lineament (Figure 29) is a 3 to 7 mile-wide zone which trends east across the regional structural trend of N 30° E. Dean et al. (1979), who considered the zone to be somewhat illusory, defined the zone by the terminations, changes in axial trends, or pronounced surficial fault development in the Webster Springs, Williamsburg, and Browns Mountain anticlines. In western Greenbrier and Pocahontas Counties, the northern boundary of the zone lies along trend variations
Figure 30. Structure section across the Brown’s Mountain anticline, about 16 miles north of Friars Hole. From Kulander and Dean (1972).
of structural contours on the Pennsylvanian Sewell Coal (Price and Heck, 1939; Price, 1929). Dean et al. (1979) did not believe that the Modoc zone resulted from transverse ramps or trend changes of longitudinal ramps. They suggested that the lineament is the boundary between greater cover shortening in the Williamsburg block than in the Webster Springs block.

Structural Setting of the Friars Hole Area

The Friars Hole area is about 10 miles northwest of the axial trace of the Browns Mountain anticline. Through much of the intervening region (Plate 1) beds strike N 20° E and dip up to 6 degrees to the northwest. Many small folds are superposed on this regional trend. The folds have amplitudes of less than 30 feet and occur at minor thrusts in the Greenbrier carbonates. The folds are detectable in the caves (often only by leveling surveys) but are rarely detectable at the surface.

Along the western side of Brushy and Droop Mountains (Plate 1), a zone of mesoscopic thrust faults is well exposed in Friars Hole Cave system and numerous surface exposures. The geometry of the zone and the outcrop pattern of the Greenbrier Group at Friars Hole point to the existence of an anticline beneath Droop Mountain (Rose, 1978; Jameson, 1979; Worthington, 1984). Using surface leveling, published sections of the Greenbrier Group (Leonard, 1968; Heller, 1980), sections of the Union and Pickaway Limestones (Jameson, unpublished), and the Pocahontas and Greenbrier County Reports (Price and Heck, 1939; Price,
Worthington (1984) constructed a structural contour map for the top of the Greenbrier Group. The map defines a low amplitude anticline (underneath Droop Mountain) plunging south into the Modoc lineament. It may be underlain by a major thrust fault cutting upsection from the shales underneath the Greenbrier carbonates.

Union and Pickaway Limestones

Snedegar Cave is in the Union and Pickaway Limestones of the Mississippian Greenbrier Group (Figures 31, 32). These formations are massive pure (in terms of \( \text{CaCO}_3 \)) oosparites, biosparites, and micrites interbedded with laminated to thin-bedded argillaceous micrites and dolomicrites.

Leonard (1969) studied the Union and Pickaway Limestones in eastern West Virginia, including a core from Sun Oil Company No. 1 at the north end of Droop Mountain. His X-ray diffraction patterns of insoluble residues and petrographic analyses indicate that argillaceous units contain illite, kaolinite, montmorillonite, chert, pyrite, feldspars, and quartz in silt- and sand-sized grains. Up to half of the residue may be quartz. Half or more of the residue is illite and kaolinite in a 2:1 to 3:1 ratio. Except for locally abundant chert and pyrite, other noncarbonate components in the argillaceous units are present in negligible amounts. Argillaceous units typically contain 25% insoluble residues but may contain up to 60%. This contrasts with values of less than 5-10% for biosparites, oosparites, and most micrites. Hempel (1974) obtained similar results.
Figure 31. Stratigraphic column of the Union Limestone. The column was measured in Sandgar Cave, from the Swallet entrance through the North Canyon, Amphitheater, and Trunk Continuation to the start of the Cobble Crawls.
Figure 32. Stratigraphic column of the Pickaway Limestone. The column was measured in Friars Hole Cave, between the Pool Room and the end of Mauck's Discovery. The floor of the Pool Room is at the top of unit C, which is also exposed at the top of Two Time Pit. In Snedgar Cave, the Pickaway Limestone is exposed at the end of the Trunk Continuation and farther downstream. The column was not measured in Snedgar cave because of difficulty in recognizing units and tracing them through the cave; the difficulties are due to the locations of key exposures within areas of faulting, exfoliation, collapse, or sumps.
Argillaceous units of the Union and Pickaway Limestones in Snedegar Cave contain abundant clay minerals, as shown by X-ray diffraction patterns of residues (Hobart King, personal communication) and by staining of rock samples with malachite green hydrochloride (Bouma, 1969). Clay minerals are parallel to laminae in the laminated micrites and are evenly disseminated in the matrices of homogeneous micrites and dolomicrites. Clay minerals are also concentrated along stylolites and stylolitic joints.

The passages chosen for segment analysis are in Union units D, E, F, and G (Figure 33). Nearly all of the length of these passages is in unit E (basal 9 inches), unit F, or unit G (the top 3 feet). Units D and E are pure oosparites and biosparites. Unit F consists of pure oosparites, biosparites, and biomicrites, with lenses of clay-rich biomicrites. Unit G contains homogeneous clay-rich micrites and dolomicrites. Locally, laminae are abundant and contain quartz silt, pyrite, and hematitic pseudomorphs after pyrite (Hobart King, personal communication, 1980).

Bedding Plane Partings

In caves, the prominence of the exposure of fractures depends on (1) fracture width, (2) dissolutional widening, and (3) the degree of alteration of the texture, color, or composition of the material adjacent to the fractures. The prominence of fracture exposure therefore depends on a variety of factors. Lithologic factors include rock composition and texture (Rauch, 1972, 1974). Structural factors
Figure 33. The position in the Union Limestone of the passages of Figure 28. SE = Swallet entrance. C1, C2, C3, C4, C5 = Canyon 1, etc. T1, T2 = Tube 1, Tube 2. F1, F2 = Fissures 1 and 2. P1, P2 = the First and Second Paleoshafts. S3, S4 = Shafts 3 and 4. HR = Headwall Room. CA = Canyon A. CB = Canyon B. DER = Dry entrance room to the Saltpetre Maze. SMP = Saltpetre Maze Passage. Lithologic units and bed partings are from Figure 31.
include those affecting original fracture width, which depend on fracture origin. Structural factors also include those affecting the secondary widening or deformation of fractures by erosional unloading (Renault, 1967; Boegli, 1981) or tectonic activity (Trimmel, 1968). Hydrologic factors include ground-water chemistry and flow rates within the fractures.

Of 19 relevant bed partings in the Union Limestone (Figure 31), only bed partings B1 and B8 are prominent throughout their exposures in Snedegar Cave. The prominence of their exposures is augmented by dissolitional re-entrants, blind pockets, and anastomoses. B1 is important because it supplied ground water to several early tributaries to the Saltpetre Maze Passage (see p. 274). B1 is exposed only at the Swallet entrance on the surface headwall (Plate 4, profile P1) and nearby in the Saltpetre Maze.

In contrast, B8 is widely exposed in Snedegar Cave. It can be traced from the Saltpetre entrance down the Saltpetre Trunk to the end of the Saltpetre Room, where the Saltpetre Trunk then descends below B8 to the Amphitheater (Plate 3). From the Saltpetre Room, B8 can be traced through the upper levels of the Saltpetre Maze to the Swallet entrance, then through most of the upper passage level of the North Canyon and part of the Headwall Passage (Figure 28, Plate 4). A contour map (Plate 5) was constructed for B8 in the North Canyon and parts of the Headwall Passage and the Saltpetre Maze. In most of this area, B8 is prominently weathered and somewhat undulatory with narrow (less than 0.25 inches) re-entrants. In places, the re-entrants have a
thin coating of brown material that could be weathered argillaceous matter originally in the base of Union unit E or the top of unit F. Attempts to sample this material were unsuccessful, because the re-entrants also contain brown clay-sized sediments. These clays were probably deposited before entrenchment, based on their restricted distribution in re-entrants, blind pockets, and joint spurs at the ceilings of canyons.

Bed parting B8 is part of a set of closely spaced partings, B2 to B8 (Figure 31; Plate 4, profile P1). B6 and B7 are undulatory and locally stylolitic. Argillaceous material in Union unit E often lines them. B6 and B7 are always recognizable wherever their stratigraphic interval is present, but are rarely prominent and have few associated dissolutional features. The other partings of this set, B2 to B5, can be recognized only at the Swallet entrance, where surface weathering has widened and accentuated most fractures.

Bed partings B9 and B10 of Union unit F are stylolitic and discontinuous laterally (Plate 4, profile P1). Bed partings B11, B12, B13, and B14 are also discontinuous and locally stylolitic, but usually are visibly bounded by argillaceous material.

Bed parting B15 is prominent but laterally discontinuous. It appears where unit G is capped by an argillaceous micrite or dolomicrite with well-developed laminae. It is absent where (1) unit G is relatively homogeneous and grades into the purer micrites of unit F, or (2) unit G was eroded before deposition of unit F. Parting B15 is most prominent and has dissolutional features only where thrust faults
follow it. B16, also in unit G, is a moderately prominent parting that usually lacks dissolusional features. Parting B17, at the base of unit G, is rarely prominent.

The final two partings of interest, B18 and B19, are sharp contacts at the top and bottom of unit I, a homogeneous clay-rich micrite or dolomicrite. Unit I is exposed in Tube 2 on the lower passage level of the North Canyon. Only B18 is prominently weathered.

Systematic and Non-systematic Fractures

Joint trends for the Greenbrier Group (Figure 34) have been determined by Wolfe (1964), Ogden (1974, 1976), Dean et al. (1979), and Kulander and Dean (1980). The most recent studies recognize systematic regional joint sets trending N 30-45° E and N 60-75° E, with subparallel, bed-perpendicular stylolites. The N 60-75° E set is less common that the N 30-45° E set. A third, N 80-90° E set occurs in some argillaceous limestones. Non-systematic joints are orthogonal to systematic joints, but are not common.

Stylolites have formed on many systematic joints, mostly on the N 30-45° E set. Stylolite teeth are asymmetric to N 30-45° E fractures at many localities, and symmetric with a near-perpendicular orientation to N 60-75° E fractures. Using the columns to the N 60-75° E joints as the direction of the maximum compressive stress during stylolite formation, Dean et al. (1979) concluded that the stylolites formed by layer-parallel shortening on pre-existing, pre-Alleghenian extension fractures (the N 30-45° E and N 60-75° E joint sets) in response to
Figure 34. Trends of joints in the Greenbrier Group in east-central West Virginia. (A) Joint trends according to Wolfe (1964) for the formations of the Greenbrier Group in Pocahontas and Greenbrier counties. Longer lines = "major" joints. Shorter lines = "minor" joints. Letters designate formations of the Greenbrier Group: U = Union, P = Pickaway, Pa = Patton, SG = Sinks Grove, and H = Hillsdale. (B) Joint trends according to Dean et al. (1979) for Monroe, Greenbrier, and Pocahontas Counties. Height of bars indicate relative abundance. Flat tops of bars are not intended to imply that all joints within a class are of equal abundance; the idea is merely to show the relative locations of the joint classes so they can be compared with the joint classes identified by Wolfe (1964).
N 20°-35° E compressive stress of the southern Appalachians.

In Snedegar Cave, N 60°-75° E set joints (Figure 35A) are prominently weathered but are not abundant. Most are in the purer units of the Union Limestone. Subparallel stylolites are rare. The joints range up to 30 feet in length and height, but most are less than 10 feet high and transect few prominent bed partings. Though the joints are normal to bedding, they are not planar, but curviplanar, particularly at terminations. Many N 60°-75° E joints curve toward and terminate at other joints, forming en echelon plan patterns (Figure 36A). Intersections occur at different positions or heights along joint lengths. Thus, en echelon joint patterns make it difficult to map individual fractures.

Non-systematic cross joints link some N 60°-75° E joints. The cross joints occur singly and have lengths and heights shorter than 6 feet.

N 30°-45° E joints are rare in Snedegar Cave, though subparallel stylolites are abundant (Figure 37). The stylolites have anastomosing morphologies (Figure 36B, 36C; see Powell, 1979), so strike histograms for straight segments are bimodal, with 10 to 15 degree peak separations (Figure 35B, 35C). In Snedegar Cave (and elsewhere in Friars Hole Cave system), strike peaks are at N 45° E and N 55° E, being transposed about 10 degrees eastward of the results of Dean et al. (1979).

N 30°-45° E set stylolites are usually perpendicular to bedding and do not transect prominent bed partings. They range from a few inches
Figure 35. Histograms of strikes of joints and stylolites in Snedegar Cave. Vertical scale = number of fractures. (A) N 60-75° E set joints (right) and nonsystematic cross joints (left). The joints are in units E and F of the Union Limestone in the North Canyon. (B) N 30-45° E stylolitic joints and stylolites from Union unit F at the Second Bend of the Saltpetre Trunk. (C) N 30-45° E stylolites and stylolitic joints from Union unit G in the Fault Room of the North Canyon.
Figure 36. Idealized traces of systematic joints in plan view in horizontal beds. (A) En echelon pattern exhibited by most sets of N 60-75° E set joints. The offsets between the joints may be dextral, as shown here, or sinistral. (B) and (C) are diamond-shaped patterns (anastomosing fracture morphology of Powell, 1979) shown by many stylolitic N 30-45° E set joints and by subparallel stylolites. No scale is indicated because of the high variability of fracture and stylolite sizes and spacing. See text.
Figure 37. Stylolites of the N 30-45° E set. The stylolites are in the Union Limestone at the Fault Room of the North Canyon.
to a few feet in height, but combine to form composite surfaces with lengths up to 30 feet.

Faulyts


The thrusts in the caves are contraction faults (Norris, 1958) that produce bed-parallel shortening. Many thrusts are roughly S-shaped in cross sections drawn parallel to fault dip. The larger S-shaped faults (Figure 38) have the classic ramp and flat pattern or staircase trajectory of thrust systems (Butler, 1982; Boyer and Elliott, 1982). The ramps are in the purer limestones, where they cut bedding at angles as high as 30 degrees. The flats frequently are in argillaceous limestones or shales, but locally follow bed partings in purer limestones. In Snedegar Cave, flats follow bed partings B8, B14, B15, B16, and B17 of the Union Limestone. Flats parallel bedding in argillaceous units G, I, and K.

Ramp heights range 3 to 30 feet in Snedegar Cave and are controlled by the spacing of argillaceous units in the stratigraphic column. Argillaceous units are therefore interpreted to be softer
Figure 38. Faults on part of the north wall and the ceiling of the Amphitheater. (A) Photograph. For identification and discussion of the faults, see Figure 38B.
Figure 38 (continued). (B) Tracing of faults from Figure 38A. Compare with Plate 3. Faults A and B ramp from unit I of the Union Limestone. They pass back into bed-parallel slip and die out in the lower part of unit G. Unit G has been folded into a monocline at M. Two smaller faults (c, d) may be accommodation features formed to solve space problems resulting from displacement along faults A and B. Faults above unit G are on the ceiling and are minor, except for E. Fault E is not prominent in the photograph because it is at its northernmost extent, where it is being replaced by smaller faults. X marks the location of the photograph of Figure 43.
lithostructural units (Currie et al., 1962) than the stronger, purer limestones.

In Friars Hole Cave system, the faults are in zones that range up to 1500 feet in length (Figure 39), and contain 10 or more faults. Faults range up to at least 150 feet in length, but lengths are easily overestimated by incorrectly correlating thrusts between exposures. Within zones, the faults frequently terminate laterally into other faults at an angle (Figure 40A) or are replaced by others that are offset (Figure 40B). The faults terminate upward in bedding-parallel slip or bifurcate into smaller faults (Figure 40C). A major fault zone in Snedegar Cave extends from the North Canyon through the Amphitheater Room, then east of the Trunk Continuation in side passages (Figure 27, 39; Plate 3).

Where displacement exceeds a few feet along larger faults, rootless anticlines (Rich, 1934) form by duplication of strata (Figure 38; Plate 4, profile P5). The folds appear where thrusts ramp between thicker (3 feet) argillaceous limestones or shales. In Snedegar Cave, thrusts ramp between units G, H, and K of the Union Limestone.

Displacements along thrusts are primarily dip-slip as inferred from calcite crystal-fibre slickenlines that parallel the dip direction (Hobbs et al., 1976). Slickensides often weather to flakey or friable masses, which may easily be mistaken for weathered flowstone. Many slickensided surfaces have quartz crystals (Rose, 1978). The crystals range up to one inch in length. Displacements range up to 10 feet on upper ramps at easily distinguishable marker beds of impure limestones.
Figure 39. Zones of thrust faults in Friars Hole Cave system.
Figure 40. Terminations of faults.
or shales.

Fault surfaces are irregular at local rock anisotropies, such as discontinuous clay laminae, where faults change orientation to accommodate slip. Variations in fracture width or mineral packing by calcite or quartz also produce irregularities in fault surfaces.

Fault strikes typically change 5 to 10 degrees along fault surfaces, but may change as much as 30 degrees. Generally, strikes are subparallel to the central Appalachian fold trend of N 30° E, but strike histograms may show more than one peak. For example, in Friars Hole Cave system, a histogram of 173 fault strikes shows one peak at N 15-30° E and another at N 5° W to N 5° E (Figure 41A). The faults dip with approximately equal frequency to the northwest and the southeast (Figure 41B). In Snedegar Cave, 39 faults strike mostly north and dip mostly west (Figure 42A).

Fault-subparallel Joints

In many fault zones the stronger units are cut by conjugate joints (Figure 43). The joints are oriented subparallel to the faults (Figures 42, 44). The joints usually are confined to single beds. The joints are smaller than the faults, having maximum strike lengths of about 15 feet. In some fault zones, the fault blocks contain abundant joints (Figure 43). However, in the more common pattern the joints are restricted to fewer than three beds over an area encompassing thousands of square feet. An example is at the Swallet entrance (Figure 42B; Plate 4, profile P1), where joints are in the base of unit E of the
Figure 41. Strikes and maximum dips of faults in Friars Hole Cave system and in other nearby caves and surface outcrops at Friars Hole. (A) Histogram of strikes. (B) Stereonet of strikes and maximum dips.
Figure 42. Equal-area stereonets and rose diagrams of faults and subparallel joints in Snedegar Cave. The stereonets plot strike and maximum dip; the rose diagrams plot strike only. (A) Faults in the North Canyon, Headwall Passage, Headwall Room, Amphitheater, the Trunk Continuation and nearby, and the Quartz Room. (B) Joints in Union unit E at the Swallet entrance.
Figure 43. Fault-subparallel joints in the Amphitheater. The joints are below fault B (Figure 38B) in unit H of the Union Limestone.
Figure 44. Strikes and maximum dips of fault-subparallel joints in Friars Hole Cave system and in other nearby caves and surface outcrops at Friars Hole. (A) Histogram of strikes. (B) Stereonet of strikes and maximum dips.
Union Limestone, in the beds bounded by partings B6, B7, and B8. Most of the joints are between B7 and B8. This pattern is present at most exposures of the base of Union unit E in Snedegar Cave.

Calcite Veins

Calcite veins appear in purer limestones near many faults. The veins are abundant between larger faults where two faults ramp in opposite directions from a single horizon. For example, at Tube 2 of the North Canyon near the Amphitheater (Plate 4), one fault ramps northwest from Union unit I, and another ramps southeast from the same unit. The veins appear on the walls and ceiling of the tube in the base of unit H. The exposure does not allow measurement of the orientations of the veins. Many are vertically oriented, supporting an interpretation of tensional origin (Ramsay, 1980). Calcite-filled veins also occur in en echelon arrays replacing the fault-subparallel joints. No examples are known from Snedegar Cave, but an accessible example is in the entrance fissure of Cutlip Cave to the north of Friars Hole Cave system. This array resembles arrays discussed by Ramsay (1967) and Roering 1968).

Mechanisms of Cavern Enlargement

In caves, aqueous dissolution of soluble bedrock is the most important mechanism of enlargement (see reviews in Jennings, 1971; Sweeting, 1973; Ford et al., 1976; Boegli, 1981). Where there are clastic sediments, erosion through abrasion may operate (Newson,
1971). In addition, such processes as collapse, stress release of previously confined bedrock, frost fracturing, exfoliation, gypsum crystal wedging, or chemical alteration of bedrock constituents (such as clay minerals) may play a role in enlargement. These processes weaken the rock or produce fragments that are more readily dissolved, abraded, or transported away (Davies, 1951; Renault, 1968; White and White, 1969; Powell, 1977; Jagnow, 1978; Jameson, 1983).

Aqueous Dissolution of Carbonates

Most of these mechanisms contribute to cavern development in caves in West Virginia. Not all of the mechanisms usually operate in a given cavern setting or even within a given cave. In Snedegar Cave, nearly all enlargement of the early tubes and trenches below them has been effected through the dissolution of carbonates by ground water. Evidence for this assertion derives from the presence and distribution of anastomoses, pendants, tubes, half tubes, blind ceiling and wall pockets, joint spurs, flutes, scallops, and such features of entrenchment as undercuts and notches. Each of these features may be attributed to the activities of moving water under conditions of closed- or open-conduit flow.

A less dynamic form of dissolution also operates in Snedegar Cave. It involves carbonate dissolution by condensed moisture. The process contributes very little to increasing passage volume. Instead, it increases the surface roughness of half tubes, tubes, and the upper walls of canyons and abandoned shafts. The process is most active
during the summer, when moist surface air enters the cave and is cooled. Condensation forms on ceilings and walls. A dense fog fills parts of the Saltpetre Trunk, Saltpetre Room, Amphitheater, and Saltpetre Maze. (In the North Canyon fogs are less frequent, forming during floods, when splashing also supplies moisture to walls.) The condensation drops coalesce and form thin films of descending rivulets. The drops and rivulets dissolve calcium carbonate, resulting in textured surfaces in which less soluble matter stands in positive relief. Surface features include rivulet and drop patterns (Figure 45). Where drops are abundant, such as near the First Bend of the Saltpetre Trunk, they become supersaturated, fall to the floor, and drill small holes in the mud. The saturated water then soaks into the mud surrounding the holes. As the mud dries during the fall and the winter, calcium carbonate is precipitated around the holes. White rings appear (Figure 46). The rings are visible until late spring or early summer, when the cycle restarts. The details of the chemistry of this condensation weathering are unknown. Prokof'ev (1965) measured condensation rates in Vorontsov Cave in the Caucasus, and believes that condensation weathering could have removed 11,300 m$^3$ of bedrock in the last 2 million years.

Abrasion

Abrasion is unlikely to have contributed significantly to passage enlargement in Snedegar Cave. However, abraded scallops appear on lower walls in parts of Canyon 1 where the floor gradient steepens.
Figure 45. Rivlet and drop patterns of condensation weathering. 
R = rivlet pattern. D = drop pattern.
Figure 46. Calcite rings surrounding drip holes.
Abraded scallops also are abundant on the lower walls of unit H in Canyon 5, immediately below the drop (Plate 4, profile P5). Abrasion by sandstone clasts trapped in small potholes in unit G probably occurs during floods in Canyon 3.

Rock Collapse Along Tectonic Fractures

Large-scale collapse of block breakdown is abundant in the Saltpetre Trunk, the Saltpetre Room, the Block Room, and the Amphitheater. It is rare in the passages chosen for segment analysis. Large-scale collapse results from overloading of undermined sections of walls. Such collapse generally is along the pre-established planes of weakness of bed partings, N 60-75° E set joints, or faults. Jameson (1981) discusses collapse patterns that appear where undermining has overloaded bedrock blocks bounded by faults and N 60-75° E set joints. Additional accounts of collapse patterns are in Chapter 6 (pp. 365-366; p. 374).

Rock Collapse Along Other Fractures

In some fault zones the bedrock near the faults is cut by closely spaced fractures. In Snedegar Cave, densely fractured bedrock is in unit G of the Union Limestone in the Quartz Room. The fractured bedrock is below a large thrust fault that ramps from unit K in the Trunk Continuation first up to and through unit I and then up to the top of unit G, where there is a flat along B15 (Plate 3, Figure 47). Other zones of densely fractured bedrock are in the Saltpetre Trunk,
Figure 47. Densely fractured bedrock in unit G below a bed-parallel thrust in the Quartz Room. The ceiling has abundant quartz crystals in clusters up to 1.5 inches across.
the Saltpetre Room, and the Block Room. In the passages chosen for
segment analysis, densely fractured bedrock occurs only in the upstream
part of Canyon 1 of the North Canyon near the Swallet entrance.
Jameson (1979) suggested that this fracturing is related to the
faulting. More recent observations indicate that most of the fractures
are not near the faults. Also, the geometry of the fractures and the
associated bedrock fragments favor other interpretations of fracture
origin.

Figure 48 shows a heavily fractured wall at the Second Bend of the
Saltpetre Trunk. The photograph shows that many of the larger
fractures have a near vertical orientation, subparallel to the surface
of the wall in Union unit F. If the wall is followed around the bend
and fracture attitudes are measured, the attitudes remain subparallel
to the local surface orientation of the wall. This suggests that the
larger fractures are a type of surface exfoliation. They may result
from pressure release of previously confined wall rock, the expansion
being outward into the canyon. This explanation has the advantage of
explaining the unusual rectangular form of the cross sections of much
of the Saltpetre Trunk between the First and Second Bends. In this
region, the walls often have flat surfaces that lack the morphologic
features normally attributed to dissolution of canyon walls.

However, the explanation may fail to account for the smaller
fractures on the walls, and for the peculiar shapes of the bedrock
fragments that remain in place on the walls or form debris piles at
wall bases. A close look at the geometry of the fractures shows that
Figure 48. Fractured wall at the Second Bend of the Saltpetre Trunk.
many curve toward and die at other fractures. Thus most of the fractures are less than 3 feet in length and height. Where fractured walls are undercut, the plan pattern of the fractures consists of diamond or wedge-shaped traces similar to those of the N 30-45° E set of systematic joints (Figure 36B, 36C). A profile through the fractured bedrock shows a similar pattern. The bedrock fragments have surfaces bounded by the fractures, and thus have the shapes of wedges, curved plates, or arrowheads (Figure 49). Locally, the bedrock fragments may be blocky if N 60-75° E set joints are present.

The peculiar shapes may arise because processes other than surface unloading have operated. For example, frost wedging may be involved. This interpretation is attractive given the distribution of the zones of densely fractured bedrock. The zones have been found only in cave entrances, nearby passages, and on cliffs at entrances. In the Friars Hole area, additional zones are at Toothpick Cave, Crookshank Cave, and at several of the caves along Clyde Cochrane Run and Rush Run. If the fracturing has been aided by frost wedging, it may be a relict from glacial periods when tundra (and perhaps permafrost) was present at high elevations in West Virginia during the late Wisconsin. Relevant literature regarding these conditions is reviewed by Wolfe (1973) and includes studies of fossil-sorted patterned ground on Cold Knob (Clark, 1968). Cold Knob is 10 miles southwest of the Friars Hole area and over 1500 feet higher.

Another type of jointing results in rock collapse in argillaceous beds. The joints are curved with surfaces that face convexly out
Figure 49. Densely fractured bedrock and fragments in the Fracture Dome in Friars Hole Cave. (A) Fractured bedrock, viewed on a surface parallel to bedding on the underside of an undercut surface. Note diamond-shaped pattern of fractures.
Figure 49 (continued). (B) Fragments found in a debris pile below the Fracture Dome. Fragments frequently have the shapes of curved sheets, wedges, or arrowheads. Some fragments have sharp points (not visible because the fragments are supported by the points).
toward cave passages (Figure 50). The convexity occurs in both plan and profile views, producing a tendency toward the development of hyperbolic cross sections (Jameson, 1983). Where argillaceous beds are thick, as in the Pickaway Limestone, such jointing may be extensive. Jameson suggests that the joints are caused by exfoliation associated with chemical weathering and stress release of overloaded and relatively weak wall rock. Fragments produced by this process are typically narrow curved plates or small flakes. Large slabs are common in Rubber Chicken, Friars Hole and Canadian Hole caves. The column for the Pickaway Limestone in Figure 32 identifies argillaceous units with abundant exfoliation in Friars Hole Cave. In the Union Limestone the exfoliation is relatively rare, but can be found in units G and I. Some of the jointing in unit G in the Quartz Room (at the zone of densely fractured bedrock, Figure 47) is likely exfoliation. Other examples of curved exfoliation joints in Snedigar Cave are in unit G at the southwest wall of the Amphitheater, and in unit I at the end of Tube 2 of the North Canyon, where Tube 2 connects into the Amphitheater. In both cases the exfoliation is poorly developed.
Figure 50. Exfoliation in the Pickaway Limestone in Canadian Hole. Note the curved fractures on the left wall and the exfoliation on the floor.
CHAPTER 4

THE STRUCTURAL SEGMENTS

AND THE

EARLY CONDUITS ENLARGED FROM THEM

The Sections

Application of the method of segment analysis in Snedegar Cave led to the recognition of 32 sections. The sections are listed in Table 5, where they are arranged by passage location (see Figure 28). The sections, except for section S, are shown schematically in a block diagram in Figure 51A. Section S, the Miniature Shaft, connects sections 6B and 6C to sections 7B and 7C. Section S is too short to be shown in Figure 51A.

Types of Segments

Fractures available to form structural segments include bed partings, two sets of systematic joints (N 60-75° E, N 30-45° E), faults, and two sets of joints oriented subparallel to the two sets of faults. The fractures can form structural segments as individual fractures (single-fracture segments). They can form segments as
<table>
<thead>
<tr>
<th>Location</th>
<th>Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Saltpetre Maze</strong></td>
<td></td>
</tr>
<tr>
<td>Saltpetre Maze Passage</td>
<td>M, N</td>
</tr>
<tr>
<td>Sound Hole</td>
<td>1A</td>
</tr>
<tr>
<td><strong>North Canyon</strong></td>
<td></td>
</tr>
<tr>
<td>Rat Hole</td>
<td>1B</td>
</tr>
<tr>
<td>Canyon 1</td>
<td></td>
</tr>
<tr>
<td>Downstream of the Rat Hole, to the</td>
<td></td>
</tr>
<tr>
<td>Second Paleoshift</td>
<td>1, part of 5, 5A</td>
</tr>
<tr>
<td>Upstream of the Rat Hole</td>
<td></td>
</tr>
<tr>
<td>In Canyon 1 from the Swallet entrance to the start of section 1</td>
<td>7D, 7B, 7C, 6</td>
</tr>
<tr>
<td>The A-tubes above Canyon 1 near the Swallet entrance</td>
<td>7A, 6D, 6C, 6B, 6A</td>
</tr>
<tr>
<td>Miniature Shaft, between the A-tubes and Canyon 1</td>
<td>S</td>
</tr>
<tr>
<td><strong>Canyon 2</strong></td>
<td></td>
</tr>
<tr>
<td>Between the First and Second Paleoshfts</td>
<td>part of 5</td>
</tr>
<tr>
<td>Downstream of the First Paleoshft</td>
<td>8, 9A, 9B, 9C, 9D, 10, 11</td>
</tr>
<tr>
<td><strong>Connection Tube</strong></td>
<td></td>
</tr>
<tr>
<td>Between Canyon 1 and the Headwall Passage</td>
<td>2</td>
</tr>
<tr>
<td><strong>Headwall Passage</strong></td>
<td></td>
</tr>
<tr>
<td>On the upper passage level</td>
<td>part of 3, 4</td>
</tr>
<tr>
<td>First Paleoshift</td>
<td>part of 3</td>
</tr>
<tr>
<td>Third Shaft</td>
<td>X</td>
</tr>
<tr>
<td>Fourth Shaft</td>
<td>Z</td>
</tr>
<tr>
<td>Fissure 1</td>
<td>Y</td>
</tr>
<tr>
<td>Fissure 2</td>
<td>V</td>
</tr>
<tr>
<td>Undercut region that connects Canyon 2 to Fissure 2</td>
<td>W</td>
</tr>
</tbody>
</table>
Figure 51. Block diagrams of the sections and the segments. (A) The sections. All sections except S (the Miniature Shaft) are shown, using solid, dotted, or dashed lines. Numbers and letters are used to name the sections, whose locations are described in more detail in Table 3. Each section consists of one or more segments; the segments are shown in Figure 51B and Plate 4. The diagram is schematic, and is not to scale. The top surface represents bed parting B8, which has been smoothed considerably (see Plate 5). Vertical planes that extend above B8 represent joints. The curved planes in Canyon 1, Canyon B, and the Sound Hole represent thrust faults. See also Figure 28. FP = First Paleoshift. SP = Second Paleoshift.
Figure 51 (continued). (B) The segments. All segments except joint segment 35X-44 of section S (the Miniature Shaft) are shown. Endpoints of several key junctions of sections are labeled with horizontal lines drawn above and below the endpoint names. For example, junction 1,2,3 is at position 8, which is shown as 8. See Figure 51A, Table 5, and Figure 28. FP = First Paleoshaft. SP = Second Paleo shaft. CT = Connection Tube.
intersections of different types of fractures (intercept segments). They can form segments as closely spaced fractures (zone segments). In addition, fractures can have slightly different orientations and intersect to form intercept segments. Thus there are numerous potential types of structural segments.

