SEDIMENTATION IN KARST DRAINAGE BASINS

SEDIMENTATION IN KARST DRAINAGE BASINS ALONG THE ALLEGHENY ESCARPMENT IN SOUTHEASTERN WEST VIRGINIA, U.S.A.

By

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SCOPE AND CONTENTS:

The stratigraphy of Holocene and Pleistocene deposits in the caves and related karst features along the base of the Allegheny Escarpment provides a basis for study of depositional events immediately beyond the maximum limits of Pleistocene glaciation during approximately the last 500,000 years. This study proposes to: distinguigh between major sedimentary events as recorded in the surface and subsurface deposits of three karst drainage basins; correlate sedimentary stratigraphy where possible from passage to passage, channel to channel, and basin to basin; examine and explain some of the processes of karst sedimentation; compare subsurface deposits with deposits described in the geomorphological and sedimentological literature; and determine the effect, if any, of sediments on the solutional development of caverns and karst drainage basins in the Greenbrier limestone.

ABSTRACT

A review of the literature shows a lack of information on stream transported and deposited cave sediments. Where such studies have been made, sedimentary structures have been overlooked or misinterpreted. A study of sedimentary deposits in Appalachian caves by the author indicates that a large quantity (over 75%) of the deposits found in caves of that area is derived from overlying or adjacent clastic rock and is deposited by streams at a time not contemporaneous with the origin of the cave passages. This contradicts the views of some geomorphologists. Additional evidence from scallop measurements on the floor, ceiling and walls of passages indicates velocities of different magnitude and directions from those which are responsible for the transport of a coarse bedload common to most passages. Scallops and passage profiles also indicate that fills may shield the cave floor from further solutional activity once a thick deposit of clastic material accumulates. Such deposits protect and preserve former large-scale scallops produced during passage solution. This allows for comparisons between scallop velocities and velocities which transported the sediments. Ancient deposits at higher levels in the caves indicate that the conditions of passage solution and deposition of fills have remained

relatively constant during approximately the last 200,000 years. However, some caves show evidence for massive, single depositional events with little sorting or rounding. This suggests periglacial activity on the Greenbrier karst at elevations around 2,500 feet; an elevation considerably lower than previously described sites in the area.

A model for the development of surface and subsurface drainage and sediments across the Greenbrier limestone is developed. This is based upon the changes in the tributary karst basins progressing in a downstream direction along the Greenbrier River. Karst "sieve-type" deposition, the accumulation of bedload at the upper clastic/carbonate contact, is an important feature of this model. Periglacial debris, now inactive, which accumulated during colder periods along the escarpment face is reworked by surface streams. This provides a source of coarse bedload for the sieve deposits. Fines are winnowed out and carried into the caves or accumulate in terraces below the karst risings in the lower basins.

The use of kaolinite 3.58Å/illite 10.0Å ratios from clay mineral samples shows weathering variations which are useful in provenance determination if considered along with data on milky quartz pebbles and identifiable lithologies. Dating by Thompson (1973) from travertine deposits directly on top of, or interbedded with, fluvial

sediments helped to establish relative and absolute dating of the deposits. It appears that travertine deposition is most active during the warmer inter-glacial periods. Although sediment deposition occurs throughout the warm and colder periods, it appears that massive single depositional events occurred during periglacial periods when travertine deposition was minimal.

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LIST OF ABBREVIATIONS

C.R.G.	Cave Research Group (of Great Britain)
N.S.S.	National Speleological Society (U.S.A.)
U.S.G.S.	United States Geological Survey
W.V.A.C.S.	West Virginia Association for Cave Studies

Chapter 1. INTRODUCTION

The study of cave sediments has been undertaken in a wide range of academic fields of interest. Much remains to be done, especially in the fields of sedimentology and geomorphology.

There are innumerable studies of cave deposits of archaeological interest. Schmid (1958, 1963) has stressed the natural materials versus the artifacts, bones, etc., that are the usual focus of interest. The work of Bordes (1972) attempted to integrate climatological speculation with archaeological findings in associated layers of a deposit. Brain (1958), Corbel (1961) and Link (1967) have also attempted climatological investigation of cave deposits. Studies emphasizing cave mineralogy have been conducted by White (1962), Curl (1962), Moore (1962) and Frank (1965). Hydrological investigations have received attention from White and Schmidt (1966), and Watson (1966). Petrology and stratigraphy of cave fills has received a disproportionate emphasis from many investigators, e.g., Lais (1941), Kukla and Lozek (1958), Lozek and Skrivanek (1965), Helwig (1965) and Reams (1968). Nevertheless, a review of the European and North American literature on sediments shows a general lack of information on material deposited by running water in caves (Chapter 2).

This study emphasises the importance of cave sediments deposited by streams in ancient and modern times. The preservation of sedimentary deposits of cave systems in the relatively protected underground environment for long periods of time makes such a study of temporal and spatial variations in the parameters of the deposits possible.

A. Aspects of Fluvial Sediments in Caves

Five aspects of fluvial sediments in caves are considered in this study: the basin or drainage net approach, provenance, sedimentary structures, processes of sedimentation in caves, and comparisons of ancient and modern sediments.

1. The Basin or Drainage Net Approach

The failure of most speleologists to "look outside the cave" and to consider it in relation to the surrounding landscape and drainage net, results in an incomplete evaluation of the cave sedimentary environment. An accurate evaluation of present and past rates and volumes of deposition within the caves cannot be made without considering the related surface conditions. Previous studies have often considered individual caves or selected groups of hydrologically unrelated caves. Such an approach to sediment studies cannot produce comparative data to provide an understanding of present and past rates of deposition within the basins or caves. Most caves are related closely to a specific drainage basin. They often function, now or in the past, as part of the main trunk or tributary channel of a modern or ancient drainage basin, part of which developed underground. Measurements of surface depositional characteristics can be compared with subsurface measurements. This comparison should include data on rate of deposition, provenance, clay mineral distribution, sedimentary structures, particle properties, and vertical changes in the deposits throughout the drainage net. Such an analysis is termed the "basin approach" to cave sediments in this study.

2. Provenance

The source and distribution of identifiable rock and mineral types throughout a defined area is another aspect of cave deposits that has received little attention. Davies and Chao (1959) used heavy mineral suites in Kentucky caves and Frank (1965) worked on changes in clay mineral distribution and the quantity of the deposits in central Texas caves. Neither of these studies, nor any others, have made an analysis of provenance and movement of specific rock and mineral types found in karst basins and their related cave systems. Provenance analysis can be a useful tool in determining the initial source of the deposits, changes of the source through time, and distance of transport of specific rock types. Marker horizons of specific rock types or deposits can aid in the measurement of volumes and rates of deposition in the caves and basins.

3. Sedimentary Structures

Sedimentary structures are a common feature of spelean deposits. A considerable volume of literature on sedimentary structures characteristic of fluvial deposits, has developed in geology since the work of Sorby (1859). This has not been utilised by cave sedimentologists. Features such as ripples, dunes, and graded bedding are useful in the understanding of former flow direction and intensity. One objective of this study is to describe and interpret such features in cave deposits. This has not been done to date in any of the cave sediment studies reviewed.

4. Processes of Sedimentation

Little is known or understood about the process of deposition in caves. Surface fluvial sedimentation processes have been studied in the field and laboratory (Chapter 2). A comparison of surface and subsurface deposits in their respective basins in this investigation may yield valuable information on the nature of spelean fluvial sedimentation. Observation of flood events and their results can give data on modern sediment processes. Past processes may be inferred from the characteristics of abandoned channel and upper cave level deposits. It is the study of basins rather than individual caves which makes such comparisons possible.

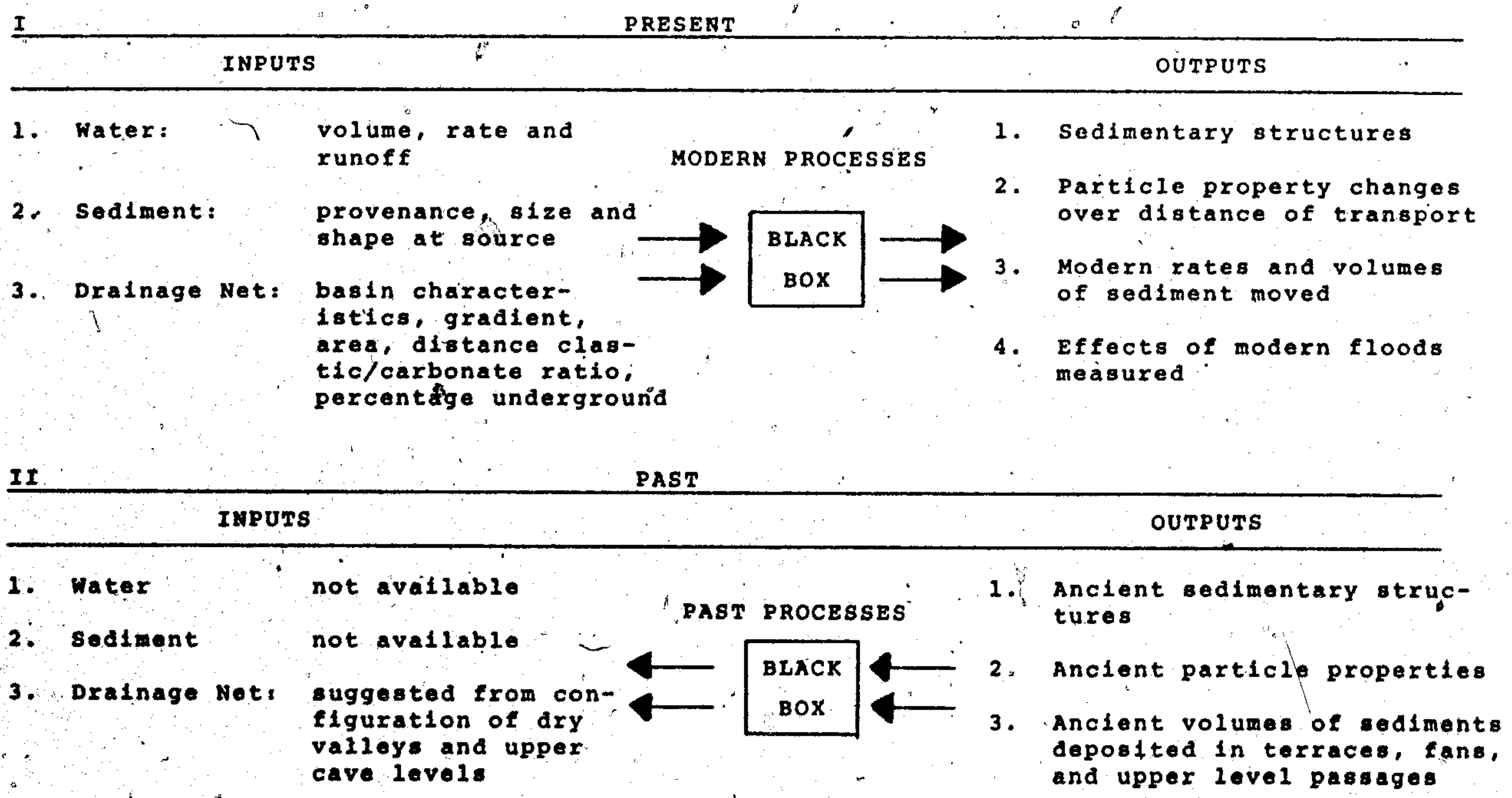
Figure 1.01 summarises these concepts. Within the PRESENT, it is possible to examine the INPUTS of modern active surface and subsurface cave streams. These include the parameters of stream flow, sediment load, and the drainage basin properties. It is also possible in the PRESENT framework to examine the resulting OUTPUTS. These include the result of flood events, sedimentary structures, and measurements of sediment volume and rate of deposition and particle properties. The actual processes of deposition are not fully understood, but full understanding is not necessary to draw comparisons between INPUTS and OUTPUTS with past OUTPUTS.

5. Ancient and Modern Deposits

Information about past and present basin conditions can be drawn from a comparison of the sedimentary characteristics of deposits in the abandoned upper "dry" levels of caves (OUTPUTS, indicative of earlier basin conditions) with the characteristics of the deposits in lower wet levels (indicative of modern basin conditions). Variations in sedimentary characteristics from one cave level to another cave level, from one cave to another cave in the same basin, and ultimately from one basin to another, may indicate climatic variations, drainage diversion or piracy, provenance changes, and/or local site variations in the conditions of deposition.

Figure 1.01

INPUTS AND OUTPUTS: SPELEAN FLUVIAL SEDIMENTATION



I PRESENT

INPUTS		OUTPUTS
1. Water:	volume, rate and runoff	1. Sedimentary structures
2. Sediment:	provenance, size and shape at source	2. Particle property changes over distance of transport
3. Drainage Net:	basin characteristics, gradient, area, distance clastic/carbonate ratio, percentage underground	3. Modern rates and volumes of sediment moved
		4. Effects of modern floods measured

II PAST

INPUTS		OUTPUTS
1. Water	not available	1. Ancient sedimentary structures
2. Sediment	not available	2. Ancient particle properties
3. Drainage Net:	suggested from configuration of dry valleys and upper cave levels	3. Ancient volumes of sediments deposited in terraces, fans, and upper level passages

In the PAST only the OUTPUTS remain for examination in the upper cave levels and in some surface terraces and fans. Dating of ancient deposits is possible by relative and absolute means. Modern OUTPUTS can be used in the interpretation of past OUTPUTS, which in turn can suggest something of the parameters of past INPUTS. The similarities and differences in these OUTPUTS can be compared and the causes of these suggested from the data available.

The application of these five concepts of study to a specific karst area comprises the major aim of this investigation. Three surface drainage basins containing underground drainage systems were chosen along the base of the Allegheny Front in southeastern West Virginia, U.S.A. The three basins were selected to obtain major contrasts in local relief, stream gradients, percentage of carbonate rock drained, drainage density and area, sediment load and its characteristics. There are traceable "identifiers" derived from overlying clastic rocks, which can be used in provenance studies within each basin; modern surface and subsurface deposits are abundant throughout each basin; and there are well preserved, ancient, dateable deposits in the many abandoned upper level passages of the caves as well as surface terraces and fans. All of these aspects of each basin combine to provide a suitable area for the application of the concepts presented in this chapter and outlined in Figure 1.01. A detailed description of each basin and its related cave systems is given in

Chapters 5, 6 and 7.

Several basic questions concerning cave sediments will be considered in this study. These are listed below:

(i) How are cave fluvial deposits similar or dissimilar to surface fluvial deposits?

(ii) At what stage in the origin and development of limestone caves are the fills deposited?

(iii) What are some of the relationships between ancient and modern deposits in caves?

(iv) Is there a cycle of deposition in caves?

(v) Can comparisons be made within individual karst basins and from karst basin to karst basin in the Appalachians, and if so what are they?

(vi) Is there evidence for climatic change recorded in the sediments of the area?

B. Choice of the Study Area and Sample Basins Within It

In order to choose the study area, a pilot study was carried out in four karst regions:

Central Kentucky, where karst features are developed in Mississippian limestone of relatively low relief;

The folded Appalachians of Pennsylvania, Virginia and West Virginia, developed largely in Cambrian and Ordivician limestones and dolomites;

The Canadian Rockies along the British Columbia-Alberta border, developed in Paleozoic limestones which are highly folded and faulted;

The Greenbrier limestone karst of southeastern West Virginia, developed in the Middle Mississippian Greenbrier Series in an area of relatively horizontal structure of moderate relief.

The Greenbrier area was chosen over the other areas for the following reasons:

1. The wide range of local relief along the Allegheny Front and the resulting variation in stream gradients. Which permits a comparative study of the effects of stream gradients on the nature of the deposits. This applies to both the surface trunk streams and the gradients of underground drainage systems. Cave deposits of the folded Appalachians and the Canadian Rockies possess a similar wide range of grain sizes. Deposits of the Kentucky karst are more restricted in size range.

2. The natural setting for studies of provenance and distance of transport of the sediment. Across-strike drainage over narrow parallel outcrops of clastic rock above the cave sinks provides a source of material which can be used as traceable "identifiers" in each basin. Milky quartz pebbles, large boulders of a specific rock type and clay mineral distribution can be used in this manner. Particle property studies should be limited to a specific rock type

from a specific outcrop if downstream changes in provenance and lithology are to be observed. The local setting of the Greenbrier karst is ideal for such an investigation. In areas of highly folded and faulted strata (folded Appalachians and Canadian Rockies), provenance and transport studies are very difficult.

3. The abundance of karstification in over 700 feet of highly soluble carbonate rock. This provides both active and fossil cave networks for comparative study of modern and ancient sediment inputs and outputs. The wide range of time covered by the period of cave deposition in this area includes all of the Holocene and the Wisconsin. At least 500,000 years have elapsed since some of the deposits were laid down (Thompson, 1971, personal communication).

4. The general lack of human occupance and/or relatively undisturbed landscape. With the exception of one major man-made event, deforestation in the late 1800's, this area has remained free of intensive agricultural use, road building, or other activities which might upset the natural processes of sedimentation.

The effects of deforestation are considered in this report.

The Choice of the Sample Basins

Three drainage basins were chosen for study using the following criteria:

Headwaters on a clastic source of traceable rock and mineral types suitable for a study of provenance and the effects of transport on the surface and subsurface deposits;

One basin containing surface and subsurface gradients of relatively low magnitude (average less than 50 feet per mile, including the headwaters);

One basin of moderate relief and medium surface and subsurface stream gradients (175 to 400 feet per mile);

One basin of high relief on the surface and in the caves (over 600 feet per mile);

A suitable range in catchment area size for the three basins;

A series of abandoned high level passages in the caves of all three basins, suitable for present-past comparisons in grain size, structures, volume of material, and source of variation;

Deposits that might be dated in an absolute or relative way through iostope dating, fossils, pollen analysis, etc.;

An open-ended cave system as part of the trunk channel of the basin, in which to study the net effect of cave deposition. In other words, a local setting which allows for a comparison between material entering a cave system and material coming out of that same system.

The three basins so chosen are each described separately in Chapters 5, 6 and 7.

Chapter 2. BACKGROUND TO THE STUDY OF CAVE SEDIMENTS

The background for this study may be divided into three categories:

A. Previous cave sediment studies, including attempts to classify cave sediments and studies which emphasize fluvial sediments in caves.

B. The karst geomorphological literature on cave origin and development as related to cave sediments, including vadose theories, deep phreatic theories and shallow phreatic theories.

C. Relevant surface sediment studies in geomorphology and sedimentology.

A. <u>Cave Sediment Studies</u>

1. <u>Classification of Cave Sediments</u>

There is no generally accepted classification of cave sediments. Various authors have grouped cave sediments according to their personal interests. Kukla and Lozek (1958) classified cave sediments on the basis of material found in caves. They used the terms "autochthonous" (derived from within the cave) and "allochthonous" (derived from outside the cave). They also divided the cave sediments into "entrance facies" and "interior facies". White (1963) proposed "clastic" (including autochthonous and allochthonous fills and "chemical" deposits). Frank (1965) refers to "tardigenic" (slowly deposited by infilling through small cracks) and "torrigenic" (rapidly deposited through larger openings). Such a scheme is problematical in that depositional rates do not necessarily correspond to the size of the openings into the passage. Link (1966, 1967) proposed a textural classification using a three end member triangle of clay, silt and sand.

In the broadest sense, all material found in caves, other than the host rock in situ, can be considered to be "cave sediments". In this study of fluvial sediments, process rather than source, texture or position of the deposits is the basis of their classification. The following classification utilises the terminology of previous investigators with an emphasis on geomorphic processes responsible for deposition in the caves.

2. A Classification of Cave Sediments

Clastics

1. Gravitational Fills: Products of weathering and gravitational transfer (without a transporting agent).

   Infiltrates: Material derived from outside the cave. This includes entrance detritus, soil, sinkhole fills, material which enters the cave via vertical shafts, joints or faults which does not show evidence of transport (see erosional fills).

Breakdown: Material derived from within the cave. This includes fine weathering detritus, large blocks and whole sections of ceiling collapse ("autochthonous" fills of Kukla and Lozek, 1958).

2. Transported Fills:

Products of erosion which show evidence of transport by water, wind or ice.

Fluvial Sediment:

Material which shows evidence of stream transport. This includes all material derived from within or outside the cave which shows rounding, graded bedding, a systematic vertical variation in grain size, or any particle or structural feature characteristic of fluvial transport.

Glacial Sediment
Aeolian Sediment
Marine Sediment
Lacustrine Sediment:

These are rarely found in most humid temperate, well-drained, inland karst regions. They are also difficult to identify where other processes have altered them.

<u>Chemical Deposits</u> (after White, 1963)

1. Carbonates
2. Evaporites
3. Iron and Manganese Hydrate
4. Ice
5. Phosphates

<u>Organic Deposits</u>

1. Floral Remains
2. Faunal Remains

Archaeological Deposits

1. Evidence of Human Presence or Activity

3. Fluvial Sediments in Caves

There has been little description or interpretation of fluvial sediments in caves. Little emphasis has been placed on any of the five aspects of fluvial sediments considered in Chapter 1. These aspects are common to most cave environments. Sedimentary structures, imbrication, and sequential variation in grain size are well illustrated in several major cave sediment studies. For example, the photographs and illustrations of Davies and Chao (1958) show clearly well preserved channel deposits, small scale cross-bedding, and fining upward sequences (see especially Figures 10-16, pp. 71-83). No mention of structure, graded bedding, flow direction or intensity is made, although a thorough analysis of grain size is included in the text. Reams (1968, p. 52) comes closest to examining structures, but some of his interpretations are of doubtful validity, e.g., by estimating the annual number of thunderstorms in Missouri at fifty, he computes that individual lamina found in the cave silts and clays represent 610 years of deposition:

$$\frac{\text{10 laminae/mm x 10 feet (total thickness)}}{\text{50 (thunderstorm/year)}} = \text{610 years}$$

Laminated silts and clays over one meter in thickness have been deposited by a single flood event and are decribed in this study. Surface deposits of many laminae resulting from a single storm event have also been observed (McKee, et al., 1965, p. 850). Blatt, et al. (1972) states:

> "In the past, there has been a tendency to interpret each lamina as produced by a separate sedimentation event, for example, a tidal cycle, or the swash and backwash from a single wave, or a single bedload avalanche. It is now clear, however, that laminae may also be produced by steady flow, particularly during traction on a plane bed in the upper flow regime. The mechanism is not well understood, but it appears to be related to factors that cause grains of similar size and shape to lodge together in patches on the bed."

Other studies in the laboratory, in closed conduits, have successfully produced ripples, dune and laminar structures. McDonald and Vincent (1972) have shown that with increasing sediment concentration at a given discharge that sequential bedform development was: ripple, dune, dune-plane, plane, dune-plane and total suspension. No antidunes were produced under pipe-full flow. This confirms the findings of Acaroglu and Graf (1968). McDonald and Vincent have also measured dune heights and found them to be 1/3 to 1 times the hydraulic mean depth. In transparent acrylic cylindrical pipes water depth is 2 to 10 times the dune heights. Comparisons with esker sediments were made, and water depths were in accord with the experimental measurements on the dune heights. There is little doubt that similar comparisons can be made with cave deposits. None have been.

White and White (1968) provide a summary of general applications of hydraulic properties that might apply to fluvial transport of sediments in caves. Structures are not mentioned, but this article provides a good beginning to the type of studies needed in cave sediments. Too often petrology is the only objective and sedimentation and geomorphology are either pure speculation, or are not mentioned at all.

Other types of deposition unique to caves should also be examined and associations with other types of fluvial deposits drawn. Helwig (personal communication) has confirmed the presence of interbedded carbonate deposits within fluvial material. The geomorphological significance of such associations has not been examined by him in detail. Ford (1963) has observed a high frequency of interbedded travertine in clastic fills. He has interpreted this as indication of a sudden change in flow conditions in the cave. He also emphasizes the lack of sorting and development of fluvial sedimentary structures in many deposits. Such observation may be helpful in understanding former cave depositional environments.

Davies (1959) made two fundamental assumptions concerning the genesis of cave fills. These are that the most active stage of cavern formation and fluvial deposition occurs at the level near the water table, and that the water table remains at the level for a long period of time. Secondly, that the oldest portion of the cave is at the highest elevation and that younger portions of the cave are at successively lower elevations. In the light of this it is commonly considered by most authors that the oldest fills are at the highest cave levels and the youngest are at the lowest levels. This assumption is based on the gradual lowering of the active cave stream as solution and abrasion continue downward. Ford (1965) has shown that this may not always be true. Considerable care must be exercised in the relative dating of cave deposits. The advantage of a total basin approach and provenance analysis is greater accuracy in determining the relative age of cave deposits.

These two factors are closely related. Provenance has been examined by Brain (1959) and Kukla and Lozek (1958). Others have mentioned source areas of the fills of a single cave, for example Deike (1960), but these authors do not attempt to relate this data beyond the spelean environment of a single cave or at most a few caves. Of the five aspects of cave sediments, provenance probably has received the most attention. Nevertheless, the geomorphological significance of provenance studies applied to many caves and their surrounding karst environment remains uninvestigated. Studies by Helwig (1964, 1965) and Reams (1968) might have shown significant provenance distribution information, if this had been a major part of the investigation, which unfortunately it was not.

B. Karst Geomorphological Literature on Cave Origin and Development

The literature on speleogenesis as it relates to cave sediments may be grouped into three categories:

Vadose theories

Shallow phreatic theories

Deep phreatic theories

This grouping is based upon the position of the theorised cavern origin and development in relation to a regional or perched water table. Although most theories acknowledge the presence of cave fills, little is said about their origin or what role they play in speleogenesis. Some theories suggest cave fills aid in the abrasion of the passages, while others indicate that fills may actually prevent solution and deepening of the passages. It appears that both concepts are valid.

1. Vadose Theories

The theories of Martel (1921), Piper (1932), Gardner (1935), and Malott (1937) emphasise the development of cave passages within the zone of aeration. Of these Martel (1921) placed the greatest emphasis on cave sedimentation. He stresses the importance of abrasion over solution in passage enlargement. Solution becomes secondary to mechanical processes after the passage reaches a size large enough to transport clastic sediments. Collapse in later stages is responsible for further passage enlargement and contributes to the bulk of clastic material found in caves. Gardner (1935) gives equal weight to solution and abrasion and likens the cave stream bed to that of a surface stream. Piper (1932) and Malott (1937) do not emphasise the role of sediments in cavern development, although Malott (1937) stresses the importance of occasional massive flood in corrosional processes by surface waters moving downward to the water table.

It is clear that both a bed load and suspended load are transported, deposited, and reworked by a vadose cave stream. If the vadose theories represent a valid interpretation of cave development, it seems likely that sediments play a significant role in the development of the cave stream bed.

2. Deep Phreatic Theories

Grund (1903, 1910), Davis (1930, 1931) and Bretz (1943) consider solution by slowly moving water under gravitational and hydrostatic forces several hundred feet within the zone of saturation to be the main cause of major passage development.

Grund (1903, 1910) and Davis (1930, 1931) disregard the work of vadose streams in cavern genesis and place importance on hydrostatic head between base level and the basin perimeter. The lack of dendritic cave networks is cited as evidence against vadose flow. Abrasion may alter the cave in later stages to a minor degree. Travertine deposits are emphasised more than clastic fills in these theories.

Bretz (1943, 1965) has supported the peneplanation concepts of Davis and their relation to cave sediment. He introduces the invasion of clay fills near the end of the phreatic enlargement phase. He says that most caves show this find unctuous deposition which filters down through joints and openings during the final stages of surface peneplanation. Reams (1968) in an attempt to disprove this idea points out that these clays are finely laminated. Unfortunately he interprets each one as a single event in itself. Both Bretz and Reams ignore the importance of laminar deposition from continuous stream flow.

In general, all phreatic theories suggest that coarse fills are not likely to be deposited in caves during a deep phreatic phase but later under conditions of vadose invasion by free surface streams. It seems quite likely that the slower flow velocities associated with large (greater than 75 cm) ceiling and wall scallops are incompatible with the velocities necessary to transport the coarse material common to many such passages which appear to be of a phreatic generation. Finer deposits, however, could be laid down under phreatic flow conditions.

3. Shallow Phreatic Theories

Swinnerton (1932), Rhoades and Sinacori (1941), and Davies (1957) have suggested that the greater part of cave development occurs in a flood water zone near the top of the water table. Swinnerton acknowledges that this may be at least 200 feet into the zone of saturation. Here lateral flow is concentrated in the upper part of the zone of saturation, and velocities capable of carrying a coarse bed load are possible. This is especially true in the latter stages of cave development when passages reach their maximum size. Davies (1957) suggested that cave fills might be of significance in the development of caves where the fill invasion represents the later stages of a phreatic cave development. Under the conditions postulated by a shallow phreatic theory, flow velocities are believed to be great enough to transport and deposit a coarse bedload, that is to say, from one to two meters per second.