Not all possible types occur in the investigated passages. Nor is it useful to distinguish all of the segment categories that do occur. For example, it is not useful to distinguish between fault segments formed on northwest-dipping faults and fault segments formed on southeast-dipping faults. There are two reasons. First, there are no observed relevant physical differences between the fault sets that might affect conduit development. Second, there are no observed relevant differences between the conduits developed on the two sets of faults.

The most useful classification of the segments recognizes seven types of structural segments. Several mined segments (abbreviated MS) are also present in the study passages; they will be described in later chapters. The structural segments are:

(1) Red segments (B).

(2) N 60-75° E set joint segments (J). Most are zone segments. The reason, of course, is that the joints rarely occur singly. Instead, the joints are closely spaced with en echelon patterns. They intersect frequently by hooking into one another at variable positions along their lengths and heights. The geometry of the joints makes it difficult to distinguish and map single joints as single-fracture joint
segments within the zones. However, where possible, single-fracture joint segments were distinguished.

(3) **N 30-45° E set joint segments** (J).

(4) **Cross joint segments** (XJ). The cross joints are nearly perpendicular to N 60-75° E joints.

(5) **Bed-joint segments** (BJ). The joints are N 60-75° E joints or cross joints.

(6) **Fault segments** (F). Segments on east- and west-dipping faults are combined into one group.

(7) **Fault-joint segments** (FJ). N 60-75° E set joints are used.

**Presentation of the Segment Analyses**

Table 6 lists the segments. For each section, Table 6 shows the segment type, the type of host fracture, and the segment length. The segment length of a structural segment is the length of the midline. Midline lengths were estimated by measuring the lengths of the center lines of the ceiling half tubes or fissures. (Center lines are lines connecting the center points of the conduits or remnants of conduits.) The lengths of the center lines of short segments (under 15 to 20 feet) are mostly accurate to the nearest 0.1 feet. The lengths of longer segments are accurate to the nearest 0.5 feet, except for N 60-75° E segments. Some of the longer N 60-75° E segments (over 15 to 20 feet) are accurate to the nearest foot, at best. The segment length of a mined segment represents the minimum amount of rock removed by dissolitional mining. The lengths were measured in straight
### TABLE 6
STRUCTURAL AND MINED SEGMENTS IN SNEDEGAR CAVE

<table>
<thead>
<tr>
<th>Endpoints</th>
<th>Type of Segment</th>
<th>Types of Fractures</th>
<th>Length (Feet)</th>
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<tr>
<td>1-2</td>
<td>J</td>
<td>N 60-75° E Jts.</td>
<td>21</td>
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<tr>
<td>2-3</td>
<td>B</td>
<td>B8</td>
<td>17</td>
</tr>
<tr>
<td>3-4</td>
<td>J</td>
<td>N 60-75° E Jts.</td>
<td>4</td>
</tr>
<tr>
<td>4-5</td>
<td>B</td>
<td>B, unnamed, below B8</td>
<td>8</td>
</tr>
<tr>
<td>5-6</td>
<td>J</td>
<td>N 60-75° E Jts.</td>
<td>4</td>
</tr>
<tr>
<td>6-7</td>
<td>BJ</td>
<td>B8, N 60-75° E Jts.</td>
<td>17</td>
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<td>7-8</td>
<td>B</td>
<td>B8</td>
<td>2</td>
</tr>
<tr>
<td>8-9</td>
<td>BJ</td>
<td>B8, N 60-75° E Jts.</td>
<td>8</td>
</tr>
<tr>
<td>9-10</td>
<td>J</td>
<td>N 60-75° E Jts.</td>
<td>9</td>
</tr>
<tr>
<td>10-11</td>
<td>BJ</td>
<td>B8, N 60-75° E Jts.</td>
<td>8</td>
</tr>
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<td>11-12</td>
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<td>B8</td>
<td>19</td>
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<td>J</td>
<td>N 60-75° E Jts.</td>
<td>58</td>
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<tr>
<td>13-14</td>
<td>BJ</td>
<td>B8, N 60-75° E Jts.</td>
<td>18</td>
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<td>14-15</td>
<td>B</td>
<td>B8</td>
<td>3</td>
</tr>
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<td></td>
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<td>18</td>
</tr>
<tr>
<td>A-B</td>
<td>B</td>
<td>B8</td>
<td>4</td>
</tr>
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<td>B-C</td>
<td>BJ</td>
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<td>C-D</td>
<td>J</td>
<td>N 60-75° E Jts.</td>
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<td>F-G</td>
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<td>BJ</td>
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<td>F</td>
<td>NM</td>
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<td>XJ</td>
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<td>Types of Fractures</td>
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<td>14-15</td>
<td>BJ</td>
<td>B8, N 60-75° E Jts.</td>
<td>10.2</td>
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<td>15-16</td>
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<td>35A-35B</td>
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<td>J</td>
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<td>43-44</td>
<td>J</td>
<td>N 60-75° E Jts.</td>
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<td>44-45</td>
<td>J</td>
<td>N 60-75° E Jts.</td>
<td>24</td>
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<td>45-46</td>
<td>J</td>
<td>N 30-45° E Jts.</td>
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<td>46-35</td>
<td>BJ</td>
<td>B8, N 60-75° E Jts.</td>
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<tr>
<td>31Y-19C</td>
<td>MS</td>
<td>None, but possible use of nonsystematic cross joints or a bed parting during mining.</td>
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<td>B12</td>
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<td>55-56</td>
<td>B</td>
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<td>F</td>
<td>20</td>
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<tr>
<td>57-58</td>
<td>J</td>
<td>N 60-75° E Jt.</td>
<td>6.5</td>
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<tr>
<td>58-59</td>
<td>F</td>
<td>F</td>
<td>33</td>
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lines from the nearest appropriate structural segments upstream or above, to the endpoints or other appropriate positions on the structural segments downstream. Examples are shown in Figure 8, p. 30.

Figures 52-59 are plan and profile midline diagrams that illustrate the segments. The diagrams are most useful for visualizing the geometric and elevational relationships of the segments that are near one another. For field identification of the segments it is best to refer to Plate 4. Plate 4 depicts the relationships of the segments to plans, profiles, and cross sections of the actual passages. A block diagram of the segments, showing their approximate relationships in three dimensions, is given in Figure 51B.

Frequencies and Lengths of the Segments

One hundred segments were identified in the 32 sections. It was not possible to measure segment length for eight segments because of small conduit size or unclear and inaccessible endpoints. The 92 measured segments have a total length of 1408.7 feet. Nearly all of this length (1382.7 feet) is on structural segments. The four measured mined segments have a combined length of 26 feet.

Table 7 summarizes the distributions and lengths of the segments, showing the numbers and lengths of each segment type in each section; the total number of segments in each section; and the total length of segments in each section. It also shows the numbers, lengths, and mean lengths of each type of segment for all 32 sections.
Figure 52. Midlines of segments in sections M and 1A. Section M is in the Saltpetre Maze Passage. Section 1A is in the Sound Hole. In Figures 52-59, the following conventions are used: Sections are represented by S followed by the names of the sections, as in SM = section M. Numbers, letters, or numbers and letters combined, represent passage positions at the endpoints of segments. Unless otherwise noted, midlines are shown as extended profiles on profile diagrams. Depths are relative to the datum at the Swallet entrance of the North Canyon.
Figure 53. Midlines of segments in section N. Section N is in the Saltpetre Maze Passage. For further information, see Figure 52.
Figure 54. Midlines of segments in sections 1B and 1. Section 1B is in the Rat Hole tube. Section 1 is in Canyon 1 of the North Canyon. For further information, see Figure 52.
Figure 55. Midlines of segments in passages near the First and Second Paleoshafs. Section 3 is in Canyon B of the Headwall Passage. FP = First Paleoshaf. Section 5 is in Canyon 1 where it is upstream of the Second Paleoshaf. Where it is downstream of the Second Paleoshaf, section 5 is in Canyon 2. SP = Second Paleoshaf. Note duplications of positions 8 and 19C on the extended profiles. For further information, see Figure 52 and Tables 5 and 6.
Figure 56. Midlines of segments in section 4. Section 4 is in the Headwall Passage in Canyon B. For further information, see Figure 52.
Figure 57. Midlines of segments in sections 6 and 1B. Section 6 is in Canyon 1 of the North Canyon. Section 1B is in the Rat Hole tube. For further information, see Figure 52.
Figure 58. Midlines of segments in sections near the Swallet entrance to the North Canyon. Sections 7D, 7B, 7C, and S are in Canyon 1. Sections 7A, 6D, 6C, 6B, and 6A are in the A-tubes above Canyon 1. Sections 7D, 7B, 7C, and S are shown as extended profiles. The other sections are projected onto a NE-SW plane containing the midlines of sections 7D, 7B, 7C, and S. For further information, see Figure 52.
Figure 59. Midlines of segments in Canyon 2 downstream of the First Paleo shaft. The First Paleo shaft is at joint segment 23-24 of section 3. For further information, including a list of the segments of sections 9A-9D and 10, see Figure 52 and Table 6.
TABLE 7
SUMMARIES OF NUMBERS OF SEGMENTS AND THEIR LENGTHS BY SECTION

<table>
<thead>
<tr>
<th>Segment Type</th>
<th>M</th>
<th>N</th>
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<th>1B</th>
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<th>2</th>
<th>3</th>
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<td>3/18</td>
<td>4/80.5</td>
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<td>1/3</td>
<td></td>
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<tr>
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<td>3/80</td>
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<td>1/7.5</td>
<td>2/17</td>
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<td>3/NM</td>
<td>6/166</td>
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<td>2/64</td>
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(CONTINUED)

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<th>Total Length of Segments (Feet)</th>
<th>Mean Segment Length (Feet)</th>
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<td>3/59.5</td>
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* The first value is the number of segments; the second is the total length of the segments in feet.

** NM = not measured
These data are summarized with histograms in Figure 60. Bed and N 60-75° E set joint segments are most abundant. Each of these segment classes accounts for over 30% of the measured segments. The bed segments have 37% of the total segment length, and N 60-75° E set joint segments have 29% of the total length. Bed-joint segments are also abundant (23%) and have 20% of the segment length. The rest of the segments are neither abundant nor lengthy. Among them, only fault segments account for over 100 feet of midline length.

Mean segment lengths range from 1.5 feet to 26.3 feet. The largest mean length is on fault segments. The mean length for all eight segment types is 15 feet.

Characteristics of the Early Conduits

The structural segments first grew as tubes or fissures under conditions of closed-conduit flow. Entrenchment then enlarged only the floors of the early conduits. Little collapse followed. Also, there was little floodwater or other enlargement of passage ceilings during subsequent development. Consequently, the early (pre-entrenchment) conduits are now represented by half tubes and fissures on passage ceilings. The half tubes and fissures provide morphologic evidence that makes it possible to infer many of the characteristics of the early conduits. The main characteristics to be inferred are conduit size, shape, orientation, and location on the guiding fractures. The following descriptions show how the host fractures influenced the shapes and orientations of the conduits at the times of onset of
Figure 60. Histograms comparing relative frequencies, total lengths, and mean lengths of segments. **BED** = bed segment. **N 60-75° E J** = N 60-75° E set joint segment. **N 30-45° E J** = N 30-45° E set joint segment. **XJ** = cross joint segment. **BJ** = bed-joint segment. **F** = fault segment. **FJ** = fault-joint segment. **MS** = mined segment.
entrenchment. (Influences of the geometries of groups of fractures on the characteristics of the conduits at the onset of entrenchment are discussed in Chapter 5, pp. 254-257).

Conduits on Bed Segments

The 28 measured bed segments are distributed among 15 sections. Total midline length is 523 feet (Table 7). Most of this length is on B8. Only 10 feet of midline length are developed on B12 in section 5, and 35 feet are on several unnamed bed partings of only local extent in sections M and N.

Early bed conduits consisted mostly of small arched and flat-floored tubes. Widths were equal to or greater than heights. The tubes ranged from 0.5 to 7-8 ft² in cross sectional area at the onset of entrenchment. Few of the tubes had associated anastomoses.

The characteristics of conduits on B8 are worth describing in detail, because of their prominence in later interpretations of flow-path history. B8 conduits were smooth-walled tubes (Figure 61). Most had cross sectional areas of about 1 ft². Their floors were relatively flat, for the floors were formed on B8 or insoluble residues coating that parting. Tube walls and ceilings were arched; most extended about 6 to 10 inches above B8. Hence B8 is nearly always exposed on tube walls, but B7 often is not. Minor dissolitional re-entrants are ubiquitous on B8 in the modern half tubes, and some small but scattered anastomoses also appear. Yet these features are not present on other fractures exposed on the walls of the remnants
TYPICAL CONDUITS ON B8

Inferred Early Cross Section  Modern Cross Section

WIDER CONDUITS ON B8 ASSOCIATED WITH ABUNDANT ANASTOMOSES

Inferred Early Cross Section  Modern Cross Section

Figure 61. Cross sections of bed conduits.
of B8 conduits. This lack of dissolitional features (on B6, B7, or on the ubiquitous fault-subparallel joints in Union unit E between B6 and B8) is strong evidence for the attribution of early flow to B8 alone. The argument that only B8 could have been transmissive is even stronger for some segments. For example, on bed segment 28-29 of section 4, dissolution upward from B8 did not even reach B7 (the ceiling is below B7), no other fractures are exposed, and entrenchment began immediately below B8.

On several segments, bed conduits on B8 are accompanied by abundant anastomoses on B8. The best examples are in the A-tubes near the Swallet entrance, on sections 6A, 6B, 6C, 6D, and 7A (Plate 4). Abundant anastomoses on B8 are also present at the upstream and downstream ends of section 6. On these bed conduits there are no isolated half tubes. Instead, the bed conduit (Figure 61) is elliptical, low, and wide. Cross sectional area is larger than normal (over 2 to 3 ft²), and the ceilings are studded with many poorly preserved pendants. The presence of the pendants suggests that the larger wide tubes developed by coalescence of numerous small anastomoses.

In plan view, early bed conduits had sinuous, "meandering" patterns. This sinuosity can be seen on maps of inferred passage walls of early conduits. For example, it may be seen on bed segments on B8 in sections M and N of the Saltpetre Maze Passage (Plate 4). It can also be seen on maps of segment midlines, for example on segment 3-4 on B8 in section 1 (Figure 54). The sinuosity does not appear to be correlated with local variations in the attitude of bedding, as has
been found for tubes and canyons in Mammoth Cave, Kentucky (Palmer, 1977, 1981). The lack of correlation can be seen by comparing the midline patterns of bed segments on B8 that are on sections M, N, 1B, 1, 2, 3, 5, 6A, 6B, 6C, and 7A, with 0.5-foot elevation contours on B8, as shown on Plate 5. Plate 5 shows that bed conduits on B8 trend down dip, along strike, obliquely in between, or even obliquely up dip. In profile view (Figures 52-55, 57, 58) these same segments show that bed conduits also "meander" vertically. Thus these bed conduits form parts of flow paths that are ungraded.

Conduits on N 60-75° E Set Joint Segments

The 29 N 60-75° E set joint segments are distributed in 20 sections. Total midline length is 427.7 feet (Table 7).

At the onset of entrenchment, the joint segments consisted of fissures or tubes. Some of the conduits formed on single joints and had simple elliptical or fissure-like cross sections (Figure 62A). In general, the long axes of the cross sections were oriented vertically. This is because the joints are near vertical. Also, flow usually had a greater horizontal than vertical component. However, there were exceptions. For example, on joint segment 27-28 of section 4, a 60-degree dipping joint transmitted ground water up dip, thus forming an early fissure with a horizontally oriented cross-sectional long axis (Plate 4, profile P3; see also Figures 100A-100G, pp. 295-301). Another exception is found where ground water was transmitted from the upper level of the North Canyon and the Headwall Passage to the middle
Figure 62. Typical pre-entrenchment joint conduits of the N 60-75° E joint set. (A) Elliptical or fissure cross section. (B) Cross section with multiple spurs or joint bells. (C) Plan and cross sections of typical reaches of joint conduits before entrenchment.
level of these passages (Plate 4, Figure 28). This happened on vertically extensive joints. The joints enlarged to form shafts (the Third and Fourth shafts), or to form shafts that then enlarged by headward erosion to become paleoshafs (the First and Second paleoshafs; see Chapter 5).

Most of the conduits, however, formed in zones of closely spaced joints. The cross sections were therefore more complex (Figure 62B). Multiple spurs or joint bells branched from conduit centers. A photograph of typical ceiling remnants of N 60-75° E set joint conduits is shown in Figure 63.

From the sizes of the remnant fissures and half tubes, cross-sectional area of N 60-75° E joint conduits must have ranged 1 to 15 ft² at the times of onset of entrenchment. Most cross-sectional areas would have been about 2 to 4 ft² in sections M and N of the Saltpetre Maze, but only 1 to 3 ft² in the rest of the sections. It is notable that cross-sectional areas varied greatly over short distances (Figure 62C). This variation depended on whether the early conduits were guided by a single joint, or by several joints. It depended on whether side spurs or bell holes were present. Finally, it depended on the amount of time for which conditions of closed-conduit flow operated (see Chapter 5, pp. 254-257).

Most of the early joint conduits had ungraded profiles. Good examples appear on segments 1-2 and 12-13 in section M (Figure 52, Plate 4). As previously noted, the joints are closely spaced. They have en echelon plan patterns, and often hook into one another so that
Figure 63. Typical remnants of pre-entrenchment joint conduits of the N 60-75° E joint set. The photograph was taken in Canyon 2 of the North Canyon trunk, downstream of 52.
they intersect at variable positions along their lengths and heights. Hence it is probable that initial flows moved irregularly along the joints. Flow would have been up, down, and along the joints in a complex fashion that used first one joint and then another. A block diagram of the earliest midline flow would thus depict a complex, three-dimensional pattern following irregularities in fractures as fractures curved and hooked into one another. However, as dissolution enlarged the earliest flow paths, forming fracture conduits, this midline flow pattern would become straighter and more smoothed. To help visualize this evolution in midline patterns, it is useful to reduce the problem to a two-dimensional one. We then consider how the pattern would appear at successive stages as shown in midline plans and plans of the walls before entrenchment. Figure 64 shows this sequence. Figure 64 also shows how the trend of the joint conduit should evolve. Note that the initial en echelon joint pattern (Figure 64A) contains a string of dextral joint hooks that determine joint intersections. This forms the en echelon zone. (Remember, Figure 64 consists of projected plan views. A plan view for a single height would have gaps, so not all of the joint hooks would intersect.) The zone as a whole trends 10 to 15 degrees to the side of the trends of the individual N 60-75° E set joints. The earliest fracture conduit (Figure 64B) had highly variable strikes that follow subtle changes in fracture orientation. The later, larger conduits (Figure 64C, 64D) follow the trend of the en echelon zone. A prominent example of this common pattern of development is in section 6 on joint segment 36-37.
Figure 64. The hypothesized evolution in plan view of the early joint conduits from the N 60-75° E set of joints.
A photograph of that segment is shown in Figure 65.

Stylolitic N 60-75° E set joints occur as isolated, broadly curved or straight stylolites that extend for some distances (10 to 30 feet) without hooking into other fractures. Consequently, conduits developed on the stylolitic joints tend to be broadly curved or are straight. In either case, joint spurs or joint bells are rarely associated with them. The en echelon joint pattern is only poorly developed, or is absent. Good examples of stylolitic N 60-75° E set joint conduits are in sections 7D, 7B, 7C, and 4. Figure 66 is a photograph of a typical stylolitic N 60-75° E set joint conduit that has been entrenched.

Conduits on N 30-45° E Set Joint Segments

The two N 30-45° E set joint conduits are in section M (segment 3-4) and section 7C (segment 45-46). Their segments are short (4 and 7.5 feet long, respectively). They appear as smooth, rounded half tubes. At the onset of entrenchment, they had cross-sectional areas of 1.5 to 2.0 ft². The one in section 7C transmitted water upward in a curving flow path. It discharged its water into a bed-joint segment developed on B8 and a N 60-75° E set joint, and is shown in a photograph in Figure 67.

Conduits on Cross Joint Segments

Only one cross joint segment, segment 5-6 of section 1, is present in the passages chosen for segment analysis. Other cross joint segments may be found in the Saltpetre Maze. Cross joint segment 5-6
Figure 65. N 60-75° E set joint conduits in a zone of en echelon N 60-75° E set joints. The joint conduits are visible on the ceiling as descending joint fissures that were entrenched; they cut diagonally from the upper left corner to the middle of the photograph. This reach is part of joint segment 36-37 of section 6 in Canyon 1. The view is downstream.
Figure 66. Half tube formed on stylolitic N 60-75° E set joints on joint segment 44-45 of section 7C.
Figure 67. N 30-45° E set joint segment 45-46 of section 7C. This segment is in the curving half tube that rises from the narrow trench of section 7C toward position 46. Part of the joint used by bed-joint segment 46-35 is visible at the top of the photograph, above 46. The view is upstream.
transmitted ground water from a N 60-75° E set joint below B8 in an upward and lateral course to position 6 at the start of a bed-joint segment (Figure 54). At the onset of entrenchment, it was a small vertical fissure.

Conduits on Bed-joint Segments

The 21 bed-joint segments are distributed in 10 sections. Total midline length is 296.8 feet (Table 7).

Early bed-joint conduits consisted of complex tubes or fissures with re-entrant spurs. The spurs developed outward from the lines of intersection of the bed partings and the joints; they are unlikely to represent regions of significant input of ground water. Most of the joints are from the N 60-75° E set. However, cross joints linking offset N 60-75° E joints were also used.

Typical modern and inferred early cross sections of the bed-joint conduits are shown in Figure 68. Where cross joints or single N 60-75° E set joints were used, early cross sections tended to be elongated both horizontally and vertically with four spurs (Figure 68A). Elsewhere, bed-joint segments are aligned along closely-spaced joints, so cross sections were more complex. Multiple spurs appeared above the bed parting and most likely also below (Figure 68B). Some bed-joint segments had only three main spurs (Figure 68C). Typical examples are on bed-joint segments 9-10 and 11-12 in section 2 (Plate 4). On these segments in the Connection Tube, the early flow paths were abandoned before entrenchment could occur. Therefore, the early
**BED-JOINT SEGMENTS**

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<th>Modern Cross Section</th>
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</tr>
<tr>
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<td>![Image B]</td>
</tr>
<tr>
<td>C</td>
<td>![Image C]</td>
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</tbody>
</table>

**Figure 68.** Typical cross sections of bed-joint segments. For explanation, see text.
bed-joint (and other) segments of section 2 have been preserved nearly intact as tubes and fissures rather than as half tubes and fissures.

On some N 60-75° E set bed-joint segments, joints above the bed-joint intersections were enlarged into fissures that now extend several feet or more upward. Two good examples are along segment 25-26 of section 1, and segment 14-15 of section 3 (Plate 4, profiles P1 and P3, respectively). On these segments, ceiling fissures narrow upward, terminating in blind spurs. The spurs are separated by bedrock bridges at varying elevations, so the ceilings have irregular heights. Fissure and spur walls are smooth and have appearances identical to those of the tubes and half tubes. The fissures and spurs are believed to have formed before the local onset of entrenchment, as water under pressure gradually widened the joints outward from the bed-joint intercepts. An alternate interpretation is that the fissures formed during entrenchment as floodwater features (Palmer, 1972, 1975). However, passages formed in floodwater settings in Friars Hole Cave system and other nearby caves (Cutlip and Lower Hughes Creek caves; Coward, 1975) have bedrock surfaces covered with small, closely spaced scallops. Were the fissures formed by floodwaters, it would be necessary to provide an explanation for the lack of small scallops in the fissures, as well as in the tubes and half tubes.

The earliest flow along bed-joint segments was likely tortuous, as the ground water followed first one intercept and then another, within the zones of intersection of bed partings and N·60-75° E joints. However, at the scale of the midline diagrams, midlines of bed-joint
segments are best represented by the straight, dotted lines used on Plate 4 and elsewhere.

Conduits on Fault Segments

The four measurable fault segments are distributed in four sections. Total segment length is 105.2 feet (Table 7).

At the times of onset of entrenchment, fault segments consisted of tubes or fissures ranging from less than 1 to over 10 ft$^2$ in cross-sectional area. Typical cross sections are shown in Figure 69A. A photograph of a remnant half tube of fault segment 52-57 of section II is shown in Chapter 6 (p. 370, Figure II3).

Conduits developed on faults nearly always have abundant anastomoses, in Snedegar Cave or elsewhere in Friars Hole Cave system. The anastomoses may be developed over large areas of the faults away from the midlines of the principal tubes. Many anastomoses are nearly as large as the principal tubes. Examples of abundant anastomoses on faults may be seen in sections 8 and 11. The abundance of anastomoses on fault conduits may be a result of local large original crack widths on fault planes.

Midline patterns in plan and profile views show that early flow on fault segments was often sinuous and ungraded. Flow proceeded along strike or up or down the dips of the faults (Plate 4).
<table>
<thead>
<tr>
<th></th>
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<td>Along Strike</td>
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<tr>
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<td>![Diagram A Along Strike]</td>
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<tr>
<td>Segments</td>
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<tr>
<td><strong>B</strong> Fault-joint</td>
<td>![Diagram B Fault-joint]</td>
<td>![Diagram B Along Strike]</td>
</tr>
<tr>
<td>Segments</td>
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</tbody>
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Figure 69. Typical cross sections of fault and fault-joint segments. See text.
Conduits on Fault-joint Segments

The three fault-joint segments are distributed in three sections. Total segment length is 55 feet (Table 7).

The early conduits used N 60-75° E set joints and west-dipping faults. The conduits had three or four main spurs (Figure 69B). Two spurs were on the faults, and one or two main spurs were on the N 60-75° E joints. Where there was only one joint, there was only one main spur. Where joints were closely spaced, the main spurs had minor spurs branching off. The spurs of fault-joint segments were not perpendicular to one another, as were the spurs of bed-joint segments (Figure 68), except in cross sections drawn looking straight down the intersections of the joints and the faults (Figure 69B).

Early flow of ground water on fault-joint segments was probably tortuous, following curved fault-joint intersections, perhaps even deviating slightly from the intersections to follow either a joint or a fault. However, at the scale of most midline diagrams, the fault-joint midlines are best shown as being straight.

Spatial Patterns of Structural Segments

The identification and mapping of structural segments leads to the reconstruction of a three-dimensional network of integrated fracture conduits. For the investigated passages, this network has been represented by the midline diagrams of Figures 52-69, and by the midlines of segments on Plates 4 and 5. These figures and plates show
that the individual segments have distinctive geometries in plan or profile views. The segments can also be linked in distinctive patterns. That is, the segments can exhibit distinct patterns of linkage. In the following pages the more important spatial patterns of the structural segments are defined and illustrated. (Some of the patterns were briefly discussed in Chapter 2, pp. 71-76.) The analysis is based on the data set of 92 structural segments and on observations of structural segments elsewhere in the North Canyon, the Saltpetre Maze, Friars Hole Cave system, and in some of the caves listed in Table 1. Influences of the spatial patterns of structural segments on the development of passages (following the onset of entrenchment) are discussed in Chapters 5 and 6.

Plan Patterns

Plan-view midline patterns are shown in Figure 70. Linear, sinuous, and en echelon patterns can appear on individual structural segments, or groups of linked segments. Offset patterns require groups of linked segments.

Linear patterns are essentially straight. Most are formed by vertical fractures or by intercepts of fractures. In Snedegar Cave, linear patterns are formed by joints, or by bed-joint and fault-joint intercepts. If a segment is short or if it trends directly down the dip of the fracture, a bed or fault segment may have a linear pattern. However, most linear segments are formed on isolated N 60-75° E set joints or their intercepts with bed partings or faults.
<table>
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</tr>
<tr>
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<td>B</td>
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<tr>
<td>EN ECHELON</td>
<td>J</td>
</tr>
<tr>
<td>OFFSET</td>
<td>J</td>
</tr>
</tbody>
</table>

Figure 70. Midline patterns of single or linked segments in plan view. The en echelon pattern is shown with joint spurs in order to emphasize the curved, offset nature of the midline pattern. For clarity, the spurs are usually omitted from midline diagrams of actual segments.
Sinuous patterns are curved or winding. In Snedegar Cave they are found only on low- to medium-dipping (1°-30°) bedding or faults.

En echelon patterns form where straight or slightly sinuous or curved joints hook into one another toward their lateral terminations. This results in offsets to the right (dextral offsets) or to the left (sinistral offsets). It should be remembered that joint segments on N 60°-75° E. set joints are designated as either zone segments or as single-joint segments, depending on the available evidence. The en echelon pattern can refer to the linked fractures within a single zone segment, or to separate linked segments in which either zone segments or single-fracture segments are represented.

Offset patterns form as follows. First, ground water is transmitted in one direction on one segment. Then it is transmitted to the side on the next segment. Finally, the third segment transmits the ground water in a direction subparallel to the direction of the first structural segment. Typically, the middle segment is shorter than the end segments. Thus, the net effect on the plan is a consistent midline direction interrupted by a sideways offset. Offset patterns use a variety of types of structural segments. Most use bed, bed-joint, or joint segments.

Drops, Lifts, and Loops

Extended profiles of midlines (Figures 52-59) show that most of the sections of segments are ungraded. That is, gradients are irregular, with reaches that rise or fall gradually or abruptly. The
following terms describe the looping of flow paths within the vertical plane.

A reach of structural segments that loses elevation in a downstream direction is a drop; whether or not the gradient is steep (Figure 71A). A reach that gains elevation in a downstream direction is a lift (Figure 71B). A reach heading downstream with a lift followed by a horizontal stretch or a drop is an upper loop (Figure 71C). A reach heading downstream with a drop followed by a lift (there may be an intervening horizontal stretch) is a lower loop (Figure 71D).

Both upper and lower loops usually contain high points and low points (Figure 21). However, high or low regions may occur if horizontal or extremely low gradients are involved. Upper and lower loops may be isolated from one another, may overlap, or may even be nested within one another (Figure 71E). Upper and lower loops have a geometry that requires pipe-full flow within the parts of the loops upstream of the highest high point within any given flow route in order for water to make it past the loops. Since the water must be under pressure and can move as a result of phreatic flow, floodwater flow, or merely flow past local ponding, the reach under pressure is designated a pressure loop (see p.76). Pressure loops may make up entire flow systems in phreatic zones. Alternately, they may be only local features active but part of the time in floodwater or vadose zones.

Drops and lifts can form on any type of structural segment. The more prominent, high-gradient, drops and lifts form on vertically extensive, high-dip fractures. In the study passages these are mostly
Figure 71. Midline patterns of single or linked segments in profile view. UL = upper loop. LL = lower loop. (A) Two drop patterns. (B) Two lift patterns. (C) An upper loop. (D) A lower loop. (E) A reach containing a long lower loop with a shorter lower loop that is nested within it. An upper loop partly overlaps the smaller of the lower loops, and is nested within the larger lower loop.
Levels of Structural Segments

A reach of structural segments (or a network of structural segments in two or more sections) at approximately the same elevation forms a level of structural segments, or segment level. In structural settings with prominent vertical fractures and near horizontal bedding, two segment levels will normally be separated by an abrupt, high gradient, drop, or lift. This assumes that the levels are part of a single continuous flow path.

It is important not to confuse the concept of a level of structural segments with the concept of a passage level. Whether a level of structural segments and a passage level coincide depends on the type of cavern development that has taken place. This point can be illustrated by developmental scenarios that are based on numerous examples from Friars Hole and Bone-Norman Cave systems. Figure 72A shows three structural segments distributed on two segment levels. These segments are enlarged by entrenchment under two different lithologic settings.

In Figure 72A, a relatively insoluble perching bed (located between the segment levels) retards entrenchment. The result is that two passage levels form; the levels are separated by a vertical shaft. In Figure 72C, entrenchment has not been impeded, and a single passage level has formed.
Figure 72. Segment and passage levels. SL1 = segment level 1. SL2 = segment level 2. PL1 = passage level 1. PL2 = passage level 2. PL = single passage level. The two levels of structural segments of (A) could be enlarged into the two passage levels of (B) or the single passage level of (C), depending on the types of enlargement, the time for enlargement, and the relative solubilities of different rock layers.
For the investigated passages, the midline diagrams of Figures 52-59 and Plate 4 show that structural segments range in elevation from about 5 to 50 feet below the elevation of the survey datum at the Swallet entrance. To identify levels of structural segments, this range of 45 feet was divided into nine five-foot intervals. The midline length of structural segments in each interval was obtained from the midline profiles. A histogram summarizing the results of these tabulations is given in Figure 73A. The histogram shows two levels of structural segments. Level 1 segments have midline elevations ranging from 5 to 25 feet below datum. Level 2 segments range from 40 to 50 feet below datum. A gap of 15 feet separates the levels. Four sets of connecting segments fall in this gap. The connecting segments are in sections 3, 5, X, and Z, and consist entirely of N 60-75° E set joint segments.

Level 1 structural segments have a vertical range of 20 feet. Because most of the sections are ungraded, one might expect this large range to be a result of looping on the profile. However, that is not the case. The range is rather due to the fact that level 1 segments formed on or close to bed parting 8. B8 descends at an average of about three degrees over the region containing the studied passages (Plate 5; Plate 4, profile P1).

Of the 1060.2 feet of structural segments on level 1, 721 feet (68%) are developed on B8 or its intercepts with joints. Deviations from B8 sum to 339.2 feet on joints, a fault, and a few minor bed partings. All of the deviations are below B8, and the distance
Figure 73. The levels and lithologic positions of the structural segments. (A) Lengths of structural segments in five-foot intervals below datum at the Swallet entrance. (B) Lengths of structural segments in five-foot intervals of unit F of the Union Limestone.
between them and B8 is never more than 5 feet.

To quantify these deviations, 11 groups of segments that loop below B8 and which have a length of 5 feet or more were identified (Table 8). Each group was divided into 5-foot increments. The vertical distance (to the nearest 0.5 feet), separating the middle points of the increments from B8, was measured off the (original 1:240 scale) midline profiles of the sections shown in Figures 52, 53, 55, 56, 57, and 58. This gave a data set of 64 increments summing to 320 feet. (About 12 feet of structural segments barely deviate from B8 and were left over as extra increments less than 5 feet long; they were omitted from consideration.) The average deviation of the increments from B8 is 2.8 feet, a low figure that is misleading.

Another measure of the deviations, the maximum deviation from B8 for each group (Table 8), gives a better idea of the relief for the looping of the flow paths. Eight of the 11 groups have a maximum deviation of 3 feet or greater. The average of the maximum deviations is 3.4 feet.

Level 2 structural segments have a vertical range of ±10 feet.

However, it should be noted that the downstream terminus of the studied passages was arbitrarily chosen at the end of section 11 within Canyon 12 of the North Canyon trunk. Were the study expanded to include passages farther downstream, then the range of level 2 structural segments would be increased to roughly 68 feet below the entrance datum (as measured at the Fault Room, Plate 4, profile P5). At the Fault Room a drop down a fault leads to a third level of structural segments.
<table>
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N = 64

Average Deviation = 2.8 Ft
Standard Deviation (of the Deviations) = 1.1 Ft

* For each group of increments, the increments are listed in order, beginning with the farthest upstream increment and continuing downstream within the section. For profiles of the sections, see Plate 4 or Figures 52-53 and 55-58.
Of the 255.5 feet of structural segments on level 2, 141 feet (55.5%) are on faults or fault-joint intercepts. The rest is mostly on joints, although there are a few segments on B12 and intercepts of B12 with joints. Thus, level 2 structural segments are not closely concordant to any single bed parting (as are level 1 segments). The midline profiles of Plate 4 show level 2 segments in sections 11, 9A, 9B, 9C, 9D, 10, 8, Y, V, and parts of sections 3, 5, X, and Z. Over these sections, structural segments exhibit much looping, with lower loops having a maximum relief of 8 feet.

Positions of the Segments in Unit F

The strong concordance of level 1 segments to B8 is reflected in the histogram of Figure 73B, which shows the locations of the structural segments in unit F of the Union Limestone. This histogram was prepared by summing the lengths of structural segments lying within five 5-foot intervals of unit F. The intervals start at B8 and extend 25 feet down to the lowest structural segments investigated. The histogram shows that 1069.7 feet (77.4%) of the segments lie on or within 5 feet of B8. Another peak with 176.6 feet (12.8%) is near B12. However, it should be noted that B12 is not used for any significant length in these structural segments. Also, it should be stressed that the segments of level 2 that are exposed in the study passages represent only a part of the actual segments of level 2. The character of level 2 peaks on the histograms of Figure 73 would change if the study extended downstream.
CHAPTER 5

ENTRENCHMENT: SOME FEATURES
AND
INTERPRETATIONS OF THEM

Introduction

Chapter 4 identified the structural segments of each section of the investigated passages. It also described the morphology of the pre-entrenchment conduits for each type of structural segment. The early conduits consisted of small ungraded tubes and fissures that were linked in a variety of patterns on two levels.

The remaining task is largely an interpretative one. The task is motivated by such questions as the following: How were the early conduits linked to form integrated flow paths? In what sequence did linkage occur? Were all sections (Figure 51A) linked before the onset of entrenchment anywhere in the network, or did some sections develop later? Finally, how were the early flow paths enlarged by entrenchment to form the modern passages?

The interpretation begins with a general account of entrenchment and its features. It continues with a description of some of the main
features of entrenchment in Snedegar Cave. The features provide evidence for a number of critical events in the history of the flow of ground water and conduit enlargement, as explained in this and the following chapter.

Entrenchment

Scope of the Concept

Under the influence of gravity, vadose streams flow downhill. They are deflected from a vertical flow direction by the "perching effect of the surface upon which flow takes place. Where flow is into a closed basin there is ponding. If discharge is sufficiently large so as to overcome any losses from evaporation, storage in sediments, or leakage into fractures exposed on the floor, overflow then occurs at the basin's lowest open point. Because vadose streams flow within the bottoms of their open channels, enlargement is mostly on the floors by downcutting. Downcutting is not the only mode of enlargement effected by vadose streams, however. In caves it is useful to summarize the varied activities of vadose streams with the term entrenchment. The depth (distance below initial level) to which entrenchment may cut is a function of the rate and time of removal of bedrock by dissolution, abrasion, or other processes. The depth to which entrenchment may cut is also a function of the perching height—the height of the conduit's floor above local base level.
Some Features and Processes

Entrainment produces a variety of features. On the scale of entire passages, entrenchment by vadose streams produces canyons. In this study, any passage whose floor has been entrenched and whose volume can be attributed primarily to processes of entrenchment is judged to be a canyon. Most canyons in Friars Hole Cave system have height-width ratios that are highly variable along their lengths. Typical values range from 4:1 to 10:1. Height-width ratios decrease where collapse, exfoliation, differential dissolution associated with variations in lithology, or other factors have increased passage widths.

Within canyons, entrenchment produces trenches, notches, undercutting, meanders, sinuous cross-sections, potholes, bedrock pans and basins, ledges, and other features (Bretz, 1942; Ford, 1965a; Jennings, 1971; Sweeting, 1972; White, 1982). The study of these features is in its infancy. Nonetheless, considerable sense can be made out of the factors and processes that influence the form, distribution, and genesis of features of entrenchment. Consequently, the features can be useful in interpreting cavern history---history during and (see below) even before the onset of vadose enlargement.

Entrenchment can operate by downcutting alone, in which the stream merely incises the floor of the conduit, using dissolutional or abrasional removal of bedrock. More often, downcutting operates along with other modes of enlargement, such as lateral undercutting (Bretz,
1952; Jennings, 1964, 1971; Jones, 1971; Ewers, 1972). It should be remembered that, in caves, enlargement of conduits encompasses processes of chemical alteration, fragmentation, and removal of bedrock. Hence collapse, exfoliation, gypsum crystal wedging, weathering of clay minerals, and a variety of other processes can contribute to entrenchment. Which modes of enlargement or processes contribute to entrenchment over a given reach of cave depend on a number of factors whose influences have received little study. The factors include the gradient of the perching surface, bedrock lithology, discharge, and the sediment load. Observations in caves of the eastern United States, Texas, and Mexico, combined with a review of recent literature, suggest the following generalizations.

On low gradient reaches, lateral undercutting may widen conduits as walls are locally undermined, producing undercuts, notches, and ledges. Lateral undercutting is common where clastic sediments armour the floor and direct the flow of water against walls (Jones, 1971; Ewers, 1972). Lateral undercutting is also common where collapse has blocked parts of the floors of conduits with breakdown (Werner, 1972; Ewers, 1972).

As the gradient of the floor increases, lateral undercutting is less likely. Instead, splash, spray, and film processes begin to influence the manner in which bedrock is removed from the walls and floors of canyons. Also, as the gradient increases, so do flow velocities and stream competence. If clastic sediments are available, abrasion and scouring may become important (Newson, 1971). Potholes,
bedrock pans and basins, and a variety of types of ledges may form. Ford (1965a) describes potholes from the Mendip caves in England.

As the gradient of the floor increases over about 45 degrees, splash, spray, and film processes may predominate in the enlargement of conduits (Brucker et al., 1972). Chimneys, vertical shafts, and features associated with them begin to appear as the floor gradients of the pre-entrenchment conduits approach 90 degrees. At low discharges, descending water may form thin films that carve flutes on the sides of vertical shafts, or that plane off projections (Brucker et al., 1972). At larger discharges, or as shaft height becomes large, sprays or waterfalls may carve bedrock pans and basins, or even deep potholes at the bases of shafts. Finally, vertical shafts are often transformed into canyons through headward erosion unless relatively insoluble capping beds or clastic sediments form perching surfaces at and upstream of the lips of the shafts. Accounts of the processes of shaft formation and the morphologic features associated with shafts appear in Pohl (1935, 1955), Merrill (1960), Reams (1965), and Brucker et al. (1972).

Features Expressing Relief on the Walls of Canyons

In canyons, variations in passage width are often expressed by distinctive features on the walls. The features may express positive relief (ledges, various projections) or negative relief (undercuts, notches, various hollows and indentations). For present purposes, the least important of the above features are the minor projections of
relatively insoluble material that consist of clay seams, stylolites, chert nodules, or fossils (Figure 74). These may project in any cavern setting. In the investigated passages they have little interpretative value. Also of little concern here are the minor ledges and indentations that appear where adjacent beds have varying solubilities (Figure 75). In contrast, the most important features are the extensive collections of indentations, ledges, and projections that form undercuts and notches.

Undercuts, Notches, and Features Generated from Them

Morphology and Genesis

Undercuts and notches are common in canyons, where they are associated with bedrock meanders (Bretz, 1942). Bretz briefly describes notches and discusses their significance as vadose features. He uses a different terminology, however, distinguishing "horizontal grooves" and "ridges." Jennings (1971) depicts similar features and calls them "channel grooves." White (1976) calls them "horizontal wall grooves." None of these studies fully describes the features. Observations of undercuts, notches, and bedrock meanders in Friars Hole Cave system suggest the need for a more complete description. A complete description, however, is beyond the scope of this study. The following account concentrates on those characteristics of undercuts and notches that are relevant to the interpretation of the North Canyon.
Figure 74. Minor projections of relatively insoluble material. The photograph shows one wall of a trench in unit B of the Pickaway Limestone, in the canyon leading to the Pool Room of Friars Hole Cave. 1 = fossil fragments. 2 = clay seam. 3 = bed-parallel stylolite. 4 = bed-perpendicular stylolite that trends subparallel to the N 30-45 E set of systematic joints; the stylolite cuts across the clay seam above position 4.
Figure 75. Minor ledges associated with relatively insoluble argillaceous interbeds in the Union Limestone. The photograph shows part of a floodwater maze near the entrance to Culpit Cave. Argillaceous interbeds (c) contain illite and kaolinite clays; the surrounding bedrock consists of purer oosparites and biosparites. Note extensive scalloping (s), enlarged joint spurs (j), and the end of a stick (st) jammed into a joint spur. The stick is flood debris. It is essential not to confuse the indentations between the argillaceous interbeds with undercuts and notches, which are sometimes morphologically similar.
The morphologic features of undercuts and notches are summarized schematically in Figure 76. Photographs of the features from Snedegar Cave appear in Figures 77-80.

Undercuts and notches are formed by curved bedrock surfaces. Figure 76A shows an idealized undercut as seen in cross section. The cross section is drawn for a passage bend at which a bed segment has been only slightly incised. On the outside of the bend is a cusp and an undercut surface. Together the cusp and the undercut surface form the undercut. The cusp forms a rounded or sharp edge or projection. The undercut surface forms an indentation. This surface has an upper region where the surface has a low angle relative to the horizontal, and it has a steeper region where the angle of the surface increases downward. The undercut surface may terminate downward at the floor (Figure 76A) or at another cusp (Figure 76B). Where undercutting has been extensive, deep undercuts form; undercut surfaces may then terminate by passing into the tops of ledges (Figure 76C). Figure 76D shows an idealized notch in cross section. A notch consists of an upper cusp, an undercut surface, and a lower cusp or a ledge. Cusps, undercut surfaces, notches, and ledges extend from a few to several hundred feet along the walls of canyons in Friars Hole Cave system.

Free-surface streams shift their positions and directions of flow as entrenchment progresses. In caves, such stream shifting is influenced by (1) the helicoidal pattern of turbulent flows; (2) pre-existing bends in the flow path; (3) obstructions caused by collapse; and (4) sediment armouring (Ongley, 1968; Deike and White,
Figure 76. Undercuts and associated features in cross section. B = bedding plane parting. J = joint. (A) An undercut (outside of passage bend) and a convex surface (inside of bend). (B) Series of cusps and undercut surfaces. (C) Undercut surface passing downward into a ledge within a wide trench. (D) Notch.
Figure 77. Undercuts above the First Log Jam in Canyon 1. The view is obliquely up and upstream, from the wide trench into the narrow trench. The scale has a length of 0.62 feet; it is jammed within an undercut surface. NT = narrow trench. SW1 = surface of widening 1. C = cusp. US = undercut surface.
Figure 78. Notches, ledges, cusps, and undercut surfaces in Canyon 2 just downstream of position 59. The view is downstream. NT = narrow trench. SW2 = surface of widening 2. L = ledge. N = notch. US = undercut surface.
Figure 79. Features of entrenchment in Canyon 1, near position 39. The view is downstream. Note boulders of Webster Springs sandstone. The boulder at x is a few feet downstream of a point directly beneath 39. The boulder at y is in the foreground of Figure 80. The black lines outline surface of widening 1 (SWI) on either side of the narrow trench (NT). US = undercut surface. N = notch. C = cusp.
Figure 80. Features of entrenchment in Canyon 1, near position 40 of section 6. The view is downstream. J = N 60-75° E set joint. NT = narrow trench. SW1 = surface of widening 1. C = cusp. US = undercut surface.
1969; Baker, 1973; Palmer, 1976; Smart and Brown, 1981; Jones, 1971; Ewers, 1972). The stream shifting directs water to one side of the passage, which then becomes an outside bend, for all practical purposes, whether or not there initially was a bend in the passage. Lateral undercutting and downcutting combine to carve the undercuts and notches.

In Snedegar Cave, undercuts and notches are best developed on reaches where the pre-entrenchment flow paths were sinuous (bed segments or fault segments) or where offset midline patterns created bends in the early tubes and fissures. For example, undercuts and notches are well developed in the trenches below bed segments 35-36 and 40-3 of section 6; bed segment 3-4 of section 1; bed segment 11-12 of section M; bed segment 22-23 of section 3; fault segment 50-51 of section 8; and fault segments 52-57 and 58-59 of section 11. Undercuts and notches are also prominent below the offset midline patterns of segments of section 3. At all of the above locations, the trenches are themselves sinuous in cross section, and contain reaches with bedrock meanders.

Examination of bedrock meanders in Friars Hole Cave system suggests the following generalized model for their development. Figure 81 shows, at the top, a plan, cross section, and profile of an initially sinuous tube on a bed parting. (Similar models could be drawn for fault segments or for segments with offset midline patterns.) Beneath are plans, cross sections, and profiles for three stages of entrenchment. For each stage, the shapes and locations of
Figure 81. Model for the development of bedrock meanders. Top: The hypothetical early flow path is a sinuous tube on a bedding plane parting (bed segment 1-2). Beneath the early tube: Three stages of entrenchment. Undercuts form on outsides of bends, leaving cusps. Cusps die out into convex surfaces (CS) on insides of bends. Gaps appear between cusps where cusps did not form, or where cusps have been destroyed. The dashed lines on the plans of the second and third stages of entrenchment show the positions of the walls of the initial trench. HT = height of a notch, as measured by the vertical separation between two cusps. For explanation, see text.
undercuts, notches, or cusps are indicated. Several features deserve comment. First, in any given stage, cusps and undercut surfaces are discontinuous along the passages. Undercuts on outside banks of bends die out or pass directly into smooth convex surfaces that form on inside banks of the next bends downstream. This distribution of cusps and undercut surfaces leaves gaps in their positions as plotted on plans or profiles. (It should be noted that the cusps have been projected onto the extended midline profiles of the canyons; therefore the true lengths of the cusps and the gaps do not show up on the profiles.) Second, through time the pattern of the distribution of cusps, undercuts, and notches is translated downward, downstream, and laterally. This translation results in a tendency for the development of sinuous cross sections (not fully depicted), assuming entrenchment continues for an extended period. This translation also gives the passage an appearance of true meandering for successive plan views that are drawn for wall positions of the actively enlarging bases of the trenches in passages where scalloping or other evidence of flow direction is lacking or ambiguous. The downstream and sideways shift in conduit sinuosity is useful, for it provides a reliable indicator of the direction of vadose flow (White, 1982).

Synchronously formed cusps and undercut surfaces often can be traced over considerable distances, even where gaps of a few tens of feet interrupt their continuity. The tracing relies upon the tendency for the vertical separation between cusps (the heights of notches, Figure 81) to remain constant from one notch to the next one.
downstream. Also, cusps have profiles that are nearly at grade. Many cusps can be correlated with synchronously formed cusps by projecting profiles across regions where cusps never formed, or where they have been destroyed.

Estimates of the gradients of 22 cusps in the North Canyon and the Headwall Passage were made after measuring the lengths of cusps with a fibron tape and obtaining their elevational drops with a U-tube. The gradients (Table 9) are low, ranging from 0.41 to 2.83 degrees. The mean gradient is 1.04 degrees. Where it was possible to correlate cusps across gaps, gradients were obtained for separate cusps that are believed to have formed synchronously. Within each such group of cusps, gradients are nearly equal. The cusps are discordant to bedding.

Relations to Lithology

Throughout Friars Hole Cave system, undercuts and notches are well developed in the purer biosparites, biosparites, and micrites of the Union and Pickaway Limestones, particularly where bedding is massive. Undercuts and notches are poorly developed or are absent where bedding is heterogeneous, and argillaceous and purer units alternate in thin beds. In clay-rich units, especially those with exfoliation, cusps and notches are extremely rare. This lack of cusps and notches in the clay-rich units is most apparent on the outside banks of major passage bends, in which lateral undercutting has been extensive. For example, many canyons in the Pickaway Limestone (in lower Toothpick Cave, the
### TABLE 9
LENGTHS AND GRADIENTS OF 22 CUSPS IN SNEDEGAR CAVE

<table>
<thead>
<tr>
<th>Type of Cusp</th>
<th>Number</th>
<th>Length (Feet)</th>
<th>Gradient (Degrees)</th>
<th>Mean Gradient For Groups</th>
<th>Location</th>
</tr>
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<tbody>
<tr>
<td>Single*</td>
<td>1</td>
<td>14.3</td>
<td>2.61</td>
<td></td>
<td>Canyon 1</td>
</tr>
<tr>
<td>Group**</td>
<td>2A</td>
<td>15.1</td>
<td>1.33</td>
<td></td>
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</tr>
<tr>
<td>Group</td>
<td>2B</td>
<td>18.0</td>
<td>1.25</td>
<td>1.29°</td>
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</tr>
<tr>
<td>Group</td>
<td>2C</td>
<td>20.0</td>
<td>1.29</td>
<td></td>
<td>Canyon 1</td>
</tr>
<tr>
<td>Single</td>
<td>3</td>
<td>9.55</td>
<td>1.20</td>
<td></td>
<td>Canyon 1</td>
</tr>
<tr>
<td>Group</td>
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<td>1.15</td>
<td></td>
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<tr>
<td>Group</td>
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<td>0.89</td>
<td>0.96°</td>
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</tr>
<tr>
<td>Group</td>
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<td>26.13</td>
<td>0.83</td>
<td></td>
<td>Canyon 1</td>
</tr>
<tr>
<td>Group</td>
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<td>10.5</td>
<td>0.93</td>
<td></td>
<td>Canyon 1</td>
</tr>
<tr>
<td>Group</td>
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<td>9.5</td>
<td>0.78</td>
<td>0.97°</td>
<td>Canyon 1</td>
</tr>
<tr>
<td>Group</td>
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<td>9.5</td>
<td>1.21</td>
<td></td>
<td>Canyon 1</td>
</tr>
<tr>
<td>Single</td>
<td>6</td>
<td>16.2</td>
<td>2.83</td>
<td></td>
<td>SMP***</td>
</tr>
<tr>
<td>Group</td>
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<td>18.45</td>
<td>0.78</td>
<td></td>
<td>SMP</td>
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<tr>
<td>Group</td>
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<td>8.5</td>
<td>0.84</td>
<td>0.82°</td>
<td>SMP</td>
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<tr>
<td>Group</td>
<td>7C</td>
<td>10.2</td>
<td>0.84</td>
<td></td>
<td>SMP</td>
</tr>
<tr>
<td>Group</td>
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<td>12.9</td>
<td>0.67</td>
<td></td>
<td>SMP</td>
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<td>0.68</td>
<td></td>
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<tr>
<td>Group</td>
<td>8C</td>
<td>21.95</td>
<td>0.78</td>
<td>0.72°</td>
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<tr>
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<td>0.76</td>
<td></td>
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</tr>
<tr>
<td>Group</td>
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<td>0.41</td>
<td></td>
<td>SMP</td>
</tr>
<tr>
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<td>0.43°</td>
<td>SMP</td>
</tr>
<tr>
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<td>9C</td>
<td>9.7</td>
<td>0.41</td>
<td></td>
<td>SMP</td>
</tr>
</tbody>
</table>

- **Mean Length** = 13.6 ft
- **Mean Gradient** = 1.04°
- **Standard Deviation** = 4.8 ft
- **Standard Deviation** = 0.61°

*Single = isolated cusp.

**Group = set of isolated cusps believed to have formed simultaneously.

***SMP = Saltpetre Maze Passage
Rubber Chicken Highway. Mauck's Discovery of Friars Hole Cave, A Neasy Strole and McKeever's Passage in Canadian Hole) have prominent undercuts in the purer units, but lack undercuts in adjacent clay-rich units.

In the North Canyon, heterogeneous lithology appears to have inhibited the development of cusps and notches in part of Canyon 1 (Plate 6). The affected reaches are near the top of Canyon 1 in the narrow trench, near junction 1,2,5 (position 8), and along parts of sections 1 and 5. Here, patches of clayey biomicrites appear in unit F of the Union Limestone (Figure 34). Many cusps are shorter than usual, and die out into the clayey biomicrites. Remnants of small potholes are also present.

Distribution near the Paleoshafs

Undercuts and notches, in the top few feet of the trench of Canyon B of the Headwall Passage, extend downstream continuously (excluding the short gaps described above), below bed segment 23-24 of section 3, clear to the top of the First Paleoshaf (Figures 82, 83). Undercuts and notches, in the top few feet of the narrow trench of Canyon 1 of the North Canyon, extend continuously through the final downstream reaches of section 5 to the top of the Second Paleoshaf (Figure 84, Plate 6). The paleoshafs lack undercuts and notches. Instead, vertically oriented flutes appear on the walls of the paleoshafs. The flutes have been partly destroyed by floodwaters, and by condensation weathering. Flutes also appear on the walls of the two canyons in the
Figure 82. The First Paleoshift (P1). The view is up, toward the top of the paleoshift at 23. Flow in section 3 was along bed segment 22-23=(ceiling), then down joint segment 23-24. The joint is at J. Position 24 is not labeled because of the problem of projection; it is in mid air, roughly directly below J, where the joint intersected a fault. The fault (F) is nearly parallel to the plan of the photograph; it appears as a trace on the walls at several locations. Surfices subparallel to the fault are labeled "T". Canyon B of the Headwall Passage grew by headward retreat from an early shaft over joint segment 23-24. Cusps (C) and undercutting appear on the wall of the trench near the ceiling; they extend clear to the top of the paleoshift. Cusps at lower elevations (Figure 83) do not extend as far downstream. Instead, there is a region of no cusps (nc), which has vertical fluting (Figure 83). The log is debris from flooding; it is jammed into a fault spur on the right, and at a joint spur at X on the left. Flow from 24 was down fault-joint segment 24-50 of section 8; using the joint at X. Part of the ceiling fissure and narrow trench below joint segment 32-24 is visible at the lower right near 32. The "bedrock flange" (BF) locates this photograph with respect to the photograph of Figure 83.
Figure 83. View of Canyon B of the Headwall Passage. The view is obliquely up at the reach just upstream of the First Paleoshift (P1), in section 3. The bedrock flange of Figure 82 is at BF. Cusps above the flange extend downstream to the top of the First Paleoshift. Cusps at the level of the flange die out into it. C = cusp. VF = vertical flute. F = fault.
Figure 34. View of parts of the Second Paleoshift and Canyon 1. The view is obliquely up to the top of the Second Paleoshift (P2) at 28. Early flow was along 28 on bed segment 8-28 of section 5, then down joint segment 28-29. Position 29 is to the lower left, out of view. Cusps (C) and undercut surfaces in the top of the narrow trench extend downstream all the way to the paleoshift. A few feet lower, just upstream of the paleoshift, is an area of no cusps (nc), in which vertical flutes are present; these flutes are only faintly visible here, because of condensation weathering, the action of floodwaters, and their distance from the camera (about 20 feet). The flat wall at jw is a joint-determined wall. Collapse along N 60°-75° E set joints removed parts of the earlier walls of the canyon.
First 10 or 15 feet upstream of each paleoshaft.

Observations of the distributions of the undercuts, notches, and flutes near the paleoshafts suggest the following interpretation. As the early shafts grew by headward erosion (to become the paleoshafts), and the lips of the shafts were lowered, undercuts and notches were not able to form as far downstream. The resulting pattern of growth of undercuts and flutes (as shown on profiles) in the enlarging canyons is shown schematically in Figure 85. Figure 85 also shows the enlarging basins that form at the bases of many vertical shafts, and the pattern of undercuts that appear in canyons that drain the shafts. Figure 85 shows only the earliest stages of headward retreat at the paleoshafts. Later stages were different at each paleoshaft, as discussed in Chapter 6.

Distribution in Trenches below Upper and Lower Loops

Figure 86 is an idealized representation of the distribution of undercuts, cusps, and notches relative to the lift and drop segments of a typical set of upper and lower loops. The following is pertinent.

1. Those notches and undercuts that lie beneath the segments of the upper loops have elevations that are higher than the elevations of parts of the half tubes of adjoining lower loops. For example, cusp A is higher than all of the half tube of bed segment 1-2. Cusp A is also higher than most of the half tubes of joint segments 2-3 and 4-5; and is higher than all of the half tube of bed segment 3-6. (2) Such notches and undercuts, as are illustrated by cusps A, B, and C, have
Figure 85. Hypothesized early growth at the First and Second Paleoshfts. The paleoshfts grew initially as joint fissures that transmitted ground water from segment level 1 to segment level 2 (see Chapter 6). After the onset of entrenchment, the joint fissures became vertical shafts. The shafts had flutes on their walls and basins at their bedrock bases. As entrenchment lowered the floors of the bed conduits on the upper passage level, undercutts and cusps were carved. Flutes formed on shaft walls. Headward retreat and lowering of the lips of the shafts resulted in an upstream migration of the farthest downstream points of cusps, producing the pattern of cusps shown. As headward retreat progressed, basins deepened and migrated upstream. Originally, tubes and fissures drained the shafts. However, as the shafts were transformed into paleoshfts, the drains became canyons. Undercuts and cusps that formed in the drain canyons had their farthest upstream ends migrate farther upstream as entrenchment progressed.
Figure 86. Model of the distribution of undercuts and notches, as represented by cusps, relative to the lift and drop segments of a typical set of upper and lower loops. The initial (hypothetical) flow path was on tubes and fissures along bed segment 1-2, joint segment 2-3, bed segment 3-4, joint segment 4-5, bed segment 5-6, joint segment 6-7, and bed segment 7-8. Entrenchment carved undercuts and notches, here represented by cusps A-F. For explanation, see text.
cusps that slope downstream at low gradients. The cusps terminate at the half-tubes of the drop segments in a downstream direction. For example, cusps A, B, and C terminate downstream at drop segment 4-5. The cusps also terminate at the half-tubes of the lift segments in an upstream direction. For example, cusps A, B, and C terminate upstream at lift segment 2-3. (3) Those notches and undercuts that lie just below the lowest parts of the lower loops extend continuously (disregarding the usual gaps on synchronously forming cusps) across the trenches beneath the upper loops. For example, cusps E and F extend from beneath bed segment 1-2, across but below the upper loop, downstream to positions beneath bed segment 5-6 of the lower loop. Examples of the above relationships are given for Canyon 2 of the North Canyon in Figures 87A and 88, and for Canyon B of the Headwall Passage in Figure 87B.

Figure 87A shows the approximate positions of several cusps on the north wall of the narrow trench for a region just downstream of the first Paleoshift. The first Paleoshift formed on joint segment 23-24 (Figure 82). Fault-joint segment 24-50 of section 8 transmitted ground water downward to position 50; past 50 is a lift on fault segment 50-51. Above fault-joint segment 24-50 is a smooth-walled joint fissure (Figure 88). The fissure is believed to have formed before the onset of vadose flow. The fissure lacks undercuts, even where its walls are lower in elevation than nearby walls of the narrow trench below the fault-joint segment. The undercuts of the narrow trench terminate in a downstream direction near the former intercept of the
Figure 87. Approximate projected positions of cusps on projected profiles of parts of Canyon 2 and Canyon B. (A) Cusps on the north wall of the narrow trench below (drop) fault-joint segment 24-50. Compare with Figure 88. (B) Cusps on both walls of the trench of Canyon B between positions 26 of section 4 and 13 of section 3. S3 = section 3, S4 = section 4, S5 = section 5, S8 = section 8. SW2 = surface of widening 2. For explanation, see text.
Figure 88. Canyon 2 downstream of the First Paleoshift. The view is upstream to the east along fault-joint segment 24-50. The caver is standing below the First Paleoshift; the white dot above her is at position 24. The photograph of Figure 82 was taken from the position of the caver. The joint fissure (JF) above the fault (F) lacks the cusps that appear on the north wall of the narrow trench. The five cusps (C) shown in Figure 87A are labeled. Note the position of surface of widening 2 (SW2 on left and dashed white line on right) near the floor. The wide region above it is not part of the wide trench, but is a result of extensive undercutting (see Plate 4, plans and cross sections), followed by collapse along joints (fractured right wall) and bed parting B12. The wedge-shaped bedrock on the ceiling may be near collapse. Similarly-shaped bedrock masses appear as breakdown near position 50, and farther downstream in Canyon 2. The photograph was taken from 50.
The reach of canyon shown in Figure 87B for Canyon B includes parts of sections 3 and 4. Section 4, transmitted ground water into section 3. The upstream segments of section 4 are nearly horizontal; they are followed downstream by a lift on a joint segment to bed parting B8 at position 28. Position 28 is a high point; from it there is a drop consisting of several bed and bed-joint segments that extend downstream into section 3. Undercuts within the trench below the upper loop lie at higher elevations than the half tube of the lower loop. The undercuts terminate upstream against the half tube of the lift segment. Finally, the lowest undercuts near the floor extend from the upper to the lower loop in the lowest part of the canyon.