4. Summary of Theories

It seems likely that finer fills may play an active role in either the abrasion or the protection of cave passage floors under any one of the conditions assumed by the various theories of cave development. A free surface vadose stream or a confined shallow phreatic flow is thought to be capable of carrying a coarse clastic bed load. Several of the major theories of cave development, Martel (1921), Bretz (1943), and Davies (1957) have emphasised the importance of cave fills. White and White (1968, p. 115) suggest that fills may well be important in the primary stages of cave development. They conclude that "the concept of a moving bed load allows a revision of some of the earlier statements that appear in the speleological literature and that a sedimentary layer in the floor of the cave is present at all stages". Lange (1954) has suggested that sediments may play an important role in shielding the cave floor from solutional activity. He considers the shielding effect optimum in the slow phreatic case. Ford (1965, 1968) has shown that clastic filling tends to "grade" the cave profile by blocking the bases of irregular phreatic loops. These clastic plugs then force the cave stream to by-pass the lowest parts of the system and "smooth" the passage profile.

C. Surface Studies in Geomorphology and Sedimentology

Much of the work of fluvial geomorphology centres around the erosional aspects of basins, streams and their erosional morphology. The studies of Horton (1945), Strahler (1950), Sundborg (1956), Melton (1958), Broscoe (1959), Hack (1960), Johansson (1963, 1965), Leopold, Wolman and Miller (1964), Oberlander (1965), Chorley (1966), and Morisawa (1968) illustrate the erosional emphasis in the field of geomorphology. The work of Schumm (1960, 1963, 1969) is the exception to the general statement. He has used sedimentological properties to make empirical statements concerning channel properties (Jopling, 1971, personal communication).

Sedimentologists, on the other hand, have emphasised the depositional aspects of streams. Such a division between the two disciplines seems well defined; however, much of the morphological aspects of sediments relevant to geomorphology are overlooked by investigators in that field. Valuable contributions to the study of the morphology of sediments have been made in the last decade, which have not generally been utilised by geomorphologists. An excellent review of the work prior to 1965 can be found in Allen (1965) and Middleton, ed. (1965). Of particular use in this study are the works of McKee and Weir (1953), Ingram (1954), Lattman (1960), Frazier and Osanik (1961), Bouma (1962), Doeglass (1962), Harms and Fahnestock (1965), Jopling (1965), McKee, Crosbey and Berryhill (1965), Walker (1965, 1969), Raudkivi (1967), Jopling and Walker (1968), Pittman and Ovenshine (1968), Coleman (1969), Allen (1970), McGowen and Garner (1970), Smith (1970), Blatt, et al. (1972).

Concepts such as "flow regime" and the importance of sedimentary structures and their hydrodynamic significance have not been fully utilised by geomorphologists. Neither have these concepts been applied to the investigation of cave sediments. The analysis of particle properties of cave fills has been undertaken to some extent (Davies, 1957; Schmid, 1958; Davies and Chao, 1959; and Brain, 1958). A recent criticism of Brain by Butzer (1970, 1971) suggests that some of the work that has been done should be reconsidered. Almost everything, therefore, remains to be done in the field of sediment morphology of cave deposits. Structural properties are treated in this study for the first time in the speleological literature along with some aspects of particle property analysis, clay minerals, and provenance.

Blatt, et al. (1972) has proposed a classification of primary sedimentary structures. This is shown in Table 2.01. It should be emphasised that most bed forms are restricted to sand-sized particles. These are common to most cave deposits in this investigation.

The concept of "flow regime" and the bedforms related to it was proposed by Simons and Richardson (1961) (Figure 2.01). The lower flow regime includes bedforms such as initial plane beds, ripples, and dunes. The Froude number is well below 1.0 , and surface water waves are out-of-phase with the waves of the bed. The upper flow regime is characterised by another phase of plane beds, antidunes and "chutes and pools". At Froude numbers of about 0.8 antidunes begin to form. These are roughly in phase with surface water waves.

Much of the findings have been based upon flume studies in the laboratory. The flume environment seems more analogous to the cave environment than that of a surface stream. The constriction of the flow owing to the absence of a flood plain in the flume and cave results in an unusual deepening of the stream during peak flow periods, thus changing the flow regime and affecting the sediment characteristics of each. In the case of a cave stream, water may be

Table 2.01

CLASSIFICATION OF PRIMARY SEDIMENTARY STRUCTURES

I. Stratification

- A. Bedding and Lamination

  (Beds > 1 cm > Laminae) includes graded bedding

- B. Cross-Stratification

  Tabular, Wedge, Trough, Climbing, etc.

- C. Irregular Stratification

  Soft sediment folding
  Convolute lamination
  Load structures
  Ball-and-pillow
  Sedimentary sills and dykes
  Mud cracks
  Bioturbation (burrows, roots and other biogenic modifications of stratification)

II. Marks on Bedding Planes

- A. Tool Marks

  Striations
  Grooves
  Brush, Prod, Bounce and Roll Marks

- B. Scour Marks

  Flutes and scallops
  Large scours (cut-and-fill, channels)
  Rill marks, crescentic marks (current crescents)

- C. Bedforms

  Ripples, dunes, antidunes, grain lineation, harrow marks, swash marks, and other wave marks

- D. Biogenic Marks

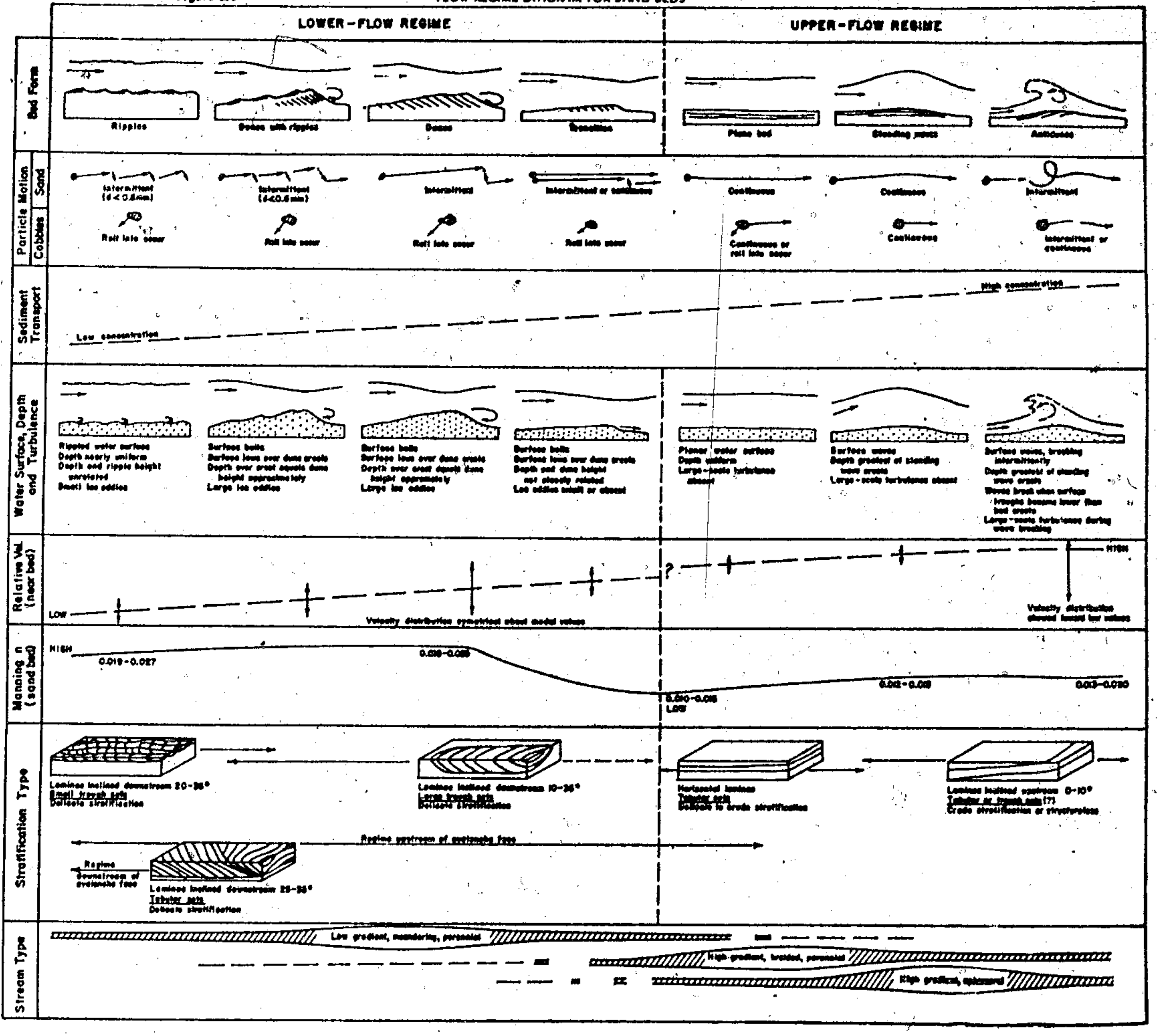
after Blatt, <u>et al</u>. (1972)

forced to flow at a higher level or under hydrostatic head.

This brief review of some of the background literature from cave sediment studies, theories of cave origin and development, and from studies in sedimentology is intended to point out the relationships of these studies to karst geomorphology. Running water is the important common feature of all of the studies reviewed and is indeed the focus of this study. It is hoped that this investigation will bring the valuable contributions of previous studies in the fields of hydrology, karst geomorphology and sedimentology closer together.

Figure 2.01

FLOW REGIME DIAGRAM FOR SAND BEDS



Chapter 3. THE GREENBRIER KARST OF SOUTHEASTERN WEST VIRGINIA

A. Topography and Stratigraphy of the Greenbrier Area

1. Topography

There are three important macro-landform units in the study area (Figure 3.01):

The Allegheny Front and minor outliers. These form the western boundary;

At their foot, complex valley and strath surfaces in the limestones, variably karstified;

To the east, the sharply entrenched valley of the Greenbrier River.

The distance between the crest of the Front (the drainage divide) and the Greenbrier River varies from two to fifteen miles. Local relief over these distances varies from 2200 to 2800 feet.* The Front is always expressed as a steep feature rising to 1500 feet or more above the limestones. South of Marlinton, the Greenbrier River channel is always 200 or more feet below adjacent strath surfaces in limestone, or, occasionally, in shale. The strath is well

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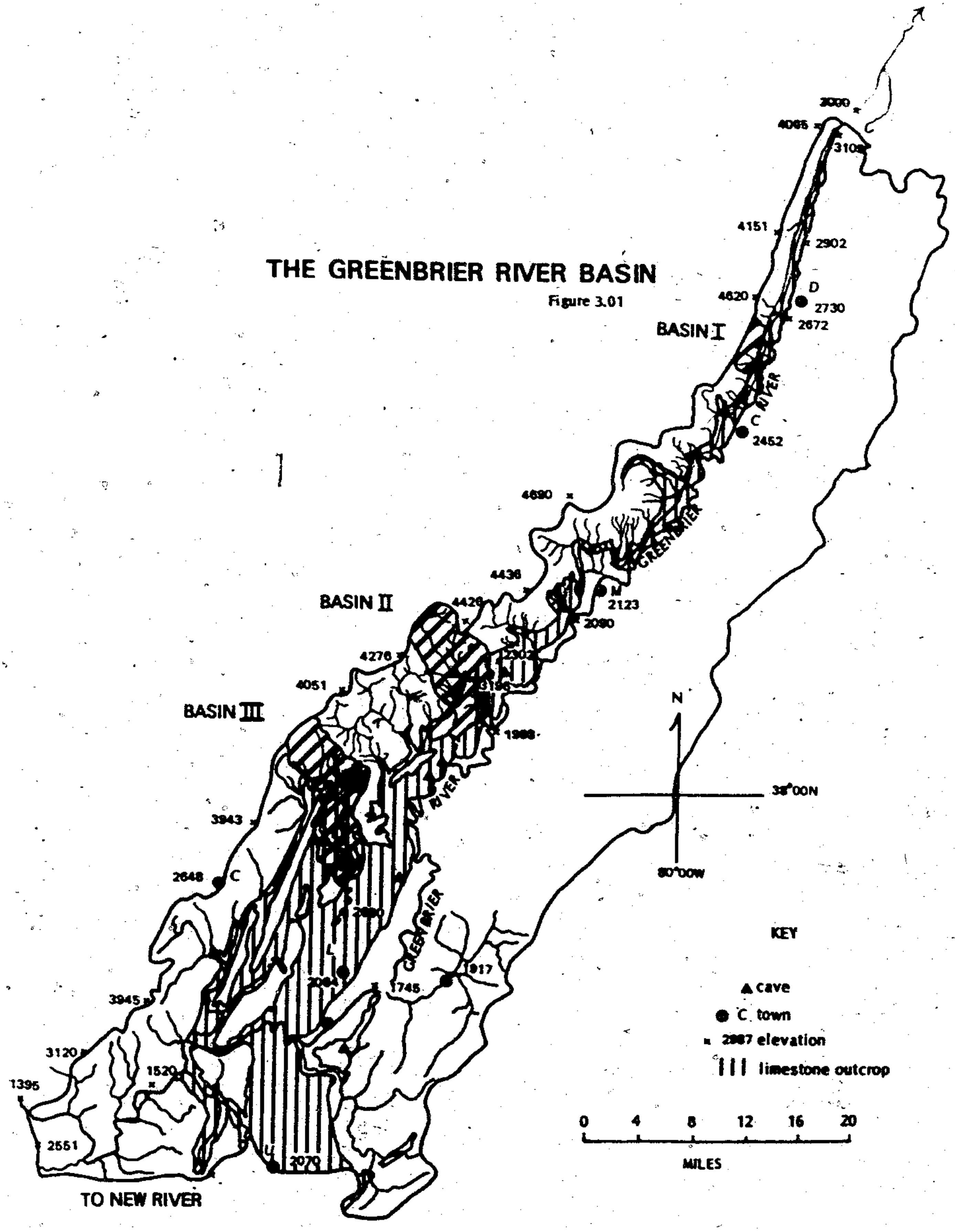
*The use of units in this study follows the format of the U.S.G.S. (Anon, 1958).

THE GREENBRIER RIVER BASIN

Figure 3.01



developed at and south of Marlinton and has long been interpreted as the ideal "Harrisburg peneplain" equivalent by geomorphologists (Fenneman, 1938). The three basins chosen for study have their headwaters at the top of the Front and empty eventually into the Greenbrier River. The mean fall of each basin exceeds 2200 feet. Overall relief ranges from a maximum of 4842 feet at the head of Basin I to a minimum of 1998 feet at the mouth of Basin III. Figure 3.01 shows the Greenbrier River basin and the location of the three karst basins chosen for study.

2. The Overlying Cap Rock

Table 3.01 lists all rocks with their appropriate thickness in the central part of the Greenbrier basin. Resistant clastic outcrops produce three major benches in the face of the escarpment. These are, from the uppermost: The "Pottsville scarp", consisting mainly of the Guyanot sandstone-conglomerate (Pennsylvanian); the "Princeton scarp" made up of the Princeton conglomerate of the Mauch Chunk Series (Upper Mississippian); and the lower "Bluefield scarp" capped by the resistant Droop sandstone at the base of the Mauch Chunk Series. The upper two benches contain abundant quartz pebbles, up to 64 mm. long axis (Figure 3.02). The lower Droop sandstone is a medium to fine grained sandstone.

Table 3.01

ROCKS WITHIN THE AREA DRAINED BY BASINS I, II, AND III

STRATIGRAPHY		LITHOLOGY	THICKNESS
PENNSYLVANIAN	Kanawha Group	coal, sandstone, shale	250'
Pottsville Series	New River Group, includes the "Guyanot sandstone" known as the "Pottsville conglomerate" *	massive sandstones, quartzites and some coal	940'
	Pocahontas Group	sandstone, coal	0-340'
		Average Total Thickness	1500'
Mauch Chunk Series	Bluestone Group	90% shales, 10% sandstones	80-675'
	Princeton Group*	quartz pebble conglomerate	70- 80'
	Hinton Group	shale, sandstone, limestone	500-850'
	Bluefield Group, includes Droop Sandstone*	shale, sandy limestone	50-100'
		Average Total Thickness	2800'
MISSISSIPPIAN	Alderson Limestone		50-150'
Greenbrier Series	Greenville Shale		0- 40'
	Union Limestone		150-200'
	Pickaway Limestone		50-135'
	Taggard Formation		10- 35'
	Patton Limestone – Patton Shale		90-150'
	Sinks Grove Limestone		40- 90'
	Hillsdale Limestone		30-100'
		Average Total Thickness	600'
MacCrady Series	MacCrady Shale*	shale	60-250'
		Average Total Thickness	150'

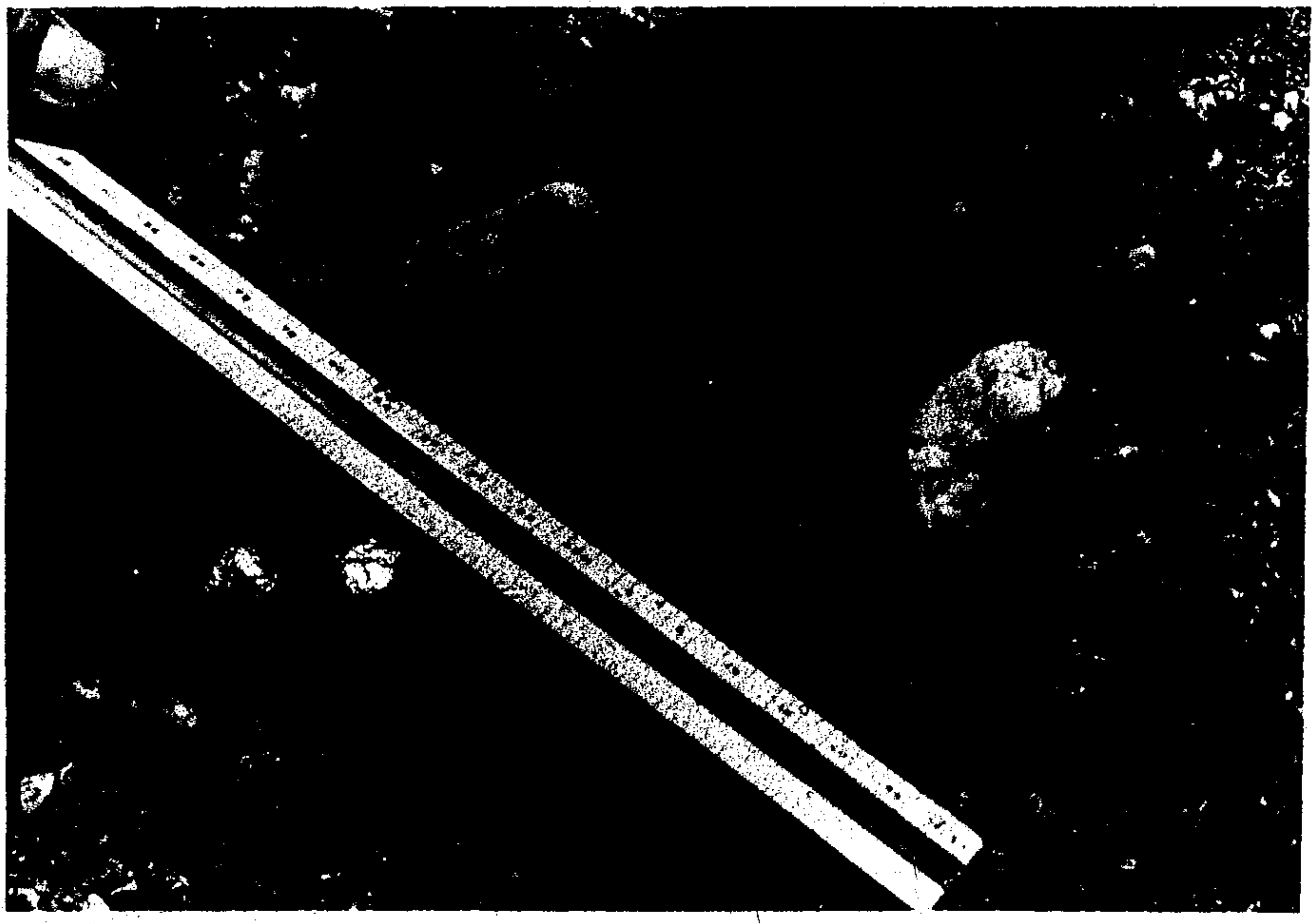
Table 3.01 Continued

STRATIGRAPHY		LITHOLOGY	THICKNESS
Pocono Series	Pocono Sandstone*	sandstone, shale	200-400'
		Average Total Thickness	400'
DEVONIAN			
Catskill Series		sandstone, shale	400'
Chemung Series		sandstone, shale	2000-3000'

*Major identifiable tracers in the sediments of the Greenbrier drainage.

Figure 3.02

THE PRINCETON CONGLOMERATE



This rock is found at the head of all three basins. It is the nearest source of rounded milky quartz pebbles suitable for "natural tracers" in paleodrainage channels and conduits.

These are the clastic suppliers for all the sediments transported down the Allegheny Front, along the basin channels, through the caves, and eventually into the Greenbrier River. The clastic outcrops are generally crossed by streams flowing across the strike in stratigraphically descending order. A few exceptions to this sequence are to be found near the base of the escarpment where some of the underlying MacCrady shales of the MacCrady group stand high enough in elevation to supply the stratigraphically higher, but topographically lower, Greenbrier limestone karst with runoff and sediments.

Detailed descriptions of the clastic rocks and the minerals used as tracers in provenance and transport studies are included in Chapters 5, 6 and 7.

3. <u>The Greenbrier Series</u>

The Greenbrier limestone outcrops along the base of the Allegheny Front for a distance of one hundred miles from Durban in the north, where it is approximately 350 feet thick, to Alderson in the south, where it exceeds 1000 feet in thickness. The width of the exposure also varies north-south from a few hundred feet to more than ten miles. The Greenbrier Series, comprising the middle portion of the Mississippian System in West Virginia, is made up mostly of marine calcareous siltstones, impure shaley dolomitic limestone, impure argillaceous limestone with purer bluish grey limestone with fragments or concretions of chert in the southern part of the area (Donaldson, 1969). The two basal members of the series have been grouped into the Denmar formation by Flowers (1956). However, the earlier terminology by McCue, et al. (1939) of the West Virginia Economic and Geological Survey is used in this study for convenience. As such, there are 11 members in the Greenbrier Series, all of which are present in the three basins chosen for study. This is true in spite of the fact that the thinning northwards causes a considerable variation in local limestone stratigraphy. Locally, the presence of interbedded shales causes underground waterfalls to develop over impervious shale bands within the caves. Surface evidence of these shale bands appears as "lost waterfalls", waterfalls with no surface stream above or below them (White, 1961). The shales also produce local variations in subsurface drainage conditions. The breaching of such impervious bands can mean a sudden drop in local watertable. Wells which penetrate the shale must be extended in order to reach a new water level. There is evidence, therefore, that a strong relationship between lithology and hydrology exists in this area.

Figure 3.03 is a generalised stratigraphic column from Pocahontas County measured between Basin I and Basin II. This is representative much of the Greenbrier Series throughout the area of study. Six generalised stratigraphic columns

GENERALISED STRATIGRAPHIC SECTION OF GREENBRIER SERIES IN STUDY AREA

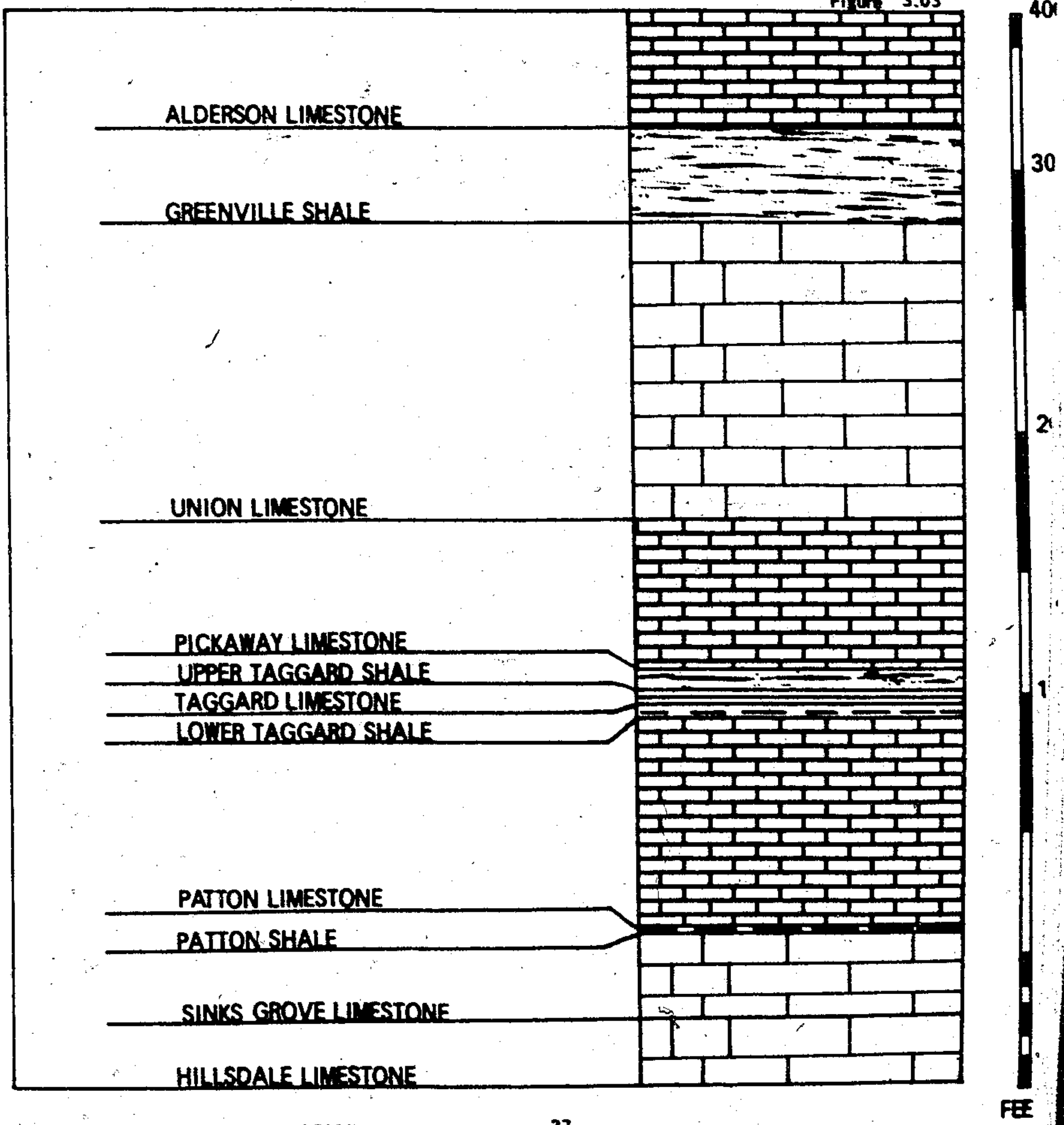


Figure 3.03

THICKNESS FROM DATA COLLECTED
AT EDRAY BY LUCKE 1939

are given in Figure 3.04. Columns two and three in the figure are representative of the stratigraphy of Basins I, II and III. The rapid thinning of the series northwards along the axis of the geologic basin of deposition can be seen. Fisher, et al. (1969) gives a detailed analysis of paleocurrent data and other petrologic data for the Mississippian basin. Donaldson, et al. (1969) also gives a description of the northern part of the petrology in West Virginia in more detail.

The relative solubility of the 11 members of the series is summarised in Table 3.02 and a brief description is given here of each member in each basin.

a. Alderson Limestone - Basin I and Basin II

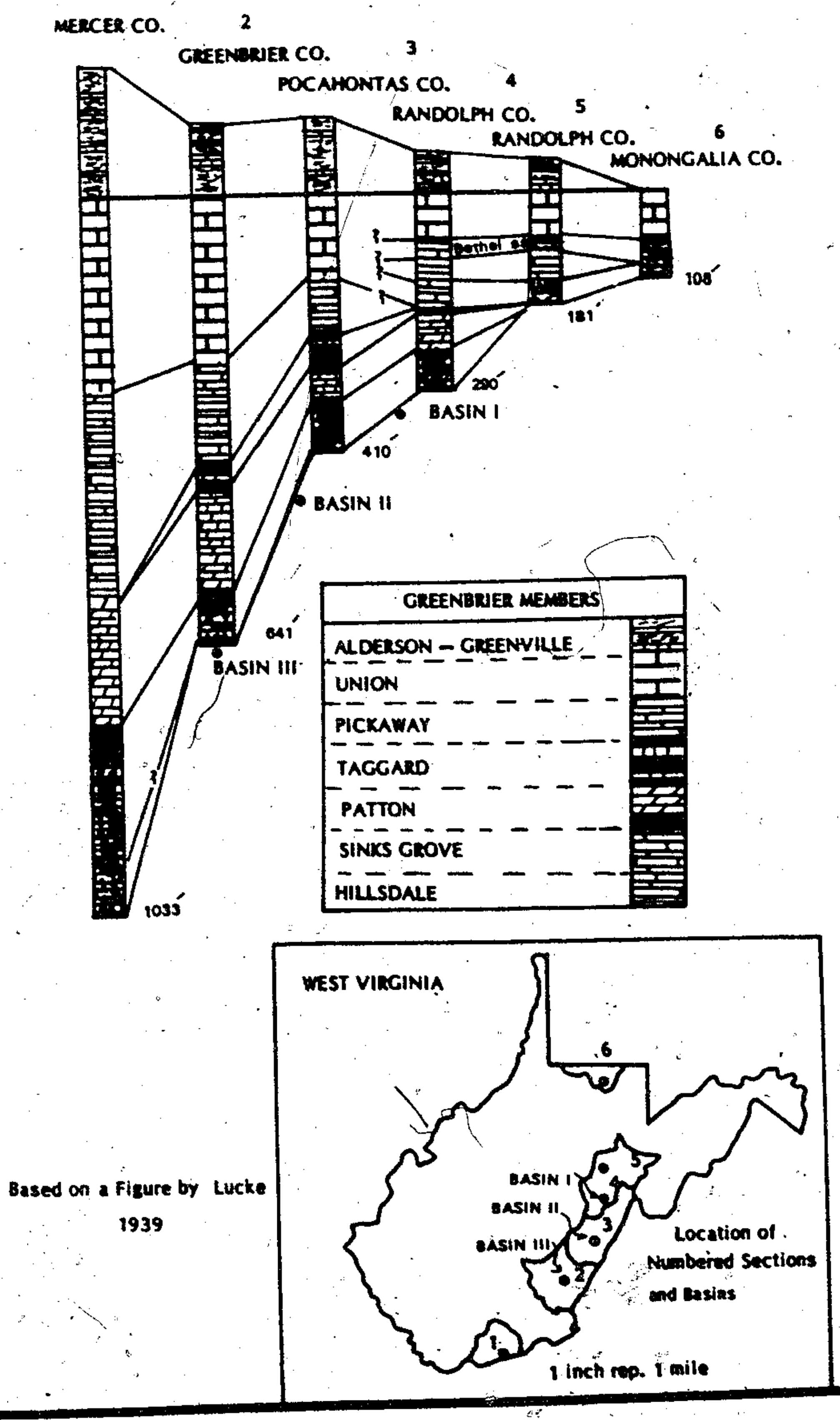
This is the youngest member of the Greenbrier Series and like all the others was first defined by Reger (1926). It is a dark grey calcareous limestone, high in silica and weathers to a dirty yellow colour. Portions are highly crystalline and fossiliferous. A plant fossil zone has been recognised in the area of study and elsewhere (Reger, 1926). The Alderson limestone is easily recognised in the field owing to its position directly beneath the Lillydale shale, basal member of the Mauch Chunk Series. From Basin II to Basin I it thins slowly to the north from 55 feet to 42 feet (Table 3.03).

b. Greenville Shale

The Greenville shale resembles a siliceous limestone far more than a shale, although its composition ranges

GENERALISED STRATIGRAPHIC SECTION OF THE GREENBRIER SERIES OF WEST VIRGINIA

Figure 3.04



Based on a Figure by Lucke 1939

Table 3.02

RELATIVE SOLUBILITY OF THE MEMBERS OF THE GREENBRIER SERIES[a]

Greenbrier Member	Calcium Carbonate Content	Solubility[b]
Alderson Limestone	90.88%	Medium
Greenville Shale	Not Available	Low
Union Limestone	86.76% , 86.27%[c]	High
Pickaway Limestone	89.3%	High
Upper Taggard Shale	79%[d]	Low
Taggard Limestone		Medium
Lower Taggard Shale		Low
Patton Limestone	94.19%	High
Patton Shale	Not Available	Medium
Sinks Grove Limestone	82.9%	High
Hillsdale Limestone	70.64%	Medium

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[a] Data based on Price (1929) unless otherwise noted.

[b] Based on a total of soluble parts: 100-75% soluble - high; 75-50% soluble - medium; 50-25% soluble - low.

[c] From Reger (1931, pp. 700-704).

[d] Total for all three members.

Table 3.03

THICKNESSES OF THE MEMBERS OF THE GREENBRIER LIMESTONE IN BASIN I AND II

(Recorded in Feet)

	South of Basin I		Basin II	
Greenbrier Member	A	B	C	D
Alderson Limestone	42	55	55	40
Greenville Shale	35	20	30	20
Union Limestone	113	125	130	150
Pickaway Limestone	57	87	100	75
Upper Taggard Shale	18	23	25	10
Taggard Limestone		8		5
Lower Taggard Shale		8		10
Patton Limestone	80	42	190	100
Patton Shale	3	0	5	5
Sinks Grove Limestone	33	29	50	50
Hillsdale Limestone	29	10	15	50
TOTALS	410	407	600	515

Column A is from data recorded by Lucke; see McCue, Lucke and Woodward (1939, pp. 36-39).

Column B is from data recorded by Paul H. Price; see Price (1929, pp. 44-45).

Column C is from data recorded by Price (1929, p. 114).

Column D is as measured by the author.

widely within the area, being more like that of a shale in the south, especially along U.S. Route 219 on Droop Mountain, and along West Virginia State Highway 39 above Mill Point. It ranges in colour from brown to dark red, with an abundance of marine fossils. Its thickness ranges from 30 to 55 feet, becoming thicker in the north toward Basin I (Table 3.03).

c. Union Limestone

This is the purest of the limestones in the Greenbrier Series (McCue, et al., 1939). It is grey, weathers white, and is frequently oolitic and crystalline with a shaley layer near the top. It is easily distinguishable from the overlying Greenville shale, however, owing to the latter's darker color and sandy nature. In the Basin II area there is a zone at the top of the Union limestone which has attained crystalline character which causes it to be known in the stone industry as "marble" (Price, 1929). The "marble" zone is as much as 30 feet thick, grading into the lighter Union limestone at the base. This "marble" has only been observed in a small outcrop near Basin II (Price, 1929). The Union limestone is the most widely distributed of the members of the Greenbrier Series (McCue, et al., 1939) and ranges from 113 feet thick in the north to 130 feet at Droop Mountain in Basin II.

d. Pickaway Limestone

Directly beneath the Union limestone is another fairly pure member of the Series. It is perhaps the most readily recognisable of the limestone members of the series, due to the presence of partings or "sheets" caused by thin shale bands along the bedding planes. However, the exact contact with the overlying Union limestone has not been located in the field by the observer. There is a shaley layer near the Pickaway-Union contact reported by Price (1929) and located by the writer in the study area, which was used as an approximate boundary between the two members (Wolfe, 1964). The Pickaway thins from about 100 feet in Basin II to 57 feet in Basin I.

e. Taggard Formation

The Taggard formation of the Greenbrier Series is composed of three recognisable members, from the top downward: Upper Taggard Shale, Taggard Limestone, and Lower Taggard Shale. This formation is a good "marker" in the field, because it consistently appears as two red shales separated by a narrow band of light-colored limestone. Neighbouring limestone members of the series are then easily recognised through their stratigraphic position above or below the shale beds. Usually the shales are each no more than ten feet in thickness, the entire formation being less than 30 feet thick throughout most of the area. It plays an important role in control of surface and subsurface drainage due to its relative impermeability and insolubility.

f. Patton Limestone

The Patton limestone is probably most easily identified in a weathered condition. It forms lapies in several locations. It weathers to a light grey and appears smooth. However, many small fossil fragments remain, causing a rough surface with small sharp protrusions. In Pocahontas County, the Patton limestone contains the highest percentage of calcium carbonate.

g. Patton Shale

Thin and lenticular, the Patton shale is an important stratigraphic marker located just beneath the Patton limestone and just above the Sinks Grove member. It is high in insoluble materials and acts as a barrier to percolating vadose water where present. It was not located in Basin III, although 12 feet of shale in its stratigraphic position was measured in Basin II.

h. Sinks Grove Limestone and Hillsdale Limestone

Owing to the lack of a recognisable contact or line of separation, these basal limestones of the Greenbrier Series are most frequently grouped together (McCue, _et al_., 1939). They are not alike, however, and each has a distinctive group of characteristics. The Sinks Grove, thinning from about 50 feet to 30 feet northward, is a dark, hard, and thick bedded limestone, that weathers to a grey colour. The Hillsdale being lighter in colour, with an abundance of chert nodules and colony corals (Lithostrotion), is easily distinguished from other members in the field. It represents the bottom of the Greenbrier Series, thinning from 29 feet in Basin II to 15 feet in Basin I, and lying on the thick, red MacCrady shale throughout the area of study. It is easily recognisable in the caves where chert nodules and Lithostrotion protrude from the cave walls.

The preceding description of stratigraphy is generalised and applies to much of the Greenbrier River drainage area. However, the thickening of the entire Greenbrier Series southwestward increases the potential for karstification in that direction. Interbedded clastic members thicken to the northwest and increase lithologic separation of underground drainage. The thickness of the entire series ranges from 205 feet in the north of Basin I to 750 feet in Basin III (McCue, et al., 1939). The presence of gentle folding and minor faulting in the area of Basin III is also responsible for the increased width of the karst surface. Tributary streams flowing to the Greenbrier River cross the series several times due to these structural variations to the south. This, in effect, provides more than twice the thickness of available limestone (1500 feet) in which karst and cave development can take place in Basin III.

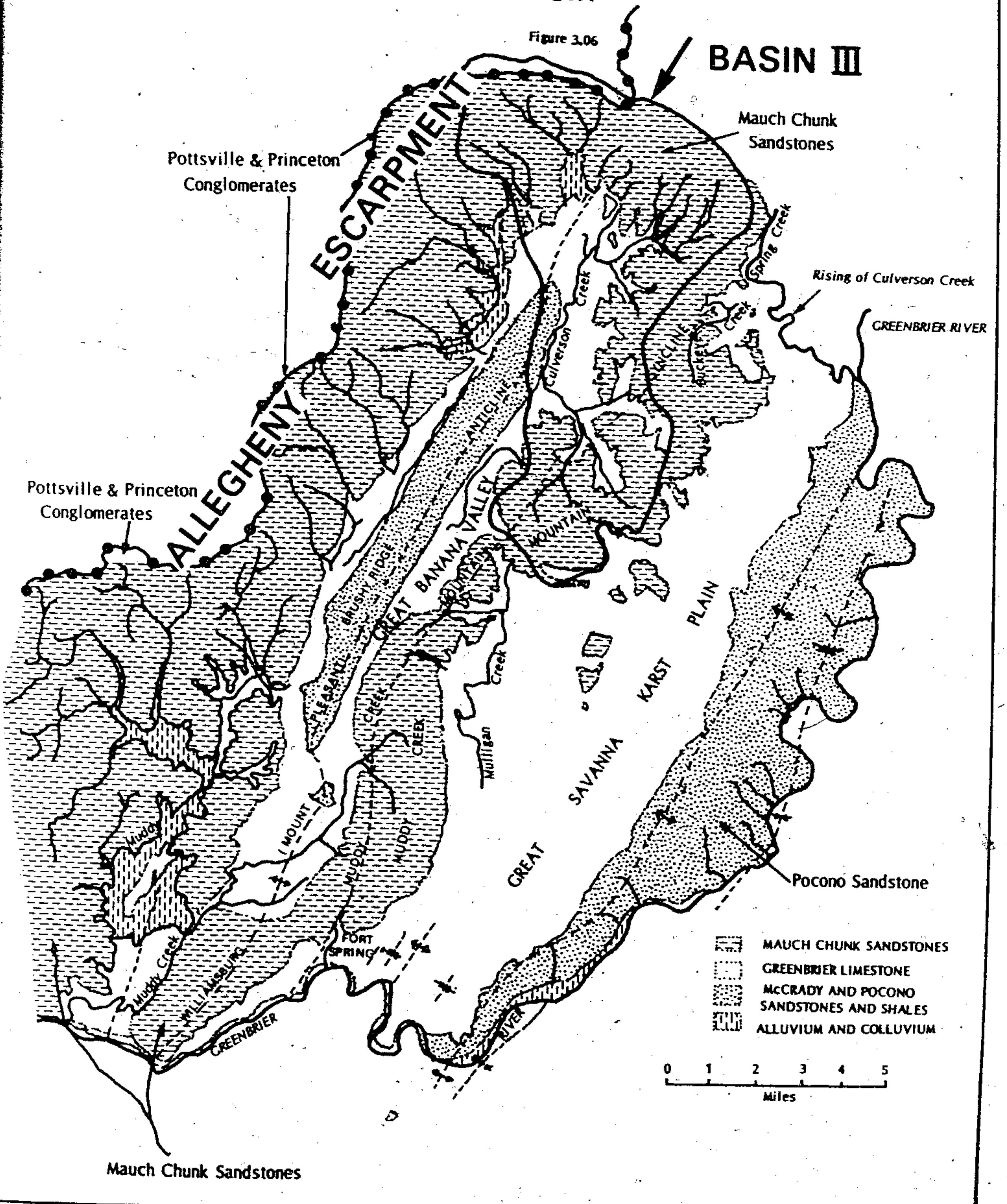
4. Rock Structure

The topographic expression of the Allegheny Front does not always coincide with structural faulting or folding in the area. The most significant rock disturbances lie east of the Allegheny Front and the Greenbrier limestone karst. Figure 3.05 is drawn from the Allegheny Front toward the Browns Mountain anticline. The latter is the most noticeable rock structure to the east. Folding within the Greenbrier limestone increases to the southwest. The Greenbrier River parallels these folds along the regional strike and immediately lies east of the limestone exposure. The dip of the Greenbrier limestone is generally 4° to 10° to the northwest. However, in the south, this varies considerably due to the presence of the Williamsburg (Mount Pleasant) anticline and the Muddy Creek Mountain syncline (Figure 3.06).

In Basin III the axis of the Williamsburg Anticline crosses the main trunk stream at right angles, midway along the basin. This causes a change in dip from northwest to southeast. This ranges from 10° to 40° along the west bank of the channel. The Muddy Creek Mountain Syncline which lies to the east of the Williamsburg Anticline, still within the limestone, produces a second reversal in the dip, back to northwest at 10° . The increase in thickness and these two additional structures at the base of the escarpment account for the much broader exposure of limestone in the south along the trunk channel of Basin III. The result is an extensive karst topography

Lithology and Structures in the Southern Part of the Greenbrier River Basin

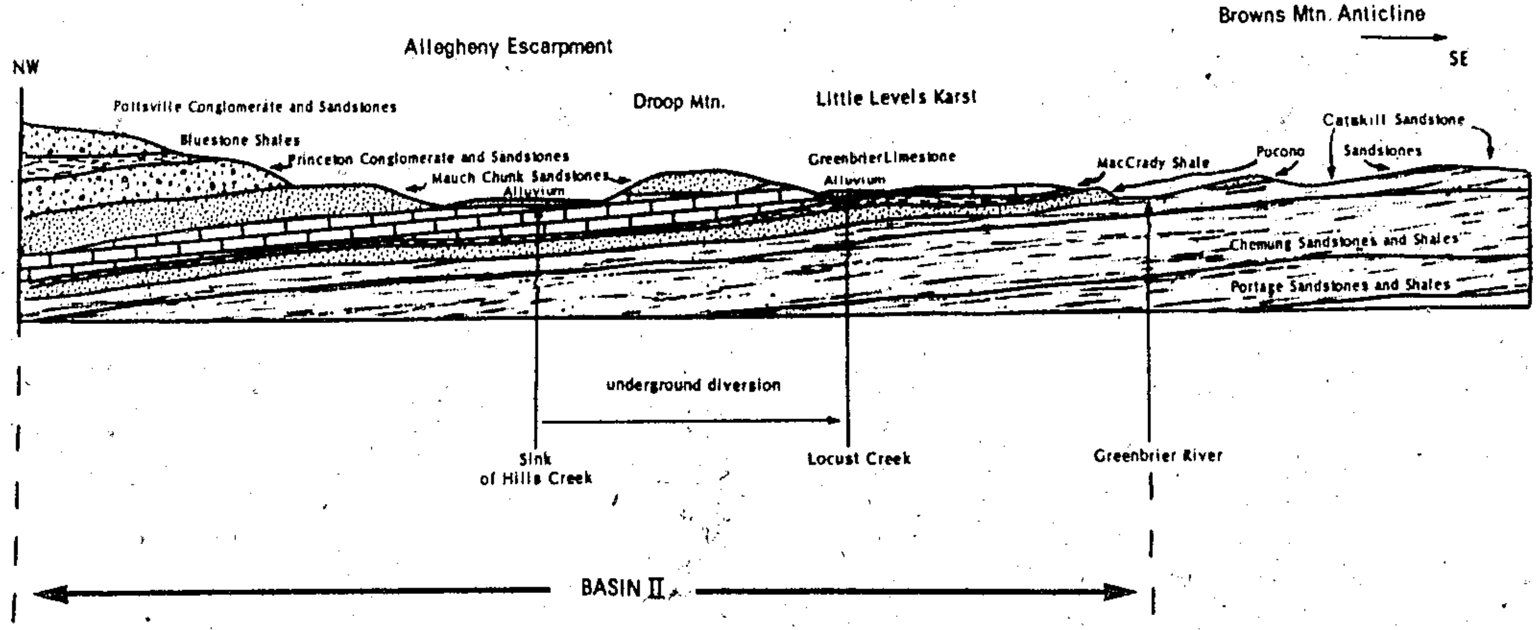
Figure 3.06



Geologic Cross Section across The Allegheny Escarpment

Through BASIN II

Figure 3.05



Horizontal and Vertical Scale 1 inch rep. 1 mile more than ten miles in width in Basin III. Additional effects of these rock structures as they relate to the groundwater and sediments are discussed in Chapter 7.

Jointing of the Greenbrier limestone is a common structural feature in the study area. Joints in the caves are responsible for the direction of many of the passages. On the surface as well as in the caves the orientation of joint patterns is similar. N 65° E is the common major joint plant with minor joints at N 45° W and N 40° E. Table 3.04 is a summary of surface joint readings in the northern part of the study area.

B. Climate and Vegetation

The climatic record at Marlinton, which lies near the centre of the study area, shows a thirty year mean air temperature of 48°F, with a July mean of 67.6°F and 27.7°F mean to January. The thirty year mean precipitation is given as 47.28 inches with a July maximum of 5.31 inches and a November minimum of 2.93 inches. The thirty year mean frost free period is 146 days, from May 15 to October 8. It is important to stress that these figures are mean values and taken at Marlinton (2125 feet). There are extreme variations over short distances with the mean precipitation figure exceeding 60 inches in the mountain localities and falling to under 30 inches in sheltered valley environments (Price, 1929).

Table 3.04

JOINT READINGS

Greenbrier Series Member	Joint Sets Major	 Minor
Hillsdale Limestone and Sinks Grove Limestone	N 60° E	N 45° W N 40° E
Patton Limestone	N 70° E	N 45° W N 40° E
Union Limestone	N 70° E	N 40° W
Pickaway Limestone	N 65° E	N 40° W
Alderson Limestone	N 65° E	N 05° W

Mean annual discharge measured over a 38 year period at Alderson near the mouth of the Greenbrier basin is 2,080 cubic feet per second. Maximum observed discharge was 70,000 cfs. March, 1918. Minimum observed discharge was 26 cfs. in August, 1930. Of approximately 47 inches of mean annual rainfall for the entire basin it is estimated that 30.07 inches is removed by runoff by the Greenbrier River network (Price and Heck, 1939, pp. 79-80). Extremely variable runoff conditions occur. These are considered separately in each basin in more detail.

Lewisburg (2250 feet), which lies about twelve miles south of Basin III, has a thirty year mean air temperature of 51.6°F , with a July mean of 71.2°F and a January mean of 32.7°F . The thirty year mean precipitation is given at 39.70 inches, with a June maximum of 4.00 inches and a November minimum of 2.47 inches. An average frost free of 160 days from April 29 to October 6 is reported (Price and Heck, 1939).

Variability in runoff is a reflection of the extreme flood events which have occurred across the basin due to Atlantic and Gulf coast hurricanes. Hurricane Camille in 1969 is a case in point. Although no overall hurricane records are available for the area, it is known that homes established along Spring Creek in Basin III which were over 150 years old were washed away by this particular flood. Several new channels were cut into surface flood plains.

In the caves, passages blocked by fills were opened and new flood levels were established. The effects of this and other storms must be considered as major sedimentological events.

Vegetational studies by Darlington (1943) at the headwaters of Basin II describe three major climax forests in the mountain areas, based upon elevation. Below 3400 feet the eastern deciduous forest dominates, with sugar maple, oak, American basswood or linden and cherry. At 4100 feet on Cranberry Mountain, the climax is a transition forest of yellow birch, sugar maple, beech, red spruce, and hemlock. Above 4200 feet spruce becomes more common than maple. Kennison Mountain has 65% spruce with a low undergrowth of yew, <u>taxas canadensis</u>. Most of the limestone has been cleared for agriculture. The line between forest and fields generally coincides with the top of the Union limestone in the southern part of the area. This does not invariably hold true. In the north, Basin I is 90% forest covered with only a few small clearings for pasture. The eastern deciduous forest dominates at lower elevations where the limestone has not been cleared.

Several studies of past climatic and geomorphic phenomena have been undertaken by previous observers in this area of the Appalachians. Clark (1968) described fossil sorted patterned ground on Cold Knob (4345 feet). This peak is the source for the headwaters of Basin III. These features are developed in the detritus of the Pottsville Series. Darlington (1943) and Core (1955) have described tundra type vegetation from pollen in cores taken from Cranberry Glades at 3400 feet in elevation, two miles above the headwaters of Basin II. These were dated at less than 10,000 years of age. Clays were found beneath a post-glacial peat profile dated at 9434 ± 840 years B.P. Pollen diagrams by Guilday (1964, p. 140) indicate a taiga-type vegetation existed during late or full glacial times. However, he has more recently suggested that a rapid climatic change occurred over a short period after 11,000 years ago. He cites the extinction of several plant and animal species at this time as an indicator of rapid warming (Guilday, 1971, p. 245). Whitehead (1965, p. 419) states that a displacement of the boreal forest as far south as South Carolina was likely and that "a major southward displacement of many boreal species and profound climatic changes can no longer be disputed".

Tundra and perhaps permafrost conditions probably existed along the Allegheny Front above 3400 feet during the late Wisconsin and presumably during comparably severe climatic phases earlier in the Quarternary. It has not been demonstrated that such conditions extended onto the limestones which lie below 2500 feet in Basin III.

C. Drainage of the Area

The Greenbrier River is part of the Mississippi

River drainage system. The three basins chosen for study are tributaries of the Greenbrier River. Figure 3.01 shows the surface drainage of the Greenbrier River basin. On the limestone, surface drainage is severely interrupted; elsewhere a dendritic pattern exists. Southwards, a trellis pattern has developed owing to the erosion of open folds. Backwearing of the Allegheny Front by streams had produced broad exposures of the limestone. These widen southwards along the Greenbrier River Valley.

Under normal runoff conditions there are no surface courses maintained across all members of the Greenbrier Series. The sample basins illustrate this point. Trout Run in Basin I, Hills and Bruffey Creeks in Basin II and Culverson Creek in Basin III (each the major stream of their respective basins) flow directly into cave systems. Occasionally, under conditions of extreme flood, these underground routes become filled or blocked, and large splays of alluvium are spread out in surface distributaries. However, all surface flow is eventually diverted underground by way of the large blind valleys which are cut deeply into the surface. These provide natural topographic barriers as the major sink points retreat. In the case of Basin II, however, the blind valleys have been known to fill completely under very heavy flooding. These valleys are not unlike the "poljes" of Yugoslavia in this respect.

Most streams descend from the plateau over the shales and sandstones of the Mauch Chunk Series. They reach the Alderson Member of the Greenbrier Series, whereupon they usually sink beneath the surface. In so doing, they either drop abruptly into vertical shafts, as in Basin I, or more commonly the water seeps into the rock and loose gravel of the stream bed or enters a cave at the same gradient as the surface stream. In either case, the water reappears at the base of the Alderson limestone, out onto the surface supported by the Greenville shale. After a short traverse and vertical drop ranging from 30 feet to 100 feet the streams reach the top of the Union limestone.

Along the Union-Greenville contact, a zone of vertical shafts have developed, apparently caused by running water widening the major joint set at N 60° E to N 70° E (Table 3.04). These draw off all surface drainage and act as entrances to large underground stream channels and horizontal cavern passages. The combined thickness of the Union and Pickaway limestones is greater than 200 feet throughout the areas of Basin II and III. They are also relatively high in solubility. These factors account for the lack of surface runoff below the Greenville shale.

At the base of the Pickaway limestone some streams resurge, flow over the Upper Taggard shale, and fall as short waterfalls or flow in a short channel over the Taggard Formation. These falls and channels are unique in that there are no surface streams above or below them; the water sinks immediately below the Taggard Formation into the Patton limestone. These "lost waterfalls" are generally not found in Basin III. Lithologic factors in drainage control appear to be absent to a large degree in Basin III.

Resurgences may be found at two lower zones before the streams pass through the remaining part of the Greenbrier Series. In Basin II there is an area of surface runoff along the Patton shale outcrop. Although support of drainage across this member is generally weak or non-existent, there are seepage lines and wet weather springs associated with this relatively thin band of interbedded shales. These are small and are regarded as of local derivation.

At the base of the Greenbrier Series, surface drainage is completely re-established and is supported on the underlying impermeable MacCrady shales. Along the Greenbrier-MacCrady contact is a line of resurgences which includes more than 60% of all the springs listed by the West Virginia Geological Survey in Pocahontas County (Price, 1929) and a large number in Greenbrier County. These springs give rise to most of the streams that flow across the MacCrady shales and Pocono sandstones before entering the Greenbrier River.

The river bed has cut into the Pocono and Catskill sandstone and shale to a depth of 250 feet to 500 feet below the Greenbrier limestone in the north. In the south, owing to structural flooding, the river actually flows on the Greenbrier Series at the mouth of Basin III. Farther south the river continues to move upwards stratigraphically onto Pennsylvanian rocks. Eventually the Greenbrier drainage flows westward as part of the overall New-Kanawha-Ohio network. The eastern perimeter of the Greenbrier River basin is the drainage divide between the Mississippi River network and Atlantic drainage networks. Tributaries east of the River and north of Basin III are developed entirely on clastic rocks.

Chapter 4. PROCEDURES

A. Defining the Karst Drainage Basin

Morisawa (1968, p. 152) states: "A river basin represents the area drained by a stream and its tributaries. It is bounded by a divide, which separates it from adjacent watersheds." This definition must be modified for karst basins. Here there are both surface and subsurface divides. These seldom coincide. They may fluctuate seasonally, depending upon the amount of precipitation and resulting runoff and the ability of underground routes to carry surface runoff. One karst basin may overspill into another when peak runoff occurs. The method of defining a "karst basin" is therefore important.

The dynamic nature of karst basin change suggests that there are many remnants of former basins scattered over the karst landscape. Piracy, diversions, breaching of impermeable shale bands, sediment blockages of underground routes and various other events result in a constant re-routing of karst basin networks and alteration of their divides. As such, one must consider ways to outline or define the modern basin and the former basin related to the same trunk drainage. This is especially true if an accurate description and interpretation of sediment distribution and movement is to be undertaken.

1. The Modern Basin

The method of defining the modern basin was to:

i) Choose a large underground trunk stream; locate its headwaters, sinks and risings; carry out field reconaissance, dye-tracing and mapping of the underground drainage network.

ii) Outline the connecting surface drainage nets from topographic maps, aerial photographs, field reconaissance and dye-tracing results. This is done by working up stream from the mouth of the drainage net and including all parts of the surface and subsurface network that feed the trunk channel. This combination of channels makes up the active modern karst network as it may exist at a given time.

iii) Consider the maximum extent of the combined surface and subsurface drainage under flood conditions as the perimeter of the present active basin.

2. The Former Basin

The method of defining former drainage basins related to the same major trunk conduit as the modern basin was to:

i) Consider the possible extent of the former abandoned drainage network upon which the active modern network is superimposed. Such features as surface terraces and dry valleys, evidence for stream piracies and reversals, any unusual topographic configuration and the subsurface data on abandoned cave levels and their sediments are combined to provide information on the extent of the former drainage net.

ii) Consider the present and past stream profiles, especially the elevation of key points such as stream junctions and cave levels.

iii) Make revisions of the assumed former basin network after a detailed analysis of the sediments has been carried out. Provenance of traceable rock and mineral types helps to define former channels in basins which are carefully chosen for this purpose.

B. Sampling Procedures in the Field

1. Active Channels

a. Sediment Traps

Sediment traps were constructed at the mouths of the three basins under study. Traps were also placed at the major sinking points at the headwaters of the three basins as well as at selected points within the caves. The traps consisted of a sheet of heavy duty polyethylene (13 feet by 13 feet) used to line a section of the stream bed. A trench was dug at the down stream end of the trap to a depth of two feet. Rocks were placed around the traps in order to hold the plastic in position, and a small dam was constructed under the downstream end of the trap. The resulting sudden drop in stream velocity caused fine sand and silt to be deposited in most traps during normal flow conditions. The main function of the traps was to provide a plane upon which some of the suspended load and bedload sediment would be deposited due to the drop in stream velocity behind the dam. Several of these traps were washed out by floods while others lasted over three years with little damage. The traps were observed on the average of once a month and after any major flood event. The results of these observations are recorded in the appropriate chapter dealing with specific basins.

The various methods of measuring bedload described by Hubbell (1964) were considered to be too bulky and inconvenient for use in remote surface locations. For the underground stream sample sites the polyethylene traps are light in weight, convenient to carry and to construct. The results proved satisfactory for general measurement of bedload movement under most normal runoff conditions.