From the above and other observations, the following conclusions may be made. First, entrenchment gradually lowered the floors of the upper loops, creating undercuts and notches. Second, while the lowering took place, nearby lower loops continued to grow as tubes and fissures under conditions of closed-conduit flow.

The Transition from Tubes to Narrow Trenches

Consideration of Widths of the Narrow Trenches

Below the half tubes and fissures are the narrow trenches (see pp. 41-44). The narrow trenches average 1.5 feet wide and range 0.6 to 3.0 feet wide. Reaches wider than 2 feet are rare. Such reaches are associated with intersecting joint spurs, variable lithology, or
Considering the relief provided by undercuts and notches, the narrow trenches are remarkably constant in width. The greatest variations in width that are not associated with joint spurs, variable lithology, or collapse, are found on reaches with meanders. On reaches with well-developed meanders, the walls of the narrow trenches are often irregular in shape. The walls take complicated shapes because the undercut surfaces and convex surfaces of the walls curve in variable directions. Locally, undercuts appear on opposite walls at nearly the same level, resulting in a slight widening.

The narrowest of the narrow trenches have the least variations in width. These trenches are on reaches that are straight on the plan (mostly along joint or bed-joint segments, but also below some fault-joint segments). A prominent example is in Canyon 1, section 6, over bed-joint segment 37-38, joint segment 38-39, and bed-joint segment 39-40 (Plate 4). Over this reach, an unusual group of nearly straight N 60°-75°-E set joints extended vertically below B8 for distances ranging 10 to 15 feet. The narrow trench over this reach is consistently only 0.9 to 1.3 feet wide. Undercuts and notches are present, but undercutting is minimal. Why is trench width so small? Why is the undercutting so subdued? Why is the narrow trench so straight?

The reach in question discharged into a sinuous narrow trench below sinuous bed segment 40-3. The undercuts and meanders of this narrow trench are among the best preserved of any in Canyon 1. The narrow trench has widths that are 0.2 to 0.5 feet wider than are
trenches within the upstream straighter reach. There are no tributaries where, so it is, not possible to invoke increased discharge to explain the increased widths. Nor can variations in lithology explain the increased widths within the narrow trench of bed segment 40-3, for lithology appears uniform over the reaches in question.

Another explanation begins with the observation that the unusually straight zone of straight N 60-75° E set joints extended 10 to 15 feet vertically downward from B8. The joints extended through and are aligned along the region presently occupied by the narrow trench. The joints are therefore concordant to the narrow trench, the base of which is shown in photographs in Figures 79, 80, and 93. This suggests that the joints concentrated and confined vadose flow at the center of the narrow trench throughout the stage of narrow entrenchment, thus producing the observed features. Such confinement could occur only if entrenchment was effected by low-discharge vadose flows. If this interpretation is correct, then it is likely that significant amounts of small clastic sediments were not present during narrow entrenchment along these reaches. Had the clastic sediments been available, they would have clogged the vertical joints and directed flow against the walls, producing greater undercutting, greater widening, and greater variation in width than are present. In Figure 89, the hypothesized sequence of development of the narrow trench (below bed-joint segment 37-38, joint segment 38-39, and joint segment 39-40) is compared with the development of the narrow trench below bed segment 40-3.
Figure 89. Hypothesized sequences of development for cross sections of the narrow trench below two reaches in Canyon 1. Top: sequence over bed-joint segments 37-38 and 39-40. The bed parting and joint are at (1). At (2) is a cross section of the early bed-joint conduit, showing four spurs. Cross sections 3-10 show successive stages of entrenchment. During most of narrow entrenchment (cross sections 3-7) the joint exposed in the floor provides a weakness that is more readily exploited in downcutting than is surrounding massive bedrock. Consequently, flow is constrained by the straight joint, which guides the small vadose flows, and which inhibits lateral undercutting. For this process to work, the joint in the floor must be exposed as a joint spur, and cannot be clogged with sediments. During the final part of narrow entrenchment (cross sections 8 and 9), the floor is lowered below the joint. Cross section 10 shows the canyon early during the stage of wider entrenchment. Bottom: sequence over bed segment 40-3 of section 6. The bed parting is at (1). At (2) is the early tube. Cross sections 3-9 show successive stages of narrow entrenchment. Cross section 10 shows an early stage of wider entrenchment. Most of the sinuosity of the canyon over bed segment 40-3 is found in the wider trench.
Contrasts in Surface Relief and Texture

The walls and ceilings of the half tubes and fissures are typically rounded. They have the overall smooth surface texture associated with tubular conduits that are attributed to phreatic development (Bretz, 1942). In general, surfaces curve smoothly, with few of the abrupt or sharp edges typical of vadose features. Scallops are absent, or are subtle features with long wavelengths (over 0.5 feet). The walls and ceilings of the half tubes and fissures also have less local relief than do the walls of the narrow trenches, and so have a more smooth appearance. The narrow trenches appear rougher in that they are covered with cusps, undercut surfaces, notches, ledges, and short-wavelength scallops.

Some Effects of Condensation Weathering

Over many reaches, both the half tubes and the narrow trenches have been affected by condensation weathering. Their finer surface textures have been roughened by rivulet and drop patterns (Figure 45). Locally, condensation weathering has rounded the edges of cusps and scallops.

Figure 90A shows additional effects of condensation weathering on scallops in Canyon 2 near the First Paleoshift. The scallops are near the base of the narrow trench at an elevation reached annually by floodwaters. The scallops are about 4 feet above the floor, on a vertical wall, well above bedrock that is liable to be abraded by
Figure 2.30. Effects of condensation, weathering, and flooding on scallops. (A) Scallops in the narrow trench of Canyon 2 near the First Paleo shaft. The arrow indicates flow direction during formation of the scallops. Scallop morphology has been partly altered by condensation weathering. Unaltered parts of scallops have smooth, dark surfaces (S). Altered parts have white crusts formed by the drop (D) and rivet (R) patterns, which are on the leaf surfaces below crests (Cr) of some scallops.
Figure 90 (continued). (B). Model of flow dynamics used to explain the distribution of the rough surfaces of the drop patterns on the scallops (after Blumberg, 1970, and Curl, 1974). 1 = point of separation of flow, 2 = region of turbulence, 3 = point where flow impinges on ascending surface of the next scallop downstream, 4 = lee eddy.

The distribution of the drop and rivulet patterns may be explained as a competition between condensation weathering and dissolution during floods. Condensation weathering occurs during the summer and early fall; flooding occurs sporadically with snow melt and rain in the late winter and spring or with thunderstorms in the summer. The condensation weathering probably develops uniformly on the scallops, but the drop- and rivulet patterns are selectively removed by normal processes of scallop formation during floods. According to Blumberg (1970) and Curl (1974), scallops form under the flow dynamics shown in Figure 90B. Flow past the crest of the scallop separates at point 1, becomes turbulent at 2, and impinges on the ascending surface of the next scallop downstream at 3. Dissolution rates are highest at point 3, and least along that part of the scallop within the lee eddy near 4. Thus, the smooth ascending surfaces of the scallops of Figure 90A lie in regions of greatest solution, where turbulent flow directly impinges, and the rougher surfaces lie in regions of least solution on descending surfaces below scallop crests, where flow recirculates in the lee eddies. The flow dynamics suggest that the rough surfaces of the drop and rivulet patterns survive along the lee eddies, because dissolution from floods is intermittent and sufficiently slow to preclude removal of the patterns from the regions of lowest solution rates.
Continuities and Discontinuities in Walls

Bed, bed-joint, fault, and fault-joint segments have minor spurs developed laterally from the bases of the pre-entrenchment conduits (Figures 61, 68, 69). Thus there is a discontinuity in the transition of conduit walls from the half tubes to the tops of the narrow trenches. In contrast, for many joint segments, there is a smooth transition of conduit walls from the half tubes or fissures to the tops of the narrow trenches. The smooth, continuous walls are most noticeable on single-fracture joint segments, where there are no medium- or low-dipping fractures on which joint spurs could form. On such segments, the continuity of conduit walls from the half tubes to the trenches is considerable. It is often difficult to decide precisely at what elevations entrenchment began. The task is even more difficult where the surfaces of the half tubes and the narrow trenches have been heavily modified by condensation weathering.

The Significance of Down-dip Shifting on Fault Segments

Midlines are lines that represent the inferred positions of the early flow paths along fractures or intercepts of fractures (Chapter 2, p. 15). Centerlines are lines drawn down the centers of conduits or parts of conduits, as seen on plans (Figure 91A). In the investigated passages, most of the early tubes and fissures were narrow, with widths of only a few feet. At the scale used for plans (1:240 on base maps), the plans of the early conduits usually have centerlines that
Figure 91: Relationships between the centerlines of tubes and trenches relative to the midlines of segments. (A) Hypothetical examples of centerlines and midlines that coincide on tube plans. At the left are plans of a tube on a bedding plane parting, showing the central positions of the centerline and the midline. At the right are cross sections, showing the central positions of the centerline and the midline. These need not coincide, but usually come close to coinciding for small tubes. (B) Hypothetical example in which the centerline of the top of the trench coincides with the midline and centerline of the overlying half tube. The centerline of the top of the trench can be represented on the cross section by a vertical line through the center of the trench. (C) Hypothetical example on a fault segment, showing the down-dip shift (on the fault) of the centerline of the top of the trench relative to the midline of the fault segment. The offset is most easily seen on the cross section, where the midline does not overlap the line through the center of the trench.
**PLANS**

**GROSS-SECTIONS**

**A**

*BEFORE ENTRANCE*

- Centerline
- Center of the tube
- Midline of bed segment
- Location of midline

**B**

*AFTER ONSET OF ENTRANCE*

- Centerline of top of trench
- Location of midline
- Vertical line through center of the trench

**C**

*ALONG FAULTS, AFTER ONSET OF ENTRANCE*

- Centerline of trench
- Thrust fault
- Midline of half tube on fault
- Location of midline
- Vertical line through center of trench
On many reaches of segments (bed, bed-joint, joint, and fault-joint segments), the tops of the narrow trenches also have centerlines that coincide with the midlines of the segments (Figure 91B). This pattern of development is not characteristic of fault segments that are developed subparallel to the strikes of the faults. Instead, the centerlines of the trench tops are shifted (relative to the midlines) in a direction down-fault dips (Figure 91C). In most cases the shift is a few inches but it may be as much as several feet. The down-dip shift highlights the tendency of vadose water to flow within and effect dissolution only at the bottom of its channel. The down-dip shift supports the previous assumption that early vadose flows had low discharges. Probably discharges were barely sufficient to cover the entire floors of the tubes and the developing trenches. On segments with flat floors, the water would spread out evenly. The centerlines of the tops of the trenches would then form directly below the midlines of the structural segments (Figure 91B). However, on segments with slanting floors such as on fault segments developed subparallel to fault strike (Figure 91C)—the water would fill the down-dip sides of the conduits, leaving the up-dip sides dry. The centers of the vadose streams would be offset in a down-dip direction relative to the midlines of the fault segments. The tops of the trenches would thus form below the centers of the vadose streams, in an offset position.

Such a developmental pattern is possible only if the discharges that effectively dissolved bedrock were small. The analysis does not
assume that all discharges through the conduits were small—flooding undoubtedly occurred. The argument, however, is as follows: morphologic evidence (discussed above and later in the chapter) suggests that only small discharges (that covered the floors of the conduits to a shallow depth) could have removed the majority of the bedrock during narrow entrenchment. These discharges may not have been the dominant discharges within the conduits, but the dominant discharges over long periods of time may have accomplished little enlargement or even been supersaturated with respect to calcite carbonate and thus been incapable of enlargement. The term effective-enlarging discharges is therefore proposed to describe the discharges that actually dissolved the bedrock. Further discussion of the effective-enlarging discharges and hydrologic conditions during narrow entrenchment is on pp. 253-254.

From Narrow to Wide Trenches: Surfaces of Widening

Over most of Canyons 1 and 2, the narrow trenches average about 1.5 feet wide. The narrow trenches terminate downward at surfaces of widening (Chapter 2, p. 44). The surfaces of widening mark the transition from narrow to wide trenches. The wide trenches range 6 to 25 feet wide, and average, at their widest, 12 feet. Over some reaches, the contrast in conduit width is abrupt along the surface of widening. In places the widening is gradual, for it is spread out over several undercut surfaces.
Three surfaces of widening are shown on Plate 4. Surface of widening 1 is in Canyon 1. Surface of widening 2 is in Canyon 2. Other surfaces of widening are in Canyons 3 and 4, and in many passages in the Saltpetre Maze. However, they are not directly relevant to the development of the investigated passages and so will not be discussed. No recognizable surface of widening has yet been located in the Headwall Passage; if one exists, it is buried beneath the surface of the clastic fill.

The surfaces of widening represent undercut surfaces. Locally, the characteristics of the original undercut surfaces have been modified by collapse, particularly near the Swallet entrance (Plate 6). There, densely fractured bedrock lines the walls of the wide trench below surface of widening 1. The affected region extends downstream from the Swallet entrance nearly to position 32 (Plate 4, profile P1; Plate 6). Within this region, surface of widening 1 is close to stylolitic bed parting B9. Over most reaches, the surface is discordant to B9. It is locally concordant to B9 in the trenches below sections 7B and 7C, where collapse along B9 has clearly taken place (Figure 92). In the region of concordance, surface of widening 1 is a rough surface that is remarkably planar given the irregularities in the locations of collapse. The gradient of the surface through sections 7B, 7C; and 6 is about 2.4 degrees, as estimated from elevations of the centerline through the base of the narrow trench. The unmodified undercut surface is best exposed along the north wall of Canyon 1 between positions 35 and 36, for this region of the cave.
Figure 92. Collapsed region of surface of widening 1. The view is downstream, to the southwest, in section 7B in Canyon 1 near the Swallet entrance. Collapse along stylolitic bed parting B9 has occurred at CSW1. The dashed line is at surface of widening 1 where widening is gradual along an undercut surface (US). Densely fractured bedrock appears on both walls of the wide trench. The narrow trench (NT) shows its normal width downstream of position 43. Note the sinuous half tube between 43 and NT; the half tube is on stylolitic N 60-75° E set joints. Note also the widened part of the narrow trench in the foreground, upstream of 43. The widening is a result of collapse following undercutting. The cusp faintly visible at C terminates downstream into the half tube of joint segment 43-44. Early flow over this region was just below B8 on joint segment 35B-43; the enlargement on B8 at the ceiling occurred before the onset of entrenchment. For further discussion of development in this area, see the discussion of junction 7A,6D,7B,7D (Chapter 6), which is directly above the spot from which the photograph was taken.
Downstream of position 39, a surface of widening 1 is an undercut surface below which conduit width often increases only gradually (Figures 77, 79, 93). Maximum widths in the wide trench range 5 to 20 feet in this region of Canyon 1. Surface of widening 1 can be traced without difficulty through section 6 downstream of 39 as well as through section 1 downstream to position 7 (Plate 6). Beyond 7, Union unit F has beds with lenses of clayey biomicrites. Surface of widening 1 is poorly developed here, particularly below segment 7-8 of section 1 and over part of segment 8-28 of section 5. It is therefore more difficult to trace surface of widening 1. Nonetheless, surface of widening 1 can be traced over the final reach of section 5 to the top of the Second Paleoshift.

Surface of widening 2 (Plate 4; Plate 6; Figure 88) is well exposed over much of the investigated part of Canyon 2. It is formed by a prominent undercut surface... Below surface of widening 2, conduit width is usually 5 to 10 times greater than in the narrow trench. In places, conduit width is 20 to 30 times greater below surface of widening 2. The surface extends from a point near the base of the Second Paleoshift, where it is partly obscured by elasic sediments filling the floor basin downstream to the end of Canyon 2, where it dies at a drop segment on a fault (beyond position 59, the downstream terminus of the segment analyses; see Plate 4, profile P4). Although surface of widening 2 is near the base of unit F of the Union Limestone, it remains within unit F throughout its length. Surface of widening 2 is not concordant to any lithologic subunit or bed parting.
Figure 93. Surface of widening 1 between positions 39 and 40 in Canyon 1. The view is obliquely up and upstream, to the northeast. Position 40 is directly above the position from which the photograph was taken. Position 39 is at the location of the white square, which appears low because of the angle of the photograph. Initial flow over this reach was on bed-joint segment 39-40. The N 60-75° E set joints extended nearly to the base of the narrow trench over most of the reach and constrained flow, resulting in a narrow trench that is narrower than usual. The dashed line is at the edge of surface of widening 1. The widening is spread out over several undercut surfaces (US) to achieve the maximum width of the wide trench. Compare this photograph with the photographs of Figures 79 and 80, which show parts of the same reach. C = cusp.
It has a gradient of about 1.0 degrees.

**Hydrologic Conditions During Narrow Entrenchment**

Several previous morphologic observations have implications for the interpretation of the hydrologic conditions at the onset of and during narrow entrenchment. These are:

1. The widths of the half tubes and fissures are approximately equal to the widths of the tops of the narrow trenches. The widths of the narrow trenches are nearly constant throughout their lengths and heights.

2. The narrow trench of bed-joint segment 37-38, joint segment 38-39, and bed-joint segment 39-40 is unusually narrow. Its growth appears to have been constrained by unusually straight and vertically extensive N 60-75° E set joints.

3. Bedrock surfaces of single-joint segments are so continuous (in lacking spurs or other surface irregularities) from the fissures downward into the narrow trenches, that it is often difficult to distinguish the positions at which entrenchment began.

4. The centerlines of the tops of the narrow trenches of fault segments are shifted slightly downward relative to the midlines of the fault segments.

The following conclusions are suggested by the observations above:

1. At the onset of entrenchment, the effective enlarging discharges must have been small. Flow depths could have been no more
than a few inches. Flow widths must have been sufficient, on the average, to completely cover the floors of the conduits.

(2) The above flow conditions must have continued throughout the stage of narrow entrenchment. (Had effective enlarging discharges not covered the entire floors, on the average, then narrowing would likely have occurred. Conversely, had discharges increased, then widening would have occurred. Finally, had extreme variations in the effective enlarging discharges occurred, then trench width would have been more variable within the narrow trenches.)

Conduit Enlargement During Narrow Entrenchment:

A. Synthesis Illustrated

The distribution of cusps relative to the lift and drop segments of upper and lower loops (pp. 228-234) indicates that free-surface streams gradually incised the floors of the upper loops. During the incision, nearby lower loops continued to grow as tubes and fissures under conditions of closed-conduit flow. The tubes and fissures enlarged along their ceilings, walls, and floors. In contrast, the trenches enlarged only downward. The trenches thus deepened, during which time the tubes and fissures increased their cross-sectional areas. The cross-sectional areas of tubes and fissures on lower loops are slightly greater than cross-sectional areas of tubes and fissures on upper loops.

The pattern of growth just described has several consequences. One is that the floors of the trenches of upper loops were lowered
faster than the floors of the lower pressure loops. Another is that the process smoothed out and graded the flow paths during the stage of narrow entrenchment. An example of the entire process is presented in Figure 94; other examples are discussed in Chapter 6. Figure 94 shows the hypothesized history of development of a reach of passage near the Swallet entrance (sections 7B, 7C, and 6 of Canyon 1). Before describing Figure 94 in detail, it is helpful to present the following generalizations about conduit growth during the stage of narrow entrenchment:

1. Lowering of the high points at the downstream ends of pressure loops tended to:
   
   (a) eliminate some pressure loops;
   
   (b) reduce the lengths of remaining loops;
   
   (c) lower the elevations of water surfaces below ceilings of conduits, thus creating air bells; and
   
   (d) create new pressure loops where lower loops were nested within one another.

2. The vertical relief of the pressure loops that were present at the onset of entrenchment influenced the amount of time it took for the early conduits to be transformed into a single continuous canyon (because the vertical relief determined the amount of bedrock to be removed by entrenchment).

Each of these generalizations is illustrated in Figure 94.

Figure 94A shows the midlines of the segments on the profile. At the onset of entrenchment (Figure 94B), there were four regions of
Figure 94. Profiles illustrating the hypothesized development of part of Canyon 1 during narrow entrenchment, simplified. (A) Reach is near Swallet entrance and covers sections 7B (S7B), 7C (S7C), and part of section 6 (S6). Note that sections 5A, 6A, and 6C (Plate 4) have been omitted; their development is considered in Chapter 6. J = joint segment, B = bed segment, BJ = bed-joint segment, PL1 = pressure loop 1. PL2 = pressure loop 2. PL3 = pressure loop 3. PL1A = pressure loop 1A, derived from pressure loop 1. PL1B = pressure loop 1B, derived from pressure loop 1. RE = region of entrenchment. AB = air bell. (A) Profile of midlines. (B) The conduits at the onset of narrow entrenchment. (C) The conduits after a small amount of entrenchment has eliminated pressure loop 3, shortened the length of pressure loop 2, split pressure loop 1 into pressure loops 1A and 1B, and created several air bells. (D) The conduits after the removal of pressure loops 1A and 1B. Note the shortening of pressure loop 2. (E) The conduits after the removal of pressure loop 2. (F) The conduits at the end of narrow entrenchment, with a completely graded floor profile.
entrenchment. Each region of entrenchment was separated by one of the three initial pressure loops. The pressure loop that was farthest downstream, pressure loop 3, had a relief of less than 1 foot. It was eliminated first by entrenchment, because the other loops had reliefs of about 5 feet (pressure loop 2) and 2.5 feet (pressure loop 1). As entrenchment continued, pressure loop 1 was split into two shorter pressure loops, pressure loops 1A and 1B (Figure 94C). During this time, pressure loop 2 decreased in length. Several air bells formed.

Continued lowering of the floors of the trenches (Figure 94D) removed pressure loops 1A and 1B; it also removed pressure loop 2. By the time represented by Figure 94D, more than half of the volume of the passage upstream of the pressure loop had been formed by processes of entrenchment. A speleologist at that time would have recognized the passage as a single canyon that lead to a small, water-filled tube. Had the speleologist been small enough to dive through the sump thus formed, he would have encountered a second canyon downstream. It is not until the next stage (Figure 94E) that the speleologist would have recognized this part of the passage of Canyon 1 as a single continuous canyon. Figure 94F shows the passage at the close of narrow entrenchment, after grading of the floor profile had been completed.

The Grading of the Narrow Trenches
Relative to the Onset of Wider Entrenchment

The grading of the flow paths of Canyons 1 and 2 was completed before the onset of wider entrenchment. This conclusion may be
inferred from the fact that surfaces of widening 1 and 2 lie at grade below the lowest points of those pressure loops that had the greatest relief at the onset of entrenchment. Table 10 lists the pressure loops that were present at the onset of entrenchment in Canyons 1 and 2 of the North Canyon, and in Canyon B of the Headwall Passage. The pressure loop with the greatest relief in Canyon 1 had a high point at position 37 of section 6 and a relief of 5 feet (see profile P1, Plate 4). The pressure loop with the greatest relief in Canyon 2 had a high point at position 52 of section 8 and a relief of 8 feet (see profile P1, Plate 4). In each case the low point of the pressure loop was about 3 feet above the surface of widening. From this final observation, it is clear that the conditions that produced narrow entrenchment continued for a period of time in which about 3 feet of entrenching occurred after the floors had been graded on the upper passage level in Canyon 1 and the lower passage level in Canyon 2.

At the onset of wide entrenchment, Canyon 1 extended continuously from the Swallet entrance downstream to the position occupied by the present Second Paleoshift. There a shaft transmitted water down to Canyon 2.

The Introduction and Transport of Clastic Sediments

An argument was presented above (p. 236) concerning the presence of small (gravel-sized or finer) clastic sediments within part of the narrow trench of section 6 in Canyon 1. The argument was that small clastic sediments would have clogged a joint spur that guided and
# TABLE 10

PRESSURE LOOPS PRESENT AT THE ONSET OF ENTRENCHMENT

<table>
<thead>
<tr>
<th>Number of Loop</th>
<th>Location of High Point</th>
<th>Relief in Feet</th>
<th>Passage Level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Canyon 1 of the North Canyon</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>S6, 46</td>
<td>2.5</td>
<td>Upper</td>
</tr>
<tr>
<td>2</td>
<td>S6, 37</td>
<td>5.0</td>
<td>Upper</td>
</tr>
<tr>
<td>3</td>
<td>S6, 39</td>
<td>0.5</td>
<td>Upper</td>
</tr>
<tr>
<td>4</td>
<td>S1, 6</td>
<td>0.5</td>
<td>Upper</td>
</tr>
<tr>
<td><strong>Canyon 2 of the North Canyon</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>S5, 24</td>
<td>3.0</td>
<td>Middle</td>
</tr>
<tr>
<td>6</td>
<td>S11, 58</td>
<td>8.0</td>
<td>Middle</td>
</tr>
<tr>
<td><strong>Canyon B of the Headwall Passage</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>S3, 28</td>
<td>3.8</td>
<td>Upper</td>
</tr>
<tr>
<td>8</td>
<td>S3, 21</td>
<td>3.1</td>
<td>Upper</td>
</tr>
</tbody>
</table>

* Locations are given by section and position. For example, S6, 46 means section 6, position 46.
constrained the growth of an unusually narrow reach of narrow trench. This would have promoted undercutting, resulting in a wider trench than is actually present. Therefore, it is unlikely that significant amounts of small clastic sediments were present. Because the joint extended the full height of the narrow trench (see Figure 80), the argument is applicable throughout narrow entrenchment.

Without further support, that argument would strike many readers as rather tenuous. The conclusion is important, however. It forms a major presupposition of the interpretation below, and should be more adequately grounded. A full grounding cannot be offered here, for it would require a quantitative analysis of discharge rates and sediment transport capabilities up lifting segments of lower loops—and the data and mathematical bases are not available. Nonetheless, the main points of a qualitative analysis are telling and are readily presented.

The assumption is made, on the basis of the topographic and hydrologic settings (Chapter 3), that the ground water that formed Sneadegan Cave came from sinkpoints in the bed of Cove Run. Those sinkpoints developed as joints and faults were widened in the upper Union Limestone in the stream bed. The joints and faults transmitted the water to bed parting B8 (and in a few places B1). During the earliest growth of the initial flow paths, when the piezometric surface was near the (land) surface, the conduits were large enough to have transported only suspended load. As the joints and faults enlarged, and discharge increased, they became capable of transporting sediments as bed load. However, significant quantities of sediments were
unlikely to have been transported until late in the development of the network for the following reasons. At the surface, sediment sizes must have been highly variable, ranging from mud to boulder-sized clasts (see Wolfe, 1973). Many plates of Webster Springs sandstone were present. They would have jammed in narrow spots, clogging the near-surface joints and faults. They would also have jammed farther down at sharp bends in the flow paths. Such bends existed (even after the onset of earliest entrenchment) where flow changed fractures, particularly from joint- or bed-joint-segments to bed segments. Even when both joints and faults near the surface, and the present-entrenchment bones had "enlarged" sufficiently for sediment transport, there were lower loops to trap sediments. The lower loops must have trapped sediments very near the sinkpoints. It is thus likely that significant quantities of clastic sediments were not transported through the network until after the removal of the pressure loops during narrow entrenchment.

The Onset of Wide Entrenchment

What conditions brought about the onset of wide entrenchment? The large size of the wide trenches compared to the narrow trenches suggests, at first glance, that a marked increase in discharge must have been involved. This is unlikely. Such an increase would have filled the narrow trenches to a considerable height. Although widening might then have taken place all along the heights of the parts of the narrow trenches that were inundated, such an explanation cannot account
for the forms or distributions of the undercut surfaces in the upper parts of the wide trenches. The undercut surfaces that make up the surfaces of widening are not at the same elevations on both sides of the passages. Nor are they completely continuous along the lengths of the wide trenches. For example, Figure 78 shows a notch at N in the top of the wide trench along surface of widening 2 in Canyon 2. Its undercut surface is part of surface of widening 2, yet another undercut surface to the right of N is also part of surface of widening 2. The notch could have formed only by a gradual undercutting of the wall of the passage below the base of the present narrow trench.

Such morphologic features suggest that the transition to wider entrenchment was a gradual process. That process was likely marked by the introduction of significant quantities of clastic sediments. The sediments were probably sands, gravels, and small plates of Webster Springs sandstone that allowed the low discharges to maintain smooth surfaces on the outside cut banks, whose gently dipping cusps could also be formed (see Figures 80, 81).

During this time, there must have been a competition for vadose flows between various sinkpoints in the leaky bed of Cove Run, particularly for the sinkpoints feeding the surface headwall (the sinkpoint for the Headwall Passage), Canyon 1, and the Saltpetre Maze Passage. Under such circumstances, the lowest route will usually win route competition; if it enlarges faster than routes farther upstream.

The lowest route was Canyon 1, and discharges within it increased as the higher routes were abandoned. As the wide trenches formed, they
were then able to transmit increasingly large sediments, particularly during floods.

The Floor Profiles of Canyons 1 and 2

The profiles of the floors of Canyons 1 and 2 are shown on Plate 4 (profiles P1 and P4). In Canyon 1 the floors are mostly imbricated fluvial sediments in which plates of Webster Springs sandstone predominate (Figures 92, 93). In Canyon 2, bare bedrock floors prevail with the exception of sediments 1 to 3 feet thick, between the First and Second Paleoshales, and just downstream and to the south of the First Paleoshale in the wide trench.

In Canyon 2 the bedrock floor is subparallel to surface of widening 2. In Canyon 1 the bedrock floor could not be subparallel to surface of widening 2 throughout the length of the canyon, unless the wide trench were over 30 feet high and almost completely filled with sediments at the Swallet entrance. This is unlikely. Because knowledge of the bedrock floor profile is desirable for the interpretation of the development of the wide trench in Canyon 1, some effort was made to locate its positions. The effort met with only partial success. Because of the importance of the topic and the limited number of positions located, it is important to fully document and interpret what data do exist.

The bedrock floor is directly observable, with relatively little effort, in two regions. One region is near and below position 40 in section 6 of Canyon 1 (Plate 4, profile P1), where the bedrock floor is
often exposed, but if not, it can be exposed within a few minutes by
digging out the latest flood debris. Between these regions and the top
of the First Log Jam, sediments are usually only 1 to 2 feet thick,
filling shallow basins or joint spurs along the floor. The second
region is directly below and underneath the First Log Jam. There,
sediments and vegetative debris are usually trapped behind large wedged
logs. Occasionally, the logs shift during floods. For short periods
thereafter, it is possible to descend within the First Log Jam and climb
upstream between logs to a position underneath the upstream end of
the logs. There, a steep bedrock slope is encountered. The slope is
interpreted to be the local bedrock floor, whose uppermost extent is a
knick point in the floor profile of Canyon 1 (Plate 4, profile P1).

The relief below the top of the knick point along the sloping floor is
7 to 8 feet.

Attempts were made at several locations to dig through the
sediments. The sediments are tightly packed and extremely variable in
size. When it became obvious that excavation would require digging
major holes rather than small-diameter test pits, the digs were
abandoned at 2 feet or less, as being too arduous and time-consuming.
Attempts to insert metal bars were even less useful because the bars
stopped at the first Webster Springs sandstone plates buried beneath
the sand and gravel.

Another method of estimating the sediment thickness was suggested
by the presence of several partly occluded holes along the walls of
Canyon 1. The hole nearest the Swallet entrance (Hole 1 on Plate 4)
...resulted...to be a separate joint fissure, so its depth (were it fully excavated) is not helpful. The next hole (Hole 2) is at the first bend in the passage downstream of the Swallet entrance. That hole had been excavated previously by Doug Medville (personal communication, 1980) and others, to a bedding plane parting about 10 feet below the floor at the bend. Inspection of that hole revealed a sediment slope that descends about 4 feet to a drop-off along a vertical bedrock wall. If the top of the bedrock wall is at about the elevation of the bedrock floor at position 35, then the bedrock floor at position 35 is about 11 feet below surface of widening 11 (Plate 4, profile P1). About 20 feet farther downstream, near position 36, Hole 3 has been excavated to a depth of about 6 feet. The hole opens along a joint fissure directly into the sediment-filled part of the wide trench of Canyon 1. Although the bedrock floor is not exposed, it is clear that the sediment must extend to a position at least 11 feet below surface of widening 1 near position 36.