Sediment samples were taken for size and composition analysis from the traps, but the main function of the traps was to provide a means of estimating the overall volume and rate of movement of material in transit through the caves and associated basins.

b. Spot Sampling and Sedimentary Structures in Active Channels

Bag samples were collected at frequent intervals along the three major trunk channels of each basin and selected tributaries. These included large samples of gravel (5 kilograms), smaller samples of fines and samples for X-ray diffraction. Sedimentary structures were photographed and measured at convenient locations on the surface and in the caves. The percentage of milky quartz in a given size range was measured along selected channels. The maximum size, the lithology, the roundness and angularity of channel boulders was recorded at frequent intervals along selected surface channels and active cave conduits. More precise procedures are described below under ephemeral and abandoned channels. The location of the sample sites for each basin are shown in the chapters dealing with specific basins.

2. Intermittent and Abandoned Channels

Sample collection was carried out in the ephemeral and abandoned channels at the following locations:

i) In the caves, along all major abandoned trunk channels and along major ephemeral trunk channels.

ii) On the surface, along dry valley terraces, and old terraces along present active channels.

iii) At random, at sites shown on the sample collection sites for each basin (Chapters 5-7).

a. Soil Monolith Samples

Channel[1] samples or soil monoliths as described

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[1] "Channel" here refers to a container type, not to a stream channel.

by Brewer (1964) were removed from compacted clays, silts and sands. These channel samples measured eight centimeters thick by ten centimeters wide and one meter in depth. Such sites were enlarged in a vertical direction in order to collect a series of these monoliths. One series of samples was taken to a depth of six meters. Figure 4.01 shows a typical monolith taken from Poor Farm Cave in Basin II. At first the channels were constructed of wood; later, metal channels were used as suggested by Bunting (1970, personal communication). Soil monolith sampling provides a complete section of sediments, removed without disturbance of the structure of the deposits. Such procedures cannot be used in poorly consolidated material such as coarse sands and gravels.

Purpose: Laboratory analysis, X-ray diffraction of selected structures, beds of laminae, selected particle size and graded bedding analysis.

b. Spot Samples

Large soil test bags were used for collection of coarser unconsolidated samples ranging from one to five kilograms in weight. Tin cans were also used to collect finer material. These were useful for taking a series of samples down through a column of consolidated fines where monolith sampling was impractical. The cans were pressed into the silts or clays; a small core sample is then obtained. Series of these were collected and labelled; the position

Figure 4.01

SOIL MONOLITH SAMPLE FROM POOR FARM CAVE

and distance from the ceiling of the cave, or location in a terrace was recorded. Smaller samples were collected in plastic freezer bags for X-ray diffraction.

Purpose: Grain size and shape analysis, provenance, quartz pebble distribution, fossils, percent quartz content, X-ray diffraction, graded bedding and structures.

c. Fossil Collection

Several bone layers were found in Poor Farm Cave, Basin II, and a few isolated specimens were found elsewhere. Most of the fossil samples were found while other procedures were being carried out. The position of all fossils was recorded, in depth, by attitude with respect to imbricated grains and sedimentary structures and travertine deposition. An attempt to ascertain whether or not the fossil was stream transported and deposited contemporaneously with the surrounding clastic material was made for each site.

Purpose: To provide a rough means of relative dating of the clastic deposits. If a complete fossil is found in situ within a deposit a "relative" date is provided. All fossils were sent to the Carnegie Museum in Pittsburgh, Pennsylvania, for examination by J. Guilday, Invertebrate Paleontologist.

d. Travertine Samples

Samples of travertine which was deposited on top of clastic stream deposits in caves or found interbedded at significant locations were collected. The location of these collection sites is indicated on the appropriate cave map. Purpose: Uranium isotope (235/238) dating carried out by Dr. P. Thompson of the Geology Department, McMaster University, Hamilton, Canada.

3. Karst Alluvial Fans or "Sieve" Deposits

The widespread development of karst alluvial fans was noted after field work was underway. These phenomena result from the diversion of surface waters underground, leaving the former bedload on the surface, much like the "sieve" deposits (Hooke, 1967, p. 454) of arid and semi-arid areas. A special study of these features was made from topographic maps, aerial reconnaisance, and photography. Sampling methods on the fans were similar to those described for ephemeral and abandoned channels (above). A detailed description of these features is contained in the description of Basin II and III.

4. Field Procedures in the Interfluves

a. Slopes

Where surface sedimentary covering significantly affects the topographic slope, this material was measured for angle of repose and estimates of thickness of the mantle. Studies on movement were not made, but the distribution and orientation of boulders of specific rock types and their distance from the parent outcrops was recorded. This was done in the boulder fields, the alluvial aprons and karst sieves.

Purpose: Provenance, X-ray diffraction comparison, and an evaluation of the relative amount of gravitational fill entering the caves directly from slope movement rather than by stream transport.

b. Mountain Tops

Several studies of periglacial phenomena by others at the headwaters of Basin II and Basin III have been noted in Chapter 3. Samples of bedrock outcrops at the headwaters of the three basins were collected for X-ray diffraction of clays in the bedrock and in the weathered regolith produced by the weathering of these outcrops. Quartz pebbles which act as traceable identifiers in the streams and caves were collected from freshly weathered Pottsville and Princeton conglomerate outcrops. A complete series of the clastic overliers down the escarpment to the limestone contact was collected for each basin.

Purpose: Provenance studies, downstream changes in the particle properties of selected rock types and quartz pebbles, and X-ray diffraction comparisons.

c. Surface Karst Regolith

Additional samples of material were collected from the limestone surface other than at the channel sites already described. Bedrock samples of three members of the Greenbrier limestone series were taken in each basin for X-ray diffraction analysis. Surface samples of weathered clays from the surface regolith were also collected for X-ray analysis. These were taken for comparison with the clay mineral ratios found in the caves, on the mountains, and along the channels from weathered and unweathered samples. The abundance of chert nodules which could provide another source of quartz was also noted in the interfluves. Chert nodule samples weathered from the Union and Hillsdale members were taken for laboratory comparison with quartz fragments derived from the overlying clastics.

5. Additional Techniques Employed in the Field

Additional techniques employed in the field were as follows:

a. Aerial photography and field observation from a small aircraft after an extensive flood of the area.

b. The use of topographic maps and aerial photographs to draw comparisons between modern and former drainage networks. Air photographs were also useful in mapping the extent of large surface karst sieve deposits.

c. Survey of surface features such as cave entrances, abandoned dry valleys, and terraces, with respect to active cave conduits and surface stream channels. These mapping operations were carried out with a Brunton compass mounted on a camera tripod for vertical and horizontal readings. Distances were measured with tape. This was done to C.R.G., Grade 6 survey level, unless otherwise stated in the survey (Cullingford, 1962).

d. Sediment mapping in the caves. In order to locate the sample site accurately and to show the general distribution of material throughout the caves, detailed maps of the important caves were prepared. A base map of the cave was drawn up to C.R.G., Grade 6 level for each trunk cave section under study. Reliable base maps which had been prepared by caving groups such as W.V.A.C.S. and McMaster Climbing and Caving Club were used where available. The sediments were measured and shown on the respective base maps. Sediment profiles were included on the cave passage profiles to show the general structure and location of the deposits.

e. Absolute elevations. Two Paulin Aneroid Altimeters were used in the field to check elevations of terraces, streams, sinks, risings and cave levels.

f. Local hydrology. Observations of the local hydrology for parts of Basin II and Basin III were recorded automatically by instrumentation furnished by the U.S.G.S. and maintained by J. Coward in connection with his Ph.D. research on the hydrology of this area of West Virginia. These records have been maintained since the Fall of 1969. Information on modern runoff conditions is given in each chapter. Two major floods occurred while field recording was in progress during the Summer of 1969.

C. Laboratory Procedures

1. Size and Shape Analysis

a. Sieving procedures followed Folk (1968) with half Phi unit separation on most samples unless otherwise stated. Milky quartz was separated by hand in the larger size fraction of material, down to -1.50 (2.83 m.m.). The percentage of quartz fragments by weight was measured in addition to the number of fragments in each half Phi size unit. Roundness of quartz grains was measured for some samples after Powers (1953). The percentage of obviously broken rounds was noted in a manner similar to Pittman and Ovenshine (1968). For very large gravels a background grid of graph paper divided into one-hundredths of an inch was used for size analysis and estimating roundness. The V.A. tube described by Guy, *et al*. (1966) was tried and found to be generally unsatisfactory for the laboratory procedure in this study, owing to the wide range of size of material found in the cave deposits. The results of some of these data are contained in Appendix A.

b. Pipette analysis of fines was carried out on some of the samples finer than 4.00 (.6 m.m.) size. Generally this was done on samples where the clay fraction was greater than 10% of the total sample. This is a very time-consuming procedure and the methods of Felsher (1967, personal communication) and Folk (1968) were used with some modification.

c. Thin section preparation of unconsolidated cave deposits was abandoned after several unsuccessful attempts at impregnation and mounting. It is suggested that samples which are cemented naturally by calcite cementation from ground water percolation could be used for thin section preparation.

2. Structural Property Analysis

a. The soil monoliths were examined and analysed in the laboratory. A count of the number of laminae per centimeter was made. These samples were not examined under the microscope; however, accurate sampling of light and dark layers was done with a hand lens and slides for X-ray diffraction of selected layers were prepared. The alternate light and dark layers in the monoliths were not noticed in the poor lighting conditions in the caves where they were collected. Color photography and laboratory procedures suggest that they are dessication features. They are illustrated and described in Chapter 6.

b. Sedimentary structures. Measurement, photography and mapping of ripples, dines, imbrication and graded bedding was done in the caves and some surface channels of the three basins. Further analysis was performed from photographs taken in the caves. The results of this information are included in the description of the sediments in each of the chapters dealing with the basins.

3. X-Ray Diffraction Analysis

Pretreatment and separation of the $< 2\mu$ fraction. The method of sample pretreatment and slide preparation for X-ray diffraction analysis is that used in the Geology Department of McMaster University. This follows the Technical Memo. 67-a, prepared by R. Vemuri (1967, personal communication). This pretreatment procedure is outlined in Table 4.01.

After completing this pretreatment, five glass slides of each of fifty-six samples were prepared in the following manner:

Slide 1: untreated

Slide 2: heated to 350°C for 12 hours

Slide 3: heated to 350°C for 12 hours, then 550°C for 1 additional hour

Slide 4: treated with Ethylene Glycol for 12 hours

Slide 5: treated with KCl

Table 4.01

PRETREATMENT OF SAMPLES

(After Vemuri, 1967)

Wash in distilled water*

		Sandstones	Limestones	Shales and Clays
I.	Crushing	Jaw crusher (Braun Chipmunk VD 60/83) Roller crusher (Charles W. Cook and Sons)		mortar and pestle
II.	Removal of Carbonates	Soak about 20 gms of the crushed rock in 400 ml. of 0.25 N CH_3COOH up to 1 week depending on carbonate content	up to 5 weeks	a day or two
III.	Washing	------------------wash free of acid repeatedly------------------------		
IV.	Dispersion	Disperse using an ultrasonic probe (Fisher Scientific BP-10/CW-10) (Use a water cooling jacket lest the beaker containing the material should become too hot under ultrasonic vibrations) 40 to 60 minutes	40 to 60 minutes	10 to 20 minutes
V.	Size Fractionation	Transfer the suspension to one litre cylinders and dilute. Stir and let settle** for 225 minutes. Remove the top 5 cm. of suspension (around 170-200 mls.) which would supposedly contain < 2μ size particles.		
VI.	Recovery	Recover the < 2μ size fraction by centrifuging (Sorvall superspeed RC2-B automatic regrigerated centrifuge 10,000 RPM, 5 minutes).		
VII.		Mix the clay in order to avoid density seggration while centrifuging.. Use a small part for preparation of slides for clay minteral identification. Dry the remaining part in a dessicator.		

*Distilled and demineralized water is used all through the operations.

**No deflocculating agent is added at any stage. In case suspension settled down too fast, the clear supernatant water is decanted and fresh distilled water is added.

These were then subjected to X-ray diffraction by Mr. F. Tebay of the Geology Department, McMaster University. This was done with CuK radiation with a Ni filter at 30KV and 15 milliamps.

The diffraction peaks were examined for the following seven minerals:

1. Kaolinite: peaks at 7Å, 3.58Å and 2.38Å. These peaks die by heating to 550°C.
2. Illite: 10Å and corresponding higher order peaks.
3. Montmorillonite: 14Å expanding to 17Å on glycolation.
4. Chlorite: peaks at 14Å, 7Å, 4.75Å, 3.54Å. No change on glycolation, K saturation or heating to 350°C.
5. Vermicluite: peaks at 14Å, 7Å, 1.57Å. No change on glycolation. K+ saturation reduces to 10Å. Heating to 350°C reduces to about 12Å depending on the kinetics.
6. 10Å - 14Å Mixed Layer Clay: band on either side of 12Å with small peaks at 8Å, 6Å, and 3Å. Glycolation sharpens the 10Å and 14Å peaks reducing the band, and heating to 350°C reduces it to 10Å.
7. 14Å Mixed Layer Clay: if chlorite and vermiculite peaks are not sharply defined in their higher order reflections, it may be assumed that a major part of the minerals with 14Å reflection are in a mixed layer condition.

Since there is considerable variation in method, the accuracy of quantitative X-ray diffraction data is questionable (Brown, 1961; Carroll; 1970). The quantitative estimation of different mineral concentrations is based on the principle that the diffraction peak intensity of a mineral is related to the amount of that mineral. Because of the variation in crystallinity, composition, impurities, etc., such a relation does not strictly hold good for clay minerals (Vemuri, 1967), and as such it would at best be semi-quantitative only.

Peak heights of the various minerals were identified and measured. Since peak heights vary depending upon the way the slides are pretreated, duration and intensity of heat, and other factors, ratios the different minerals on the same slide are considered the most accurate means of comparing clay mineral data. This scheme is the one suggested by Vemuri (1967, personal communication) and is summarised in Table 4.02.

It was found that the kaolinite/illite (3.58Å/10Å) ratios for all three basins were the most reliable. They were consistently present throughout the area, and were free of reflections from surrounding peak heights. Other strong peak heights occurred at 4.78Å (chlorite), 3.34Å (quartz), and 14Å. Ratios for chlorite/kaolinite (4.78Å/3.58Å) were also examined. The results of the X-ray diffraction data are shown in Appendix B.

Table 4.02

CLAY MINERAL RATIO SCHEME

Mineral Ratio	Peaks Used	Comments
kaolinite/illite	3.58Å/10Å	3.58Å peak of kaolinite is used because it is supposed to have 100% intensity, and is also free of reflections from chlorite, vermiculite, etc.
mixed-layer 10Å-14Å/illite	12.12Å/10Å	The height of the peak around 12Å (between 10Å peaks)
chlorite/kaolinite	$\frac{4.78\text{Å}}{3.58\text{Å}} / \frac{100}{80}$	The intensity of chlorite peak at 4.78Å is only 80%. Hence the correction. Ratio of the peak height at 7Å to that of 14Å
montmorillonite/ illite		Peaks at 17Å and 10Å from the diffractogram after glycolation

Chapter 5.

BASIN I
THE TROUT RUN SYSTEM

A. The Modern Basin

Modern Basin I is defined as the watershed within the maximum perimeter of the combined surface and subsurface runoff draining into the Greenbrier River via the mouth of Trout Run.[1] As such, the basin includes portions of four surface drainage networks and the subterranean drainage of connected cave systems. Figure 5.01 illustrates the combined surface and subsurface networks.

The surface channels have developed a parallel drainage pattern oriented to the east in response to steep slope profiles along the front of the escarpment. The headward portions of most channels where gradients exceed 1,000 feet per mile, move boulder-sized material during periods of high runoff.

Subsurface conduits, in contrast, show a strong strike controlled linear pattern, oriented north-south. The gradients of these conduits average less than 100 feet per mile. Drainage from the surface enters the subterranean con-

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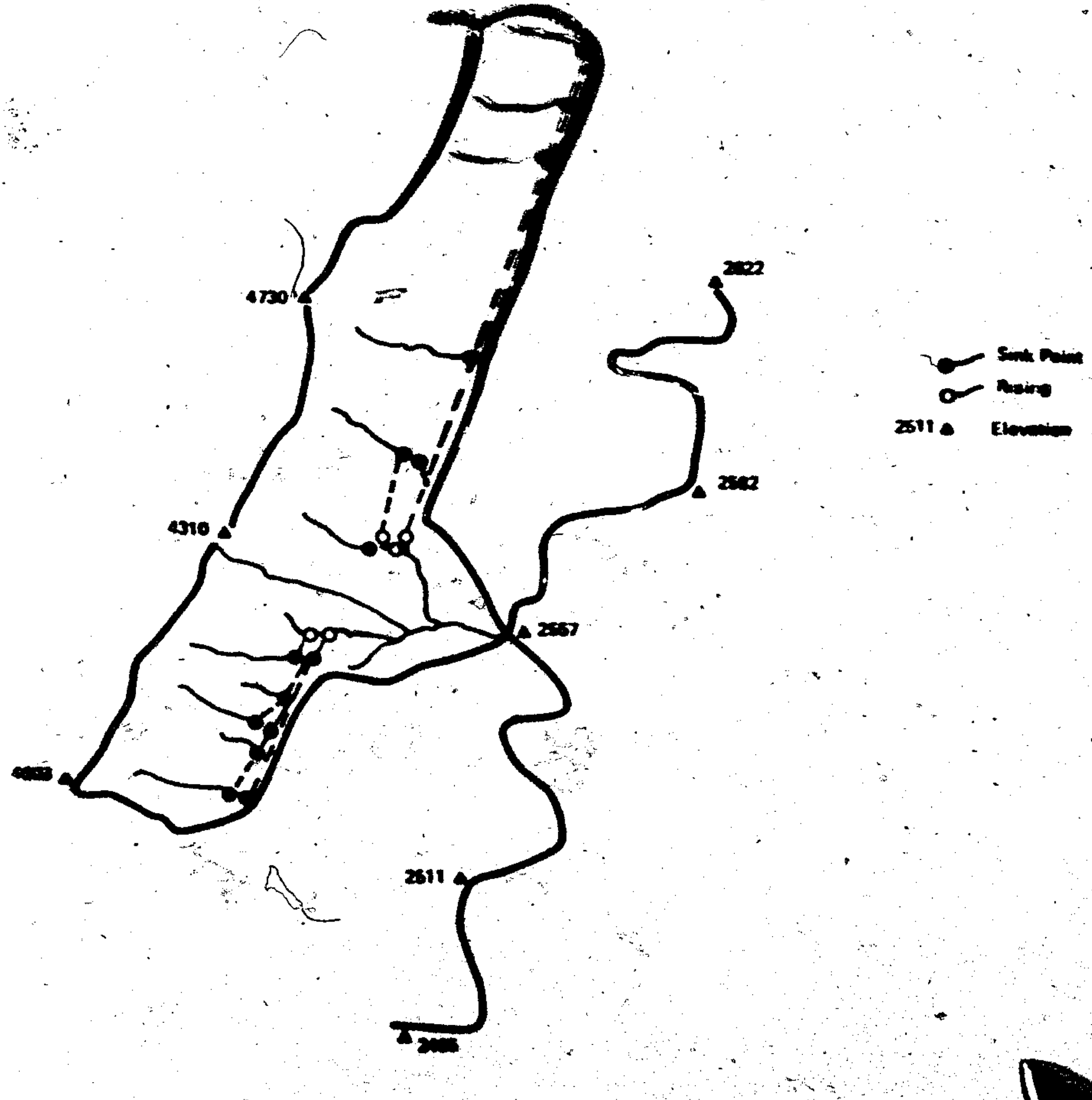
[1] B.M. 2557 feet, 1/3 mile south of Nida, West Virginia, 38° , 27' , 30"N. , 79° , 52' , 45"W. , Cass Quadrangle, West Virginia, U.S.G.S., 1922.

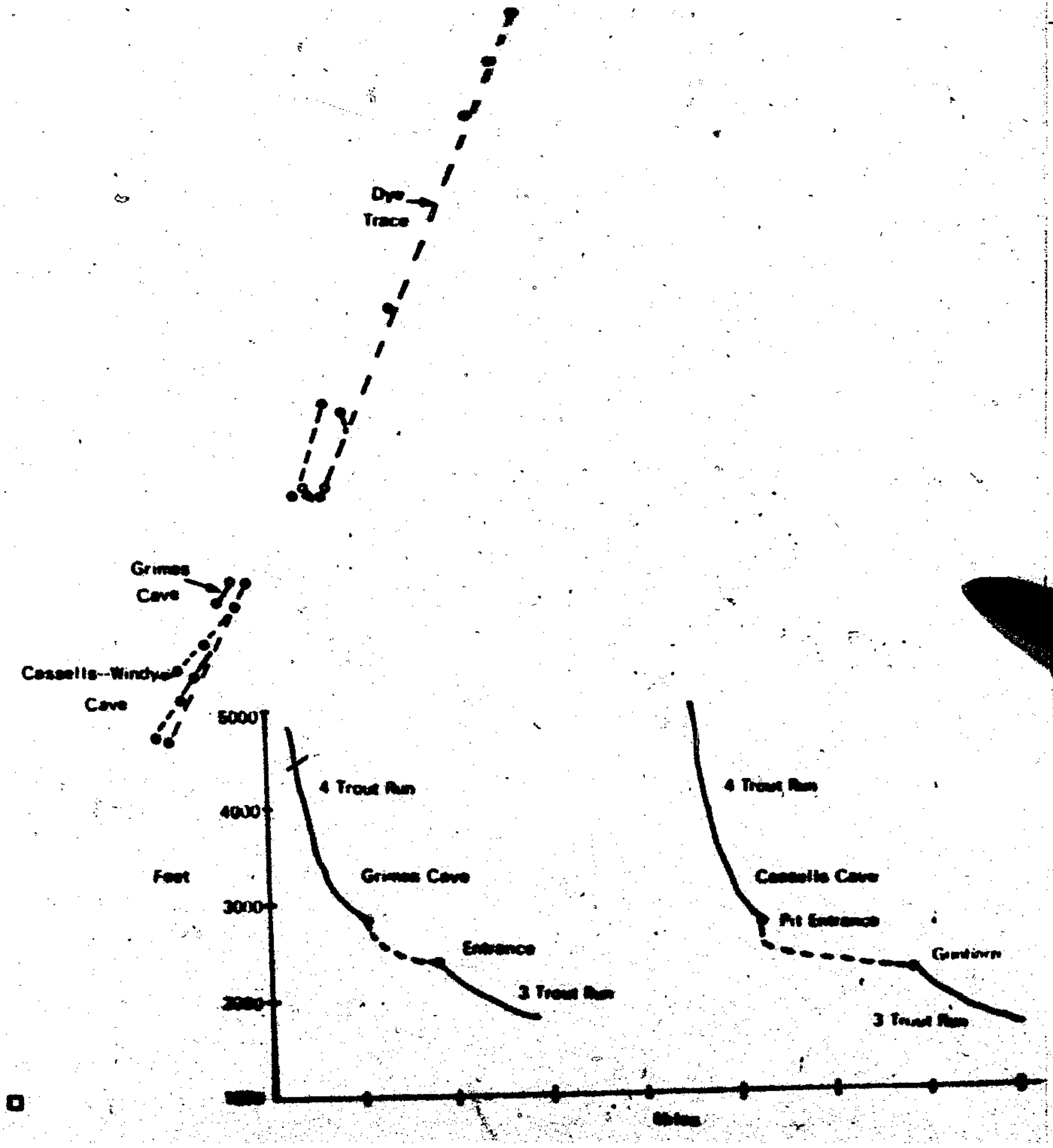
BASIN I (Surface and Subsurface Drainage)

Figure 5.[illegible]



SUBSURFACE DRAINAGE
(From Cave Maps and Dye Tracing)

Figure [illegible]



SURFACE DRAINAGE
(As Shown On Cass Quadrangle U.S.G.S (1922)

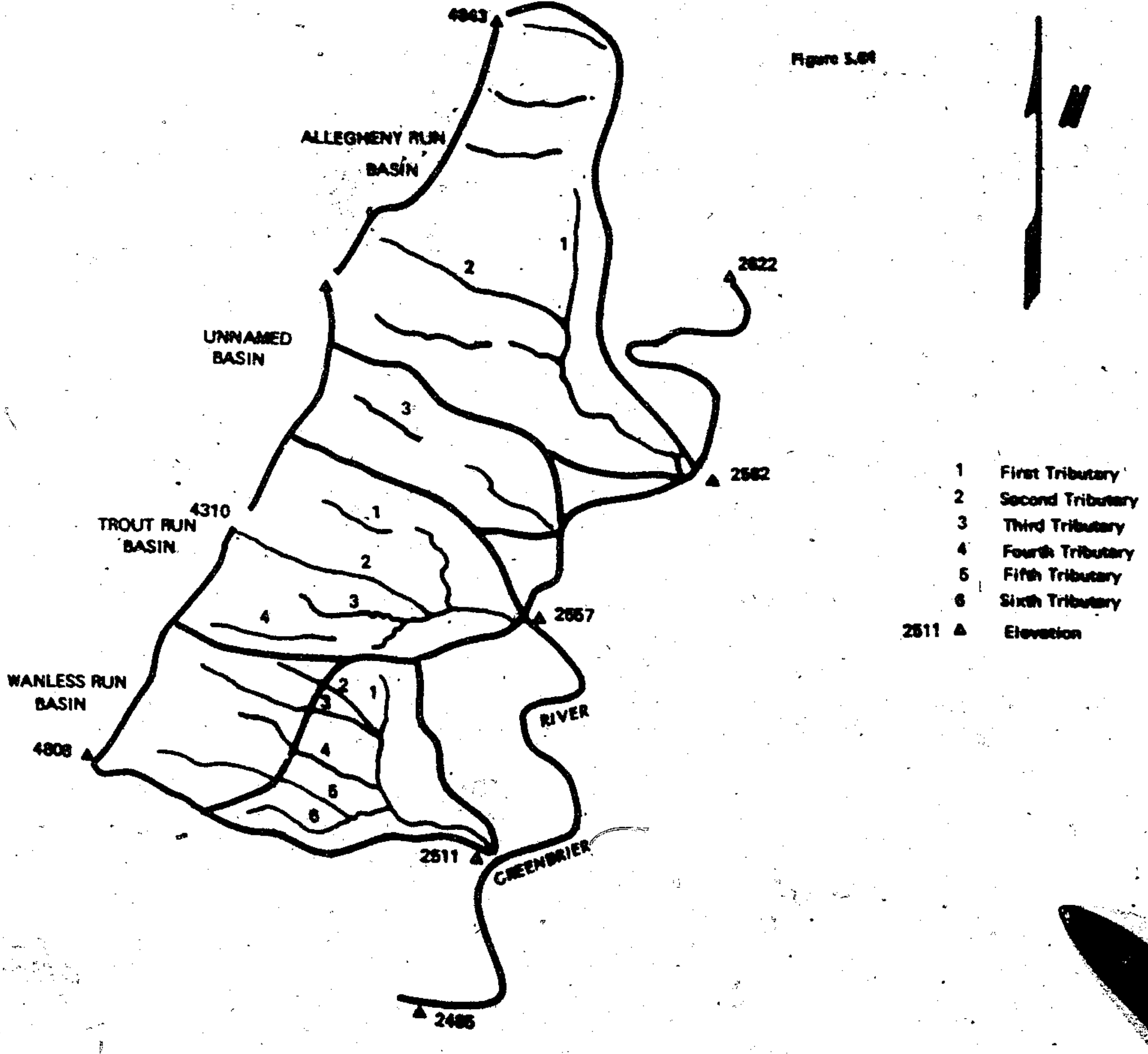


Figure 5.04

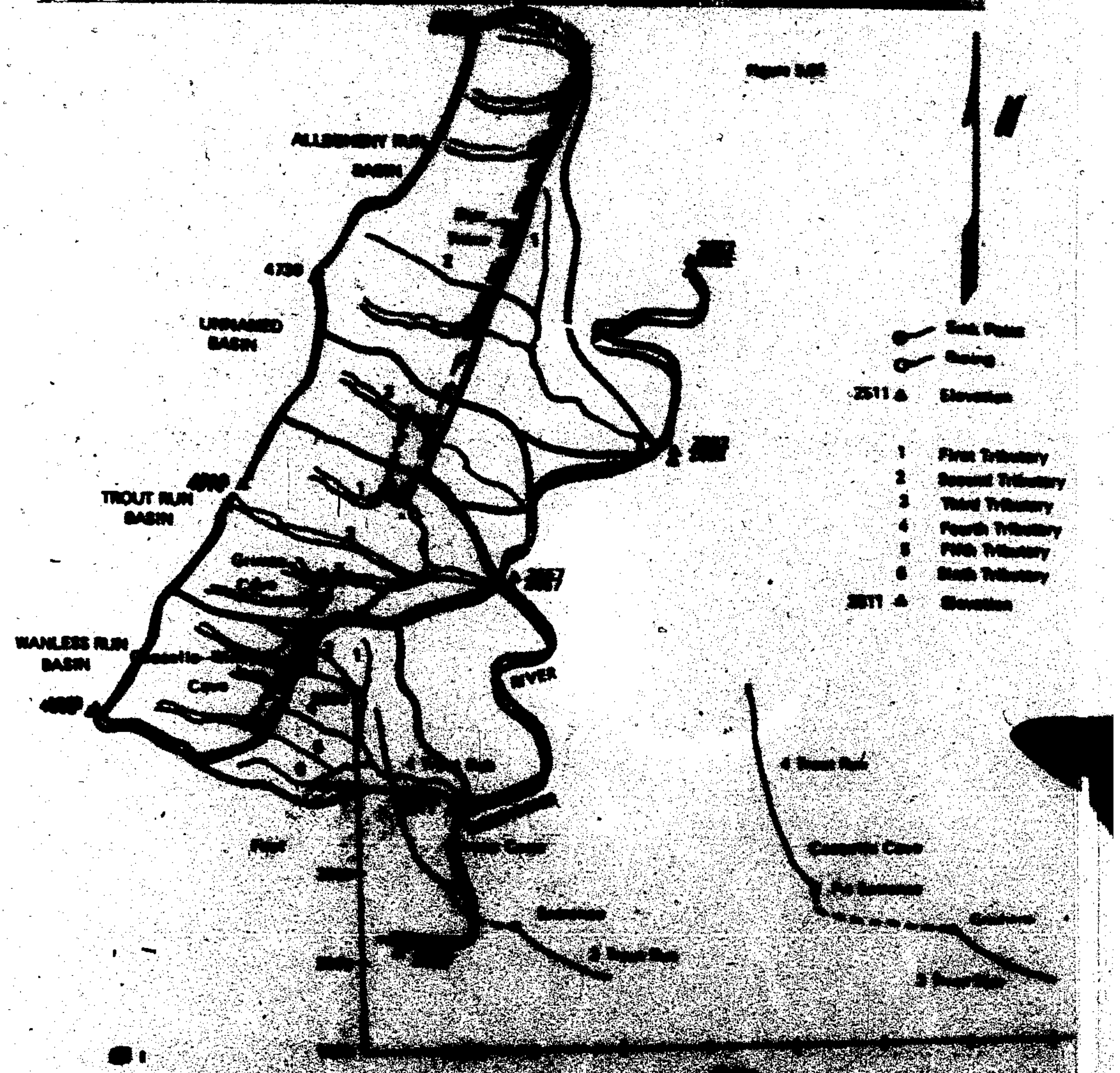
BASIN I (Surface and Subsurface Drainage)

Figure [illegible]

SUBSURFACE DRAINAGE
(From Cave Maps and Dye Tracing)

Figure [illegible]

SURFACE DRAINAGE
(As Shown On [illegible] U.S.G.S. [illegible])



duits via waterfalls into vertical shafts or through shallower, clogged sink points along the surface streams. Boulder-sized sediment enters the caves which extend beyond the base of the pit entrances. Other caves have much of their sediment load withheld by "sieving" at the entrance sinks.

Resurging drainage returns to the lower portions of trunk valleys via risings where the subterranean conduits have been breached by down-cutting surface valleys. The risings are generally located at the base of the Greenbrier limestone series, but some of them are located at least 100 feet above the contact with the underlying MacCrady shales. Such risings are frequently perched on terrace sediments found along the sides of valleys. Surficial sedimentary layers show consistent downstream variations of particle properties along the trunk valleys.

The sediments of the modern surface and subsurface portions of the network are not well-integrated. Boulders accumulate at cave entrances. Gravels to silts are the most common grain size deposited along the risings unless additional surface drainage and sediments are added from another source. The profile of the trunk stream is not that of a typical graded "concave upwards" surface stream, such as is developed on the surface on clastic rocks in the surrounding non-karst basins of the Appalachians. There are at least two nick points in response to the upper and lower clastic/ carbonate contacts. Other minor nick points within the carbonate portion of the basin are present in response to interbedded clastic shales.

The sedimentary and hydrologic differences between the surface and subsurface portions of the modern basin suggest that there has only been a recent connection between two formerly unrelated networks. Evidence from the abandoned portions of both networks suports this hypothesis. This observation is, however, only apparent after a close examination of the sedimentary and hydrological properties of the surface and subsurface portions of the modern and abandoned surface channels and upper level cave passages within the basin.

The present drainage network of Basin I may be divided into the following parts:

1. Surface Drainage

This includes all of the surface networks of streams and runoff associated with Trout Run and parts of the surface headwaters of the surface basins immediately north and south of the Trout Run network which are connected to Trout Run via cave systems (Figure 5.01).

2. Subsurface Drainage

a. The underground diversion of the Fourth Tributary of Trout Run to the Third Tributary of Trout Run via Grimes Cave.[2]

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[2] Surface tributaries are numbered from north to south for convenience of reference, unless they are given a specific name on the topographic maps.

b. The underground drainage of the Cassells-Windy Cave system. This diverts surface waters of the second, third, fourth and fifth tributaries of Wanless Run to the Third Tributary of Trout Run. This drainage resurges one-half mile downstream from the rising of the Grimes Cave drainage along the same tributary of Trout Run.

c. The underground drainage associated with the diversion of the unnamed basin immediately north of Trout Run and Allegheny Run basin. This drainage joins the First Tributary of Trout Run. No known caves are associated with active portions of this system.[3]

These drainage networks of Basin I make up the skeleton of the basin. Figure 5.02 illustrates the complexity of the drainage of the system in detail.

B. Geology of Basin I

The northern part of the area of study which includes Basin has several geologic variations which affect the karst and drainage. In the Greenbrier series, there is a rapid thinning of limestones and a thickening of shales and sandstones northeastward along the axis of the original

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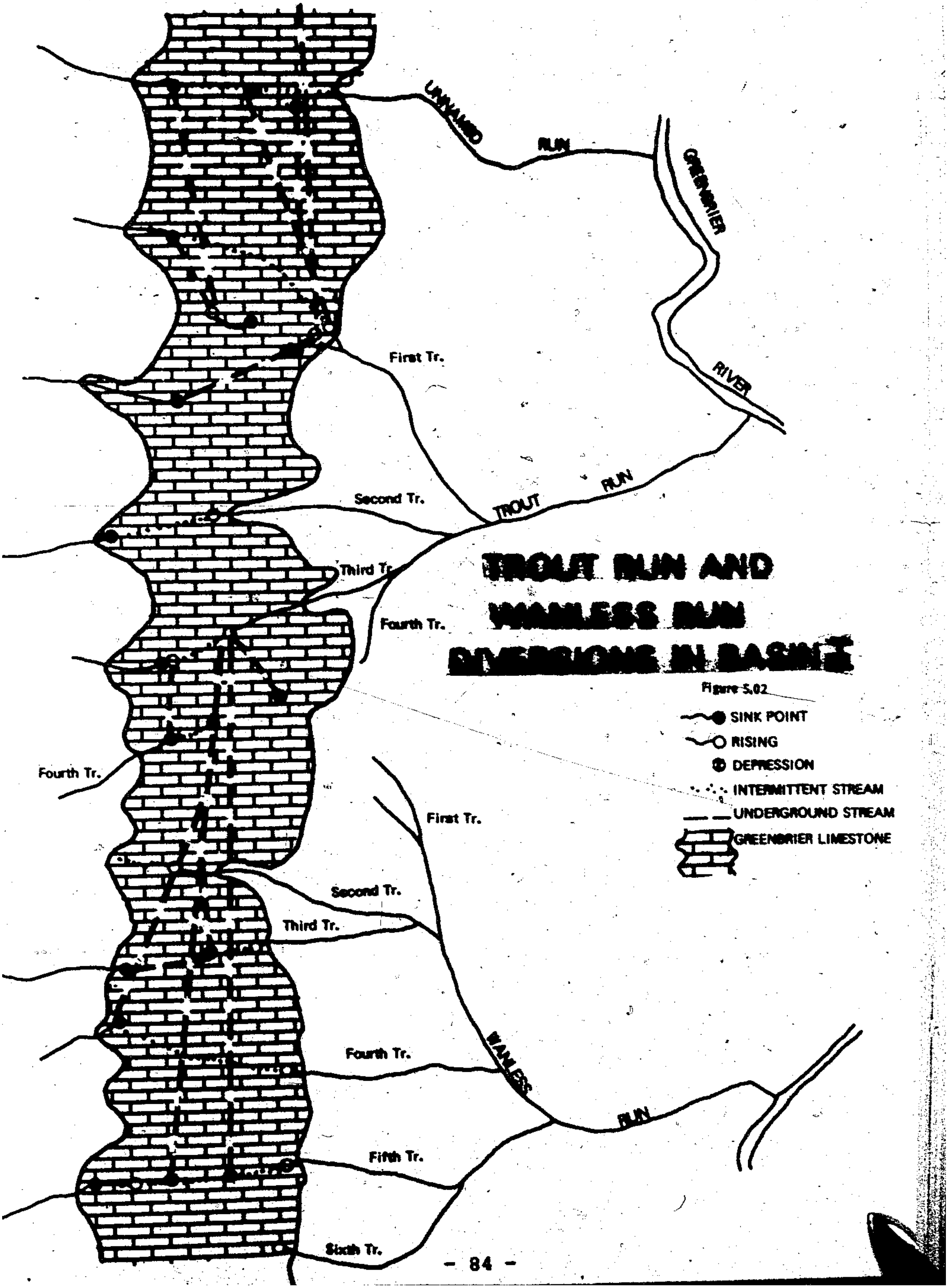
[3] Dye testing by Mr. Michael Ballister of the National Ratio Astronomy Observatory at Greenbank in 1970 and 1971 has confirmed that the resurgence at the head of the First Tributary of Trout Run is fed by drainage from the two surface basins immediately to the north of the Trout Run network. This additional drainage area supplies little sediment to Basin I, but is responsible for an average of 35% of the total runoff of the basin.



TROUT RUN AND WANLESS RUN DIVERSIONS IN BASIN 7

Figure 5.02

Mississippian basin of marine deposition (Donaldson, 1969, p. 61).

The Greenville shale has been considered analogous to the Cypress sandstone in a measured section taken six miles north of Basin I (Price and Reger, 1929). The Taggard shale members of the southern part of the study area in Basins II and III may correlate with the Bethel sandstone also described in the area of Basin I (Price and Reger, 1929, p. 177). Both shale members range from 30 to 50 feet thick in Basin I and are relatively impervious to ground water circulation and thus confine cavern development to areas immediately above or below them within the series. No caves are developed in or through them.

Only four limestone members of the Greenbrier Series have been identified within the area of Basin I.[4] Price and Reger (1929) have measured a total thickness for the series of 205 feet at Durbin, six miles north of Basin I. The same section is present in the Trout Run with an increased thickness to 288 feet. Table 5.01 shows these two sections.

The presence of the thick lenses of sandstone and shales in the country rock of Basin I is a probable cause of the pronounced strike oriented subterranean drainage pattern. Most major passage development in Basin I has taken

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[4] Price and Heck (1939) have described eight limestones in the series in the areas of Basin II and III.

Table 5.01

MEASURED SECTIONS OF THE GREENBRIER SERIES

Greenbrier Series	General Description	Durbin Section[1] (Thickness	Trout Run Section[2] in Feet)
Limestone, Alderson	Hackly at top, weathering yellow contains Orthotetes, Composita, crinois and gastropods. Base is dark grey massive and cross-bedded.	40	45
Sandstone, Cypress	red, shaly	20	36
Limetone, "Upper Union" (Gasper portion)	red, cross-bedded, siliceous, streaked with clacite at top but grading into grey; weathers white; pure oolite	50	70
Sandstone, Bethel	red, shaly, calcareous	10	12
Limestone, "Lower Union" (Fredonia portion)	grey, weathers white, oolitic	35	105
concealed		40	
Limestone, Patton	greenish-grey, earthy	10	20
	TOTAL THICKNESS	205	288

---

[1] Price and Reger, 1929, p. 117.

[2] This author, in Basin I.

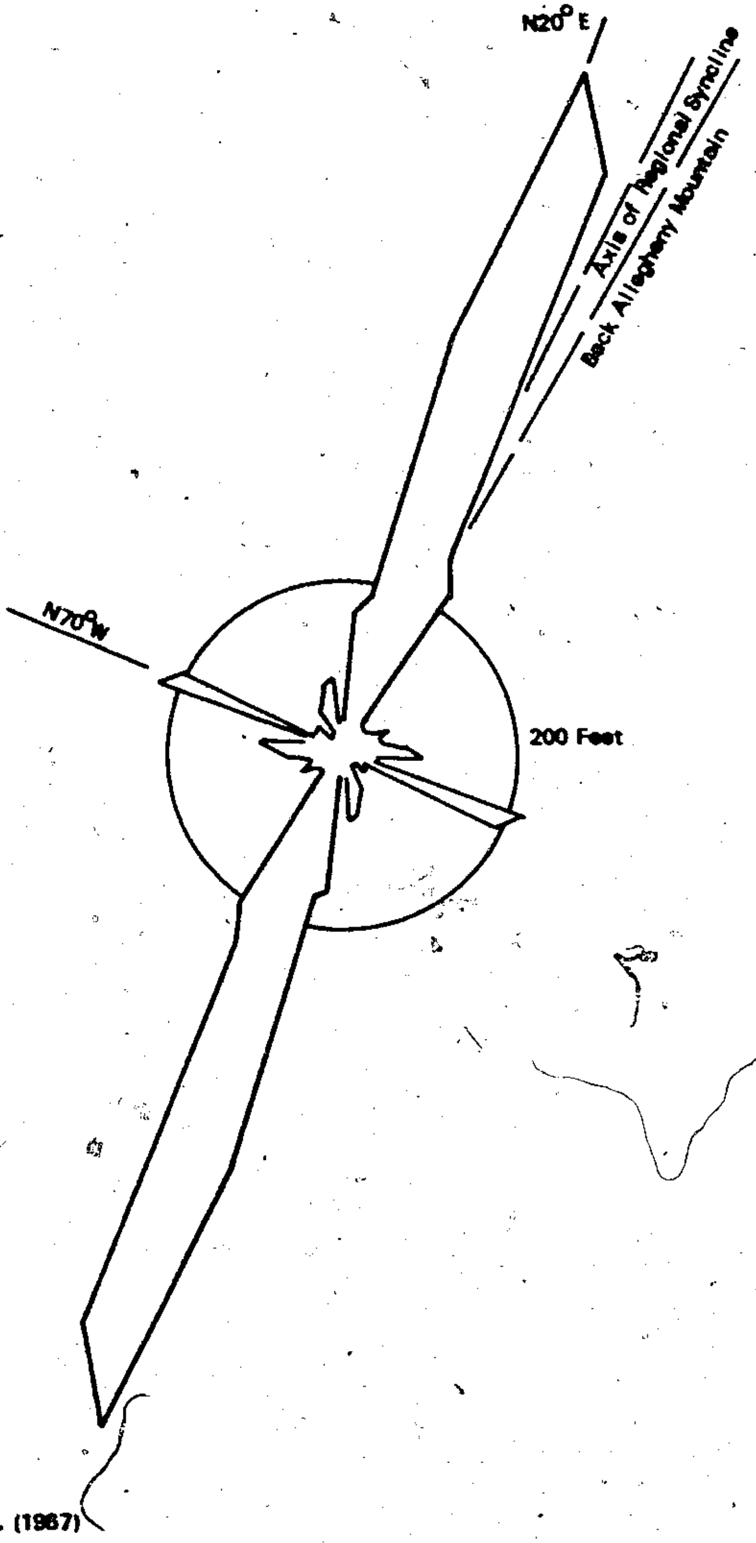
place within the upper and lower Union limestones (Table 5.01). Strike control and lithologic factors are reflected in the positioning and orientation of cave passages in Basin I.

The regional dip of most of the rocks along the Allegheny Front within Basin I is at approximately 8° to the northwest. Duncan, et al. (1967) emphasises the importance of joint control in passage directional development in Cassells Cave. The major joint set is at N 20° E, parallel to the axis of the North Potomac Syncline which locally parallels the escarpment along Back Allegheny Mountain. A minor joint set is developed at N 70° W. The joint passage relationship is shown in Figure 5.03. This rose diagram shows the greatest length and direction of passage to be developed along the direction of the major joint set (Duncan, et al., 1967).

Obviously the location of passages is dependent upon the location of soluble limestone members within the Greenbrier Series. In addition, insolubility and impermeability of surrounding beds appears to be a strong factor in passage positioning. The presence of interbedded insoluble members within the series seems to be responsible for the channeling of solution along distinct conduits. The continual drop of regional water tables results in the abandonment of higher routes as newer lower level subterranean routes are developed. This action determines which impermeable beds can act as controls during the development of passages.

ROSE DIAGRAM SHOWING PASSAGE LENGTH AGAINST DIRECTION

Figure 5.03



After Duncan et. al. (1987)

C. The Surface Drainage and Sedimentation of Basin I

Table 5.02 summarises drainage data for the surface and subsurface portions of Basin I. The Trout Run portion of the basin consists of third-order surface networks. In plan, the network is shown as the central surface basin on the left of Figure 5.01. It is necessary to consider the surface portions of Basin I separately, in a discussion of drainage and sediment movement. Processes such as solifluction, soil creep, and freeze-thaw phenomena, which result in gravitational transfer and mass movement unique to the surface environment, operative now and in the past, are responsible for the total sedimentation load of the cave system.

The upper portion of both the Trout Run and Wanless Run surface networks drain across the Pottsville conglomerate outcrops (Figure 5.04). This factors is responsible for the high percentage of milky quartz pebbles traceable along the major surface channels. In addition to transported material, large amounts of gravitational fills have been added to the stream channels during periods of former large scale surface movement. This is clearly evident from the widespread occurrence of large angular boulders along the hillsides and sub-rounded boulders of similar magnitude found along the major surface runoff channels of Trout Run and Wanless Run.

Aerial photographs show large rockfields of this material, the movement of which appears to predate the es-

Table 5.02

HYDROLOGY AND TOPOGRAPHY OF BASIN I

Surface Drainage	Channel Length (Miles)	Area (Sq. Miles)	Total Fall (Feet)	Mean Gradient	Mean Discharge (cfs.)
Trout Run	2.2	1.8	1,943	170/1000	4
Wanless Run[1]	2.5	0.9	2,285	170/1000	4
Other Surface Streams[1]	5.4	2.1	1,750	N.A.	4
Subsurface Drainage	**Conduit Length (Miles)**	**Area (Sq. Miles)**	**Total Fall (Feet)**	**Mean Gradient**	**Mean Discharge (cfs.)**
Grimes Cave	.2	0.4	60	60/1000	2
Cassells Cave System	1.1	1.2	185	32/1000	2
Total of Basin I (surface and sub-surface drainage)	11.4	4.8	2,285	133/1000	12

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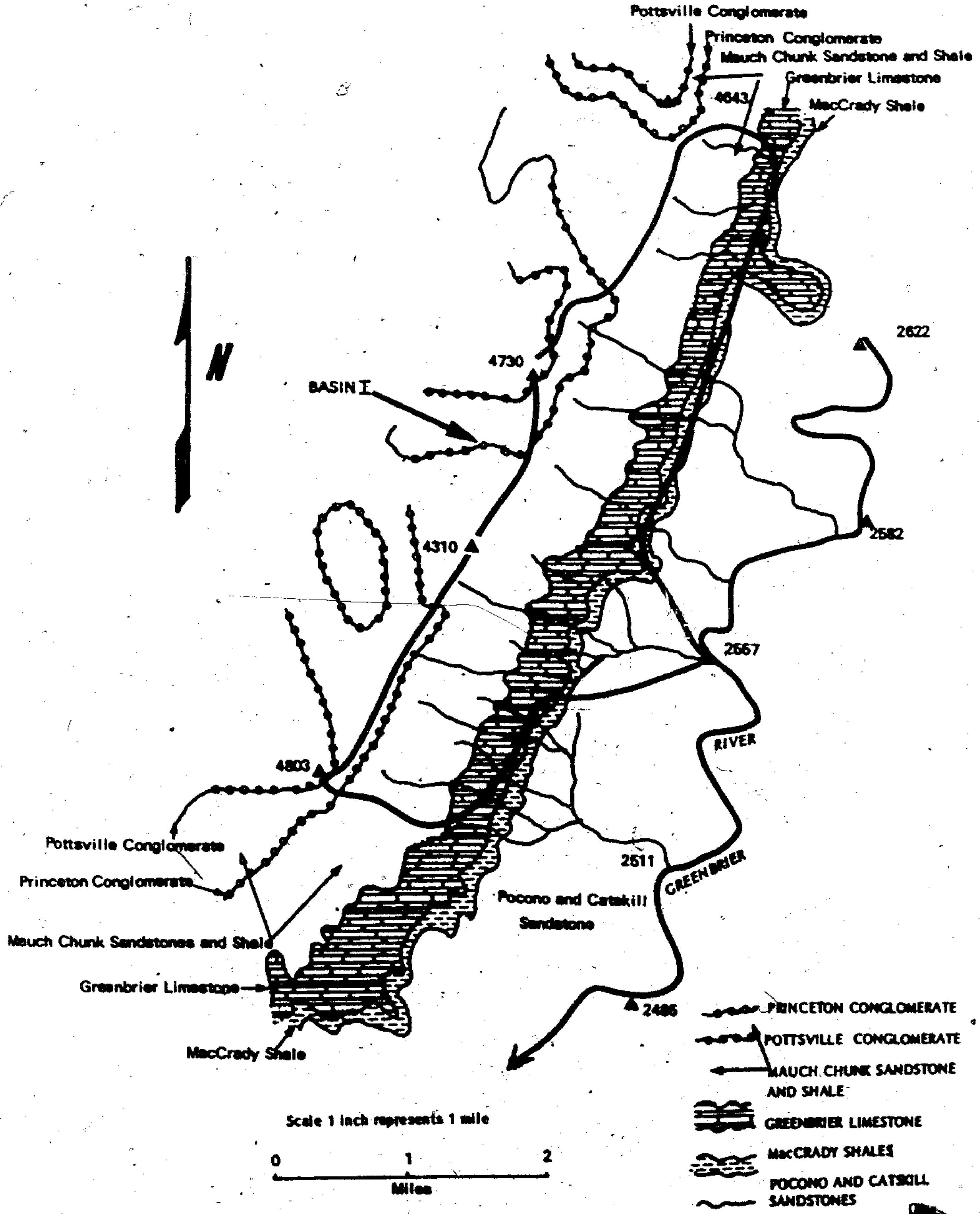
[1] Wanless and other surface streams have only part of their drainage associated with Basin I. (See Text and Figure 5.02)

LITHOLOGY AND STRATIGRAPHY OF BASIN I

Figure 5.04



tablishment of climax forest vegetation. This is evidenced in the large virgin tree stumps whose roots surround many of the large blocks. There is little evidence for the modern movement of these large blocks. Figure 5.05 shows a portion of a rockfield composed mainly of large sub-angular blocks of Princeton conglomerate. This is two miles from the present outcrop and rests upon Adlerson limestone. Figure 5.06 is a photograph taken one-half mile further downslope. Large boulders similar to the one shown in the upper right hand corner of the photograph are traceable downslope to the stream (Fourth Tributary of Trout Run) and then downstream to the pit entrance of Cassells Cave. Table 5.03 is a sample of thirty such blocks measured downstream along the Fourth Tributary. These blocks were chosen at random downstream to the dry entrance of Windy Cave. None of the blocks showed evidence of any appreciable movement.[5] Many could not have been disturbed for the last three hundred years.[6]

Sedimentation along the Third Tributary of Trout Run is unique in that large surface terraces 60 feet in height have developed along the valley sides. These are very gentle, with less than 2° of slope in the surface

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[5] Based upon four years of observation of their local setting relative to the surrounding forest vegetation.

[6] Evidence from overgrowth of climax species of hemlock and oak stumps and roots surrounding the boulders.

Figure 5.05

BLOCKS OF CONGLOMERATE AT THE HEAD OF TROUT RUN

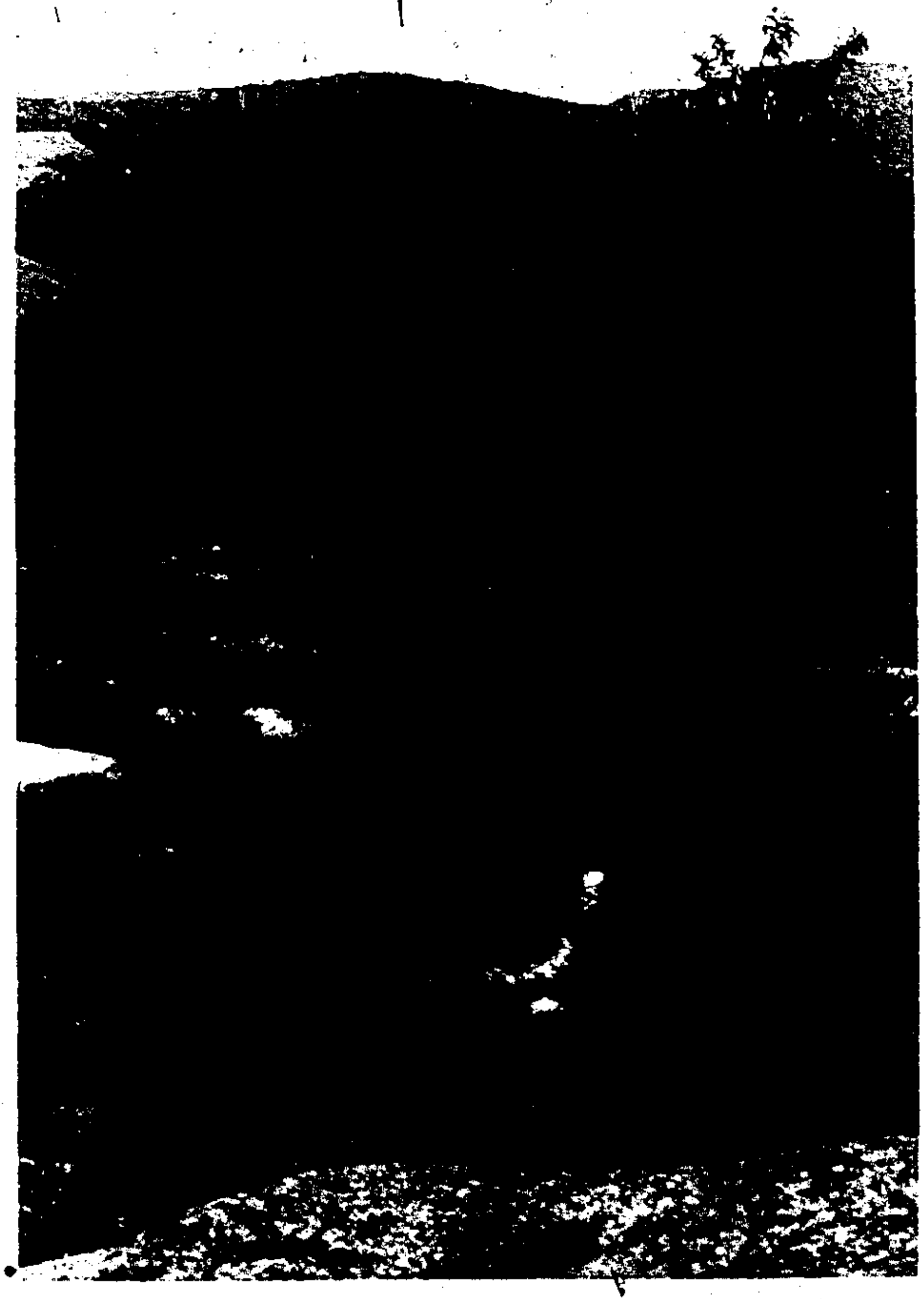


Figure 5.06

STREAM BED OF THE FOURTH TRIBUTARY OF TROUT RUN

Water here is sinking and is diverted to Grimes Cave.

Table 5.03

MEASUREMENT OF BOULDERS ALONG THE FOURTH TRIBUTARY OF TROUT RUN

Sample Number	Long Axis (Feet)	Intermediate Axis (Feet)	Short Axis (Feet)	Angle of Repose[1]	Direction[2]
1	14.3	6.0	12.0	-29°15'	104°
2	13.4	6.5	10.4	-23°00'	100°
3	15.7	7.0	16.3	+ 6°00'	155°
4	13.7	5.7	9.8	+18°00'	183°
5	9.7	4.3	9.8	- 5°30'	142°
6	18.2	6.0	10.4	-23°00'	160°
7	13.5	4.5	11.0	-27°00'	155°
8	15.9	5.5	13.0	+10°00'	125°
9	20.5	15.0	17.7	-30°00'	52°
10	9.2	3.2	9.0	-33°00'	115°
11	9.3	4.4	8.0	0°30'	115°
12	11.8	4.5	8.4	0°00'	120°
13	10.7	3.1	8.0	- 2°00'	85°
14	12.0	6.0	9.3	-11°00'	125°
15	9.1	4.5	8.9	-22°00'	190°
16	17.5	3.9	8.3	-22°00'	185°
17	14.7	6.2	10.0	-13°00'	75°
18	12.2	5.8	6.9	-08°00'	180°
19	16.7	10.5	14.5	-16°00'	100°
20	9.4	2.9	4.0	-14°00'	140°
21	13.7	3.5	11.7	0°00'	150°
22	9.9	3.3	9.8	+ 5°00'	108°
23	9.3	4.4	8.2	+ 4°00'	110°
24	10.2	2.8	6.4	+ 5°00'	180°
25	11.0	3.9	10.7	-20°00'	90°
26	12.0	4.0	6.0	-17°00'	120°
27	9.5	4.6	7.6	-11°00'	130°
28	14.0	5.0	12.9	-19°00'	105°
29	9.8	4.4	9.0	+20°00'	135°
30	9.4	7.3	4.0	- 4°00'	150°
MEAN	12.6	5.3	9.7	-10°00'	130°

[1] The mean slope of the hillside is -12°00' .