Using the above data and the known floor profile of Canyon 2, a bedrock floor profile was drawn for Canyons 1 and 2 of the North Canyon (Plate 6). This profile indicates that processes of entrenchment did not transform the separate, nearly graded, floor profiles represented by surfaces of widening 1 and 2 into a single graded floor profile during the time of excavation of wider trenches (stage III). It is, of course, not expected that such a floor profile would have a uniform slope. The expected profile, assuming sufficient erosional time, uniform lithology, and faster erosion on high-gradient reaches than on...
low-gradient reaches, is a concave-up curve approximated by an exponential curve; this also assumes that the floor profiles of canyons behave much like the profiles of surface streams (see Palmer, 1976, for analyses of floor profiles of several New York caves).

Possible reasons for the lack of grading of the floor profile (as a concave-upward curve) include (a) lithologic barriers, and (b) insufficient erosional time brought about by progressive upstream diversion of the Cove Run stream (see Chapter 3, p. 92). The former possibility is unlikely, despite the presence of a few lenses of clay-rich biomicrites within unit F of the Union Limestone (Figure 34). Nonetheless, it is clear that a lithologic barrier exists in the form of unit G. Farther downstream in the North Canyon, there is an abrupt transition from the middle passage level to the lower passage level (Figure 28). This transition is in Canyon 5, where early flow along the strike of a thrust fault changed orientation and descended the fault from segment level 2 to segment level 3 (see p. 202). At this location, clay-rich unit G impeded headward retreat of the lip of an abrupt drop-off in the floor, producing a kind of "shaft" at the Fault Room (see Plate 4, profile P5). Although Canyon 1 is developed entirely in unit E, and thus could not have been directly affected by unit G, incision of the floor profile of Canyon 1 has been indirectly affected by the presence of unit G in Canyons 2, 3, 4, and 5. Were unit G missing, then headward erosion and entrenchment, from the drop segment down the fault between segment levels 2 and 3, would have at least partly graded (as an upward concave curve) the bedrock floor.
profiles between the middle and lower passage levels. This process would have resulted in lower elevations for the upstream bedrock floors of Canyons 4, 3, and 2 (passing upstream). In turn, the profile of the lower part of Canyon 1 would have been affected. The above conclusions are supported by the observations of Jameson (1981) of features present on fault segments where flow was down fault dips between segment levels, and argillaceous perching units were thin (1 foot or less) or absent. In such circumstances (e.g., in four locations in the Dung Ho Way of Friars Hole Cave), incision has produced trenches with concave-upward-profiles.
CHAPTER 6

THE DEVELOPMENT OF THE INVESTIGATED PASSAGES:

A RECONSTRUCTION

Introduction

Purpose

This chapter reconstructs the development of the investigated passages. As explained in Chapter 3 (pp. 94-95, 102-103), the main passages of interest are Canyons 1 and 2 of the North Canyon. Canyon B, associated conduits of the Headwall Passage, and the Saltpetre Maze Passage are of interest mostly to the extent that they relate to the North Canyon. The reconstruction is as complete as available evidence makes possible. The reconstruction is incomplete to the extent that analyses of development downstream of position 59 in Canyon 2, or downstream of position 1 in the Saltpetre Maze Passage, might affect the interpretation of Canyons 1 and 2.

A Outline of the Main Events

The earliest conduits for which evidence exists were tubes and fissures. The tubes and fissures formed ungraded flow paths on two
segment, levels. They enlarged under conditions of closed-conduit flow. Their early growth and integration, which we have yet to reconstruct, is stage 1 development.

Stage II began with the earliest onset of vadose conditions. Because the flow paths were ungraded, with upper and lower loops, vadose conditions did not begin simultaneously throughout the network. Instead, some conduits continued to enlarge as tubes and fissures within pressure loops. Simultaneously, the tubes and fissures on upper loops were entrenched, transforming them into half-tubes above trenches. During stage II, vadose flows had low effective-enlarging discharges (pp. 245-246) that carved narrow trenches. The conditions that produced narrow trenches continued long enough to remove the pressure loops and grade the floors of the trenches. In Canyons 1 and 2, at the end of stage II, there were narrow trenches on the upper and middle passage levels, which were separated by a shaft where Paleoshift 2 is now located.

Stage III began with the onset of conditions that produced wider trenches. Clastic sediments were introduced, resulting in the under-cutting of the walls of the narrow trenches. Surfaces of widening 1 and 2 gradually formed. As the wide trenches were incised, discharges increased, and coarser sediments were introduced. The present bedrock floor profile was formed along Canyons 1 and 2 by a combination of headward erosion of the lip of the shaft separating the passage levels, and incision below surfaces of widening 1 and 2.
Interpretative Goals

To give a more complete history of development, evidence is needed that would make it possible to:

1. identify the earliest sections integrated to form a flow system consisting of one or more flow paths;

2. determine the sequencing of integration of other early flow paths;

3. determine which flow paths were active at the onset of earliest entrenchment;

4. determine which flow paths formed after the onset of earliest entrenchment; and

5. determine the manner by which some flow paths were selected and then enlarged to become the investigated passages, while others were abandoned early.

The Structure of the Chapter and the Order of Discussion of the Evidence

Much of the necessary evidence is derived from the morphologic features preserved on the half tubes and tubes at the junctions of sections. Other evidence is derived from features of entrenchment below the junctions or present nearby. It is thus useful to organize the bulk of this chapter as descriptions and discussions of the evidence at junctions.

For each junction, the setting is first described to provide a context. Next, the evidence is presented through a description of
morphologic features and segments. Then, the evidence is used to draw conclusions. Because the evidence and conclusions build upon and reinforce one another, the discussion grows rapidly in complexity. At any given point it is essential to keep in mind the nature of the passage setting, the overall developmental context, and the evidence and conclusions of earlier parts of this and preceding chapters.

Although the descriptions are lengthy, they have been made as brief as possible. To increase their intelligibility, the descriptions of the evidence are accompanied by block diagrams and photographs. Wherever possible, reference is made to photographs and diagrams from previous chapters. The block diagrams are schematic. They are not to scale, and the segments do not have the exact three-dimensional positions indicated. However, the block diagrams have been made as accurate as limited time and drawing skills allowed.

For those who have not had the opportunity to view the investigated passages, the following procedure is recommended. For each conjunction, study the block diagrams representing the sequences of development. Pay particular attention to the initial midline diagram and to the final diagram that represents the modern or last relevant stage of the sequence. Become familiar with accompanying photographs (or appropriate photographs from previous chapters). Finally, read the discussions last, even though it is the discussions—and not the block diagrams—that are of primary importance.

Given the specified interpretative goals, the best order in which to present the evidence is as follows. The discussion begins with the
farthest upstream, junction on the earliest discernible flow path on level 1. (Figure 95). It continues downstream along that path to the end of level 1 conduits, before returning to consider junctions within the tributaries to the earliest flow path. The discussion then considers the connections of level 1 conduits to level 2 conduits, beginning with the First and Second Paleoshafs, and ending with the Third and Fourth Shafts and associated conduits. The discussion concludes with the development of sections downstream of the base of the First Paleoshaf. These latter sections are considered together due to the complexity of their interconnections within a short region on level 2.

The final part of this chapter reconstructs the overall history of the investigated passages. That history is most accurately represented by the profiles of Plates 7 and 8, but is perhaps easier to visualize with the block diagrams of Plates 9 and 10. In order to simplify the discussions at the end of the chapter, and to make it easier to compare the overall history with the history at each junction, stage and substage designations are introduced as each junction is discussed. Reasons for some of these designations will not become clear until late in the chapter. When reading the discussion of each junction, it is helpful to glance ahead at the block diagrams and profiles that represent the overall development, in addition to the diagrams for each junction.
Figure 95. The order of the discussion of the evidence pertaining to the integration of the sections. Most of the discussions consider evidence at or near the junctions of sections. For example, discussion 1 considers evidence on sections M, N, and 1A at junction M,N,1A. Other discussions consider evidence away from the junctions, along one or more sections. For example, discussion 11 considers evidence needed to interpret the development along section 8 in Canyon 2. For more detailed section locations, see Figure 51A. CT = Connection Tube. FP = First Paleoshift. SP = Second Paleoshift.
The Main Evidence and Conclusions Pertaining to the Integration of the Flow Paths and their Enlargement at Junctions

Junction M,N,1A

Setting. Junction M,N,1A is in the Saltpetre Maze Passage at its intersection with the Sound Hole at 15 (Figures 28, 51B, 52, 53, 96; Plate 4). Sections M and N transmitted ground water west and then south toward the Block Room of the Saltpetre Maze. The water most likely came from sink points of Cove Run at or near the Dry entrance to the Saltpetre Maze, at least during early stages. (This conclusion is based on (a) the morphology and continuity of the conduits between the Dry entrance and the start of the Saltpetre Maze Passage; (b) the presence of prominent anastomoses and dissolitional re-entrants on B1 along these passages; and at the headwall at the Swallet entrance; and (c) the geohydrologic setting, as discussed in Chapter 3, pp. 87-94, p. 116.)

Features. (1) Section M ends with bed-joint segment 13-14 and bed segment 14-15 in a downstream direction. Bed segment 14-15 can be seen only by placing a ladder and then climbing up to several joint-guided bell holes near the junction. On the north wall of one bell hole is a fault-guided tube, the Sound Hole tube. The Sound Hole tube contains a fault segment 45-15X of section 1A. The tube is at least 15 feet long. It is too small to be negotiated. The fault spays out of bed
Figure 96. Hypothesized sequence of development at junction M,N,1A (position 15.) (A) The segments. In section M (SM): joint segment 12-13 (position 12 is too far to the right to depict in this diagram, and plays no role in the discussion, so is not shown; a similar consideration applies to position Q of section N), bed-joint segment 13-14, bed segment 14-15. In section N (SN): bed-joint segment 14-A, bed segment A-B, bed-joint segment B-C. In section 1A: fault segment 15-15X. (B) The early tubes and fissures with all three sections integrated. (C) The tubes and fissures a short time before the onset of stage II entrenchment. (D) The conduits soon after the onset of stage II. Entrenchment has begun on an upper loop over parts of segments 13-14, 14-15, and 15-A. Lower parts of sections M and N continue to enlarge under conditions of closed-conduit flow, but eventually are also entrenched to form parts of the canyon of the Saltpetre Maze Passage. Note the lack of entrenchment on fault segment 15-15X of section 1A. The high point in the conduit has kept the small-discharge vadose flows from section M from continuing through section 1A. Hence section 1A was abandoned and remains as a tube.
parting B8 and dips west. On the sides of the tube are many small anastomoses. The principal tube itself climbs 3 or 4 inches astant the dip of the fault. It then loses elevation and curves around a corner to the northwest.

(2) The tube is neither a blind fissure nor is it plugged. When the North Canyon is in flood, the sound of flowing water can be heard through the tube (hence the name, Sound Hole). Smoke introduced in the Rat Hole tube, at junction 1,6,1B blows through bed segments 2-3, and 2-4 of section 1B. The smoke then comes out the Sound Hole tube.

(3) Sections 1A and 1B are near one another at about the same elevation (Plates 4, 5). The morphologic features at junction 1,6,1B require a nearby upstream source of ground water supplying section 1B.

(4) Section N (Figure 53) rises on lifting segments near its end (B8 segment H-1). Past L, the early conduit continued as a lifting segment on B8 to a high point in the Block Room of the Saltpetre Maze. The elevation of the high point is not known with sufficient accuracy to be able to precisely locate the elevation and location of the upstream end of the pressure loop that the high point created at the onset of entrenchment. However, that elevation was estimated by leveling through the passages with a Suunto clinometer. The elevation is -13.5 feet ± 1 foot (relative to datum). The elevation of position 15 is -12.2 feet (Plate 5). Therefore, at the onset of entrenchment, position 15 should have been in a region of entrenchment.

(5) Sections M and N were entrenched; section 1A was not.

Interpretation: (1) Section 1A transmitted ground water to
section 1B before the onset of entrenchment in the Saltpetre Maze.

Section 1A was abandoned. Assuming slow discharge vadose flows at the onset of entrenchment (Chapter 5), a mechanism for the abandonment can be suggested. The mechanism is that flow depth was insufficient at 15 for water to flow past a high point nearby on the fault tube of section 1A. Further discussion of the onset of entrenchment at this and other branchpoints in regions of entrenchment at the onset of stage II is on pp. 302-304, p. 307, pp. 315-324 and 379-383.

(3) Figure 96 shows the inferred sequence of events at junction M,N,1A. Figure 96A shows the segments. Figure 96B shows the early conduits, which form part of the earliest recognizable integrated network. That is the stage IA network. Figure 96C shows the tubes and fissures at the end of stage I. Figure 96D shows an early stage of entrenchment.

Junction 1,6,1B

Setting. Junction 1,6,1B is at the entrance to the Rat Hole at position 3 of the North Canyon, at the ceiling (Plate 4, Figures 54, 57, 97, 98). This is a critical junction for several reasons. First, morphologic evidence from it and the surrounding segments plays a pivotal role in deciphering the relationship between the Saltpetre Maze Passage and the North Canyon. Second, that evidence strongly constrains the reconstruction of flow path history, both before and after the onset of entrenchment. Third, the junction is a useful one
Figure 97. Hypothesized sequence of development at the Rat Hole at junction 1,6,1B. Junction 1,6,1B = J1,6,1B = position 3. (A). The segments. In section 1 (SI): bed segment 3-4. (Position 4 is far to the left and is not shown; see Figure 54.) In section 6 (S6): bed-joint segment 39-40, bed segment 40-3, bed segment 40A-2. In section 7B (S1B): bed segment 3-1-2, bed segment 2-3. (Position 29 is too far to the right to show.) (B) The earliest recognizable (stage 3IA) flowpath, which consists of sections 1B and 1.
Figure 97 (continued). (C) The conduits at junction 1,6,1B after the integration of section 6 to sections 1B and 1, early in stage IB. Section 6 grew and integrated into the slightly older flow path of sections 1B and 1, as indicated by (1) the distributary-like nature of the conduits at the downstream end of section 6, and (2) other features (see text). (D) The conduits at junction 1,6,1B after the anastomoses of the distributaries of section 6 had coalesced to form low, wide tubes. The coalescence likely was gradual during stages IB and IC.
Figure 97 (continued). (E) The conduits at junctions 1, 6, 1B after the onset of entrenchment in sections 1 and 6. Section 1B remains as a tube because section 1A was abandoned in the Saltpetre Maze Passage. Bed segment 40-3 was used instead of bed segment 40A-2 because the low-volume vadose flows followed the route that was lower immediately downstream of branchpoint 40A of the anastomotic network shown in Figure 97C. See Plate 5 for a representation of the elevational relationships of the segments. (F) The conduits during wide entrenchment.
Figure 98. View of junction 1,6,1B at position 3. The photograph was taken with a wide angle lens, which has introduced some distortion. The view is obliquely up at the Rat Hole tube. The Rat Hole tube comes out of the wall of the top of the narrow trench, just below the label "3'. Section 1 is visible as a bed 8 half tube extending from 3 toward 4. Section 6 (S6) is visible as a wide arch coming in from the left. The distance of the camera from the arch, combined with the angle and the foreshortening, make it impossible to discern the two subtle half tubes within the arch on section 6. Note that the arch has a ceiling which is lower than the ceiling of the half tube on bed segment 3-4. At Jt, collapse on N 60-75° E set joints has resulted in local widening of the narrow trench (NT). The collapse-induced widening has also occurred near and below the label "S6". Had the collapse not occurred, the walls of the narrow trench would have remained, making it impossible to see the half tubes in the ceiling from the vantage point. Note the cusps (C) on the walls of the narrow trench. The cusps indicate that entrenchment extended across section 6 into section 1. There is no hint of entrenchment across section 1B into the Rat Hole tube. These features indicate that section 1B had to have been abandoned before or at the onset of stage II entrenchment.
for illustrating the interpretation in the field. It is well exposed and is readily accessible. Unlike most junctions, it can also be usefully photographed.

Features. (1) From position 3, section 1, heads downstream as a half tube on B8 (Figure 97F). The half tube is approximately constant in size throughout its length from 3 to 4 (Plate 4). It extends vertically up through B7 and B6.

(2) Upstream of 3 on section 1B is the Rat Hole tube (Figure 97E), which is on B8. The tube (bed segments 1-2 and 1-3, Figure 97A) has the same size and shape as the remnant half tube of section 1. However, it was not entrenched. The ceiling and upper walls of the tube form a surface that passes continuously into the ceiling and upper walls of the downstream half tube. The tube trends obliquely away from the North Canyon toward the Saltpetre Maze Passage (Plate 4).

(3) Upstream of 3 on section 6 is bed segment 40-3. At its upstream end, bed segment 40-3 is a prominent half tube (Figure 97F). The half tube is narrower and shorter in height than is the half tube of bed segment 3-4 of section 1. The ceiling of the half tube does not reach up to B7. Over the downstream fifth of its length, bed segment 40-3 changes from a prominent half tube to a wider and relatively flat arch.

The wider arch contains two smaller but subtle arches. These wind toward the more clearly defined half tube of section 1. The arches gradually rise above B7 before merging into the north wall of the half tube of section 1 (bed segment 3-4). The smaller arches
intersect the bed segment 3-4, half tube at nearly right angles (Figure 97C).

South of position 40 (Figure 97A, F), there is a re-entrant on B8. The re-entrant forms a widened ceiling region with many small pendants, remaining from coalescence of anastomoses. From this widened region there is a small tube (bed segment 40a-2) that trends south toward position 2 of section 1B. The tube connects to the section 1B tube at a right angle. (The widened region and the tube are hard to see due to breakdown wedged in the upper part of the canyon near 40. However, the tube is visible at 2.) The enlargement in the widened region is too great, given the number of anastomoses formerly present, and the breakdown is too much in the way, to be able to determine precisely where the small tube branched away from segment 40-3. Hence it is most useful to locate position 40a merely somewhere within the widened region. Because of the small size of the tube of bed segment 40a-2 and its proximity to the final anastomoses of segment 40-3, it is not useful to designate a separate section.

(5) Notches and undercuts on the walls of the narrow trench of Canyon 1 are continuous and descend from section 6 to section 1 (Figure 98). No entrenchment occurred on section 1B, either within the tube or into it from section 1 at junction 1,6,1B.

Interpretation. (1) Segments 1-2, 2-3, and the half tubes of segment 3-4, formed a continuous pre-entrenchment tube. The tube transmitted ground water from position 4 into what later became Canyon 1 of the North Canyon. The water came from section IA, hence from
section M of the Saltpetre Maze Passage (see pp. 274-278).

(2) The inferred larger size of the above tube (compared to the inferred sizes of the tubes of segment 40a-3 of section 6) is suggestive. Assume that the tubes grew at nearly equal rates and that they discontinued tubular growth simultaneously at the onset of entrenchment. Then the larger tube would have begun its growth earlier. (The assumptions are reasonable but cannot be tested entirely. The tubes are in the base of unit D of the Union Limestone. The bedrock appears to be of uniform composition in the relevant region. The elevations of the segments and the features of entrenchment at junction 1,6,1B require simultaneous onset of entrenchment, as argued in interpretative point (4) below. However, the discharge rate and solutinal capacity of the ground water could have differed sufficiently to have affected growth differentially, though that is unlikely.)

(3) The half tubes and remnant tube of segments 40-3 and 40a-2 of section 6 curve toward and approach the tube and half tube of sections 48 and 1B (respectively) and finally intersect them at approximately right angles. This suggests that section 6 may have been an independently developing flow path. The flow path would have modified its direction of growth within B8 to grow toward and become a tributary to a pre-existing and larger conduit (where the hydraulic head was lower)—that is, sections 1B and 1. This sequence could have occurred in accordance with head-loss arguments of the types advanced by Ewers (1972) or Palmes (1975). What is important here morphologically is the following. Section 6 appears to end by "breaking up" into a
distribution network of anastomoses of the type studied by Ewers (1972). If this is plausible, then the most reasonable interpretation is as follows. There was a flow path from section IA to section IB (Figure 97B). A slightly later-developing tributary consisting of section 6 (and its tributaries) was then integrated (Figure 97C). Coalescence of anastomoses next produced conduits as shown in Figure 97D.

(4) Assuming the above interpretation is correct, then the continuity of entrenchment from section 6 to section 1 (and the lack of entrenchment on section IB) require a cessation of flow of unsaturated groundwater on section IB from the Saltpetre Maze Passage. This cessation must have occurred before or at the same time as the onset of entrenchment. Otherwise, entrenchment near junction 1,6,1B would have occurred onto section IB as well. This would likely have produced a narrow trench in section IB, but there is no such canyon. Alternately stated, there should not have been any flow through section 1A to section IB to section 1. The reasons are that (a) the elevations of the two flow paths are nearly equal, and (b) there are no nearby downstream bedrock dams (Figure 21) that could have affected development here by allowing only section IB to continue developing under tube-full conditions. Plates 4 and 5, and Figures 52 and 54, allow comparisons of the elevations of the relevant reaches of the paleo-flow paths.

(5) Figure 97E shows the passages at junction 1,6,1B shortly after the onset of narrow entrenchment (stage II). Figure 97F shows the
modern form of the passages.

Junction 1,2,5

Setting: Junction 1,2,5 is best reached by walking downstream in Canyon 1 to the First Log Jam (Plate 4, profile P1). At the log jam one climbs to the ceiling and then climbs through the base of the narrow trench on ledges to position 8. At 8 a small slab of breakdown is wedged in the top of the narrow trench. Position 8 is junction 1,2,5 (Figure 34-56, 99). Position 8 is also the upstream end of the Connection Tube, which joins Canyon 1 of the North Canyon to Canyon 3 of the Headwall Passage. The Connection Tube is formed entirely by section 2.

Features. (1) Section 1 terminates downstream with bed segment 7-8, which is on B8 (Figure 99A). The half tube has the usual features of B8 conduits. Less than 1 foot wide, it extends upward through B7 and B6. Secondary anastomoses are confined largely if not entirely to B8. Although the fault-subparallel joints are extensively exposed throughout the half tube between B8 and B6, they lack dissolitional pre-entrants.

(2) Section 1 begins with bed segment 8-30, which is also on bed parting B8. The characteristics of bed segment 8-30 are unusual. The half tube is smaller than normal. In fact, the half tube is narrower than the half tube of segment 7-8 and does not extend upward through B7. The half tube has fewer secondary anastomoses on B8.

(3) Bed segment 8-9 curves northeast to bed joint segment 9-10 of
Figure 99. The hypothesized sequence of development at junction 1, 2, 3, 4, 5. Junction 1, 2, 3, 4, 5 (J1, 2, 3, 4, 5) is at position 8. (A) The segments. Sections 1 and 5 are in the North Canyon. Sections 3 and 4 are in the Headwall Passage. Section 2 in the Connection Tube (CT) provides one linkage between the North Canyon and the Headwall Passage. (Other linkages occur at junction 3, 5, 8 at the base of the First Paleoshift, and nearby at the bases of Shafts 3 and 4. A full understanding of the events at junction 1, 2, 3, 4, 5 depends on events at these other locations, and at junction 2, 3, 4, 5.)
Figure 99 (continued). (B) The conduits at junction 1,2,5 early during stage IA. During stage IB (not shown) these conduits enlarged slightly and blind-fissures above 88 began growing on N 60-75° E set joints. (C) The conduits at the onset of stage IC, which began with the integration of section 5 to junction 3,5,8.
Figure 99 (continued). (D) The conduits at junction 1,2,5 after further enlargement of the joint fissures during stage IC. (E) The conduits early during narrow entrenchment in stage IIA. Because section 2 rises to a high point, 0.65 feet higher than junction 1,2,5 near position 13 (Plate 5), and section 3 descends from junction 1,2,5, the low-discharge vadose flows followed section 3. Section 2 was thus abandoned and remains as the Connection Tube.
section 2 (Figure 99A). A sharp bend is present at 8. The outside of the bend to the northeast consists of a widened region in which the bedrock between B6 and B8 has been removed (Plate 4). No notches are found in this wall re-entrant. There are a few bedrock pans with depths of 1 to 2 inches on the floor of the re-entrant.

(4) Notches in the narrow trench below junction 1,2,5 can be traced from section 1 across into section 5, despite the presence of several poorly preserved, pitchholes amid lenses of clay-rich biomicrites in unit F of the Union Limestone.

(5) Section 2 in the Connection Tube is ungraded. As shown in Figure 55 and on Plates 4 and 5, section 2 descends to and then climbs along the axis of a syncline. It next crosses the axis of an anticline to a high point in section 3 past position J3 (junction 2,3,4; see pp. 294-304). The elevation of the high point is about -20.75 feet relative to the entrance datum. The elevation of junction 1,2,5 is -21.4 feet, which is 0.65 feet lower. Section 2 therefore consists of lifting segments within a lower loop.

(6) The Connection Tube has ceiling fissures on N 60-75° E set joints. The fissures are smooth-walled. They lack the small scallops typical of floodwater conduits of the Friars Hole region. (Similar fissures appear in section 4 on bed-joint segments 4-5 and 6-7.) However, a few large scallops with lengths ranging from 0.2 to 0.5 feet indicate paleoflow from section 1 into and through section 2.

Interpretation (4). The unusual characteristics of the half-tubes along bed segment 8-30 indicate a lack of morphologic continuity (of
3. The early conduits from section 1 to section 5.

2. A continuity in the remnants of the early conduits can be seen from section 1 to section 2, even though section 2 was not entrenched. Section 2 (the Connection Tube) begins with bed segment 8-9. Parts of the half tubes of bed segments 8-9 and 7-8 are on the underside of the slab of breakdown that is wedged in the top of the narrow trench. By examining the slab and the ceiling, the following can be inferred. The walls and the ceiling of the tube of bed segment 7-8 in section 1 passed continuously into those of the tube of the first part of bed segment 8-9. Over this reach there was no change in the size of the inferred early conduit. The continuous tube to tube combination just described was then partly destroyed, first by entrenchment, and second by collapse of the slab.

3. Section 1 discharged its ground water into section 2 as a single continuous tube before the onset of entrenchment (Figure 99B). Section 5 also formed before the onset of entrenchment, but formed slightly later than sections 1 and 2. The sequence is suggested by the inferred smaller size of the pre-entrenchment tubes of section 5. More conclusive evidence is based on features near junction 3,5,8 (see pp. 324-341). Figure 99C shows the conduits near junction 1,2,5 after the integration of section 5.

4. The ceiling fissures on N 60-75° E joints enlarged gradually before the onset of entrenchment. The widened re-entrant region to the northwest of junction 1,2,5 probably enlarged mostly before entrenchment. The gradual growth of the ceiling fissures and the re-entrant is
...indicated in Figure 99C and 99D.

At the onset of entrenchment, the depth of the dissolutionally enlarging ground water must have been less than 0.65 feet at junction 1,2,5. Otherwise flow would have made it past the high point near 13 and the Connection Tube would have had its floor incised. Figure 99E shows the conduits near junction 1,2,5 early during narrow entrenchment (stage IIA). Further discussion of the lack of entrenchment in the Connection Tube is given in the discussion of junction 2,3,4.

Junction 2,3,4

Setting junction 2,3,4 is at 13. Position 13 is at the junction of the Connection Tube with Canyon B of the Headwall Passage (Plate 4; Figures 55, 56, 100). One way to reach this junction is to crawl through the Connection Tube from Canyon I of the North Canyon. A more pleasant way requires climbing Shaft 4 to enter the floor of Canyon B.

Features (4) Section 2 in the Connection Tube was not entrenched. Sections 3 and 4 were entrenched. Notches and undercuts descend from section 4 to section 3, indicating vadose flow in that direction. The highest notches terminate in an upstream direction against the half tube of joint segment 27-28. (see p. 232; Figure 100G).

(2) Section 2 ends downstream in bed segment 12-13. The ceiling and walls of the tube of bed segment 12-13 pass continuously into the half tube of bed segment 13-14 of section 3. The cross-sectional area of the tube of bed segment 12-13 is about equal to the cross-sectional...
Figure 100. The hypothesized sequence of development at junction 2,3,4. Junction 2,3,4 is at position 13, where the Headwall Passage and the Connection Tube intersect. The development at junction 1,2,5 has been included for correlation with the sequence shown in Figure 99. The segments: S1 = section 1, S2 = section 2, S3 = section 3, S4 = section 4. Sections 3 and 4 are in Canyon B. Section 2 is in the Connection Tube.
Figure 100 (continued) (B) The conduits at junction 2, 3, 4 (position 13) and nearby during stage IA.
Figure 100 (continued). (C) The conduits at junction 2,3,4 (13) after the integration of section 4 (stage IB). Note that the final tube of section 4 intersects the section 2 to section 3 conduit at a right angle. In this and subsequent stages (Figure 100D-100G), the tube or half-tube of the final reach of section 4 remains smaller in diameter than the tube or half-tube of the final reach of section 3 and the beginning reach of section 4.
Figure 100 (continued).  (D) The conduits at junction 2,3,4 (13) after the integration of section 5 (stage 1C).  Note the growth of joint tissues above bed parting 8 (top surface) on N 60-75° E set joint segments.
Figure 100 (continued). (E) The conduits soon after the onset of entrenchment (stage IIa) at junction 2, 3, 4. Section 2 is abandoned and remains as the Connection Tube. At the time shown, a high point at 28 is the downstream terminus of a pressure loop in section 4.
Figure 100 (continued). (F) The conduits after about 3 feet of entrenchment at junction 2,3,4 (stage IIb). The floor of the trench in section 4 is below 28, at about the same elevation as the floor of the tube of section 4 upstream of 27. Hence, the pressure loop has been eliminated, and the tube upstream of 27 is in a region of entrenchment.
Figure 100 (continued). (G) The conduits after further entrenchment during stage E. Note the larger sizes of the half-tubes within the upstream part of section 4 compared to the rest of the half-tubes.
area of the half tube of bed segment 13-14. Anastomoses appear on B8. The ceiling rises above B6 to the axis of a small anticline (Plate 15). It crosses the ceiling conduit near 13 and plunges to the south. The segments of section 2 are lifting segments near 13. The beginning of section 3 is a gently descending drop segment, bed segment 13-14.

(3) Section 4 ends down paleo-flow in bed-joint segment 29-13. The half tube of segment 29-13 is smaller than the half tube of bed segment 13-14. On bed segment 29-13, the ceiling is below B7, except at the end, where the ceiling rises to merge into the upper wall of the tube to half tube combination of bed segments 12-13 and 13-14. The half tube of segment 29-33 intersects the half tube to tube combination at a right angle.

Interpretation. (1) The earliest pre-entrenchment flow path extended from section 1 to section 2 to section 3 (Figure 100B). Conduit size was nearly uniform across these reaches before the onset of entrenchment. The main evidence is the continuity in size and morphology of the relevant tubes and half tubes over these reaches.

(2) Section 4 is integrated into a previously established and larger flow path in a fashion similar to the linkage of section 6 to section 1 and section 1B (see pp. 278-288). At the time of linkage (stage 1B), the conduits would have resembled those of Figure 100C. The main evidence is the right angle intersection and the smaller size of the remnants of the bed-joint conduit at the end of section 4.

(3) Flow through section 2 must have ceased either before or at the same time as the onset of entrenchment on sections 3 and 4. This
interpretation follows from the elevational relationships of the three sections, and from the flow directions. Had flow continued through section 2 at the onset of entrenchment on sections 3 and 4, then section 2 would have grown larger as a tube under conditions of closed-conduit flow in that area lower than the high point at the crest of the anticline. The cross-sectional area within the Connection Tube should have been greater, especially in the lowest parts. Yet cross-sectional area is nearly constant along bed-segments in section 2. It is also nearly constant along bed-joint segments in section 2, although bed-segments are slightly smaller in cross-sectional area. Another consideration is as follows. Had flow continued through section 2 at the onset of entrenchment on sections 3 and 4, then there would have been incision of the high point at 13. Also, features of entrenchment would have been present in section 2. Yet no such features exist.

(4) Section 4 integrated (linked) before section 5 (Figure 100C, 100D). Evidence for this assertion is presented below in the discussions of the First and Second Paleoshaft, section 5, and junction 3, 5, 8.