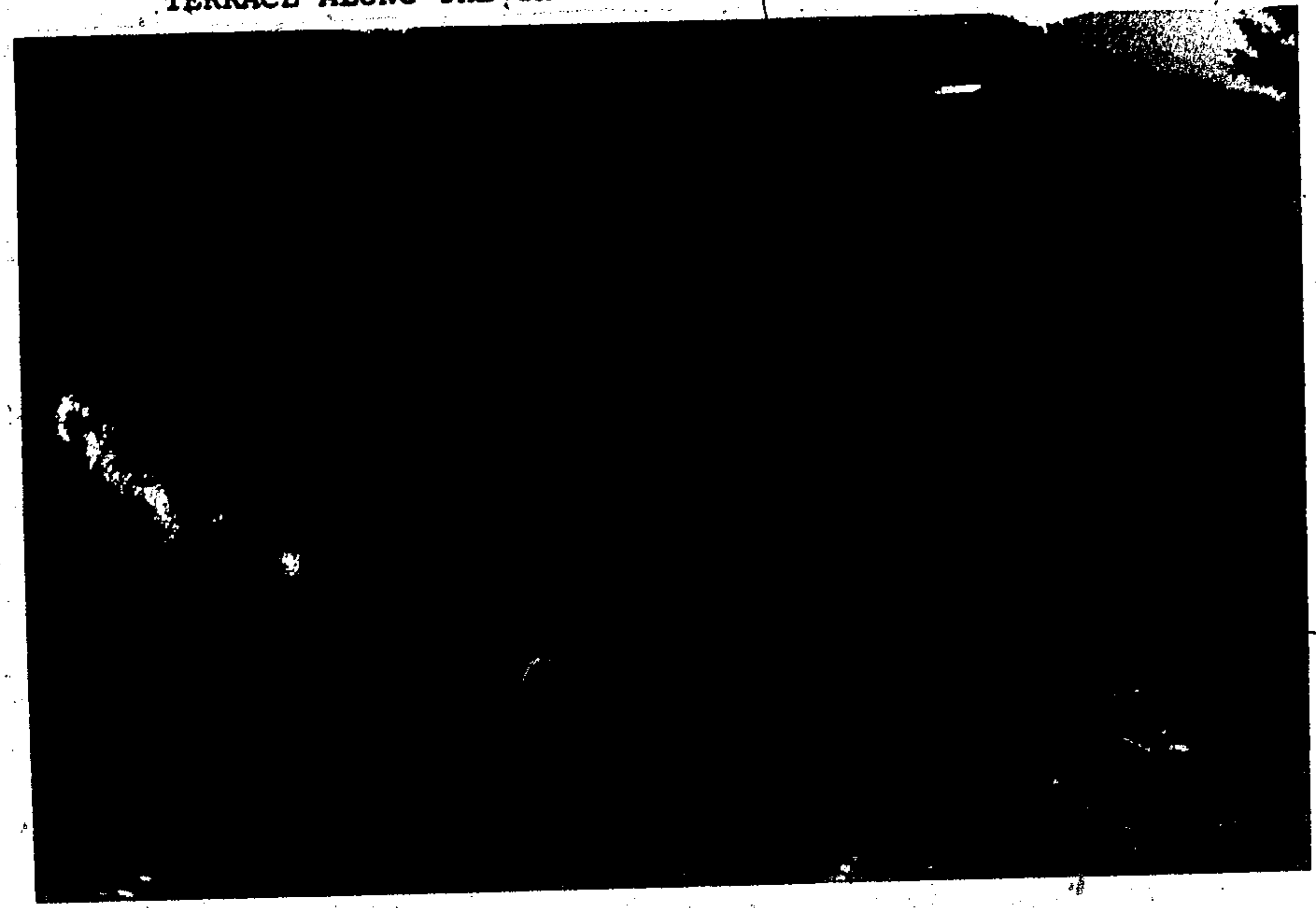
[2] The downhill direction is 130° .

(Figure 5.07 and Figure 5.08). The material of which they are composed is finer and rounder than most other deposits in the valley. A large terrace was sampled above the entrance to the Cassells-Windy Cave. The base contains gravels and coarse sand. The upper 30 feet consists mainly of silts. Only ephemeral drainage now flows past them in the Third Tributary of Trout Run. The lack of coarser, angular material that is common at the base of much of the escarpment is convincing evidence for the water sorted and transported origin of these deposits.

It is hypothesised that this finer, rounded material in the terraces was derived from the boulder fields at the head of the basin. This may have been of a mass wasted origin due to cold temperature conditions at higher elevations in the past. Much of the coarser material remains above the limestone, unable to pass freely through the cave networks. This is due to massive accumulation of debris at any sink points (Figure 5.06) and to the loss of surface stream competence and capacity below these sink points. The rock fields at the head of the basin remain very much intact, as shown in Figure 5.05. Figure 5.09 is a geomorphic map along the Fourth and Third Tributaries, illustrating the location of surface and subsurface sedimentary features along the main trunk of Basin I.

Figure 5.07

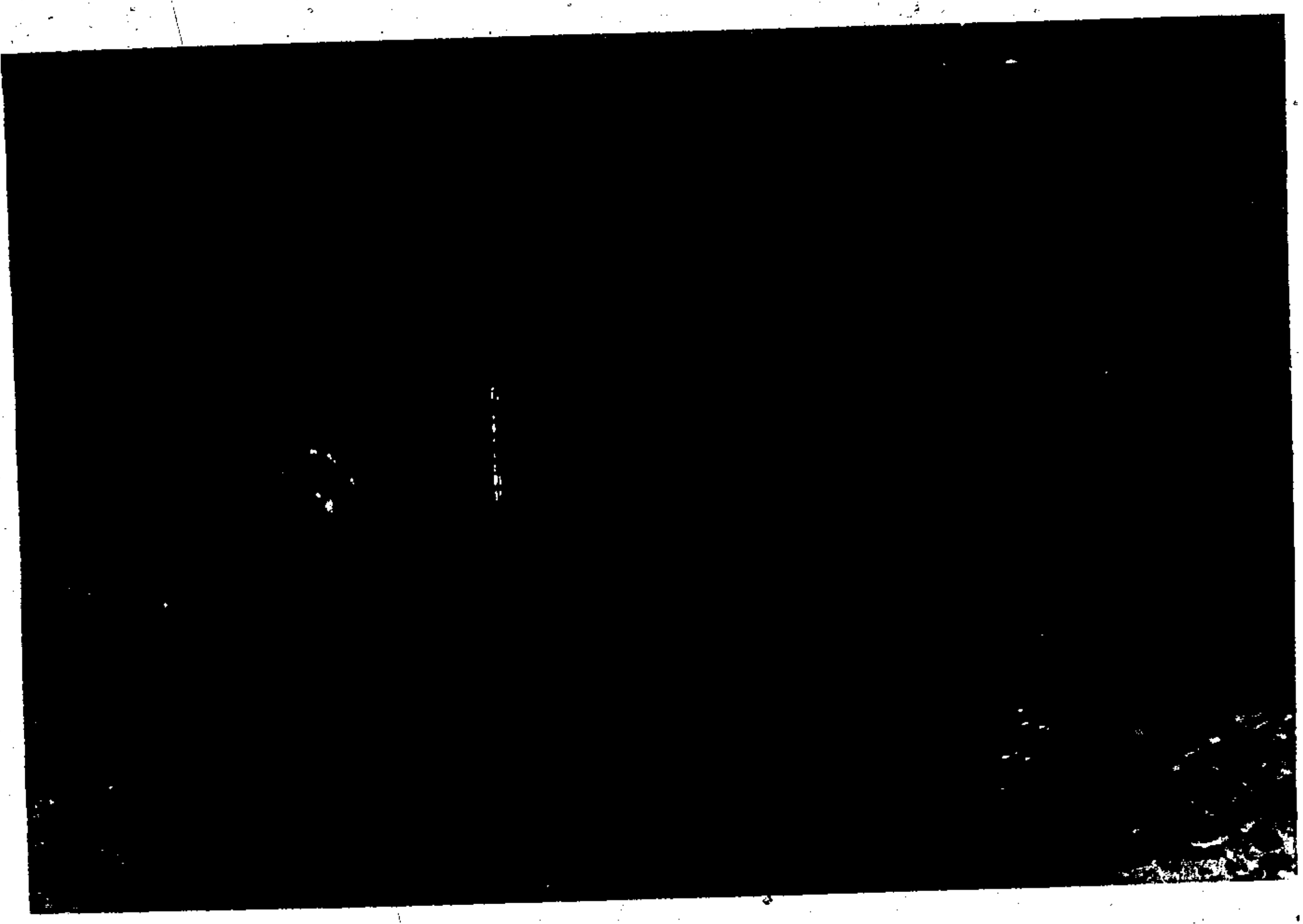
TERRACE ALONG THE THIRD TRIBUTARY OF TROUT RUN



This is between the Grimes Cave outlet and Cassells Cave Rising. The stream flows along the front of the terrace from left to right. The Gunbarral Rising is approximately 200 feet to the right of this photograph.

Figure 5.08

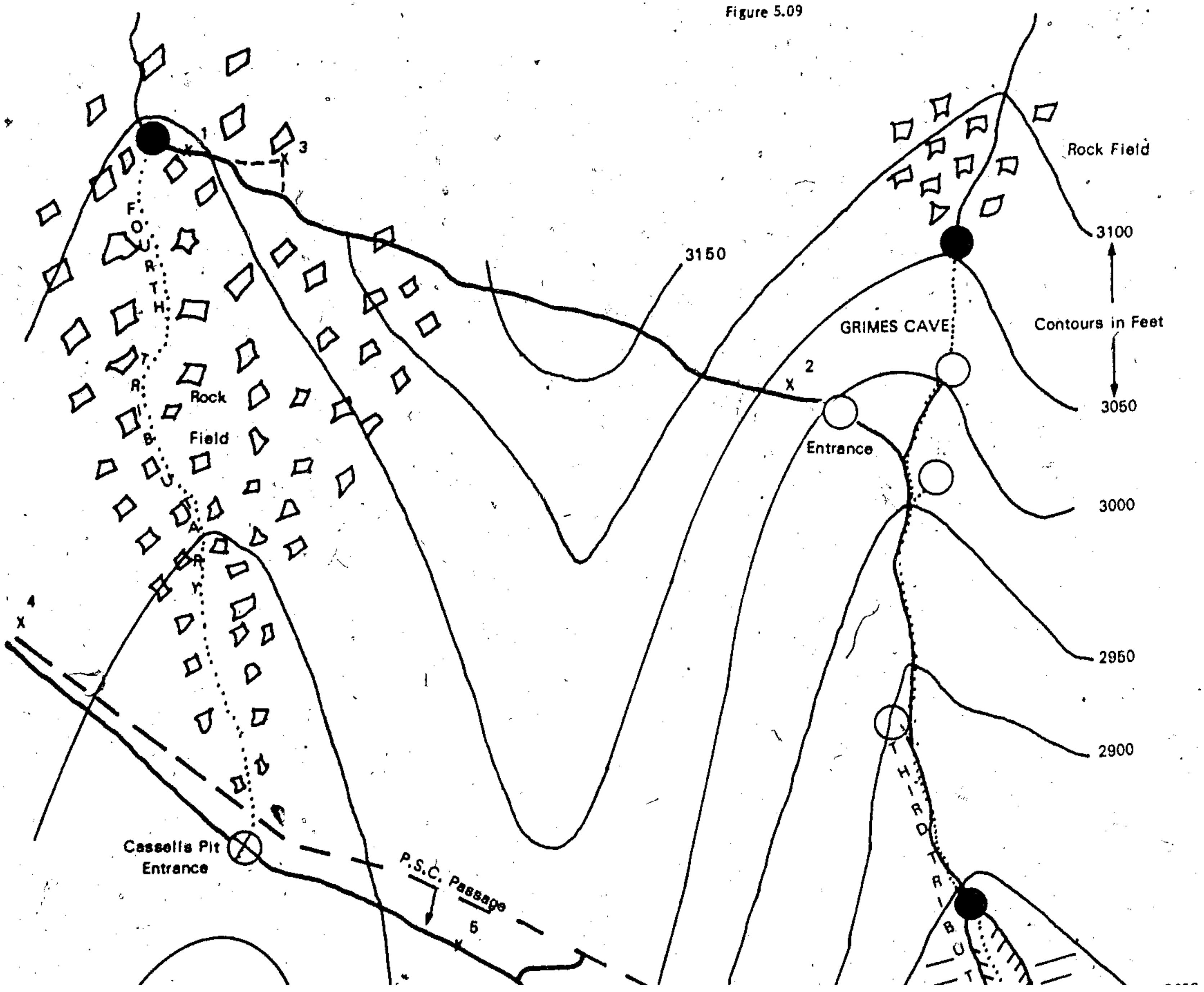
THIRD TRIBUTARY OF TROUT RUN



Approximately 30 feet of alluvium flanks the small stream above the Cassells Cave Rising.

GEOMORPHIC MAP OF THE AREA BETWEEN FOURTH AND THIRD TRIBUTARIES OF TROUT RUN

Figure 5.09



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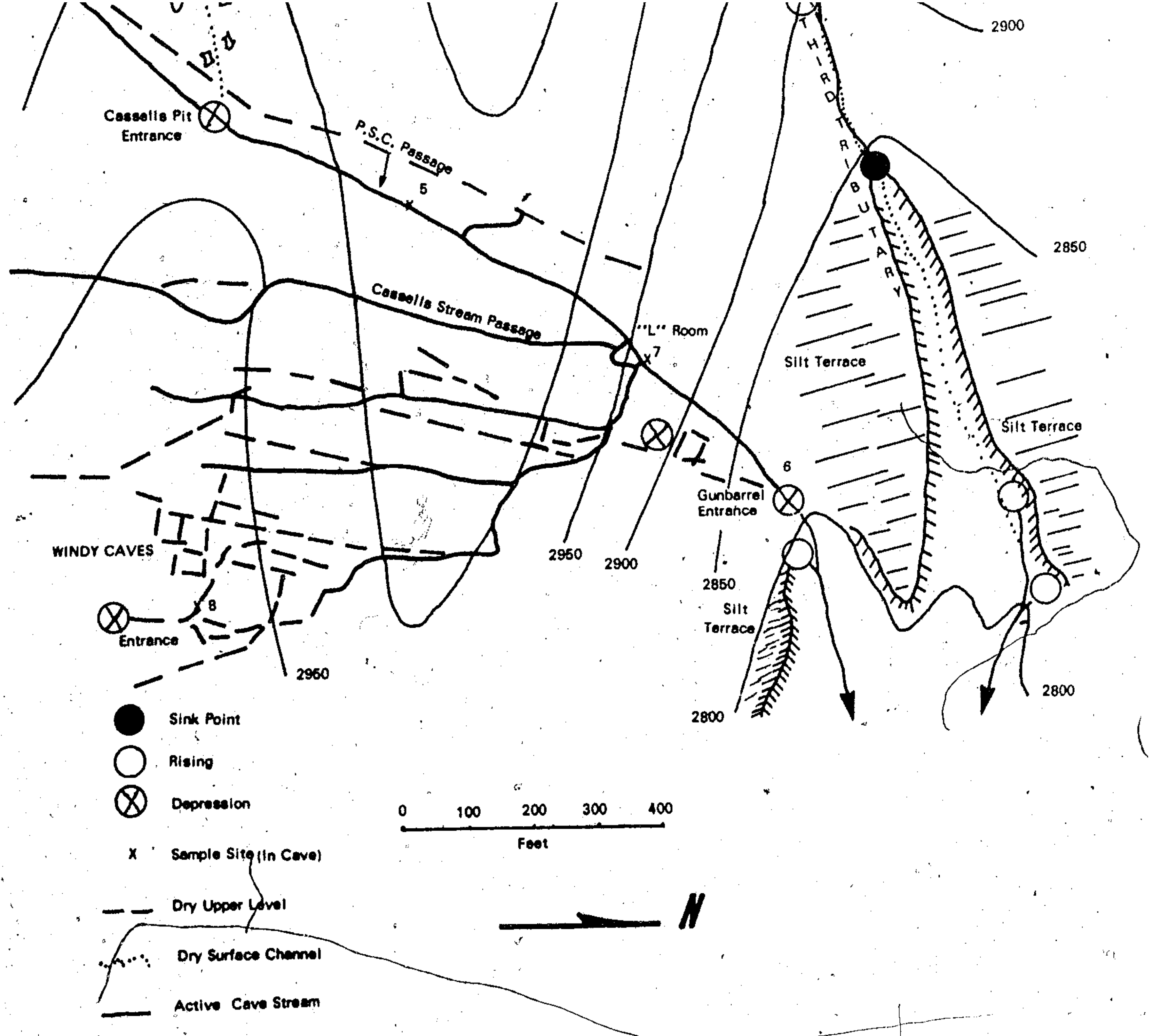
2900
2850
2800
Cassells Pit Entrance
P.S.C. Passage
5
Cassells Stream Passage
"L" Room
7
6
Gunbarrel Entrance
THIRD TRIBUTARY
Silt Terrace
Silt Terrace
Silt Terrace
2950
2900
2850
2800
2800
WINDY CAVES
8
Entrance
2960
Sink Point
Rising
Depression
X Sample Site (In Cave)
Dry Upper Level
Dry Surface Channel
Active Cave Stream
0
100
200
300
400
Feet
N

D. The Subsurface Drainage and Sedimentation of Basin I

Although six entrances to caves are located within Basin I, there are effectively one two main cave systems which operate now or have functioned in the past as sediment transport conduits. These are: Grimes Cave, the diversion of the Fourth to the Third Tributary of Trout Run; and the Cassells-Windy Cave system which diverts water and sediment from Wanless Run to Trout Run.

1. The Grimes Cave System

(Data Summary Table 5.04)

a. Surface Features and Entrance Environment

Grimes Cave is entered at the downstream end via an eight-foot square opening at the base of a cliff formed by a 36 foot thick exposure of Cypress sandstone. A ridge of scree 15 feet in depth, covered by vegetation and soil, has formed 30 feet back from, and parallel to the outcrop. At the entrance, angular blocks cover the ridge. These are produced by recent spalling off of the overlying sandstone, which appears to be more common around the cave opening. A permanent stream flows out of the cave and sinks into the scree ridge. This stream joins the Third Tributary of Trout Run 100 feet north of the entrance and 15 feet lower in elevation at 2,975 feet. The entrance appears to have been produced by the intersection of a passage developed along

Table 5.04

DATA SUMMARY OF GRIMES CAVE

Entrance location	38°27'32"N , 79°54'01"W , Cass Quadrangle W. Virginia-Virginia, U.S.G.S., 1922
Entrance elevation	2990 feet
Total length	1000 feet
Range of relief	from 3050 feet to 2990 feet = 60 feet of local relief
Stream gradient (including waterfalls)	60/1000
Average gradient (excluding waterfalls)	10/1000
Maximum observed stream discharge	10 cfs.
Estimated mean stream discharge	2 cfs.
Average flow through time	1 hour, 30 minutes
Maximum size of bedload at entrance (stream flow at of entrance)	36 cm.
Maximum size of quartz pebble conglomerate	25 cm.[1]
Mean size of bedload at sink point	12 cm.
Mean size of bedload at rising (entrance)	4 cm.

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[1] Small boulders of consolidated conglomerate pass completely through Grimes Cave.

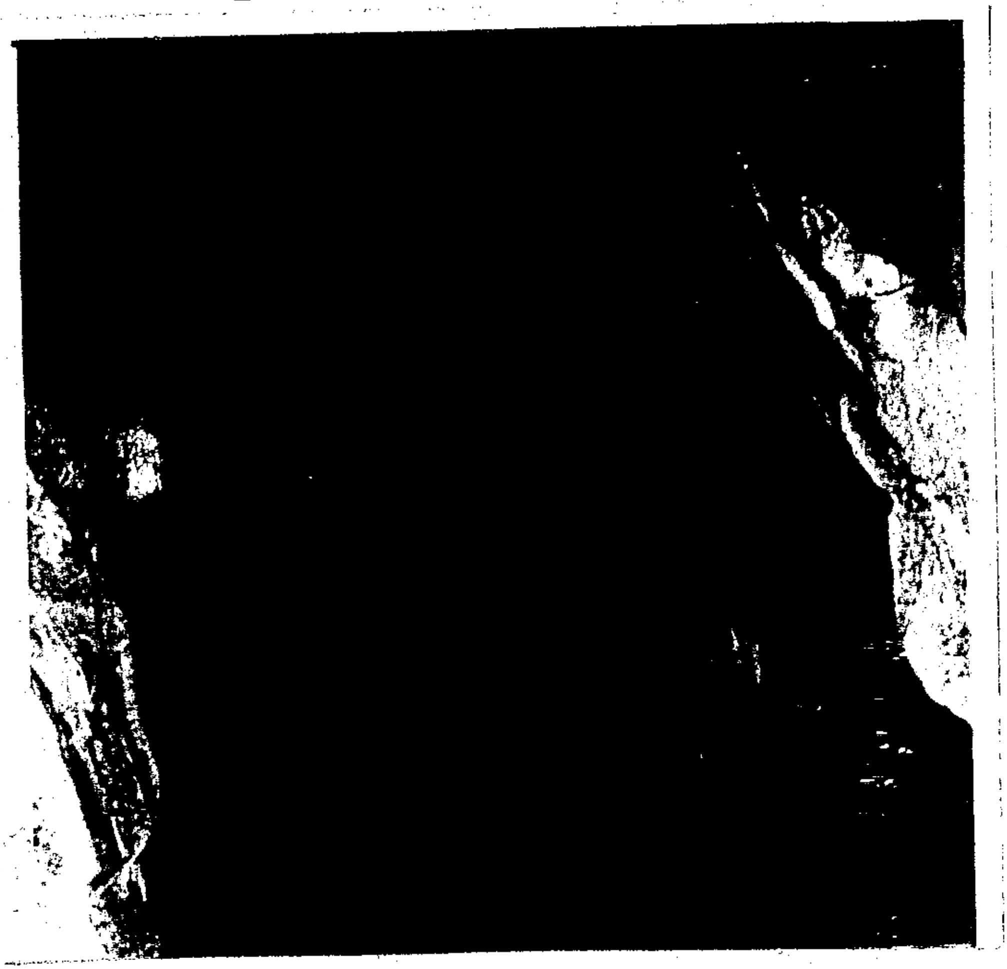
the strike in the Upper Union limestone with the downcutting and headward retreat of a waterfall over the Cypress sandstone. This stream breached the cave, and water from the Fourth Tributary of Trout Run joined the Third Tributary via Grimes Cave. This explanation is supported by the abrupt change of channel gradient (subsurface to surface) which occurs at the point of intersection (Figure 5.01). The continuation of a cave system northwards beyond the confluence appears now to be filled by scree and colluvium. Figure 5.10 is a photograph taken from inside the entrance of Grimes Cave, looking out. The stream flowing away from the foreground is sinking into the ridge of scree. The Third Tributary of Trout Run is immediately below the trees in the background. Note the extreme angularity of the bedload in the foreground.

b. Description of the Cave

Figure 5.11 is a plan of Grimes Cave (Davies, 1958, p. 270). The main passage has developed along the prevailing regional joint set at N 25° E . The mean passage height is approximately six feet although it is slightly less than this along the sections controlled by the minor joint set. The Fourth Tributary flows through the entire length of the cave. At several upstream localities meander cutoffs have created abandoned dry channels where graded beds of gravels coarse sands and silts have been deposited. These are reworked by frequent flooding

Figure 5.10

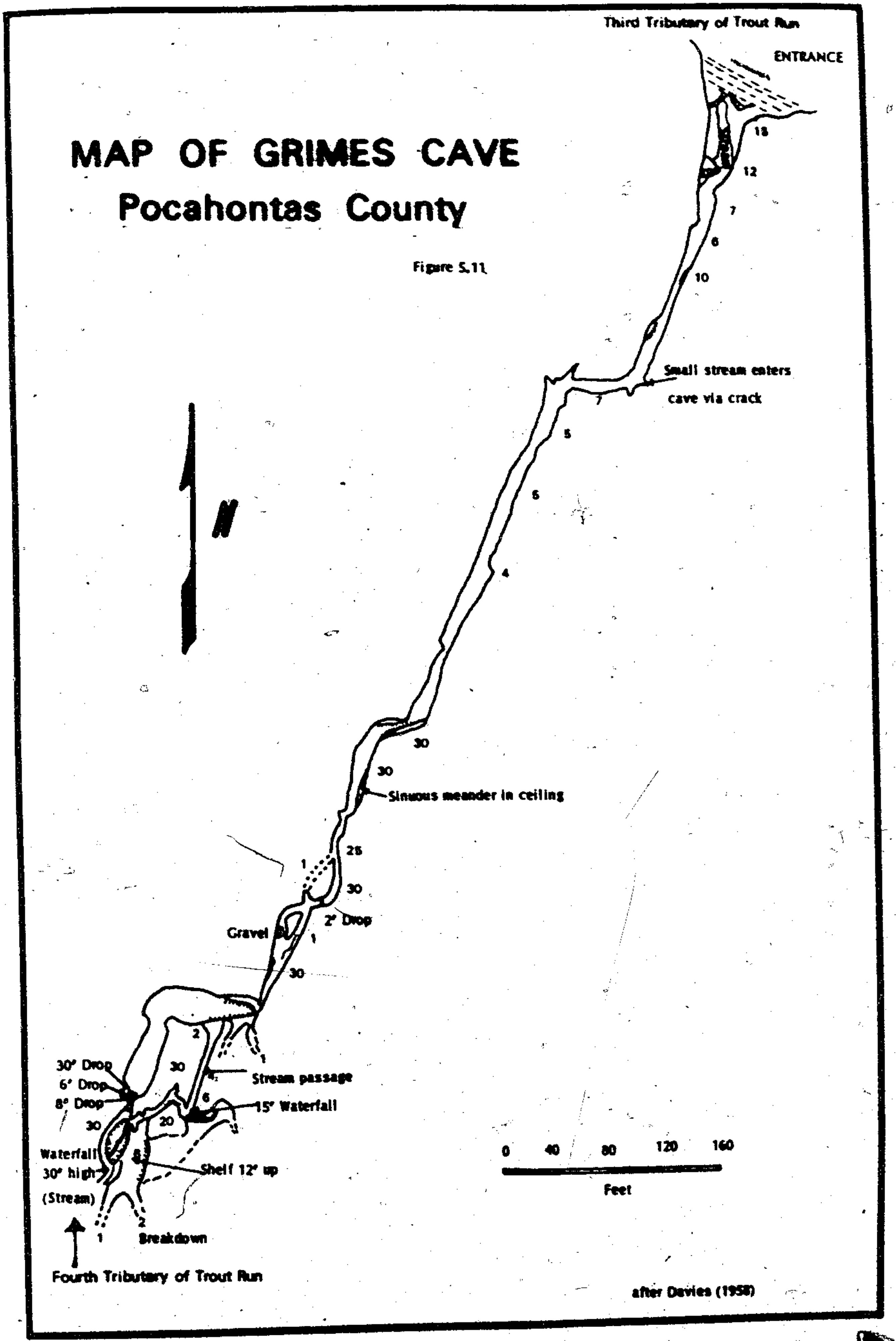
ENTRANCE TO GRIMES CAVE



Stream diversion of Fourth Tributary of Trout Run flowing out to join the Third Tributary outside. Entrance in the background.

MAP OF GRIMES CAVE
Pocahontas County

Figure 5.11



several times each year and are considered to be of recent origin. Figure 5.12 is a passage profile and sediment section in the rear of Grimes Cave. The stream itself drops 60 feet along 1000 feet of passage in the cave. Two waterfalls approximately 20 feet in height enter the rear of the cave from the sink in the stream bed of the Fourth Tributary. Travertine deposition is rare throughout the cave. Ceiling breakdown is abundant and more common near the entrance where there is evidently frequent freeze-thaw activity (Figure 5.10). Most of the bedload material is fixed. Twenty-eight percent of the bedload lithology is sandstone and sandy limestone. Much of this material can be classed as "gravitational fills"[7] in that, although the material is found in the stream bed, it shows little evidence of stream transport and is of an autochthonous derivation. The characteristic of angularity provides the main basis for distinction between gravitational fills which appear to be _in situ_ and the transported fills derived from the surface environment and elsewhere in the cave. Although scalloping and grooving is well-developed on these boulders by post depositional solution, the general volume and dimensional reduction in the stream does not alter their original angularity. All such fragments can be classed as "very angular" and "angular" (Powers, 1953).