(5) Assuming low-discharge vadose flows at the onset of entrenchment (Chapter 5), and the configuration of conduits depicted in Figure 100D, a mechanism for the abandonment of section 2 can be suggested. The mechanism is that flow depth was insufficient at 8 for vadose flow to make it past the high point at 13 within section 2. Further discussion of the onset of entrenchment at this and other branchpoints, that were in regions of entrenchment at the onset of entrenchment, is
on pp. 379-383.

(6) Shortly after the onset of entrenchment, the conduits near junctions 2, 3, 4, and 1, 2, 5 should have resembled those shown in Figure 100E. Entrenchment began first on the upper loop of sections 3 and 4 for this region of the Headwall Passage. At the same time, the conduits of the lower loop upstream of 28 in section 4 continued to grow under conditions of closed-conduit flow. Thus the tubes of section 4 grew to a larger size upstream of 28 than downstream of 28.

Figure 100F shows the conduits at the onset of entrenchment of the lower loop. Figure 100G shows the conduits after incision had begun on the lower loop, leaving larger half tubes than are found on the ceilings of upper loops.

Junction 6,6A,7C

Setting. Junction 6,6A,7C is at the first bend in the passage downstream of the Swallet entrance, at position 35 (Plate 4, Figures 58, 101). To get to 35 it is necessary to use a ladder, for collapse at the first bend has locally widened the passage (see Figure 67).

Features. (1) Section 7C consists mostly of ungraded segments on a lower loop (Figure 58). Near the downstream end of section 7C, joint segment 45-46 lifted ground water up to bed-joint segment 46-35 (Figures 58, 67, 101). Section 7C was entrenched.

(2) Section 6 begins with bed segment 35-36. Bed segment 35-36 consists of a wide B8 conduit that has several central principal half tubes and abundant anastomoses (see pp. 175-176). Section 6 was
Figure 101. The segments near junction 6,6A,7C. The junction is in the ceiling of Canyon 1, at the first bend downstream of the Swallet entrance. --- S6 = section 6 --- S6A = section 6A --- S7C = section 7C.

Compare with Figure 106, where the hypothesized sequence of development of this region is illustrated.
entrenched.

§ 3. Section 6A is one of the S-A tubes. (Figure 28). It was not entrenched. From Z5, section 6A trends south and then east. Section 6A consists of bed segment 35Z-35. The segment is a wide B8 conduit that is too small to enter. It is only 5 to 6 inches high and has abundant anastomoses. It is directly continuous with the half tube of section 6, a fact that can be appreciated only by seeing the conduits at ceiling level. To do this it is necessary to place a ladder and climb up to position 35 on the south side of the passage. Section 6A cannot be seen without the ladder because the canyon is too wide for climbing at the passage bend. The widening results from collapse of part of the north wall of the narrow trench of section 7C and the east wall of the narrow trench of section 6. The collapse followed undercutting during wider entrenchment; it used N 60-75° E set joints (see photograph, Figure 67).

§ 4. The narrow trench of section 7C has notches which can be traced continuously (despite some collapse) into section 6. The highest notches below bed-joint segment 46A35 are higher than almost all of the ceiling of the two upstream segments of section 7C (joint segments 344-45 and 45-46).

Interpretation. (4) Section 6A was tributary to section 6 before the onset of entrenchment in section 6. This is suggested, in part, by the continuity of morphologic features from section 6A to section 6.

(2) The lack of entrenchment in section 6A requires that section 6A was abandoned before or at the time of the onset of entrenchment in
this region of the cave. Had flow continued on section 6A, entrenchment would have occurred there.

(3) Section 7C formed before the onset of entrenchment. Had section 7C not been present, and had entrenchment begun, then section 6A would have been entrenched. (The possibility that section 7C would have formed as a shortcut to section 6B with integration at the onset of entrenchment—that is, simultaneously—is highly unlikely. See, however, the discussion of junction 7A; 6D; 7B; 7D, where something similar occurred on section 7D.)

Junction 6B; 6C; S and Junction 7B; 7C; S

Setting. Junction 6B; 6C; S is at position 35X in the ceiling of Canyon 1 near the Swallet entrance. Junction 7B; 7C; S is one foot lower at position 44 (Plate 4, profile Pl; Figures 58, 102). Between the junctions is section 8, the Miniature Shaft.

Features. (1) The Miniature Shaft (Figure 103) is a small shaft formed by descending vadose water. Poorly developed flutes have been partly obscured by condensation weathering. The Miniature Shaft is formed on a N 60-75° E set joint.

(2) Section 7B is immediately east (up paleo-flow) of the base of the Miniature Shaft. Section 7B consists of ungraded joint segments below B8. Section 7C, down paleo-flow of 44, also consists of ungraded joint segments below B8.

(3) By replacing a ladder, it is possible to climb to and put one's head inside the Miniature Shaft to see into sections 6B and 6C.
Figure 102. The segments near junctions 6B,6C,S and 7B,7C,S. These junctions are in Canyon 1 near the Swallet entrance. Section S (SS) is the Miniature Shaft. J = joint. B8 = bed parting 8. S6C = section 6. S7B = section 7B. S6Bi = section 6Bi. S7Ci = section 7Ci. Compare with Figure 106, where the hypothesized sequence of development of this region is illustrated.
Figure 103. The Miniature Shaft. The view is obliquely up. The north wall of the Miniature Shaft is at NW. The Miniature Shaft formed when vadose water in section 6C was diverted down a N 60-75° E set joint from 35X to 44 (directly below 35X, hence not labeled). Headward retreat of the lip (L) of the shaft was about 8 inches, but incision below bed parting 8 was only 1 inch at the lip. Before the Miniature Shaft formed, sections 7B and 7C formed an integrated flow path along the joints. The walls of the remnant half tubes (HT) from the early joint tubes are delimited by dashed white lines. The dashed lines lie along the top of the narrow trench, which has been locally widened as a result of collapse along joints. The north wall of the shaft extends below the elevation of the top of the narrow trench; this indicates that the Miniature Shaft did not form until after the narrow trench had been incised at least 3-4 inches.
These sections are part of the A-tubes on B8. They consist of wide tubes with abundant anastomoses. There is a small vadose incision into the section 6C tube; the incision terminates at the lip of the Miniature Shaft, which appears to have migrated about 8 inches upstream from 35X (Figure 103). Smoke introduced into section 6B at 35X comes out section 6C. Section 6C trends northwest from 35X. It turns slightly northeast at the limit of sight.

Interpretation

(1) Before the onset of entrenchment, section 6C transmitted ground water into section 6B, which transmitted it on to section 6A.

(2) After the onset of entrenchment, vadose water intersected a N 60°-75° E joint at 35X and descended to form the Miniature Shaft. It is unlikely that the Miniature Shaft formed until after narrow entrenchment had cut most of the narrow trench, but it could have formed relatively early. Based on features at junction 7A,6D,7B,7D, the Miniature Shaft could have formed when minor flooding sent water into section 6D en route to section 6C.

Junction 7A,6D,7B,7D

Setting: This four-way junction is at position 35B in the ceiling of Canyon 1 near the Swallet entrance (Plate 4, profile PI; Figures 58, 104). The main features at the junction can be seen only by placing a ladder and climbing to 35B. Other features of interest near the junction are below 35B, where collapse has locally widened the narrow trench and just upstream of the end of the entrance chamber.
Figure 104. The segments near junction 7A, 6D, 7B, 7D. This junction is in Canyon 1 near the Swallet entrance. Positions 35A and 42 are at the downstream end of the entrance chamber (Figure 105). Sections 7A and 6D are on B8, and their segments are in parts of the A-tube (see Figure 28). Sections 7D and 7B are in Canyon 1. S7A = section 7A, S7D = section 7D, S6D = section 6D, S7B = section 7B.
Features. (1) The Swallet entrance has ledges along the north and south walls at the level of B8 (Plate 4). On the south wall is a tube whose floor has been entrenched only a few inches below B8 at scattered locations. The tube trends south and connects into the Saltpetre Maze. Enlargement in the entrance chamber, the nearby parts of the Saltpetre Maze, and the entrance region generally, was too extensive for a complete segment analysis. Therefore, the segment analysis was begun at the downstream end of the entrance chamber.

(2) A photograph of the downstream end of the entrance chamber is shown in Figure 105. At that location, the North Canyon begins with two conduits. The upper passage extends from position 35A to 35B, forming section 7A (Figure 104). A distinct principal tube is represented by a widened central arch above B8 as bed segment 35A-35B. To the north of the segment, B8 has been widened considerably, forming part of the A-tubes. Ceiling pendants and anastomoses are abundant. A central arch, the remnant of a principal tube, trends north from position 35B. It forms section 6D. A minor trench a few inches to 6 inches deep has been incised on bed segment 35A-35B on section 7A.

However, there is no entrenchment on section 6D. The entrenchment on section 7A is greatest near 35B and least near 35A, indicating headward erosion. The highest notches near junction 7A,6D,7B,7D (35B) descend from section 7A to section 7B, immediately below 35B.

(3) Section 7B begins with joint segment, 35B-43 (see photograph, Figure 92), which descends from B8. Above the downstream end of the joint segment, the ceiling is flat and determined by B8. No
Figure 105. The downstream end of the chamber at the Swallet entrance. The view is to the southwest. Two conduits head downstream from the entrance chamber. The higher conduit is on bed segment 35A-35B; it is developed on bed parting 8 (B8), but is not visible here because of the bedrock hiding it near and to the right of the label for position 35A. The lower conduit has an unusual joint segment extending from 42 (in mid air, approximately at the location of the white square) to 35B (not visible). Below the joint segment are the narrow and the wide trenches, separated by surface of widening 1 (SW1). Features of entrenchment begin within inches of the top of the lower conduit. For example, the black line outlines two undercut surfaces separated by a cusp (c). The unusual morphology of the joint segment, and the high locations of features of entrenchment, combined with other evidence (see text), suggest that joint segment 42-35B integrated as section 7D and enlarged during stage II. Note that the wide trench has been filled nearly to the top with boulders of Webster Springs sandstone. The logs (L) wedged in the ceiling are flood debris.
Anastomoses appear on B8 here. By climbing with a ladder, it can be seen that there is no continuation in the flow path along B8. The highest notches that extend from section 7A to section 7B die at the half tube of the descending joint half tube.

(4) The lower passage at the start of the North Canyon (Figure 105) consists of a narrow joint half tube above a shallow narrow trench above surface of widening 1. The half tube belongs to joint segment 42-35B of section 7D. The half tube is smaller than most joint half tubes. It jacks the normal smooth, rounded walls, and has features of entrenchment as high as only a few inches below the ceiling. A barely widened stylolitic joint extends up through much of the bedrock bridge that separates section 7D from section 7A (Plate 4, profile P1). The joint does not reach the bed conduit of section 7A.

Cusps on the south wall of the entrance chamber descend continuously through the narrow trench of section 7D to the narrow trench of section 7B.

Interpretation: (4) Before the onset of earliest entrenchment, section 7A led to section 6D, which led to sections 6C, 6B, 6A, 6, and then L. This interpretation is based, in part, on the morphologic similarities of the conduits of the above sections.

(2) Sections 7B and 7C also formed before the onset of entrenchment. This conclusion is based on the smooth, rounded half tubes of the segments of the sections. It is also based on the necessity of entrenchment onto pre-existing conduits on section 7C (as shown by evidence discussed in the interpretation of junction 6,6A,7C), and on
sections 7B and 7A.

(3) Section 7D: formed after the onset of entrenchment on sections 7A and 7B. This is indicated by (a) the unusual morphology of the joint half tube of section 7D; (b) the small size of the joint half tube; and (c) the presence of entrenchment at a higher level on sections 7A and 7B.

(4) The evidence and conclusions above support a comprehensive interpretation of the development of the cave between the Swallet entrance chamber and position 36 of section 6. That interpretation is shown schematically in Figure 106. Figure 106A shows the segments of this region of the cave. Figure 106B shows the early anastomoses on B8 (stage 1B). Figure 106C shows further tube growth and the beginning of the merging of the tubers. It also shows the integration of sections 7B and 7C (stage IC). Figure 106D shows the conduits before the onset of entrenchment (still stage IC) after further enlargement and merging of the anastomoses on bed segments had formed the low, wide B8 conduits seen today as the A-tubes.

(5) Figure 106E shows a situation in which a competitive loop appears in the flow paths. Ground-water in section 7A split at 35B into two competitive routes before the onset of entrenchment. One route was up high on B8 over sections 6D, 6C, 6B, and 6A; the other was lower on joint segments in sections 7B and 7C. Because the initial joint segment descended at 35B (section 7B), its floor was lower immediately downstream of 35B than was the floor of the B8 conduit on section 6D (see Plate 5). Assuming low-discharge vadose flow at the
Figure 106. The hypothesized sequence of development of conduits in Canyon 1 and the A-tubes near the Swallet entrance. (A) The A-tubes consist of anastomoses in wide tubes on B8 in sections 7A, 6D, 6C, 6B, and 6A. Each section is abbreviated with an "S" in front of the section name, e.g., section 7A = S7A. All sections of this region are shown. Section S, the "Miniature Shaft" (not labeled), is on joint segment 35X-44.
Figure 106 (continued). (B) The earliest recognizable conduits during stage IA. Dashed lines indicate parts that are inferred and are not visible from traversable conduits today. During stages IA and IB, anastomoses developed and began to merge on bed parting B8 along sections 7A, 6D, 6C, 6B, 6A, and 6.
Figure 106 (continued). (C) The conduits at the time (stage IC) of integration of sections 7B and 7C. Sections 7B and 7C form a shorter, higher gradient cutoff below B8. This suggests that these sections were selected to become the main route of Canyon 1 because of their hydraulic efficiency under conditions of sealed-conduit flow. However, an alternate explanation is more probable, and is briefly summarized in the caption for Figure 1006E.
Figure 106 (continued). (D). Further growth of the conduits during stage D. The anastomoses have coalesced into low, wide tubes. The tubes of sections 7B and 7C have also increased their diameters.
Figure 106 (continued).  

The conduits soon after the beginning of stage II B. Stage II A is not depicted, but is represented here by the entrenchment shown on section 7 A. Stage II A began with the onset of earliest entrenchment. At that time, junction 7 A, 6 D, 7 B, 7 D at 35 R was within a region of entrenchment. Because section 7 B descended more rapidly from the downstream branch point at 35 R than did section 6 D, section 6 D was abandoned by the low-discharge vadose flows that effected enlargement. Sections 6 C, 6 B, and 6 A in the A-tubes were also abandoned. Flow during stage II A then followed sections 7 A, 7 B, 7 C, and 6. However, after only a small amount of entrenchment on sections 7 A and 7 B, section 7 D integrated. That integration is the beginning of stage II B, which is shown here. As section 7 D enlarged, and the floor of section 7 B was lowered, all of the flow was then able to pass through section 7 D. Consequently, section 7 A was abandoned, and entrenchment began lowering the floor of section 7 D (see Figure 106 F).
Figure 106 (continued). The conduits after further narrow entrenchment during stage II.
Figure 105 (continued): v(G). The conduits during stage III.
...onset of entrenchment, section 6D was abandoned at the onset of entrenchment, because flow depth was insufficient at 35B for water to make it past a high point on section 6D.

(6) Vadose flow was pirated to a lower level beneath section 7A early during the stage of narrow entrenchment. This is indicated by the lack of complete entrenchment downward from section 7A, as shown by the presence of the bedrock bridge that separates section 7A from section 7D. In order for the diversion of flow to occur, section 7D had to form and integrate early during narrow entrenchment, when there was little pressure within the lower loop of section 7D. This resulted in the non-rounded morphologic features, and the smaller size than is usual of the joint half tube of joint segment 42-35. Figure 106E illustrates this stage (stage IIB) early after the onset of entrenchment.

(7) For water to flow to section 7D there must have been a drop segment, most likely on N 60-70° E set joints, somewhere nearby upstream in the Swallet entrance chamber.

(8) Figures 106F and 106G show further growth of the conduits. Figure 106F shows the conduits near the end of stage IIC - narrow entrenchment. Figure 106G shows the conduits early during, stage III - wider entrenchment.

Junction 3,5,8 and Early Flow from Level 1 to Level 2

Setting: The main trunk of the North Canyon and the Headwall Passage intersect at junction 3,5,8 (position 24). Position 24 is in
the ceiling of Canyon 2 at the base of the First Paloshaft (Plate 4, profiles P1, P2; Figures 55, 59, 82, 87, 107). The First Paloshaft grew from joint segment 23-24 of section 3. The Second Paloshaft is nearby, up paleo-flow, on section 5. The Second Paloshaft grew from joint segment 28-29. The reason the paleoshfts are so named is that they once were shafts, but have been modified. As discussed in Chapter 5, headward retreat and other processes have lowered the upstream lips of the former shafts, thereby contributing to the development of Canyons 1 and 2. Photographs of the First and Second Paleoshfts and the reaches of canyon immediately upstream of them are given in Figures 82, 83, and 84.

**Features**

(1) The half tubes of bed segment 22-23 of section 3 and bed segment 8-28 of section 5 were traversed continuously along B8 on level 1 to the tops of the First and Second Paleoshfts. Over these reaches no sediments hide any parts of the B8 half tubes. No small tubes or half tubes branch off. Nor are small anastomoses present that could have transmitted groundwater elsewhere. In both cases the B8 half tube ends directly at the joint at the top of the paleoshaft. At the Second Paloshaft several blind joint spurs are also present, but no spurs appear at the top of the First Paleoshaft. In both cases there is nowhere for groundwater to have been transmitted except straight down the joint segments that enlarged to form the paleoshfts.

(2) The bases of the paleoshfts lie on segment level 2. Between the paleoshfts is a lower loop within section 5. The high point of the lower loop is position 24 (junction 3, 5, 8). (Downstream of 24 on
Figure 107. The hypothesized sequence of development near junction 3, 5, 8. (A) The segments of sections 3 (S3), 5 (S5), and 8 (S8). For other nearby sections, see Figures 51B and 55. FP = First Paleoshift. SP = Second Paleoshift. Bed and bed-joint segments in Canyon 2 use bed parting 12 (B12).
Figure 107 (continued). (B) Stage IA tubes along sections 3 and 8. For explanation, see text.
Figure 107 (continued). (C) Early stage IC conduits. Stage IC began with the integration of section 5 between junction 1,2,5 (not shown) and junction 3,5,8. For explanation, see text.
Figure 107 (continued). (D) Late stage IC conduits, showing continued growth of tubes and fissures. For explanation, see text.
Figure 107 (continued). (E) The conduits early during stage II, PL = pressure loop. For explanation, see text.
Figure 107 (continued). (F) The conduits during the middle of stage II. For explanation, see text.
Figure 107 (continued). (G) The conduits near the end of stage II. For explanation, see text.
Figure 107 (continued). (H) The conduits soon after the onset of stage III. For explanation, see text. FP = First Paleoshift. SP = Second Paleoshift. SW1 = surface of Widening 1.
Figure 107 (continued). (I) The conduits after further stage III development. For explanation, see text. SP = Second Paleoshift. SW1 = surface of widening 1. SV = section V. SX = section X. SZ = section Z.
Figure 107 (continued). (J) The conduits later in stage III development. For explanation, see text. FP = First Paleoshift. SP = Second Paleoshift. SW1 = surface of widening 1. SW2 = surface of widening 2. SW = section W.
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Section 6: A fault-joint segment. 24-50. Descriptions and photographs of this segment and the passage around it are on pp. 231-234; the information given there is helpful background information for the interpretations below.) The lower loop begins upstream at the base of the Second Paleoshift with a bed segment on B12 (Plate 4, profile P1; Figure 55). The bed segment has anastomoses. It leads down paleoflow to a joint segment, a bed-joint segment, and a final joint segment. The joint segment lifted ground water several feet up at 24. The remnant half-tube is hard to see from below, it is best studied by climbing inside it from the narrow trench near position 32. The half-tube merges directly into the base of the First Paleoshift at 24. In other words, the morphology and size of the half tube of joint segment 32-24 indicate that the early flow was directly to 24; it was not targeted into the basin that formed during stage II below the First Paleoshift, nor into the narrow trench.

Interpretation: (1) Evidence at junctions 1, 2, 5, and 2, 3, 4 suggests that section 5 is integrated after sections 2 and 3. This conclusion is based in part on the cross-sectional areas of the early conduits of sections 1, 2, and 3; those areas were larger than the areas of the bed conduits; on section 5 and the bed/joint conduit on section 4. Assuming that this conclusion is correct, then section 5 could not have linked as late as early stage II entrenchment. The reason is that section 5 would have had to have been targeted into the narrow trench or shaft basin below position 24; below the shaft that was to become the First Paleoshift. Yet, as noted above, section 5 was not so targeted. Hence
section 5 should have integrated before or at the onset of stage II entrenchment.

(2) It is unlikely that section 5 integrated as late as the onset of stage II entrenchment. Instead, before the onset of entrenchment, flow on level 1 was continuous to level 2 in section 3 via joint segment 23-24 and in section 5 via joint segment 28-29. These conclusions are supported by (a) the morphologic continuity of the remnants of the early B3 conduits on sections 3 and 5 to the stops of the paleoshfts; (b) the lack of any alternative destinations for section 3 and section 5 ground water; (c) the presence of smooth half-tubes and anastomoses on the lower slope between the paleoshfts; and (d) the targeting of section 5 to position 24, rather than lower into the narrow trench or shaft basin.

(3) The conclusions above are important for several reasons. First, they make it possible to correlate the histories of level 1 and level 2 structural segments. Second, they rule out an alternative interpretation. They rule out the idea that the earliest level 2 conduits formed as a result of a drop in the piezometric surface, whereby the shafts formed to divert flow to a lowered piezometric surface near the elevations of level 2 conduits. Such an interpretation might be erroneously developed if it were assumed that the earliest flows on joint segments 23-24 and 28-29 were in the vadose zone, and that vertical shafts formed first.

(4) If section 5 grew and integrated during stage I, then during part of stage I there was a closed loop in the flow path. Downstream
...branching occurred at junction 1,2,5, upstream branching occurred at junction 3,5,8. One route from junction 1,2,5 used sections 2 and 3 to get to junction 3,5,8; the other used section 5. The descent between the two branch points is 16.87 feet. The section 2 to section 3 route had a length of 175.2 feet, giving a total gradient of 0.0963 (5.5°). The section 5 route had a total length of 96 feet, which giving a gradient of 0.1757 (9.9°).

(5) The steeper gradient for the section 5 route, the evidence discussed above, and the evidence at junctions 1,2,5 and 2,3,4, support the interpretation of section 5 as a diversion route that was more efficient than the section 2 to section 3 route. Why should such a route have formed? One answer is that sufficiently open fractures intersected one another and thus were available for route competition to have been effective. If this were the entire story, however, then why was the route of section 5 not used in the first place, given that it is only about half as long and is nearly twice as steep? It may be that a triggering mechanism was necessary.

(6) A possible triggering mechanism can be suggested, one that allows section 5 to be dated relative to sections 4 and 6. The mechanism requires the following sequence for events near junction 1,2,5, junction 2,3,4, and junction 3,5,8 (Figure 108):

(a) first, sections 1B, 1, 2, and 3 form (stage IA);

(b) second, section 4 links into sections 2 and 3, forming junction 2,3,4. At about the same time, section 6 links into sections 3,1, and 1B, forming junction 1,6,1B. These linkages are designated...
Figure 108. Postulated sequence of integration of sections 4, 6, and 5 into pre-existing and larger flow paths. The earliest recognizable flow path (stage IA) began in the Saltpetre Maze Passage and extended from section M into sections N and IA. From section IA (not shown), flow was to section IB, the farthest upstream section shown here. Within the region of cave considered here, the earliest recognizable flow path extended from section IB to sections 1, 2, 3, and then 8 (the latter section is not shown); this is the stage IA flow path at the top. Stage IB began with the linkages of section 6, as later discussed) at junctions 2,3,4 and 1,6,1B, respectively. Stage IC began with the integration of section 5 to junction 3,5,8.
(d) fourth, entrenchment begins, leading to the abandonment of section 2. Section 2 is left as the Connection Tube. Shafts form at joint segments 23-24 and 27-28 (stage IIA).

The mechanism results from the reorganization of the flow system brought about by the linkages of sections 4 and 6. It should be recalled that sections 4 and 6 are believed to have linked into pre-existing larger conduits where the hydraulic head was lower, in the flow path from section 1B to sections 1, 2, and 3. However, once sections 4 and 6 were linked, the flow system would have been subject to increased heads and discharges of aggressive ground water during flooding. Such a mechanism might well have allowed the section 5 route to enlarge competitively and link to junction 3, 5, 8.

Section 5A and Headward Retreat near the Second Paleoshift

Setting. Canyon I extends from the Swallet entrance downstream to the Second Paleoshift (Figure 28; profile P1 of Plate 4). The ceiling half-tubes and fissures in Canyon 1 are parts of sections 7D, 7E, 7C, 6, 4, and 5 (Figure 51A). In addition, section 5A is just upstream of the Second Paleoshift. The development of the downstream end of Canyon 1 is sufficiently straightforward that it is possible to simplify the method of exposition. The interpretation is presented with the aid of Figure 107. Descriptions of features are given below.
only insofar as they are needed to support the main inferences. Additional descriptions of features near the Second Paleoshift are in Chapter 5 (pp. 224-229).

**Interpretation.** (1) Figure 107C shows section 5 shortly after its integration in stage IC. A tube along B8 between 27 and 28 leads to a joint fissure that descends from 28 to 22. Figure 107D shows the conduits after a small amount of additional enlargement during stage IC.

(2) Figure 107E shows the conduits during early stage II narrow entrenchment. The narrow trench leads to the shaft, where a small amount of headward erosion of the lip has taken place. The lip has started to break up into several lips with a stair-step profile because of irregularities in the geometries of the guiding joints. A basin has started to form at the base of the shaft.

(3) Figures 107F and 107G show the downstream end of Canyon 1 during continued headward retreat of the shaft lip, basin development, and narrow entrenchment. By the time of Figure 107G, headward erosion has removed 10 to 15 feet of bedrock. The passage near joint segment 28-29 has begun to resemble a tall chamber more than a shaft. The shaft is well along its way to becoming the Second Paleoshift.

(4) Figure 107H shows the downstream end of Canyon 1 soon after the onset of stage III wider entrenchment. Dissolitional mining during narrow and wider entrenchment below position 51 has created mined segment 51-52, or at 51, the stream has been diverted downward along joint segment 51-52. The water ends up in the basin upstream and...
below, what is now clearly the Second Paleoshift. By the rules for designating mined segments (pp. 29-33), a mined segment now extends from JK downstream to position 22. The lengths of the mined segments and the joint segment of section 5A (Table 6, p. 156) cannot be measured. The measurement is impossible because of the way in which dissolution and collapse have enlarged this region of Canyon I, all but totally obliterating the fissure that formed joint segment 5J-5K.

(5) The evidence for the existence of section 5A is as follows:

(a) About 20 feet upstream of the base of the Second Paleoshift, Canyon I narrows in its lower portion, as shown in Figure 109. An unusual narrow gap appears between the north and south walls of Canyon I. The gap is at the intersection of B12 and a N 60-75° E set joint. The narrow spot is less than 2 feet wide.

(b) Above the narrow spot, and above B12 on the south wall, is a prominent vertical surface. The surface was formed by collapse along N 60-75° E set joints. The surface extends upward to a N 60-75° E set joint that passes behind a bedrock projection (see Figure 84). The projection formed when vadose water undermined parts of the narrow trench. Similar projections likely formed below this zone, but have collapsed. The resulting fragments appear as limestone boulders up to 2 by 3 by 6 feet in size; these are mixed with fragments of Webster Springs sandstone in the basin below the Second Paleoshift.

(c) Opposite the vertical surface, on the north wall of Canyon I (Figure 84), undercuts and other features of entrenchment are well developed. They are distributed from the top of the trench.
Figure 109. The narrow spot in Canyon 1. This spot is about 25 feet upstream of the Second Paleoshift at the farthest upstream end of its former basin. G = gap between the north (NW) and south walls at the narrow spot. B12 = bed parting B12 of the Union Limestone. JS = joint-determined vertical surface that extends upward most of the height of Canyon 1 (see Figure 84). The joints that formed the surface extended below B12, in the basinal region. The joints also extended through the gap toward the north wall, where their traces appear behind the projection of the wall at NW, out of sight in this view.
downward to nearly the level of B12. From a few feet above the level of B12 down nearly to the base of the floor, there are no features of entrenchment. The narrow spot and the few feet of walls above and below it show no signs of having been enlarged by normal processes of entrenchment. In any case, had entrenchment cut through the narrow spot in the normal fashion, the opening should have been wider.

(d) If the stream did not cut through the narrow spot, then there must have been a diversion conduit (with a branchpoint in the floor of the wide trench above B12) that transmitted the stream below B12. The prominent vertical surface trends directly through the narrow gap toward subparallel N 60-75° E. set joints on the north wall (hidden in Figure 109). The lower part of the canyon has an orientation and size consistent with that of a joint conduit; this conduit is designated joint segment 5J-5K of section 5A. No actual half tubes or fissures remain on this segment; the joint conduit has been totally destroyed.

(5) The distribution of cusps and notches on the north wall of Canyon 1 above the gap rule out the possibility of a higher joint segment. Joint segment 5J-5K could have received its ground water only after a long history of narrow and wide entrenchment. Thus a mined segment is designated for the region between 5I and 5J.

(6) One effect of the integration of section 5A is that it accelerated the headward erosion of the lip at the top part of the trench in Canyon 1, it contributed to the grading of Canyon 1 by promoting the grading of the floor profile that extends from the upper.
part of Canyon 1 on the upper passage level down to the lower parts of Canyon 1 and Canyon 2 on the middle passage level. Figure 107I and 107J show continued grading of the floor during stage III. It should be recalled, however, that the floor of Canyon 1 was not completely graded during stage III (Chapter 5, pp. 265-267).

Sections X, Y, Z, V, and W: Development near the First Paleoshaf in the Headwall Passage

**Setting**. The above sections are near the First Paleoshaf, below Canyon B of the Headwall Passage. A schematic block diagram of the conduits is shown in Figure 107J; the segment midlines appear in Figure 55. As with development from the Second Paleoshaf, the development of the downstream end of Canyon B is sufficiently straightforward that it is possible to simplify the method of exposition. The interpretation is presented with the aid of Figure 107. Descriptions of the features are given below only insofar as they are needed to support the main inferences. Additional descriptions of features (near the First Paleoshaf) that support the interpretation are in Chapter 5 (pp. 224-229).

**Interpretation**. (1) Figure 107B shows section 3 during stage IA. A tube on B8 or the intercept of B8 with joints extends downstream to 19. At 19 a drop on a fault carried water below B8 to 20, where a lift on a joint carried the water back up to a bed-joint conduit using B8 from 21 to 22. Past 22, a B8 conduit led to 23, the top of the joint fissure that transmitted ground water down to 24 on segment level 2.
(2) Figure 107C shows the conduits after the integration of sections 4, 56, (not shown; see Figure 108) and 5. Blind fissures along faults and joints have begun to enlarge outward from the earlier conduits. A later state of this growth near the end of stage IC is shown in Figure 107D.

(3) Figure 107E shows the conduits early during stage II narrow entrenchment. A narrow trench leads downstream to a pressure loop; the pressure loop is in the lower loop along the fault just below B8. A second narrow trench extends downstream to the shaft. A small basin has begun to form at the base of the shaft. In addition, a narrow trench extends across the lower part of section 5 between the bases of the two shafts.

(4) Figure 107F shows a slightly later phase of stage II entrenchment. The pressure loop below B8 has been eliminated. The narrow trench now has a graded floor profile on the upper passage level.

(5) Figure 107G shows stage II enlargement after headward erosion of the lip of the shaft has transformed the shaft into somewhat more of a chamber. The lip of the shaft no longer is a single drop; instead a slope is transitional into a steeper drop off. The basin of the shaft has been lowered below the level of fault A.

(6) During the incision of the floor below 22 during stage II (Figure 107E to 107G), a vertically extensive joint partly guided the development of the trench. During each phase, part of the floor was likely a joint spur similar to the spur along part of Canyon 1 in section 5 (Chapter 5, pp. 235-237). As the basin of the shaft deepened...
and extended upstream. Solution eventually enlarged an interconnected network of joints below the trench. The joints extended from the base of the trench on the upper passage level near 22A down to the base of the shaft basin at the latter's upstream end near 22C (Figure 55) on the middle passage level. These joints formed (Figure 107H) section X (Shaft 3: joint segment 22A-22B) and section Y (Fissure 2: joint segment 22B-22C). (For a description of Fissure 2 and Shaft 3, see Chapter 3, p. 108). Because dissolutional mining removed the trench below 22C during stage X, II, the trenchment, a flow path integrated, a mined segment extends from 22 to 22A (Figure 55). Similarly, a mined segment extends between 22C and 24 at the base of the First Paleoshift.

(7) The process just described was repeated farther upstream in Canyon B, as shown in Figure 107I. Incision produced mined segment 19A-19B. Joints were exposed in the floor; they transmitted the stream down joint segment 19B-19C of section Z, forming Shaft 4 and a joint fissure (section V, joint segment 19C-22B) that extended into the base of Shaft 3.

(8) It is not entirely clear when the shafts integrated. Yet some evidence exists for the relative chronology implied by Figure 107H to 107I:

(a) The upstream lip of Shaft 3 lacks morphologic features indicative of headward retreat; Shaft 4's upstream lip has them. This indicates that the joint which enlarged to form Shaft 4 began its enlargement early, soon after Shaft 3 began its growth. (Otherwise,
features indicative of headward retreat would have formed on the upstream lip of Shaft 3. Once Shaft 4 was enlarged sufficiently to capture the entire discharge of Canyon B, Shaft 3 was abandoned. The stream then lowered the lip of Shaft 4.

(b) The distribution of undercut surfaces along section W (Figure 107J) suggests that growth of section W was gradual, toward position 19C. Had shaft 4 integrated after section W had extended to 19C, then it is not clear how section V could have formed; the water would have followed section W into Canyon 2 near position 11Y instead.

Downstream of Position 24 in Canyon 2

Sections 8, 9A, 9B, 9C, 9D, 10, and 11 are downstream of the base of the First Paleoshift (position 24) in Canyon 2. Section 11 ends downstream at 59, the downstream terminus of the segment analysis. The segments between 24 and 59 are shown in Figures 59 and 110A. The segments have a length of 131 feet, 141 feet (80%) of which are on thrust faults or the intersections of thrust faults with N 60-75° E set joints (Table 7). There are two faults. For convenience in description, the first fault encountered when traversing Canyon 2 in a downstream direction (the fault at the base of the First Paleoshift) is fault A, the other is fault B. Each fault strikes north and dips west. The intercepts of the N 60-75° E set joints and the faults trend obliquely along the faults, about 15 to 25 degrees to the side of the fault dip trends. Each fault passes downward into bedding parallel slip in unit G of the Union Limestone. The faults are
Figure 110. The hypothesized sequence of development of conduits downstream of 24 in Canyon 2. (A) The segments. Note the addition of several segments downstream of 59. These segments are not included in the analyses of Chapter 4; they are added here primarily to make it easier to see how several breakdown blocks formed at the end of section 11 during stage III.
Figure 110 (continued). (B) Stage IA. For explanation, see text.
Figure 100 (continued). (C) Stage IB. Note the integration of sections 9C and 9D. For explanation, see text.
Figure 110 (continued). (D) Stage IC. For explanation, see text.
Early narrow entrenchment

Figure 110 (continued). (E) Stage IIA. For explanation, see text.
Figure 110 (continued). (F) A later state of stage II A. For explanation, see text.
Section 10 (S10) links

Figure 110 (continued). (G) Stage IIIB. For explanation, see text.
Figure 110 (continued). (H) Progressive deepening of the narrow trenches during stage II-B.
Figure 110 (continued). (1) Continued deepening of the narrow trenches during stage IIIB.
Figure 110 (continued). (J) The conduits after the onset of stage III.
Figure 110 (continued). (K) The conduits after continued widening below surface of widening 2 during stage III.
Figure 110 (continued). (L) Cutaway of the conduits during stage III, showing the approximate shapes and locations of wedge-shaped breakdown. FB = fault breakdown.
Although the faults overlap one another on the plan, they lie at different elevations and do not intersect.

The development of Canyon 2 downstream of 24 is of sufficient complexity that it is best to break the analysis into two parts. The first part covers section 8; the second covers the rest of the sections. After presenting the evidence for the second part, an explanation is given for the history shown in the block diagrams of Figure 110A-110L.

Section 8

Setting: Section 8 begins with fault-joint segment 24-50, which trends west from the base of the First Paleoshift. The passage is unusually wide. At first glance it appears to lack a narrow trench. The passage narrows past 50, however, and returns to the normal configuration over fault segment 50-51. A partial description of the features along fault-joint segment 24-50 was given in Chapter 5 (pp. 231-234). A more complete description follows.

Features: (1) Above the fault-joint intersection of segment 24-50 (Figures 87, 88) is a smooth-walled joint fissure. Numerous anastomoses appear along the fault. Many are well away from the fault-joint intercept, in a wide fault spur that extends into the ceiling at an angle. The fault spur (Figures 88, 111) is partly clogged with logs and other flood debris. Below the fault spur is a wedge-shaped mass of bedrock. The bottom surface of the mass is formed by Bl2. The south end of the mass is attached to the south wall, which is partly
Figure 111. View near the upstream end of fault segment 50-51. The photograph was taken from the top of the wedge-shaped breakdown near 50, looking south. The logs jammed in the fault spur along fault A are also visible in Figure 88.
determined by a major N 60-75° E. set joint. Other parts of the south wall are heavily fractured. The wedge-shaped mass may be sufficiently unsupported to be near collapse.

(2) The north wall of the wedge-shaped mass has undercuts; this wall is part of the narrow trench immediately below fault-joint segment 24-50. On the north wall of the narrow trench are cusps and notches. The cusps slope gently downstream and die out near the fault-joint intercept (Figures 87A, 88).

(3) Surface of widening 2 is only a few feet above the floor, at the base of the anomalously wide region beneath the wedge-shaped mass. Lateral undercutting below surface of widening 2 has widened the wide trench to an unusual extent. One wall of the wide trench is over 20 feet south and below the fractured wall shown in Figure 88 (see the plan of this region on Plate 4).

(4) A wedge-shaped mass of bedrock appears as block breakdown below position 50. The upper surface of the block has been altered by dissolution from the original slickened surface of the footwall of fault A. Other surfaces are formed by a bedding plane parting, a joint; and the west wall of the narrow trench.

(5) West of 50 (see plan, Plate 4), the ceiling descends subparallel to fault A, reaching the floor at an elevation below that of surface of widening 2. Surface of widening 2 can be traced from 50 around the west wall and then south along fault segment 50-51.

(6) The upstream part of fault segment 50-51 is shown in Figure 111. This segment rises obliquely up fault A to a high point, then
Throughout the segment, anastomoses are widespread on the fault on the side of the narrow trench that is up the dip of the fault. Over most of the segment, only a small fault spur is on the downdip side. At several places along fault segment 50-51, particularly near the end of the segment, there has been a downdip shift of the top of the narrow trench relative to the segment midline of the half tube on the fault (see pp. 242-246).

Interpretation. (1) The upper widened region along fault-joint segment 24-50 results from: (a) lateral undercutting and collapse during stage III, combined with (b) dissolutional removal of the fragments. Many fragments probably were produced from the jointed bedrock beneath the wedge-shaped mass in the ceiling.

(2) The first 15 feet or so of the narrow trench downstream of 50 between 50 and 51 was destroyed by collapse of the bedrock surrounding its walls on the east and west. This is suggested, in part, by the remnant features of entrenchment on the east wall of the wedge-shaped breakdown block. That block probably remains because it had fewer fractures and did not shatter during collapse.

(3) The distribution of cusps in the narrow trench below fault-joint segment 24-50 indicates that the stream gradually lowered the floor of the narrow trench below 24. This process both deepened and lengthened the narrow trench, extending it downstream toward 50.
Sections 9A, 9B, 9C, 9D, 10, and 11

Setting Sections 9A to 9D and 10 form a complex of segments that contain two closed loops (Figures 59, 110A). At varying times, the segments of the loops transmitted ground water along three routes between positions 51 and 52 on fault A. Positions 51 and 52 are only 20 feet apart. The segments of the closed loops are thus short. The evidence along the loops has been partly obscured by the way in which enlargement occurred, the close spacing of the segments, and collapse.

Features (1) The final 10 feet of the half tube of fault segment 50-51 is directly above a ledge that is updip of the top of the narrow trench (Figure 112). The half tube leads to junctions 8, 9A, 9C at 51. There, joint segment 51-53 of section 9A rises as a joint tube or fissure from the fault to a high point above B12. The joint fissure then descends a few inches to B12 at 53. Poorly developed half tubes extend along B12 or its intersection with joints in section 9B on bed-joint segment 53-54. bed segment 54-55, and bed-joint segment 55-56. A smooth-walled joint spur extends several feet above B12, along bed-joint segment 55-56. From 56, a joint segment that appears as a fissure drops 3 feet to a thrust fault at 52.

(2) Fault A has been dissolutionally widened between 51 and 52. Near 51, fault spurs appear on all sides of the passage. Closer to 52, a fault spur is present only on the north wall. Below and between 51 and 52 is a wedge-shaped block of breakdown. Its top surface is a slightly modified part of the footwall of fault A; its north surface is
Figure 112. View of conduits near 51. Section 8 (S8) is visible as a half tube above the ledge on fault A (at F). Section 9A is a joint fissure that rises above fault A. Note the down-dip shift of the top of the narrow trench (NT) relative to the half tube in section 8. Joint spurs (J) appear on the fault A ledge and on the wedge-shaped breakdown.
the south wall of the narrow trench; its bottom is surface of widening and its other surfaces are formed by N 60-75° E set joints or fractures produced during collapse.

(3) At 51, the section 8 half-tube branches into the joint fissure of section 9A, as previously noted. It also branches into the widened region along the fault. On the floor of the ledge near the branchpoint at 51 are several N 60-75° E set joints which have been enlarged downward into joint spurs. (Figure 411). Similar joint spurs appear on the top surface of the block of breakdown. From these observations, it is inferred that the conduit branching into the widened region is a fault-joint segment. The continuation of the joints above the fault, up to 53, and other considerations concerning flow-path history, also require a joint conduit from 51X to 53.

(4) Poorly preserved undercut surfaces appear on the south wall of the passage a few inches below B12 along bed-joint segments 53-54 and 55-56. Nearby, fractured surfaces left by the collapse of the block have destroyed any former features of entrenchment present elsewhere along the upper route in section 9B. A careful examination was made of the floor of the tube of joint segment 51-53 on section 9A (which is higher than B12 along section 9B; see Plate 4). Faint traces of an undercut surface suggest that entrenchment began on the floor but was soon halted. Thus a bedrock bridge was left separating joint segment 51-53 from fault-joint segment 51-51X and joint segment 51X-53.

(5) The normal narrow trench is between 54 and 52, on the north side of the passage, on the side of the fault that is down dip from the
fault-joint intercepts.

(6) Section 11 begins with fault segment 52-57, a lift on fault A. The upstream end of the segment has a prominent half tube (Figure 113), at the lowest part of the lift in the lower loop. Near 52, the half tube has a cross-sectional area 2 to 4 times larger than the areas of higher half tubes on nearby fault segments on faults A and B. At several places along the length of fault segment 52-57 there are smooth-walled blind fissures above fault A on N 60-75° E set joints. Another wedge-shaped breakdown block is present along this reach.

(7) From 57 to 58, a half tube on an inclined joint (joint segment 57-58) rises to fault B. A half tube winds along Fault B to position 59, forming fault segment 58-59. Along this region some widening occurs on fault spurs, mostly above the half tube, but also below it near 59. Yet another large wedge-shaped breakdown block is present below fault segment 58-59. It has an upper fault surface, a lower surface formed by surface of widening 2, a north surface on N 60-75° E set joints, and east and south surfaces formed by the narrow trench.

(8) At 59, section 11 divides in downstream branching into an upper bed-joint conduit and a lower fault-joint conduit. Although these conduits are past the end of the segment analyses at 59, it is helpful to include them in Figure 110. Inclusion of these conduits makes it easier to depict the development of the breakdown blocks along the final reach of section 11 (Figure 110L). No attempt is made here to describe features along the extra conduits.
Figure 113. Large half tube on fault segment 52-57 in section 11. View is to the north. Position 52 is approximately at the location of the carbide lamp. Fault A (FA) is visible as a slanting trace on the far north wall. The photograph of Figure 112 was taken from a point near 52. The half tube is large because conditions of closed-conduit flow lasted a long time in the lowest part of the lower loop. Fault B (FB) offsets bed parting 12 (B12) on the near north wall, which has many rivet patterns. Drops of condensed moisture appear on the ceiling (arrow) and in the half tube, which has abundant droplet patterns. Note that the right (east) wall of the half tube is relatively smooth, having been affected less by condensation weathering.
Interpretation. (1) The main interpretative problem is the identification of the sequence of development of the flow paths that used the two closed loops between 51 and 52. Besides the elevational and geometric relationships of the segments of the loops, the most useful evidence is the distribution of features of entrenchment. As noted above, undercutts are present (but are poorly developed) just below B12 along section 9B. An even fainter remnant of an undercut surface is on the floor of the joint fissure of section 9A. Recall that section 9A lies up paleoflow from and at a higher elevation than section 9B. Had sections 9A and 9B formed the only flow path between 51 and 52 at the onset of entrenchment here, then features of entrenchment should have been better developed on section 9A. The floor of section 9A should have been incised below the level of the base of the present bedrock bridge that separates section 9A from the lower sections 9C and 9D.

(2) The presence of the bedrock bridge and the faint undercut surfaces can be explained with the aid of Figure 114. Figure 114A shows the extended profile of the midlines of segments downstream of and near the First Paleoshift. Figure 114B shows the early stage IA flow path, which follows sections 6, 9A, 9B, and 11. Figure 114C shows the stage IB flow path after the linkage of sections 9C and 9D. That linkage forms the first closed loop in this region of the flow path of the North Canyon. Figure 114D shows the conduits at the beginning of stage II. By this time, fault and joint spurs have formed at various places along the flow path. Where these fissures extend above the
Figure 114. Profiles of the development of conduits downstream of the First Paleoshift. For explanation, see text.
midlines of the original segments, the profile shows conduit heights that appear, but are not, anomalously wide. The initial stage II flow path has two regions of entrenchment separated by pressure loop 6 (see Table 10). Considerable enlargement has occurred along fault A between 51 and 52, both on fault-joint intercepts and along the fault away from the joints. However, fault-joint segment 51X-52 has not integrated. Figure 114E shows the conduits for the time at which the water surface has been lowered (by incision of the high point near 57) to the elevation of the base of the fissure of joint segment 51-53.

The explanation referred to is as follows. Most of the discharge at the time of Figure 114E followed sections 9C and 9D; only a small amount of the water incised the floor of the fissure of joint segment 51-53. Moreover, vadose flow on the floor of the fissure occurred for only a brief time. It took only a few inches, at most, of incision of the high point at 58 (at the downstream end of pressure loop 6) to produce abandonment of flow through the joint fissure. Hence features of entrenchment are only faintly developed in the fissure. Figure 114F shows the conduits after further incision during stage II. The high point near 57 was low enough to allow incision of the floor of section 9B. Entrenchment on section 9B lasted only a brief time, however. The integration and continued enlargement of the fault-joint fissures between 51X and 52 allowed increasing amounts of the discharge to be diverted away from section 9B. Finally, the downstream high point below 57 was lowered below a level that would allow section 9B to remain active (Figure 114G).
(3) The development thus far described is shown schematically in the block diagrams of Figure 110B-110G. Figures 110H and 110I show enlargement as the narrow trench deepened and several fault spurs enlarged on lower parts of fault A near 50 and 52. Figures 110J and 110K show the conduits as the wide trench enlarged during stage III. Wedge-shaped masses of bedrock (bounded by the footwalls of faults A or B, joints, walls of the narrow trench, and surface of widening 2) were extensively undermined. Collapse ensued. Figure 110L shows the locations and approximate shapes of the breakdown blocks before further attack by solution, which continues today during floods.

A Reconstruction of the Development

Structure of the Presentation

The evidence and interpretations at the key junctions may now be used to reconstruct the overall history of Canyons 1 and 2. That history cannot be understood outside of the context of the Headwall Passage and the Saltpetre Maze Passage. It is presented as a description and discussion of Plates 7-10. Plates 7 and 8 give profiles of the relevant conduits for each stage. The evidence is presented in Chapters 4-6. The profiles of Plates 7 and 8 were used to prepare the schematic block diagrams of Plates 9 and 10. As before, the block diagrams are not to scale, though they have been constructed as accurately as possible.
Stage I and its Substages

... Shortly before the onset of entrenchment, a network of tubes and fissures formed flow paths with the pattern shown at the bottom of Plate 9. The network integrated in three substages.

**Stage IA.** During stage IA (Plate 9), section M in the proto-Saltpetre Maze Passage led to a branchpoint for sections IA and N at 15. Following the conduits of primary interest, section IA (at the Sound Hole) transmitted ground water through a now inaccessible conduit to sections 1B (Bat Hole tube); 1 (Canyon 1); 2 (Connection Tube), 3 (Canyon B); and 3, 9A, 9B, and 1 (Canyon 2).

An extended profile for the stage IA flow path is shown in Plate 7. The division of the early conduits into two levels that are coterminous with structural segment levels 1 and 2 is striking. The early conduits along segment level 1 are at or just below B8. Deviations below B8 on lower loops occur in sections M, 1, and 3. Despite the looping, the profile follows a relatively uniform descent determined by the position of B8. It is tempting to attribute the deviations from B8 to increased fracture widths (relative to B8) during the very earliest stages of dissolution, when the available bed partings and fractures were being selected to form the stage IA flow paths (see Palmer, 1984b). At that time, it would appear that the most open parting was B8, and that flow deviated from B8 in places where wider interconnected fractures left and then returned to B8.
For B8 conduits, there are two exceptions to the relatively uniform descent of stage II tubes. One exception is a short stretch of increased dip in section 1. This anomaly affected the floor profile of the narrow trench during stage II (see below and Plate 8). The other exception is created by the structural lows and highs of the synclines and anticlines in sections 2 and 3. These anomalies are important because the high point on the crest of the anticline (near 13) affected flow-path history at the onset of stage II and played a role in the selection of section 5 to become part of Canyon 4 rather than section 2 (which was abandoned as the Connection Tube; see below).

Segment level 1 is connected to segment level 2 by a joint conduit between 22 and 24. The investigated part of segment level 2 has a highly irregular profile, despite its proximity to B12. B12 is a moderately prominent parting that guides a significant length of bed and bed-joint segments downstream of 59 in Canyons 2, 3, and 4; however, it guides only a few segments in the main passages studied here. As before, it is tempting to attribute the deviations from B12 (along faults and fault-joint intercepts) to increased initial fracture widths, following arguments of Palmer (1984b). However, in the case of segment level 2 conduits, this may not be correct. Instead, B12 was likely narrower, and so B12 was used only where the much wider faults and fault-joint intercepts were not available on segment level 2, which has many fault segments downstream of the main passages studied here.

Stage LB. Stage LB (Plate 9) began with the addition of two tributaries. Sections 7D, 6D, 6C, 6B, 6A, and 6 form a tributary that
as targeted into junction 1,6,1B at 3. Section 4 forms a tributary targeted into junction 2,3,4 at 13.

Most likely, these tributaries began their growth as independent flow paths supplied by joints and faults leading to the bed of Cove Run. That growth may have begun during even the earliest growth of stage IA flow paths. However, the evidence at junction 1,6,1B and junction 2,3,4 is best interpreted as indicating that these tributaries did not link as open flow paths until stage I flow paths had formed a transmissive network with a relatively low head, toward which the two tributaries could redirect their growth and intersect at nearly right angles. Stage IB is considered to begin precisely with these linkages. The linkages are placed within the same stage because it is not clear whether or not one predates the other. Until further segment analyses have been made in the Headwall Passage and Saltpetre Maze, and until more data have been collected on the sequencing of sinkpoints of Cove Run, it would be premature to subdivide stage IB.

An extended profile for part of the network for stage IB is shown in Plate 7. The profile begins upstream with section 7A in the A-tubes near the Swallet entrance. It extends downstream to junction 1,6,1B in conduits that enlarged to form the A-tubes or parts of Canyon 1.

Along this tributary, the inferred parts (dashed black lines) have been assigned approximate lengths for their paths along B8. The tributary has only two deviations below B8. The deviations are along N 60-75° E set joints within section 6.
From junction 1,6,1B (3) downstream, the profile is similar to the one for stage IA. There are two differences, however. One is that the conduits have enlarged slightly. This enlargement is most noticeable on joint fissures, where a given increase in cross-sectional area is spread out over a greater vertical extent than on bed or fault segments. (This factor results in the erroneous impression of an unreasonable local increase in conduit size. Of course, there may be some localized increases favored on joint and fault segments, owing to local increased widths of their fractures within the spurs, compared to tighter partings on bed segments.) In any case, the linkages of the stage 1B tributaries are believed to have increased the potential for the introduction of aggressive ground water under high hydrostatic heads during flooding.) The other difference in the profile is that sections 9C and 9D have been added. These sections should have integrated by this time, given their close proximity to the section 9A and 9B conduits.

Stage IC. Stage IC (Plate 9) is characterized by the addition of two competitive flow paths. In each case, the additional flow path follows a shorter, higher gradient route, most or all of which lies below the earlier route. One path is near the Swallet entrance, where sections 7B and 7C short-circuit sections 6D, 6C, 6B, and 6A. The other path is farther downstream, where section 5 formed a route competitive with sections 2 and 3. Most likely, these additional routes began their growth during one of the earlier stages. However, the evidence at the relevant junctions indicates that the linkages did
not occur until the two stage IB tributaries (sections 4 and sections 7A, 6D, 6C, 6B, and 6A) had linked and enlarged slightly. As before, the new linkages are placed in the same stage because it is not clear whether one predates the other. In this case, it is not likely that evidence can be found to distinguish relative times of linkage.

A profile for the start of stage IC is shown in Plate 7. This profile shows the main conduits along which Canyons 1 and 2 enlarged. It is drawn from section 7A near the Swallet entrance, as an extended profile along sections 7A, 7B, 6, 6A, 5, 8, 9A, 9B, and 11. Near the Swallet entrance, sections 6D, 6C, 6B, and 6A are shown projected onto the extended profiles of sections 7B and 7C, hence their extreme shortening. A profile for a slightly later time in stage IC in Plate 7 shows the progressive enlargeing of some of the joint fissures in sections 7B, 7C, 6, 5, 8, 9B, and 11.

The Onset of Entrenchment and the Reorganization of the Stage IC Flow System

The onset of entrenchment began the transformation of the stage IC conduits into the canyons of the Headwall Passage, the North Canyon, and the Saltpetre Maze Passage. Interpretation of the onset of stage II must take into account the following features and arguments:

(1) Entrenchment did not occur on the conduit connecting the Sound Hole to the Rat Hole, on the A-tubes, or on the Connection Tube (see Figure 95).

(2) Entrenchment did not begin everywhere at the same time,
because the flow paths were ungraded. Locally, entrenchment began on the high points that were present at the downstream ends of lower loops.

(3) Entrenchment did not occur first on the upper passage level, and then on the middle passage level, as a result of a progressive system-wide lowering of the piezometric surface.

(4) The effective-enlarging discharges at the onset of stage II (and throughout narrow entrenchment) were small. On the average during dissolution, water covered the floors of the narrow trenches to only a few inches depth.

(5) Entrenchment is unlikely to have begun in Canyon I without having begun in the Saltpetre Maze Passage either previously or at the same time. This follows from the elevations of the respective conduits, and the lack of entrenchment onto section 1B at junction 1,6,1B. As can be seen in the profile for Stage IA on Plate 7, most reaches of section M conduits have elevations that are higher than junction M,N,1A at their downstream end. They are also higher than the high point near 15X in section 1A. For, conditions of closed-conduit flow to have continued throughout sections M and N after the onset of entrenchment in Canyon I, one of the following must have occurred:

(a) sections IA and IB did not exist at that time (which is contrary to the evidence);

(b) an upper loop with a high point above B8, at an elevation no lower than 5.5 feet relative to datum was present between sections IA and IB (which is unlikely); or
(c). the conduit between sections I A and I B was plugged (which is unlikely, and would require a mechanism for plug removal).

(6). Entrenchment could not have begun in Canyon B without having begun in Canyon 1. Conduits in sections 1 and 6 (and the tributaries to section 6) are higher than the conduits of sections 2, 3, and 4. Also, features of entrenchment do not extend from section 3 onto section 2 at junction 2, 3, 4. For conditions of closed-conduit flow to have continued upstream of junction 1, 2, 5 within section 1 and its tributaries, a high point within section 2 would have required an elevation higher than 6.5 feet below datum; or section 2 / would have to have been plugged. The former is impossible; the latter is unlikely.

The interpretation adopted here for the onset of stage II is that vadose flow began simultaneously throughout level 1 and 2 conduits on upper loops. The locations of the earliest regions of entrenchment and the intervening pressure loops are shown on Plate 10 for the onset of stage II A. The pressure loops are numbered according to the scheme introduced in Table 10, and numbers for pressure loops have been added for the Saltpetre Maze Passage. Plate 8 gives a profile for stage II A.

Plate 10 shows that the upstream end of each abandoned tube (Fig. 94) lies in a region of initial entrenchment. Each abandoned tube—(Sound Hole to Rat Hole connection; A-tubes at junction 7A, 6D, 7B, 7D; Connection Tube)—begins at a downstream branchpoint. This observation suggests a mechanism by which the stage IC flow paths could be reorganized to form isolated canyons (Canyon B; Canyons 1 and 2; the Saltpetre Maze Passage) connected by abandoned tubes.
The mechanism was partly explained in the interpretations of the development at each relevant downstream junction (junctions M,N,1A, 7A,6D,7B,7D; 1,2,5). A more complete explanation first invokes the conclusion that effective-enlarging discharges were small throughout narrow entrenchment. It is then noted that, where flow paths branch in a downstream direction, very small differences in the elevations of the floors of the conduits can determine how much of the vadose flow goes which way past the branchpoint. For example, if a stream is four inches deep at a branchpoint, and the floor of one downstream conduit is over four inches higher then the higher conduit will be abandoned as the stream incises the floor of the lower conduit. Even if the elevations of the floors of the conduits at the branchpoint are the same, if the floor of one of the conduits rises higher nearby downstream than the elevation of the surface of the stream at the branchpoint, then there will simply be a pond in that conduit, and the flow will follow the other conduit. Finally, if one of the downstream conduits descends more steeply from the branchpoint, chances are high that it will capture most of the flow and eventually win route competition.

For the three downstream branchpoints the following is noted. At junction M,N,1A, there is an increase in elevation from section M to section 1A where the fault tube of section 1A climbs northeast up the fault before dropping slightly at the limit of observation. At junction 7A,6D,7B,7D, the initial segment of section 7B descends below section 6D, which remains several inches higher and trends north along
the strike of B8 (Plate 5). Finally, at junctions 1, 2, 3, ... section 5 loses elevation, whereas section 2 gains elevation to the crest of the anticline (Plate 5).

From the above relations, it appears that the onset of a decrease in discharge to produce vadose flows at the branchpoints was sufficient to bring about the decoupling of the flow system. The decoupling reorganized the flow system into three active conduits (the four canyons) and three abandoned tubes.

The onset of vadose conditions may have been associated with one or more of the following: (1) a decrease in the discharge into the network, resulting from changes in runoff in Cove Run; (2) conduit growth within the network to a volume greater than that which could be maintained under tube-full conditions by the available discharge; or (3) an integration of the network into a lower conduit along or down paleoflow of the present Saltpetre Trunk.

Stage II

Stage IIA. The profile for stage IIA along proto-Canyons 1 and 2 (Plate 8) identifies 6 pressure loops, 7 regions of entrenchment, and several air bells. At this time there are no canyons. Two shafts appear between the upper and middle passage levels. The conduits are human-sized at some locations, but are not yet large enough to be continuously traversable by humans.
During stage IIA, processes of entrenchment gradually shortened, split up, and then removed some of the original pressure loops. These processes were described and illustrated in detail in Chapters 5 (pp. 254-257) and 6 (pp. 371-374), and will not be redescribed here.

Stage IIB. This stage began with the integrations of section 7D near the Swallet entrance, and section 10 on the middle passage level (Plate 10). At the beginning of stage IIB, pressure loops 2, 6A, and 6B remained. However, they were removed by the end of stage II (Plate 8).

At the time of integration of section 7D, section 7A had been only slightly incised. Section 7D was likely fed by joints that extended below B8 within the entrance chamber. These joints must have begun their enlargement during stage IIA, or perhaps even earlier. Yet they did not enlarge to a size sufficient to transmit significant quantities of water until incision had begun on the higher conduit of section 7A and on the upstream descending part of section 7D. During the early part of stage IIB, section 7D was completely filled with water. Incision of the high point at its downstream end rapidly led to incision of the floor of section 7D and eventually to a grading of the floor profile along this reach.

The high-dip region of B8 in Canyon 1 produced a break in the floor profile of the narrow trench during stage IIA. Cusp gradients on the walls of the narrow trench indicate that this break in the floor profile was gradually removed during stage IIB (early and late stage IIB profiles, Plate 8).
During stage II, the shaft that became the second Paleoshift enlarged from its initial configuration by headward erosion, a lowering of the shaft lip, and basin development (Plates 8-10). By the end of stage II, about 3 feet of incision had occurred below the low points of the initial pressure loops with the greatest relief (pressure loops 2 and 6 on Plate 8). An explorer then would have recognized these passages as containing a continuous canyon (Canyon 1) leading to a shaft that led to another canyon (Canyon 2).

Stage III

Stage III began with the introduction of clastic sediments and gradually increasing discharges. Because this account concentrates on the growth of Canyons 1 and 2, stage III will be subdivided into only 2 substages. Were the Headwall Passage (including shafts 3 and 4) and conduits downstream of 52 considered, it would be necessary to distinguish more substages (see Figure 107H-107J).

Stage IIIA. The stream from Cove Run cut surfaces of widening 1 and 2, lowering the floor 1 to 2 feet, except near the shaft between Canyons 1 and 2, where incision was greater. The upstream wall of the shaft was no longer vertical, a state that originated in the details of the geometry of the N 30-45° E set joints that guided the initial conduit.

Higher rates of erosion at the shaft (compared to lower-gradient reaches upstream in Canyon 1) led to headward erosion of the shaft lip, beginning the transformation of the shaft into a paleoshift (Plate 8).
Stage IIIB. The transformation of the shaft into a paleoshelf continued with the development of section 5A. Section 5A linked as vertically extensive joints in the floor widened and formed a conduit targeted into the shaft basin (Plate 8, Figure 107H). The linkage decreased the slope separating the upper and middle passage levels and facilitated a partial grading of the bedrock floor profile between Canyons 1 and 2.

Joints exposed in the floor were enlarged, pirating water to lower conduits that likely connect to canyons in Canadian Hole above Monster Falls. Clastic sediments were transported through the North Canyon in large quantities. Large boulders and plates filled much of the wide trench near the Swallet entrance. If the fracturing of the lower walls in the wide trench is primarily frost fracturing, rather than unloading fracturing, then future research may be able to use that fracturing to place an absolute time scale on part of the relative chronology worked out above.
CHAPTER 7

SUMMARY AND CONCLUSIONS

Structural Segments and Segment Analysis

1. Fracture conduits are small conduits that (a) transmit groundwater along integrated flow paths and (b) are aligned along fractures. Integrated flow paths are flow paths that can be specified continuously from an input to a different output. Structural segments are fracture conduits inferred in caves. Structural segments are classified as single-fracture segments, intercept segments, or zone segments, depending on the number of fractures or the manner in which flow was transmitted along a given reach. Segment analysis is a procedure for identifying, mapping, and studying structural segments. Segment analysis also includes the study of the influences of structural segments upon the morphology and pattern of cave passages as passages grow.

2. Geologic conditions conducive to the study of structural segments include (a) prominent but widely spaced fractures, (b) massive bedding, (c) minimal collapse of walls or ceilings, (d) limited sedimentation by clastics or chemical precipitates, and (e) patterns of
enlargement that preserve a majority of the initially transmissive fractures as fracture traces on the bedrock perimeters of passages. These conditions are most often fulfilled in small-diameter passages, particularly in canyons in branchwork caves.