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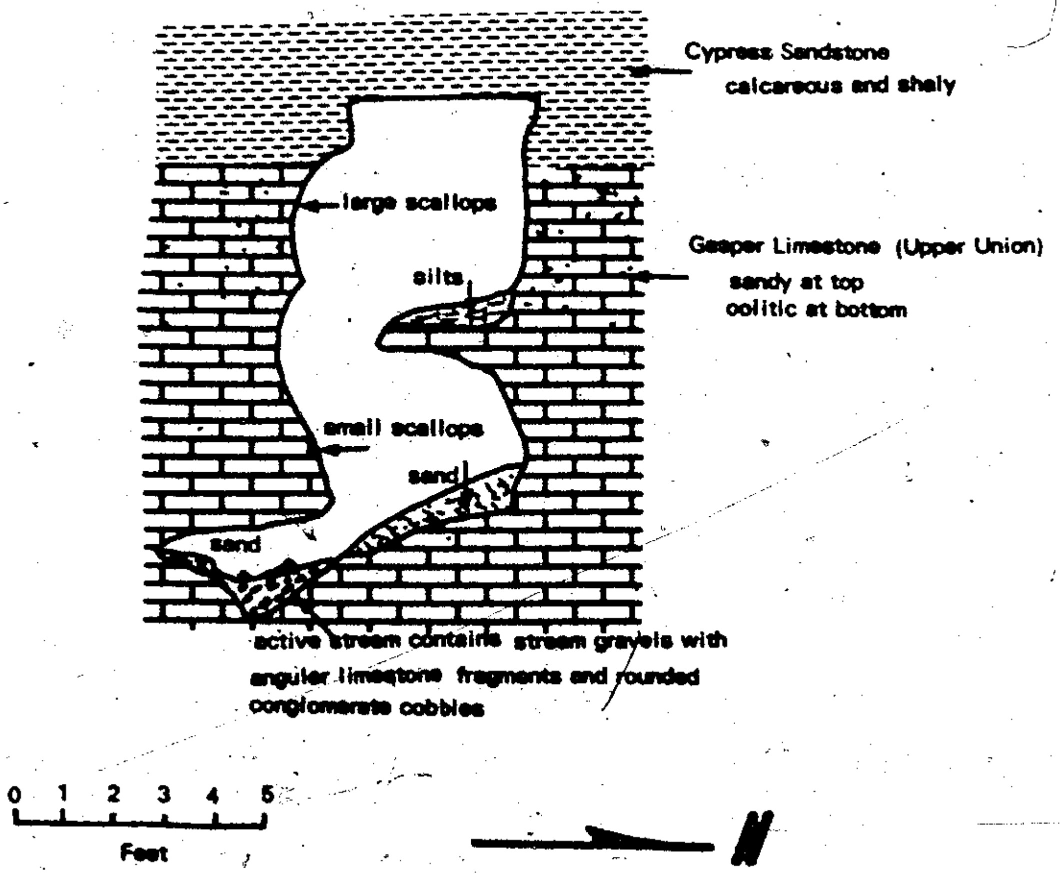
[7] See the classification of cave sediments proposed in Chapter 2.

CROSS SECTION IN REAR OF GRIMES CAVE LOOKING SOUTHWEST (UPSTREAM)

Figure 5.12



The Princeton conglomerate and Mauch Chunk sandstone comprise up to 62% of the coarse fraction. Another 10% consists of shale fragments which are derived from the Cypress sandstone in the stream bed of the Fourth Tributary immediately above the sink into the cave. The remaining material in the coarse fraction is gravitational fill. Figure 5.13 shows the predominantly rounded to sub-rounded, transported bedload in the rear of Grimes Cave near Figure 5.12. The angular rock in the left foreground is Cypress sandstone, as are some of the smaller, more angular fragments.

Transported sediment sizes fine upwards from boulders to gravels and sand point bars, with ripples and dunes. These continue to fine upwards to silts on high level ledges along the passage walls (Figure 5.12). The silts are found approximately one meter above mean stream level. Some vegetational fragments are interbedded. During Hurricane Camille[8] the cave did not fill completely. This is probably due to the restrictive size of the sink in the floor of the stream bed which is filled with boulders and sediment. During this storm and others, a greater portion of the runoff in the Fourth Tributary was channelled downstream and entered the pit entrance of Cassells Cave (Figure 5.02). Fining upwards of sediments does not continue to the ceiling. No recent deposits were noted in the upper-

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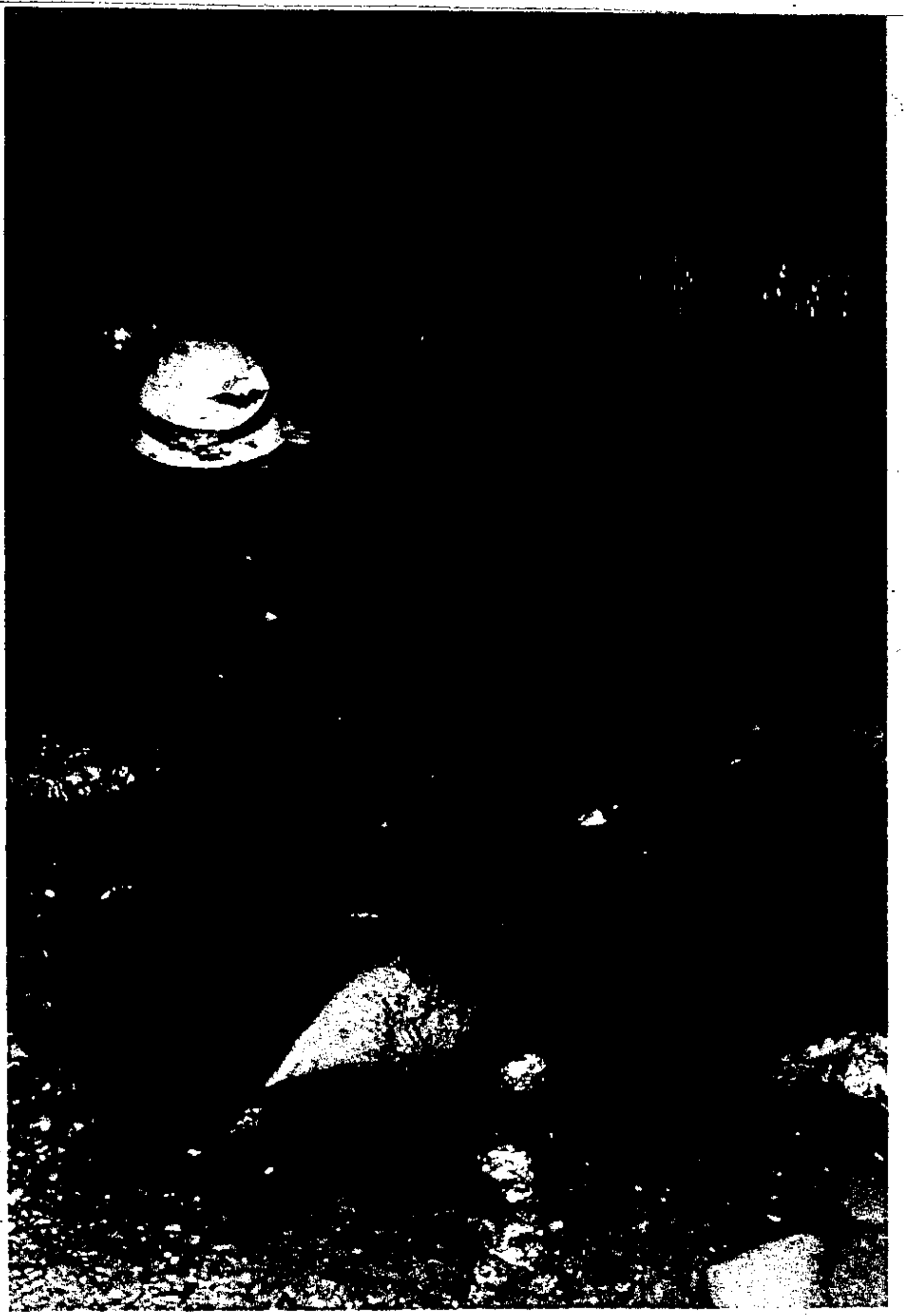
[8] Taken to be maximum high water during this century.

Figure 5.13

CLASTIC BEDLOAD OF GRIMES CAVE



This small point bar is mainly composed of pebbles and gravels derived from the Mauch Chunk sandstone and Princeton conglomerates.

most levels of the passage. This would suggest that the sieve-like deposits at the sink prevent modern runoff from completely filling the cave.

Throughout the cave "transported fills" show a higher degree of sorting than those classed as "gravitational". Cumulative percent curves based on the transported clastic sands and gravels in point bars show moderately well-sorted (Folk, 1968) throughout the cave with a slight decrease in size down stream (Figure 5.14). The "gravitational fills" are largest near the downstream end of the cave, near the entrance section shown in Figure 5.10. Mean grain size of this material at the entrance is approximately 45 cm. (long axis). Samples measured along the main channel between the rear of the cave and to within 300 feet of the entrance averaged 20 cm. (long axis). The angularity of these samples also increased at the entrance.

The dominant feature of the upper parts of the cave walls and ceiling where recent breakdown has not altered the bedrock face of the cave, is the abrupt increase in scallop size upwards. Figure 5.15 illustrates this feature. The profile of the passage suggests at least a two-phase development. Figure 5.16 shows large (25 cm. long) scallops with smaller, modern 3 to 6 cm. flutes and scallops developing directly upon them. If one assumes a long stable rate of slow flow necessary for the development of the larger scallops under phreatic conditions, as

CUMULATIVE PERCENT CURVES OF FIVE SAMPLES FROM POINT BARS ALONG THE GRIMES CAVE STREAM

Figure 5.14

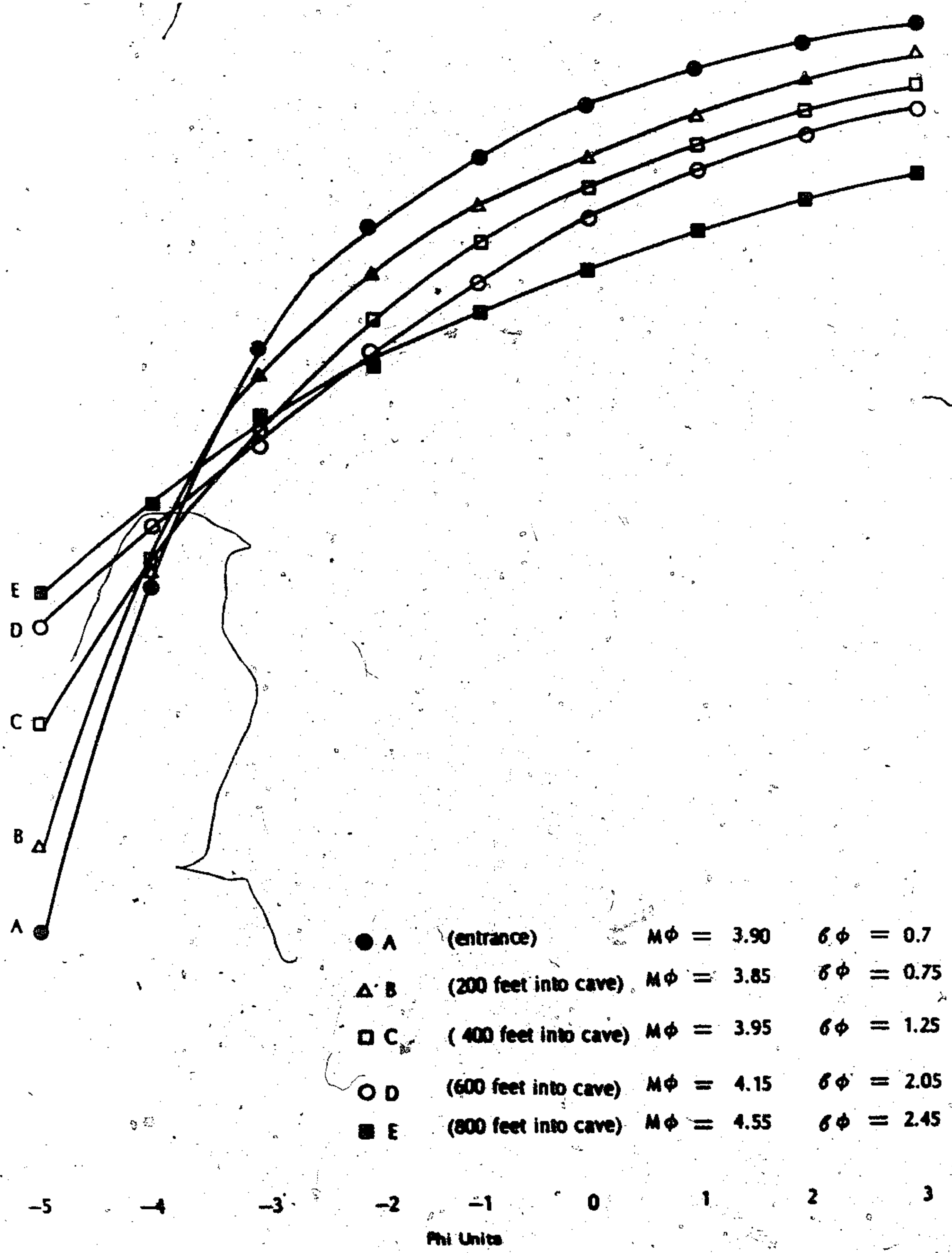
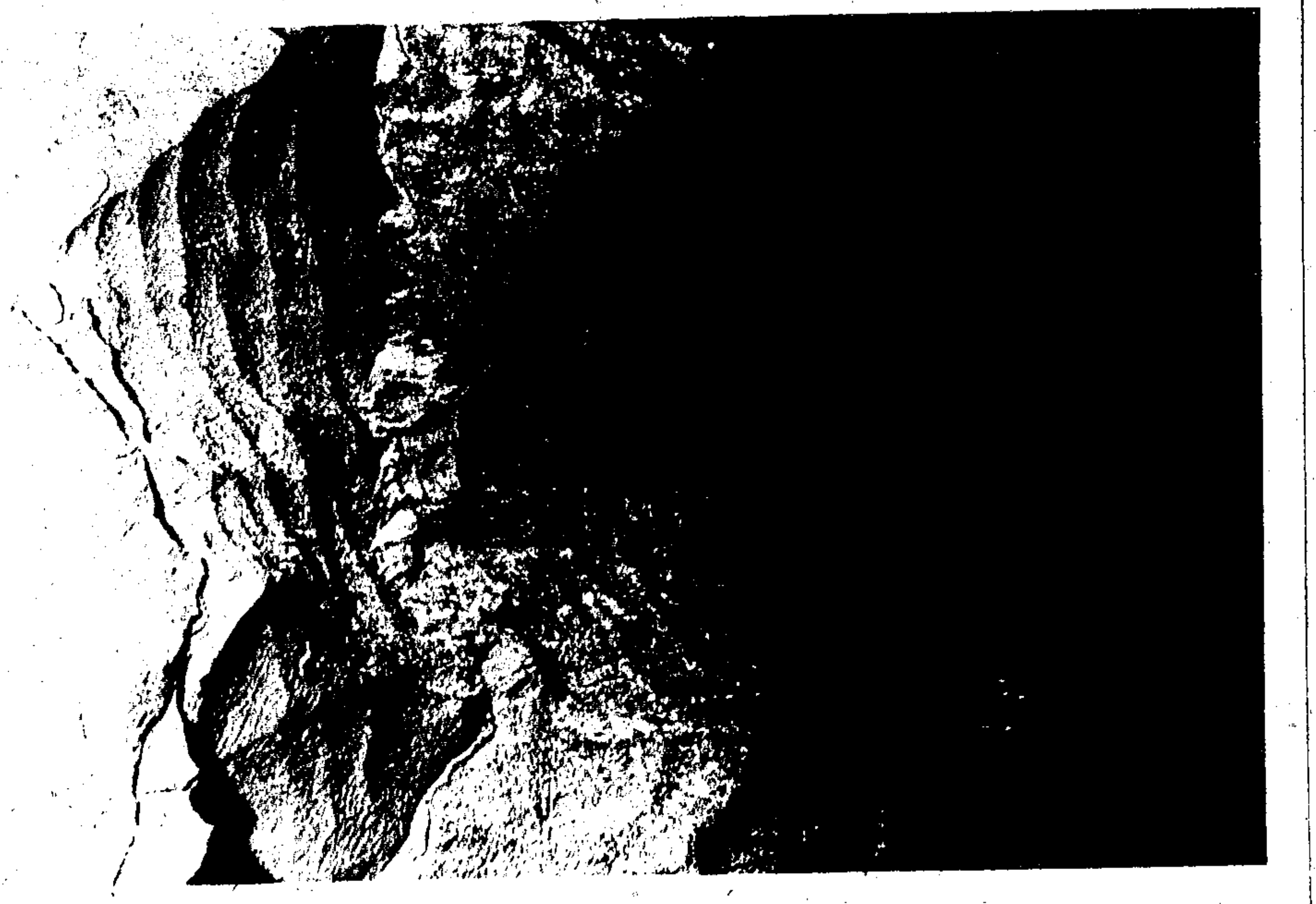


Figure 5.15

LARGE CEILING SCALLOPS ON GRIMES CAVE

Figure 5.16

TWO-PHASE DEVELOPMENT OF WALL SCALLOPS, AND FLUTES, GRIMES CAVE



Modern and paleoflow is from left to right. Large scallops are the product of pipe-full slow velocity flow. Smaller flutes are the result of vadose flow (half-way up the wall), at a high rate of flow.

Curl (1958) and Goodchild (1969) have indicated, then a two-phase history for the main passage of the cave seems to be a probable explanation. The smaller flutes and scallops are in accord with the higher velocity-free surface conditions suggested by the presence of coarser bedloads and graded sediments in the cave.

2. Cassells-Windy Cave System

(Data Summary Table 5.05)

a. Surface and Entrance Environment

Four entrances provide access to the Cassells-Windy cave system (Figure 5.02). The Cassells Pit and Windy Cave entrances lie directly downstream from the sink of the Fourth Tributary of Trout Run, which normally takes all the runoff to the Grimes Cave stream and diverts drainage to the Third Tributary of Trout Run (Figure 5.02). The first of these downstream entrances is Cassells Pit which is a vertical drop of 96 feet. The top of the pit is an opening 9 feet by 3 feet which widens downward to approximately 30 feet by 30 feet. Above the initial opening of the pit a large elongate funnel-shaped sink has developed in the intermittent stream valley floor. Figure 5.17 is a photograph taken on the upward side of this sink. Note the large, well-rounded boulders of conglomerate. Figure 5.18 was taken at the base of the sink, at the entrance. Here large 4 foot, rounded conglomerate boulders are poised at the top of the pit. Boulders of

Table 5.05

DATA SUMMARY OF CASSELLS-WINDY CAVE SYSTEM

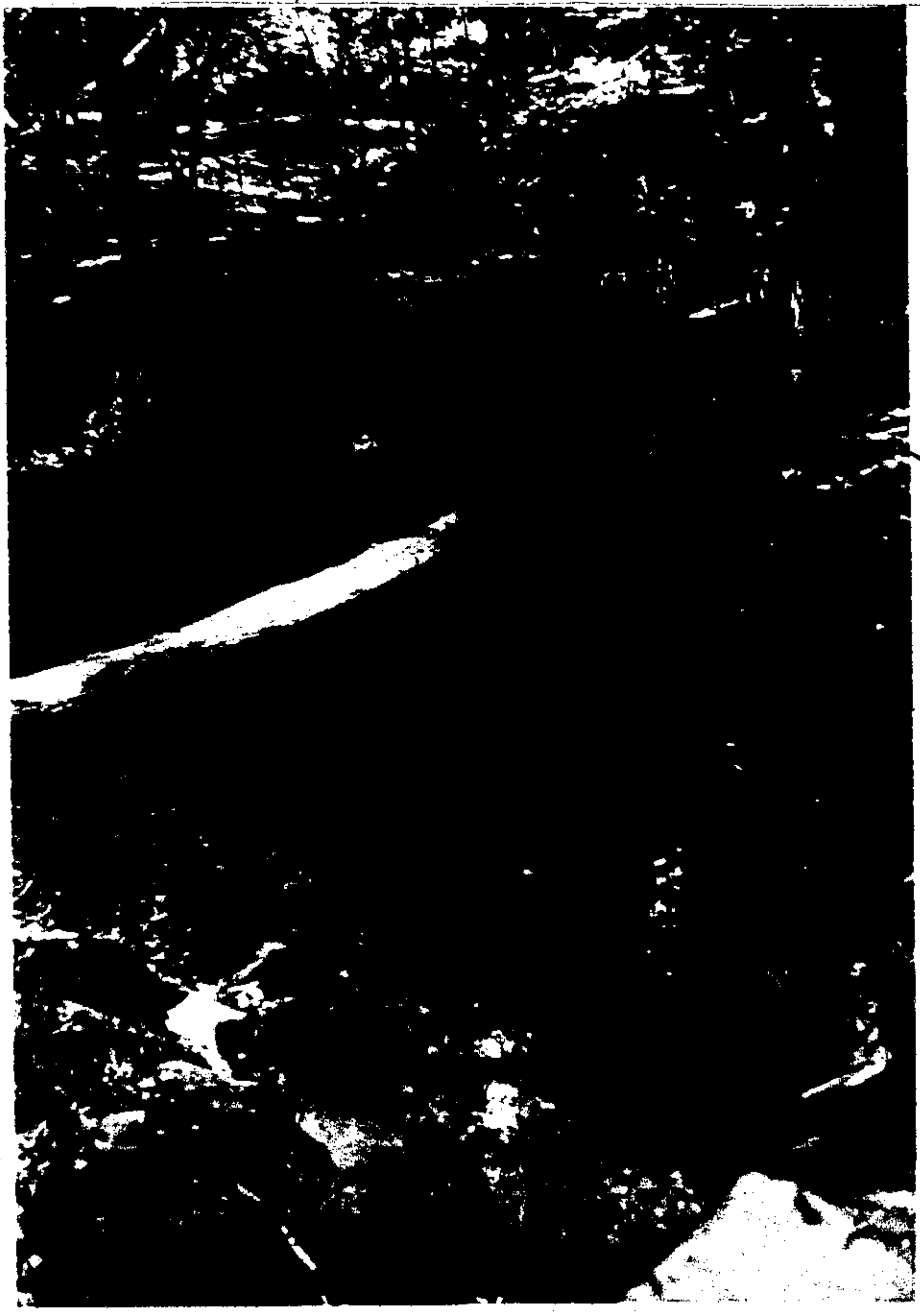
Entrance location	Cassells Pit	38°27'24"N , 79°53'48"W
	Cassells Stream Rising	38°27'32"N , 79°53'46"W
	Windy Cave	38°27'22"N , 79°53'45"W
Entrance elevation	Cassells Pit	2975 feet
	Cassells Stream Rising	2825 feet
	Windy Cave	2910 feet
Total length		35,000 feet or 6.63 miles
Range of relief		from 3000 feet to 2790 feet
Stream gradient (including waterfalls)		18/100
Average gradient (excluding waterfalls)		1/100
Maximum observed stream discharge		12 cfs.
Estimated mean stream discharge		2 cfs.
Average flow through time	Cassells Pit to rising	2 hours
	Fifth Tributary to rising	30 minutes to 2 days
Maximum size of transported bedload in the cave		1.4 m.[1]
Maximum size of quartz pebble conglomerate at rising		4.2 cm.
Mean size of transported bedload at Cassells Pit entrance		65 cm.
Mean size of bedload at rising		7.7 mm.

---

[1] Whole boulders of consolidated conglomerate have entered this cave but do not pass completely through it.

Figure 5.17

VIEW LOOKING DOWNSTREAM ALONG THE ABANDONED DRY VALLEY OF THE FOURTH TRIBUTARY OF TROUT RUN



The sink in the centre of the valley opens directly into Cassells Pit. Ephemeral drainage occasionally reaches the pit, but it never flows beyond this sink point into Windy Cave.

Figure 5.18

CASSELLS PIT ENTRANCE

The calcareous Bethel sandstone (Greenville shale equivalent) outcrops on the upstream side. The large rounded boulders are Princeton conglomerates.

similar size are found at the bottom of it. The weathered angular blocks at the right of Figure 5.18 are from the lower beds of the Upper Union limestone and are displaced only a few feet from the present outcrop in the stream bed above the pit. This material also enters the pit entrance. Ten feet below the boulder upon which the observer is standing is the outcrop of the shaley red and green Bethel sandstone. The remaining 80 feet of the pit drops through the Lower Union limestone. A small permanent waterfall enters the pit over the Bethel member and sinks into the boulders and gravels at the bottom, reappearing in Misery Alley (Figure 5.19). Figure 5.20 shows the dry bed of the ephemeral channel 1500 feet upstream of the pit entrance containing the largest sizes of modern bedload. The most recent movement of large bedload particles occurred during Hurricane Camille. The much larger blocks common along the ephemeral channel were not disturbed by this one-in-one-hundred-years flood.

b. Description of the Cave System

Figure 5.19 is a plan view of the cave system (Davies, 1965, p. 45).[9] More than six miles of passage have been mapped in this cave system. Not all of it was

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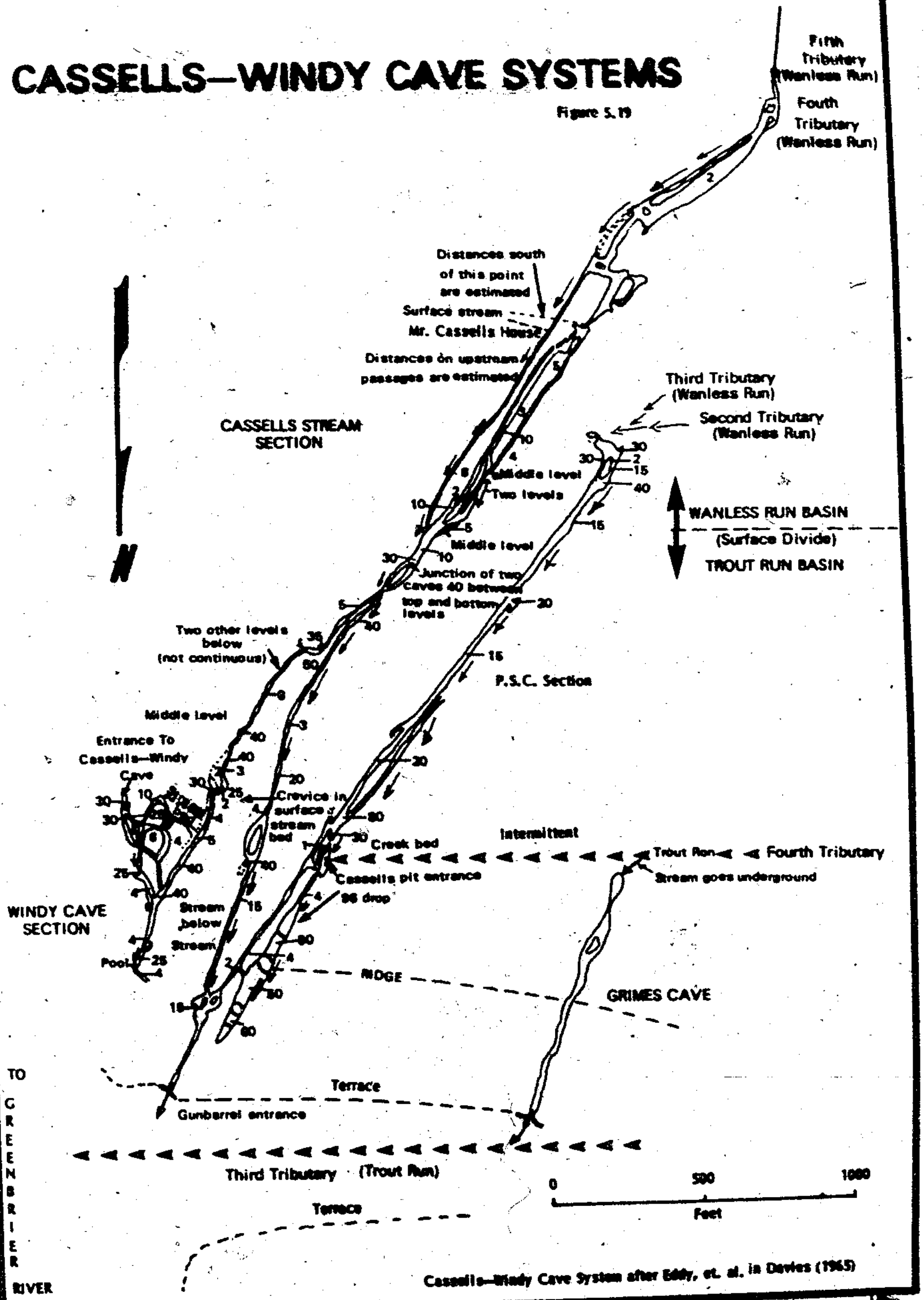
[9] This map is the result of much difficult underground surveying by Alta, Ballister, Barton, Cameron Eddy, Errington, Hager, Heffer, Long, Medville, Tapp, Williamson, and others, undertaken during 1964-1966. Without this initial field work, this study would have been impossible.