3. Structural segments are identified with a set of inference criteria. The set used depends on the geohydrologic setting and the types of cavern development. If bedrock is massive, and fracture frequencies are relatively low, then prominent fracture traces on the perimeters of tubes, canyons, or shafts are likely to represent the fractures used by the structural segments. The above statement should be true if the following primary conditions hold. Processes of enlargement should not have created new fractures that could be mistaken for the initially transmissive fractures. Neither should enlargement have been so extensive or so directed as to have totally destroyed the transmissive fractures, or to have removed them from view. The primary conditions are commonly violated in passages with extensive pressure-release jointing, exfoliation, or crystal wedging (e.g., by growth of gypsum). Passages formed by paragenesis are unlikely to be suitable for segment analysis.

4. Segment analysis requires identifying which of the prominent fractures guided early flow, and the positions of that early flow on the fractures. In tubes, the structural segments are to be sought on fractures near tube bases, where anastomoses, pendants, or dissolutional spurs indicate high permeability. In canyons, early tubes may remain as prominent ceiling or half-tubes after incision by vadose
streams. Structural segments are then to be sought on fractures near the ceiling, above the highest features of entrenchment. Useful features of entrenchment include cusps, undercut surfaces, notches, ledges, bedrock meanders, potholes, and trenches. Where fractures are vertical, the elevations of features of entrenchment are critical in locating the initial positions of flow. For each reach of tube, canyon, or shaft, the appropriate remnant of the early conduit (or part of the passage) must be roughly concordant to the fracture that is a candidate for having contained the structural segment.

5. Segments are designated according to rules that divide the cave into sections of segments where flow paths branch. Each segment is specified by naming its host fracture and its endpoints. For example, an intercept segment formed on the intersection of a fault and a joint between positions 5 and 6 in section Q is fault-joint segment 5-6. Junctions of segments are named with the names of the sections that intersect at the branchpoint. For example, sections M, N, and 1A intersect at position 5 at junction M, N, 1A.

6. To study structural segments and their influences on subsequent conduit development, it is necessary to map the three-dimensional patterns of the segments. This requires closely spaced stations whose elevations are accurately known, preferably by a detailed leveling survey. Normal cave surveys using Bruntons or Suuntos for the vertical component are not sufficient. It is necessary to map the relationships of the segments to plans, profiles, and cross sections of the passages, taking careful note of lithologic features. The lengths of the
structural segments must be measured so that accurate plans and profiles of segment midlines (symbols representing the locations of the initial flow on the fractures, as drawn on midline diagrams) can be drawn. Conduit evolution is then analyzed with the aid of (a) the diagrams, (b) observations of the morphologic features present near junctions of conduits, (c) observations of features of entrenchment, and (d) an understanding of processes effecting enlargement of conduits.

The method of segment analysis is tedious and time-consuming. It requires cooperative field assistants who are willing to work long hours in cold, windy, wet, or muddy conditions. It requires cave passages that can be visited many times in order to make exhaustive observations of morphologic features. Until (a) the passages and segments have been mapped, and (b) the segment profiles have been drawn, it is not clear what morphologic observations are necessary to identify temporal relationships between the flow paths. Nor is it entirely clear what additional data are needed to interpret flow-path history. In each case, the necessary data will depend on the particular features that have formed and that remain sufficiently unmodified to interpret.

8. In most caves, the patchy nature of the evidence renders unjustifiable the effort required by segment analysis. Yet in many caves (for example, numerous branchwork caves in West Virginia), flow paths followed a variety of recognizable fractures under changing hydrologic conditions. The modern conduits lie on several levels and
connect in sometimes bewildering fashion. Canyons lead to tubes which lead to shafts which lead to tubes. Initial, diversion, or floodwater flow paths appear in relatively small parcels of bedrock. Passage development may appear so complex as to be undecipherable—or worth, at most, a generalized analysis. Nonetheless, the evidence is there, and segment analysis can be one fruitful—if arduous—procedure for collecting and analyzing the data. Indeed, in some cases, it may be the only way for the speleologist who would transcend the vague talk of structural controls that appears in so many otherwise excellent studies.

Segment Analysis in Snedegar Cave

The Investigated Passages

9. Snedegar Cave is part of Friars Hole Cave system, an extensive branchwork cave north of Renick, West Virginia, in the eastern Allegheny Plateau. Snedegar Cave consists of a series of canyons, tubes, shafts, and rooms. Segment analyses were undertaken in the North Canyon, the Headwall Passage, and the Saltpetre Maze Passage. The main passages of interest are Canyons 1 and 2 of the North Canyon. The Saltpetre Maze Passage (in the Saltpetre Maze) and Canyon B of the Headwall Passage, were investigated because of their roles in the development of Canyons 1 and 2. Canyon 1 begins at the Swallet entrance, the present downstream surface terminus of the Cove Run basin. Segment analyses were carried out from the downstream end of
the entrance chamber through Canyon 1 and in Canyon 2 downstream to position 59, an arbitrary but convenient termination.

The Lithologic and Structural Settings

10. The lithologic and structural settings were determined by field work in Snedegar Cave and at additional locations throughout Friars Hole Cave system. The following summary concentrates on information relevant to the interpretation of the development of Canyons 1 and 2.

11. The investigated passages are in the Union Limestone of the Mississippian Greenbrier Group. The Union Limestone contains relatively pure (in terms of CaCO₃) biosparites, oosparites, and micrites interbedded with four argillaceous units. The argillaceous units contain illite- and kaolinite-rich micrites and dolomicroites. The purer units range from 5 to 35 feet thick and are massive; the impure units range 3 to 10 feet thick and are often finely laminated. The investigated parts of the North Canyon and associated passages are in the purer units E and F. The top of unit E is bed parting 1, a prominent parting exposed only at the entrance to the North Canyon and the Saltpetre Maze. The base of unit E contains closely spaced bed partings 6 through 8. Bed parting 8 (B8) is prominently weathered (with dissolutional spurs or re-entrants, tubes, half tubes, and anastomoses) throughout its extent in most of the major passages of Snedegar Cave, where it is usually exposed on walls a few inches below the ceiling. B8 is the top of unit F. The base of unit F is bed
parting 15, an undulatory contact with argillaceous unit G.

12. To the east of Snedegar Cave is Droop Mountain, which lies 10 miles west of the Browns Mountain anticline, on the Webster Springs tectonic block. Droop Mountain is underlain by a minor anticline that plunges to the south. In and near Snedegar Cave, bedding in the Union Limestone strikes north to northeast and dips up to 6 degrees to the west. Numerous small undulations including anticlines, synclines, and closed basins, are superposed on the form of the bedding, which cannot usefully be approximated by a single unfolded plane. For analysis of speleogenesis, it is necessary to undertake leveling surveys and prepare structural contour maps on each major transmissive bedding plane parting.

13. An extensive zone of mesoscale thrust faults crops out in the Greenbrier carbonates on the surface and in Friars Hole Cave system. The faults parallel bedding in the impure units. They ramp up through impure units or prominent contacts between pure units. The faults then flatten into stratigraphically higher impure units or prominent contacts between pure units. The faults occur in zones in which one fault terminates along strike, only to be replaced by another fault, which often is offset slightly. Lack of attention to the details of the geometries and distributions of faults have led some investigators to postulate major faults and extensive fault control of passages (in Friars Hole Cave system and other caves in West Virginia) where neither was present. The faults are often accompanied by subparallel joints. Both faults and joints have bimodal distributions of strike, with peaks
at N 5° W to N 5° E and N 15-30° E. The faults and joints dip with nearly equal frequencies to the east and west. The joints are often scattered within pure units near faults, but are most abundant in tabular zones between thin beds. In Snedegar Cave, one such zone is in the base of unit E between bed partings B6 and B8. This zone is present over much of the exposed extent of B8 in Snedegar Cave.

14. The Union Limestone is cut by joints that have been assigned to regional systematic fracture sets trending N 60-75° E and N 30-45° E. The N 60-75° E set joints are more abundant and occur en echelon in zones. At their lateral terminations, the joints hook toward and often intersect other joints of the same set. In places, cross joints orthogonal to the N 60-75° E set also appear.

15. Densely fractured bedrock appears near some thrust faults, and the fractures may be fault-related. Other densely fractured bedrock seems to contain unloading fractures and fractures partly enlarged by frost wedging. Clay-rich units often contain exfoliation jointing associated with chemical weathering or stress release of overloaded passage walls.

Segment Analysis and Stage I Conduits

16. Segment analysis led to the identification and measurement of 1382 feet of structural segments. Flow was guided by bed partings (37.8% of the total length), N 60-75° E set joints (29.2%), N 30-45° E set joints (0.8%), cross joints (0.2%), bed-joint intercepts (20.7%), faults (7.6%), and fault-joint intercepts (3.6%). In addition, 26 feet
of mined segments were measured. Mined segments are reaches of conduit along which bedrock was dissolutionally removed (mined) without the aid of guiding fractures.

17. The segments have plan-view midline patterns that are linear, sinuous, en echelon, or offset. On the profile, the segments formed upper and lower loops. (A lower loop is a reach over which flow descended and then rose to a high point; an upper loop is a reach over which flow rose to a high point and then descended.) The segments thus formed ungraded flow paths. The flow paths of interest formed two segment levels that descended from east to west. Connections between segment levels 1 and 2 are provided by joint segments. Connection from segment level 2 to segment level 3 (not studied) was on a fault cutting argillaceous unit G of the Union Limestone.

18. The segments initially grew under conditions of closed-conduit flow. Those conditions were maintained sufficiently long for small tubes and fissures to enlarge and link, forming a complex network with several closed loops. That period of growth and integration is stage I development.

19. Morphologic remnants of the stage I conduits are preserved as abandoned tubes or as half tubes on canyon ceilings. These remnants make it possible to reconstruct the characteristics of the conduits at the onset of entrenchment for each segment. The stage I conduits were closely concordant to their host fractures. Cross-sectional areas averaged 2 to 3 \( \text{ft}^2 \) but ranged up to 10 \( \text{ft}^2 \). (A) Bed segments were mostly on B8, and extended 6 to 8 inches upward through bed partings B7
and B6. Although B7, B6, and the fault-subparallel joints appear on the walls of the remnants of the early tubes, these fractures almost always lack dissolitional features such as re-entrants or bedding plane anastomoses. Such features are abundant on B8, so it is unlikely that these other partings and fractures formed structural segments. (B) N 60-75° E set joint segments were mostly zone segments arranged in an echelon zones. Cross-sectional areas were highly variable compared to other segments because joint spurs and bells were enlarged outward from the central parts of the segments, which were mostly vertical fissures. (C) Bed-joint segments had three or four spurs developed outward from the bed-joint intercepts. (D) Cross joint segments were vertical fissures. (E) Fault segments were tubes with slanting spurs along the sides. (F) Fault-joint segments were similar to bed-joint segments, but lay on a slant.

20. Stage I development included three substages. During stage IA, a flow path in the Saltpetre Maze Passage branched into two conduits. The conduits of interest trended northwest to the Rat Hole, then followed Canyon I to the Connection Tube. The path followed the Connection Tube, part of Canyon B of the Headwall Passage, a joint segment (at the present First Paleoshift), and then used Canyon 2 on segment level 2. Along segment level 1, the stage IA flow path is near or on B8 throughout its length. Deviations from B8 appear, mostly where joints descended on lower loops that returned to B8 farther downstream. The joints (and in a few cases, faults or nearby bed partings) were likely wider than B8 during the initial selection of
fractures to form integrated flow paths.

21. Stage IB began with the linkage of two tributaries. One tributary (in Canyon B) linked at the downstream end of the Connection Tube; the other (in Canyon I) linked at the Rat Hole. These tributaries must have begun their growth during stage IA. However, morphologic and other evidence indicates that they did not link as open conduits as early as the separate conduits making up the stage IA flow path. Stage IB linkages changed the hydrologic conditions (the flow field) in stage IA conduits. Stage IB linkages also provided a source of more aggressive ground water and higher hydrostatic heads during flooding.

22. The changed conditions favored the integration of several short cuts where prominent fractures provided shorter, higher gradient routes. Stage IC began with the linkages of two such short cuts. One formed near the Swallet entrance along Canyon I in the stage IB tributary; it used joints below B8. The other formed between the entrance to the Connection Tube and the base of the First Paleoshift; it used B8 first, then a prominent vertical joint (at the Second Paleoshift), and finally several bed, joint, and bed-joint segments on a lower loop that rose downstream to the base of the First Paleoshift.

Stage II

23. Stage II began with the earliest onset of vadose conditions. Those conditions may be associated with one or more of the following factors: (a) a decrease in discharge into the network; (b) growth of
the network to a size too great to maintain closed-conduit flow; or (c) an integration of some part of the network into a lower air-filled conduit.

24. Vadose conditions began throughout the network on the tops of upper loops. Nearby lower loops continued to grow under conditions of closed-conduit flow. Low-discharge streams incised the upper loops, transforming the tubes into half tubes and carving narrow trenches. Because the tubes of lower loops continued to grow under pressure flow, their half tubes are larger than half tubes of upper loops. Additionally, blind joint spurs continued to grow on the perimeters of the tubes of lower loops.

25. As entrenchment progressed, the narrow trenches maintained a relatively constant width of 1 to 2 feet. Undercut surfaces, cusps, and notches formed on trench walls. The narrow trenches deepened and lengthened at the expense of the pressure loops, which decreased their vertical relief and length, before being split into several smaller pressure loops or being destroyed. The low-discharge vadose flows that carved the narrow trenches carried minimal amounts of clastic sediments during stage II conditions. By the end of stage II, entrenchment had graded the floors of the narrow trenches continuously on the upper passage level from the Swallet entrance to a shaft between segment levels 1 and 2, forming Canyon 1. Entrenchment had also graded the floors of the narrow trenches on the middle passage level below segment level 2, forming Canyon 2.
26. Entrenchment did not occur on all stage I flow paths. Where flow paths branched in a downstream direction, the low-discharge vadose flows followed the routes that were lower or that lacked downstream high points at elevations higher than the branchpoints. This process of route selection resulted in the abandonment of (a) the tube connecting the Saltpetre Maze Passage to Canyon 1; (b) the A-tubes near the Swallet entrance; and (c) the Connection Tube between Canyon 1 and Canyon B.

Stage III

27. Stage III began with the introduction of clastic sediments and gradually increasing discharges. The clastic sediments promoted lateral undercutting, which lead to the production of wide trenches below the narrow ones. The trenches are separated by prominent surfaces of widening at many locations. The surfaces of widening are undercut surfaces that slope at less than 2 degrees downstream and maintain consistent gradients throughout their lengths.

28. During stage III, the shaft separating Canyon 1 and Canyon 2 was transformed by headward erosion of the shaft lip, basin retreat, and a flow path diversion, into a partly graded floor connecting Canyon 1 to Canyon 2. Canyon 2 was not similarly graded, between the middle and lower passage levels of the North Canyon, because argillaceous unit G formed a perching caprock that protected a lower pure unit.

29. Increasing peak discharges to the North Canyon from the surface stream, Cove Run, transported large clastic sediments,
including boulders, into Canyon 1, partly filling the wide trench.

30. During stage III, bedrock surfaces in the wide trench near the Swallet entrance were fractured, perhaps by a combination of frost action and exfoliation. Additionally, bedrock surfaces were modified by dissolution from condensed moisture, which increased surface roughness and formed drop and rivulet patterns similar to those produced by condensed moisture on glass.
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GLOSSARY

New Terms or Standard Terms with Special Meanings

**air bell**: an air-filled pocket in the ceiling of a conduit that otherwise is completely flooded. The pocket may take any shape. Typical forms include joint fissures, cylindrical bells, and domes.

**appropriate concordance**: the requirement that the part of a passage that is a candidate for having contained a structural segment be concordant to an appropriate fracture, line of fracture intercepts, or zone of fractures. Concordance means "aligned along". Concordance is a three-dimensional property. Concordance is not equivalent to "having the same orientation as". It is true that many transmissive fractures are roughly planar, and are adequately described by a single attitude by specifying strike and dip. Yet many fractures are not adequately so described. Fracture conduits can have any orientations along their lengths that are allowed by the changing attitudes of their host fractures.

**bedrock dam**: the bedrock which ponds a body of water within a conduit. The water body may be a small pond, a lake, or a completely flooded conduit. The top of the bedrock dam (or sediments on the bedrock) forms a high point within the flow path.

**bedrock meanders**: those parts of sinuous bedrock trenches which contain walls whose plans, as drawn for successive stages of downcutting, resemble the plans of river meanders. Bedrock meanders need not exhibit cusps or notches, but always have undercut surfaces.

**bed segment**: a structural segment that uses (is on) a bedding plane parting.

**bed-joint segment**: a structural segment that uses (is on) the intercept
branchpoint: the position at which a fracture conduit divides into two or more fracture conduits. A branchpoint is also a junction of sections of segments, or a junction of conduits enlarged from segments.

branching rule: fracture conduits are divided into sections of structural segments wherever fracture conduits branch. Alternately stated, flow paths are divided into sections wherever flow paths branch. The division of flow paths into several routes in a downstream direction is downstream branching; the joining of two upstream routes to form a third route downstream is upstream branching. For practical reasons, exceptions are made to the branching rule for very short closed loops on a single fracture, or for anastomoses on a single fracture. Exceptions are also made for branching along blind fissures (which are not, strictly speaking, structural segments) and for the branching in passages that occurs where mined segments form.

branchwork cave: a cave with a branching plan pattern, usually a result of the input of tributaries.

breakdown: in caves, bedrock fragments usually produced by collapse. By extension, the term is applied to other locally-derived fragments produced by such processes as crystal wedging, e.g., by the growth of gypsum.

canyon: by some interpretations, a canyon is a passage that is neither a vertical shaft nor a fissure, and which has large height:width ratios. So conceived, canyons can form by entrenchment or by paragenesis. Each type of canyon has characteristic features, which depend on the geohydrologic setting and changes in it. In this study, any passage whose floor has been entrenched, and whose volume has been excavated mostly by processes of entrenchment, is a canyon. The distinction is necessary because of the style of growth of many canyons, which enlarge by entrenchment of pre-existing tubes or fissures. It is in fact helpful to have a defined cutoff point (over 50% of the volume) for the transition over time of the original conduits into canyons. It is helpful to have a defined cutoff point for the transition of tubes to canyons or canyons to tubes within individual continuous passages; this is particularly true where the original tubes and fissures had ungraded profiles, and simultaneous open- and closed-conduit flow occurred nearby within the same flow path.

centerline: a line drawn down the center of a conduit or a part of a conduit, as shown on the plan.
classes of structural segments: groups of structural segments. There are three classes. The classes are distinguished on the basis of the number of fractures that guided early flow, or on the basis of the way in which that early flow was guided. The classes are: single-fracture segments, intercept segments, and zone segments.

closed loop: a flow path or conduit that branches but then rejoins; the closed loop consists of the two separate routes or conduits that rejoin.

condensation weathering: the weathering induced by condensation of moisture on cave walls and ceilings. Condensation weathering increases the surface roughness of walls, ceilings, and breakdown, producing rivulet and drop patterns.

cusp: a rounded or sharp edge or projection on the wall of a trench. Cusps are boundaries of undercut surfaces; they descend at low gradients in a downstream direction.

dissolutional mining: the process of dissolutional removal of bedrock to form part of a flow path. Dissolutional mining can link previously unjoined fractures to create a flow path. Dissolutional mining can bore through unfractured bedrock to link pre-existing conduits, forming, for example, higher gradient cut offs. The bedrock removed by dissolutional mining need not be entirely unfractured; the essential point is that the fractures did not form fracture-guided conduits.

downstream branching: the division of a conduit or a flow path into two or more routes farther downstream.

drop: a reach of structural segments that loses elevation in a down- stream direction. Also, in standard caving terminology, an abrupt loss of elevation in a passage or from one passage to another, usually requiring vertical ropework to negotiate.

drop pattern: the droplet-like pattern of bedrock surfaces resulting from condensation weathering.

endpoint: the beginning or end of a segment. An endpoint is designated by a position name. Endpoints of single-fracture segments and intercept segments can usually be specified with precision as points. However, endpoints of zone segments and mined segments are often very difficult to locate precisely. Hence their endpoints are often more accurately described as regions, and it becomes useful to speak of regions of transfer of ground water from one segment to another.
endpoint rules: endpoints are designated at positions or regions where
(1) flow changed from one fracture or fracture zone to another
fracture or fracture zone; (2) flow changed from one class
of structural segments to another class of structural segments;
(3) flow branched on a single fracture; or (4) flow passed to or
from a mined segment.

entrenchment: in caves, the process of conduit enlargement as directed
primarily downward through the activities of a free-surface
stream. Downcutting refers to the lowering of the floor as floor
material (either sediments or more importantly, bedrock) is
removed. Lateral undercutting refers to the undermining of the
walls of a conduit by a stream. Headward retreat refers to the
upstream migration of a feature (e.g., the lip of a shaft or a
drop) as entrenchment proceeds. Entrenchment is aided by any
processes that weaken bedrock floors, walls, and ledges (e.g.,
chemical and physical alteration of clay minerals; gypsum wedging;
flaking and exfoliation).

en echelon pattern of joints: the offset, overlapping pattern of joints
at their terminations as seen on plans. Joints may terminate with
or without hooking toward or intersecting other joints of the same
set.

en echelon pattern of midlines of joint segments: the offset linkage
pattern of midlines of some joint segments, as seen on plans drawn
for single elevations.

fault segment: a structural segment that uses (is on) the intercept of
a fault and a joint.

fault-joint segment: a structural segment that uses (is on) the
intercept of a fault and a joint.

features of entrenchment: morphologic forms produced by processes of
entrenchment. Examples include potholes, certain ledges, cusps,
undercuts, and notches.

fracture conduit: a small conduit that transmitted ground water along
an integrated flow path and that was aligned on a fracture, the
intercept of several fractures, or a zone of closely spaced
fractures.
fracture-conduit stage (of the development of a flow path): that stage at which integrated flow from specifiable inputs to specifiable outputs has been established, such that the bulk of the flow within a given parcel of bedrock is through discrete fracture conduits. Usually, the fracture conduits have sizes considerably larger than nearby less altered fractures that may contribute small diffuse flows. Specifiable inputs and outputs are designated by position names on plans, profiles, and cross sections of maps. The inputs can, but need not be surface inputs (e.g., sinks, shafts, swallets) or outputs (springs, resurgences).

graded flow path: a flow path having a slope that is relatively uniform and that descends consistently in a downstream direction. Usually the term is restricted to the discussion of specific reaches of flow paths or conduits, for specific stages of development. The term may refer to conduit floors and midlines. By extension, it is often useful to refer to ceilings as having graded profiles.

high point: on a midline, a point with a greater elevation than surrounding points up- or downstream. On the floor of a canyon, a high point is a point that has a greater elevation than nearby points up- or downstream.

high region: on a midline, a short reach with a greater elevation than surrounding reaches up- or downstream.

integrated flow path: a flow path that is linked continuously from specifiable inputs to different specifiable outputs. See fracture-conduit stage.

intercept segment: a structural segment that uses (is aligned along) the intercept of two or more fractures. If there is more than one intercept, the segment is a zone segment. If the fractures are planar, then the intercept will be linear.

joint segment: a structural segment that uses (is on) a joint.

junction: the branchpoint or position at which three or more sections intersect. Also, a junction is the intersection of three or more conduits. Junctions are named using the word junction and the names of the sections, for example, junction 1,2,3 is at the branchpoint where sections 1, 2, and 3 intersect.

lateral offset: a plan pattern of segment midlines in which midlines trending in a consistent direction are interrupted in the middle by a sideways offset.
lateral undercutting: the process by which a vadose stream cuts into a wall, gradually undermining it. Undercutting produces notches, undercuts, cusps, undercut surfaces, and ledges. Undercutting is common at bends of conduits on outside walls. Undercutting may occur on straight reaches if clastic sediments or breakdown armours the floor and direct the flow against walls.

level of structural segments (segment level): a reach of structural segments (or a network of structural segments in two or more sections) at approximately the same elevation.

lift: a reach of structural segments that gains elevation in a downstream direction.

linear pattern: a plan pattern of segment midlines in which the midlines have straight traces.

looping of ground water: the ascent or descent of ground water combined with a return of the ground water to the original elevation, more or less, at a point farther downstream. No actual closed loop in the flow path is implied.

low point: on a midline, a short reach with a lower elevation (within a lower loop) than surrounding reaches up- or downstream.

low region: on a midline, a short reach with a lower elevation (within a lower loop) than surrounding reaches up- or downstream.

lower loop: a reach of structural segments heading downstream with a drop followed by a lift and ending with a high point or a high region.

maze cave: one having multiple closed loops that formed contemporaneously.

midline: a line that represents the positions of flow of ground water on a structural segment, as inferred for the onset of integration of a flow path. For a single-fracture segment or an intercept segment, the midline is usually at or near the center or middle of the morphologic remnants of the early conduits, as represented on plans.

midline diagram: the schematic representation of the midlines of structural segments on plans, profiles, or block diagrams.
mined segment: a reach or segment of a conduit formed by dissolutional mining. The most common mined segments are in canyons where entrenchment has removed unfractured bedrock on the floor, and then intersected a fracture which enlarges into a fracture conduit, thus forming part of a separate diversionary flow path.

narrow trench: in Snedegar Cave, the upper, narrow parts of many canyons. Before the onset of wider entrenchment, there were only narrow trenches. Most narrow trenches were modified, with wider trenches forming below them. In some locations, particularly downstream of position 59, diversion flow paths formed, and the narrow trenches were left intact.

network maze: a maze with an angular pattern of intersecting passages.

nested loop: a lower or upper loop that is part of, and is contained within a larger lower loop.

notch: an indentation in the wall of a trench; the notch consists of an upper cusp, an undercut surface, and a lower cusp or a ledge.

offset pattern: see lateral offset.

paleoshift: the remains of a shaft left after headward retreat and lowering of the lip of the shaft.

passage level: a reach of passage (or a network of passages) at approximately the same elevation.

passage segment: a reach of passage. Also, the reach of passage that is enlarged from a specified structural segment or mined segment.

pattern of linkage (linkage pattern): the spatial arrangement of midlines of linked segments. Patterns of linkage are defined with respect to the geometries of the midlines on plans or profiles.

perching height: the height of the floor of a canyon above local base level.

plan pattern: the plan-view spatial arrangement of the midlines of one or more segments.

position name: the name of a position within the cave. Position names are used for segment endpoints, branchpoints, junctions, and occasionally to locate other features. Position names are numbers or letters; they are combined with fracture names and the word "segment" to designate specific segments, e.g., bed segment 1-2. In most cases the first position name specified is upstream of the second one specified.
**pressure loop:** a reach of structural segments (or conduits enlarged from them) consisting of a lower loop (or one or more lower loops nested within a larger lower loop) during the time period in which flow is closed-conduit flow that is driven by a pressure gradient.

**profile pattern:** the profile-view spatial arrangement of the midlines of one or more segments.

**region of entrenchment:** a part of a conduit in which entrenchment is taking place. A tube may lie within a region of entrenchment and gradually be transformed into a canyon.

**region of transfer of ground water:** the region in which ground water transfers from one segment to another. For single-fracture segments or intercept segments the regions can usually be specified as precise endpoints. For zone segments and mined segments the endpoints are more difficult to locate precisely, and endpoints designate small regions instead.

**rivulet pattern:** the pattern produced by thin films of condensed moisture that descend steeply sloping bedrock surfaces. The pattern closely resembles the rivets that form when condensed moisture coalesces and descends window panes in houses in the winter.

**section of passage:** a reach of passage that has been enlarged from a section of segments.

**section of segments:** one or more structural segments that are grouped together. If a flow path does not branch, then it will consist of a single section. If the flow path branches (or the conduit branches), then the branching rule applies, and at least three sections of segments must be designated. Exceptions to the branching rule are made in several circumstances (see: branching rule).

**segment analysis:** the process of identifying, mapping, and studying structural segments. Segment analysis includes the investigation of the factors influencing the integration of structural segments, and the study of the influences of structural segments on the growth of the early conduits into the modern passages.

**segment length:** the length of a segment. The length of a structural segment is the length of its midline. The length of a mined segment represents the minimum amount of rock removed by dissolutional mining; it is measured in a straight line from the nearest appropriate structural segment upstream or above, to the endpoint or other appropriate position on the target structural segment downstream.
**segment level:** level of structural segments.

**segment name:** the name of a segment. For a structural segment, the name is constructed by placing the name of the host fracture before the word "segment", followed by a specification of the segment endpoints: for example, bed segment 1-2, or joint segment 9-3. For a mined segment, the name is constructed by adding a specification of the segment endpoints to the words "mined segment": for example, mined segment 55a-56.

**segment terminology:** the terms used in the description and study of segments.

**segment types or types of structural segments:** groups of structural segments based on the type of host fracture or fractures. Examples include bed, bed-joint, and joint segments.

**single-fracture segment:** a structural segment that uses (is aligned along) a single fracture such as a joint.

**sinuous pattern:** a plan pattern of segment midlines in which the midlines curve or wind around.

**speleogenesis:** the origin of caves.

**structural segment:** an inferred fracture conduit. More technically, a conduit inferred along one or more fractures, such that the fracture-conduit(s) can be inferred to have guided the flow of ground water during the early fracture-conduit stage of the development of the flow path. For practical reasons, a structural segment may consist of more than one conduit on a single fracture, where it is not useful to distinguish each individual conduit. For example, closely spaced anastomoses on a single bed parting are often most usefully treated as a single structural segment.

**surface of widening:** a surface along which passage width increases, usually by a factor of two or more. Surfaces of widening are undercut surfaces, some of which have been slightly modified by collapse. In Snedegar Cave, surfaces of widening separate the upper narrow trenches from the lower wide trenches.

**target segment:** the first clearly distinguishable segment downstream of an apparent gap in the segments of a flow path.

**undercut:** part of the wall of a trench that has been undermined by a vadose stream. An undercut consists of a cusp and an undercut surface.
**ungraded flow path:** a flow path that is not graded (see: graded flow path).

**upper cusp:** the cusp above an undercut surface with a notch.

**upper loop:** a reach of structural segments heading downstream with a lift followed with a horizontal stretch or a drop.

**upstream branching:** the division of a conduit or a flow path into two or more routes (as tributaries) farther upstream.

**wide trench:** in Snedegar Cave, the lower, wide part of a canyon.

**zone segment:** a structural segment formed in a zone of fractures that are too closely spaced to reliably infer which one or more of the fractures or fracture intercepts transmitted ground water during the fracture-conduit stage of the development of the flow path.
GEOLOGIC MAP
FRIARS HOLE
and Environs
West Virginia

PLATE 1

Pennsylvania
Pottsville Group (sandstone, conglomerate)

Mississippian
Muschelkalk Group (shale, sandstone)
Greenbrier Group (limestone)
Moccasoy Formation (shale)

after:
Price (1929)
Price and Mack (1939)
Cordwell et al. (1960)
PLATE 8 STAGE II AND STAGE III PROFILES
SNEDEGAR CAVE, FRIARS HOLE, WEST VIRGINIA

STAGE II A (ONSET)

STAGE II B (EARLY)

STAGE II B (LATER)

STAGE III A (ONSET)

STAGE III B

STAGE II B (MODERN PROFILE)
PLATE 3: STAGE IA - I C
AND ASSOCIATED PASSAGES
FRIARS HOLE, WEST VIRGINIA

STAGE IA

SH Sound Hole
RH Rat Hole
CT Connection Tube
FP First Paleoshift
SM Section M
24 Position 24
J3,5,8 Junction 3,5,8

STAGE IB

STAGE IC

See Figures 28, 51, 95
PLATE 10  STAGE II IN THE NORTH CANYON
AND ASSOCIATED PASSAGES
FRIARS HOLE, WEST VIRGINIA

STAGE IIIA
ONSET OF ENTRENCHMENT
CT Connection Tube
FP First Paleoshift
SP Second Paleoshift
NT Narrow Trench
PL Pressure Loop 1
7D Section 7D

STAGE IIIB

Canyon 2
Canyon 3
CT
FP
SP
NT

Swallet Entrance
A–tubes
Rat Hole
Canyon 1

END OF STAGE II

See Figures 28, 51, 95