CASSELLS—WINDY CAVE SYSTEMS

Figure 5.19



Cassells—Windy Cave System after Eddy, et. al. in Davies (1965)

Figure 5.20

EPHEMERAL STREAM BED OF THE FOURTH TRIBUTARY OF TROUT RUN

This downstream view is between the Grimes Cave sink and the Cassells Pit sink. Water flows here only a few times per year.

examined or considered useful for the purposes of this study. The two main passages, PSC passage and the Cassells stream passage, and the upper levels of Windy Cave were studied and sampled because they contain the three modern streams of the cave. These show a strong correlation between joint orientation and passage direction. An exception to this occurs in the upper levels of Windy Cave, where the minor joint set at N 70° to 80° W is more strongly reflected in passage orientation. Figure 5.21 shows the development of a small phreatic solution channel along the major joint set. The larger rounded fragments are sandstones and conglomerates deposited by a former stream flowing toward the back of the scene. Figure 5.22 shows a larger passage at N 25° W developed along the minor joint set. The greatest volume of passage has been enlarged by water cutting downwards to the Cassells section of the cave towards the "L" room (Figure 5.19).

i) Windy Cave Section (Figure 5.19)

This part of the cave is most probably the oldest section of the Cassells-Windy system because:

1) Its general plan is a three-dimensional maze, as opposed to the linear, stacked conduits of the PSC and Stream Passage sections. These latter areas of the cave are also similar to Grimes Cave which is believed to represent one of the most recent cave developments in the basin.

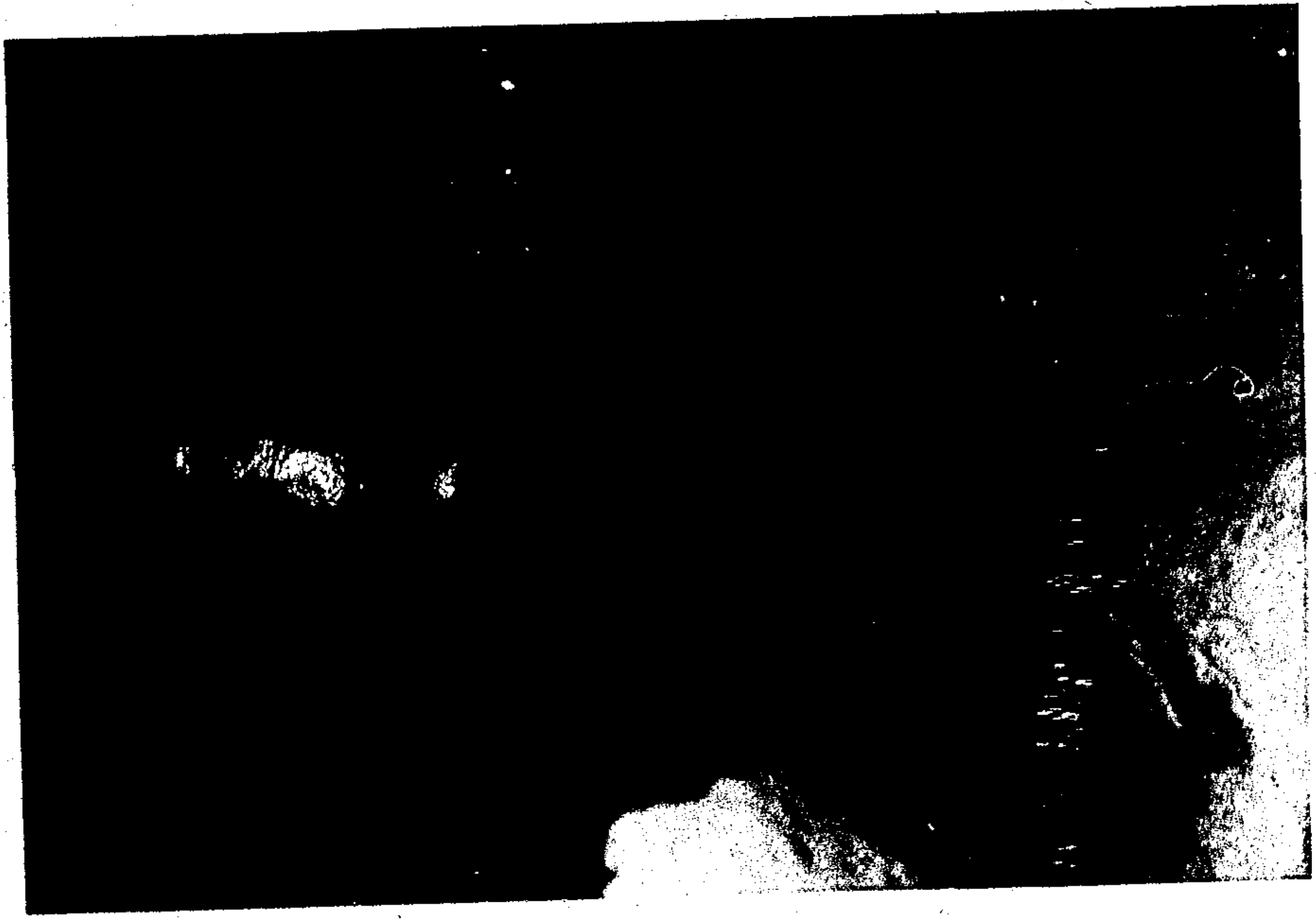
Figure 5.21

ROUNDED CLASTICS IN A SMALL JOINT CONTROLLED PHREATIC TUBE, CASSELLS-WINDY SYSTEM, UPPER LEVEL

Flow direction is to the background. The passage is 18 inches high.

Figure 5.22

VADOSE TRENCHING INTO ONE OF THE UPPER LEVEL PHREATIC TUBES, CASSELLS-WINDY SYSTEM



Note the stream gravels on the right.

2) There is no active drainage in the upper level of the Windy Cave.

3) Passage profiles suggest a phreatic origin with vadose entrenchment (Figure 5.22). The elongate solution conduits of the other sections of the cave are of a general vadose origin and thus are younger.

4) This section is situated further downstream along the Fourth Tributary than the other parts of the system (Figure 5.19). If a headward retreat of subterranean capture routes is postulated, this would be the earliest pirating route known.

5) This upper section is joined to lower sections by vertical pits, suggesting an independent origin rather than gradual downcutting, such as occurred in the other parts of the cave.

6) The transported clastic sediments are different. There is little bedload sediment remaining in the upper levels of Windy Cave. Much of this material appears to have been flushed out by surface waters which may have by-passed the pit entrance upstream along the dry valley of the Fourth Tributary of Trout Run. This no longer happens. However, in the early stages of underground piracy this process would have removed much of the bedload at the upper pit entrance allowing for surface drainage to enter the Windy Cave entrance and remove much of its accumulated fills. Only a few fines are found in the high levels. A few large

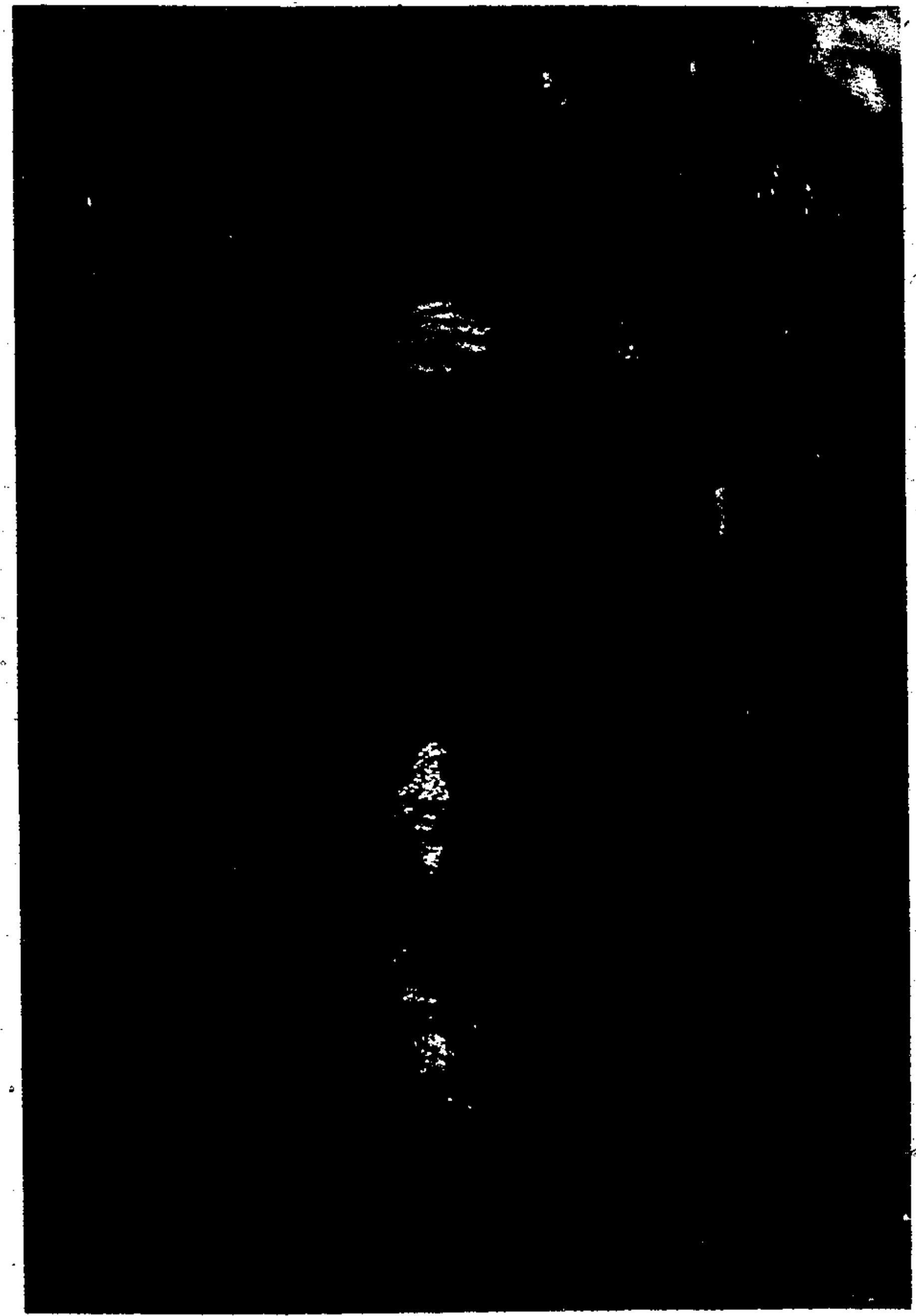
boulders such as the one in Figure 5.23 remain. There is a low quartz percentage there, suggesting that provenance may have just extended to the sources of quartz conglomerate when active drainage abandoned this part of the cave. Figure 5.23 is typical of the Windy Cave floor which is frequently indented with scallops 2 to 5 cm. in length. The large sandstone boulder was lifted from the pothole where the observer is standing. These potholes are common in the upper section and would indicate rapid downcutting during short periods of high velocity overspill vadose entrenchment. The lowest levels of the Windy Cave section contain some ephemeral drainage and transported sediment is present. None is larger than pebble-size and there is a general fining upwards sequence 8 feet deep. Figure 5.24 shows a measured section and passage profile in this level of the Windy Cave. The character of the lowest level is more typical of the nearby active Stream Passage and the PSC section. In contrast with the upper levels of the Windy Cave and the Cassells Stream Passage, however, this passage contains inactive travertine and active transported fills. Grain sizes are intermediate between the coarse bedload of the active modern passages and the generally finer or non-existent material of the upper levels of Windy Cave.

ii) The P.S.C. Section

The PSC section is located approximately halfway

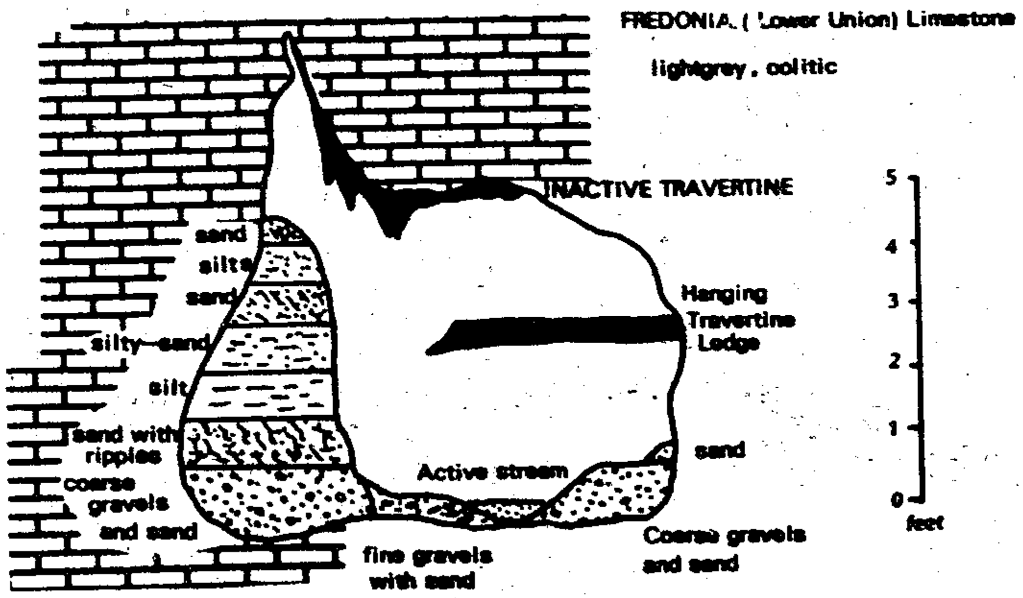
Figure 5.23

POTHOLE IN THE FLOOR OF CASSELLS-WINDY SYSTEM, UPPER LEVEL



MEASURED SECTION AND PASSAGE PROFILE IN CASSELLS—WINDY SYSTEM, LOWER LEVEL.

Figure 5.24



SURVEY POINT #304
Stream flowing towards Cassells Stream Passage

between Grimes Cave and the Cassells Stream Passage, in a nearly parallel situation. All major passages exhibit joint control in this orientation. Although this intermediate section of the cave is responsible for diverting two surface streams to the Third Tributary of Trout Run (Figure 5.19) there is not permanent drainage in the downstream section. Water enters at the head of the PSC section from the Second, Third and Fourth Tributaries of Wanless Run and from the Fourth Tributary of Trout Run at Cassells Pit. These waters sink into massive boulders and gravel near the pit entrance and are traceable to the Main Passage drainage. This stream is, therefore, responsible for the underground initial breaching of the surface divide between Wanless Run and the Trout Run drainage. Surface waters which flow beyond the surface sink points are diverted northward via the Cassells Stream Passage which lies further east (downstream) and transects these surface streams. Surface drainage rarely flows completely across the limestone in the Second, Third or Fourth Tributaries of Wanless Run. Underground diversion is total in the case of the Fourth Tributary of Trout Run.

Discharge through the PSC section is extremely variable. When overflow from the Grimes Cave sinkpoint occurs during flood or spring runoff it enters this system via the pit entrance. The ephemeral nature of flow in this stream passage, combined with ponding and two sources of drainage makes downstream changes in grain size highly variable.

Discharge through the PSC section is extremely variable. When overflow from the Grimes Cave sinkpoint occurs during flood or spring runoff it enters this system via the pit entrance. The ephemeral nature of flow in this stream passage, combined with ponding and two sources of drainage makes downstream changes in grain size highly variable.

The volume of size range of material in this passage is the greatest of any section of subsurface channel in Basin I. Figure 5.25 is a typical cross-section indicating flow direction to the north. Quartz pebbles are abundant and increase to over 70% of the gravel size fraction below the pit entrance. Boulder-size material is common in the pit area. The sandstone and conglomerate materials are well rounded to sub-rounded, with a mean size of 60 cm. at the pit decreasing immediately downstream to 10 cm. along the PSC stream bed, and to less than 2 cm. at the rising. This abrupt change in grain size is due to:

1) The restrictive size of the downstream sections of the passage.

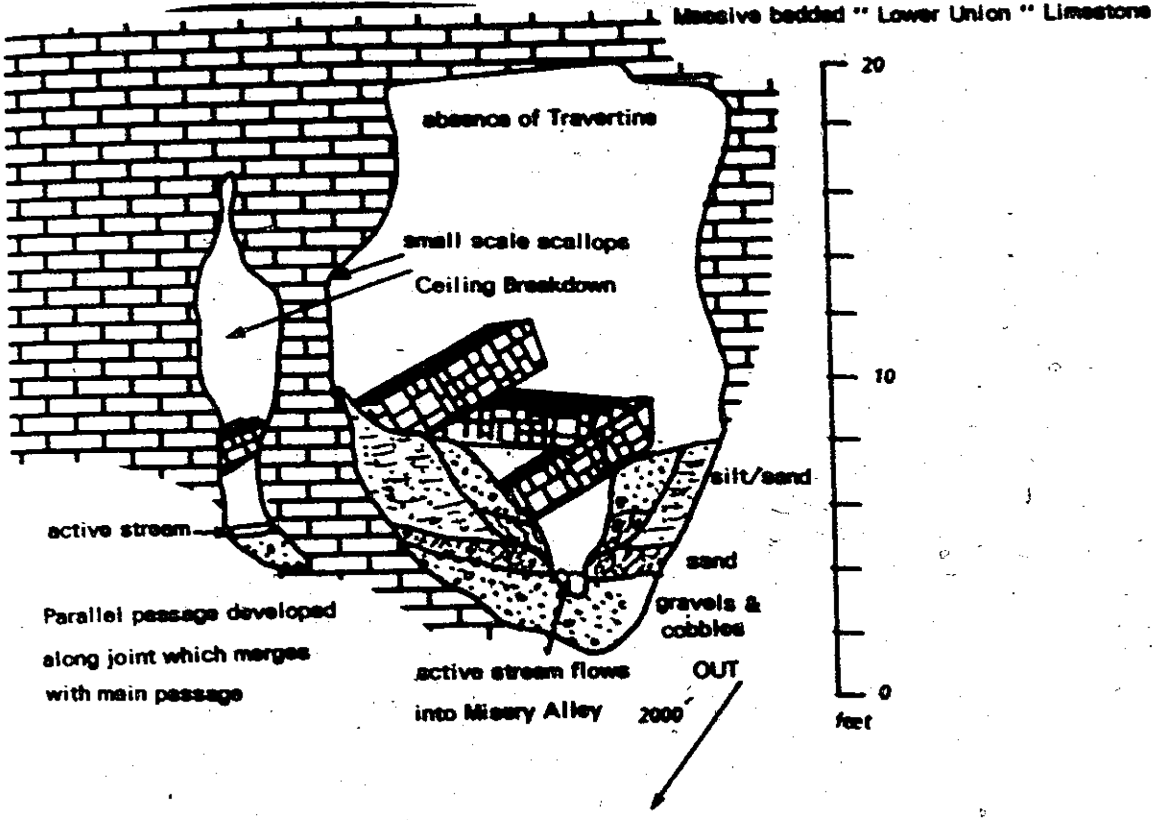
2) The low stream gradient within the cave, less than 1/100 below the base of the pit entrance.

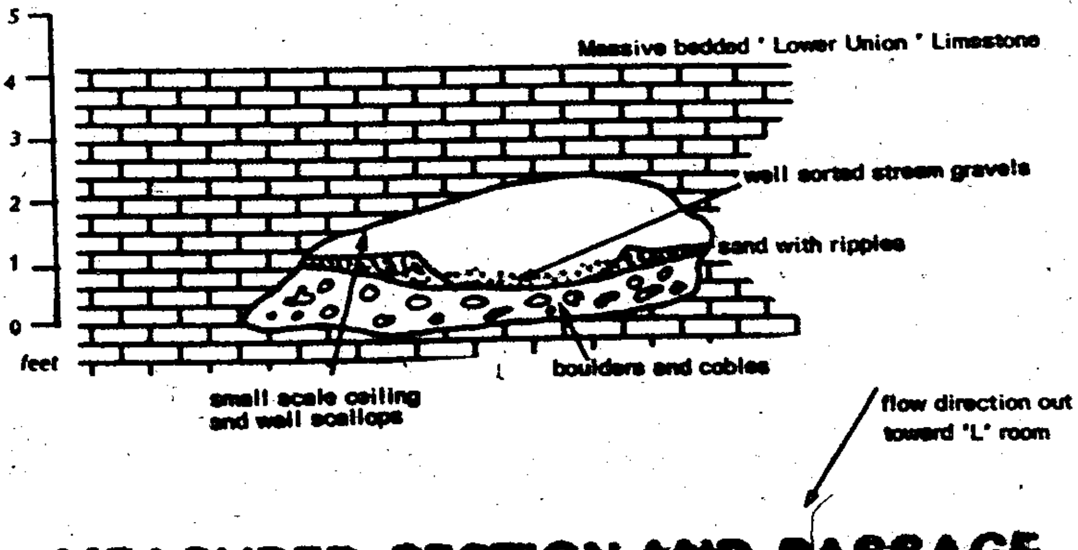
3) The boulder deposit at the base of the entrance pit screens out the very coarse fraction.

4) The fracturing of large blocks after an initial drop of 90 feet down the pit.

MEASURED SECTION AND PASSAGE PROFILE IN CASSELLS CAVE, P.S.C. SECTION (REAR)

Figure 5.25(a)





MEASURED SECTION AND PASSAGE PROFILE IN CASSELLS CAVE, P.S.C. SECTION (MISERY ALLEY)

Figure 5.25(b)

5) A recent integration of the surface and subsurface drainage networks and sediments.

This lower section of the passage could be described as a large "sediment mill" where bedload accumulates rapidly and is reduced in size. It is significant, however, that the passage remains open. The following observations were made on the effects of Hurricane Camille within it:

1) runoff entering the pit exceeded 30 cfs. No surface water was able to bypass the pit.

2) no large accumulation of sediment occurred, although reworking of earlier deposits was common.

3) in several places sediment was removed entirely. The gross effect of the hurricane was to increase the passage volume.

iii) Cassells Stream Passage

The headwaters of the Fifth Tributary of Wanless Run and possibly part of the overflow of its Fourth Tributary during peak runoff feed the main stream of the Cassells stream passage. The sink points are of a sieve-type and restrict the size of material entering the passage. The result is the dominance of sand size material in the point bars and bedload. Upper levels of the passage are devoid of any major deposit. Maximum sediment accumulation does not exceed 2 feet in depth anywhere along the lower levels. Distance from the source is also a major factor in maintaining a finer fraction of material in this, the longest single passage of the cave system. The gradient of the stream passage is similar to the PSC section; that is, about 1/100 , excluding waterfalls. Figure 5.26 is a typical cross-section in the downstream portion of this passage. Recent erosional features are more common than depositional ones. Much of the passage is currently undergoing active enlargement through solution. Scalloping, ranging from 2 cm. to 10 cm. in length is abundant. It appears that scalloping is most readily developed where sediment loads are lightest and velocities remain high. This appears to be the case throughout much of the Cassells stream passage, and is probably due to the restrictive sieving at the stream entrance to the system.

E. Conclusions

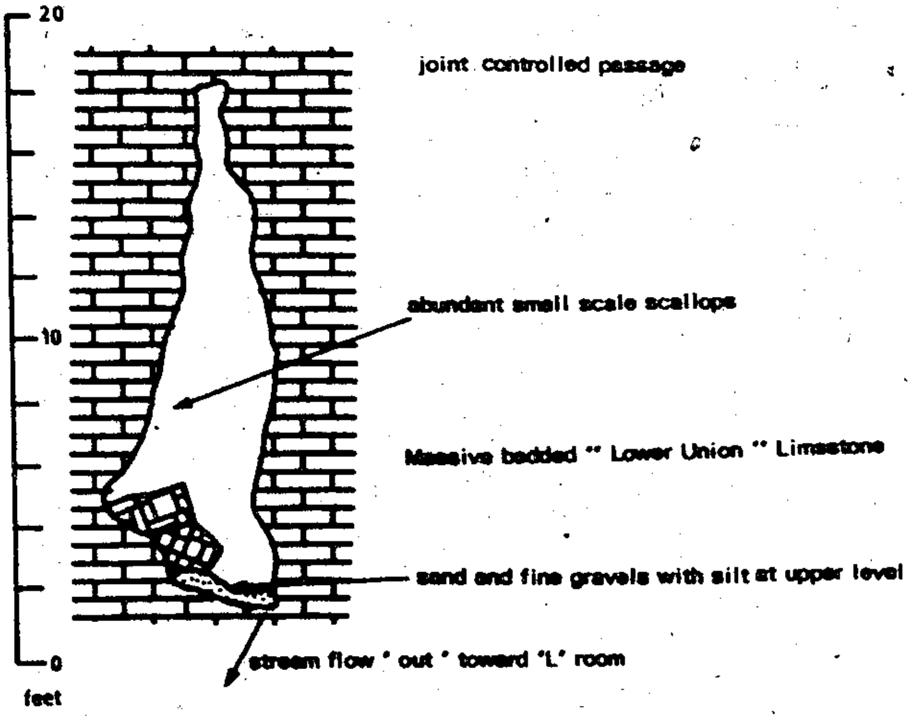
1. Modern Drainage

A wide range of rates of runoff and discharges are common characteristics in modern Basin I.

Variation in discharge and flow through times of streams in caves are, of course, to be expected. A time of only 2 hours and 15 minutes was recorded by M. Ballister for the flow-through of drainage diverted from the First Tributary of Allegheny Run to the First Tributary of Trout Run during high water conditions. This is 3.2 miles. The stream carries little sediment and usually runs

MEASURED SECTION AND PASSAGE PROFILE IN CASSELLS CAVE STREAM PASSAGE

Figure 5.26



clear during periods when other streams in Basin I are carrying a large suspended load. No rounded clastic fragments are found at the rising of this tributary.

On the other hand, variations from 6 hours 30 minutes to 2 days have been observed for flow through time of the main Cassells stream. The underground channel is 1 mile in length. This low rate is caused by the large number of pools and syphons which have to be filled and flushed by water moving through the system. During high water these are full and there is rapid discharge through the cave. During low water it may take one hour for a single pool to pass input water or dye to the next pool. Ponding is commonly due to breakdown blockage. Other causes are blockage due to vegetational debris, or nickpoints due to lithologic variations along the stream bed. Where ponding is common, as in the main Cassells stream passage, sediment deposition is likewise a common feature. Alternate sections of solutional scalloping and deposition of sands and gravels of a size which may be attributed to the same magnitude of stream velocities for their respective origins of solution and transportation, are common in PSC and Cassells sections of the Cassells Cave system and the active sections of Grimes Cave.

Variations between surface and subsurface runoff are a noticeable characteristic of the modern karst basin. Occasional surface flow occurs along most of the tributaries of Wanless Run and Trout Run below the uppermost sinkpoints. This produces flow when no flow is common throughout most of the year. Below the risings peak runoff is split between the surface peak and subsurface peak. These seldom coincide. Surface runoff, if it occurs, is more rapid by at least a factor of 10 . On the other hand, springs fed entirely by carbonate aquifers are many times more variable than those in clastic rocks.

2. Modern Sediments

Table 5.06 shows the distribution of modern lithologies identified at selected points within the basin. The conglomerates show a percentage increase of the total bedload downstream away from the outcrop two miles above the sink of Grimes Cave. Limestones quickly break down below the lower contact and sandstones diminish rapidly in size. Particles greater than 5 cm. are shown in Figure 5.06. The rapid breakdown of sandstones is due to high stream gradients. The rapid decrease in limestones is attributed to a high rate of solution. Although dissolved load was not measured, there is ample evidence to show that the waters at both major risings are not saturated with dissolved carbonates. They also are not carrying a maximum clastic bedload. This is attributed to sieving at the upstream end of the conduits. "Aggressive" water with a low sediment load results in the vadose trenching

Table 5.06

DISBRIBUTION OF AVAILABLE LITHOLOGIES

Identifiable "Transported" Lithologies	Grimes Cave Frequency of Occurrence Sink	Grimes Cave Frequency of Occurrence Rising	At Cassells Pit[1] Frequency of Occurrence Sink	At Cassells Pit[1] Frequency of Occurrence Rising	At Confluence of Trout Run and the Greenbrier River
Pottsville Conglomerate[2]	40%	50%	30%	50%	Total Conglomerates 68%
Princeton Conglomerate[2]					
Mauch Chunk Sandstone[2]					
Stony Gap Sandstone					
Big Spruce Knob Sandstone	50%	12%	20%	8%	Total Sandstones 20%
Droop Sandstone					
Webster Springs Sandstone					
Greenbrier Series					
Alderson Limestone[2]	10%	28%	Included with Upper Union Limestone		Individuals Not Identified
Cypress Sandstone (Greenville shale)	N.A.	10%	10%	10%	
Upper Union Limestone[2]	N.A.	N.A.	40%	*	Total Limestones 12%
Bethel Sandstone (Taggard Formation)	N.A.	N.A.		20%	
Lower Union Limestone[2]	N.A.	N.A.		*	
Patton Limestone	N.A.	N.A.		*	

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[1] Based on a count of 100 identifiable samples greater than 5 cm.

[2] Individual members not identified.

* All limestones included in the final total.

N.A. Lithology not available at this location.

found throughout the downstream sections of most active conduits.

Variation in the rate of sediment discharge is illustrated by sediment traps installed at the discharge of Cassells-Windy system (Gunbarrel entrance, Figure 5.02). These did not collect bedload material greater than 5 cm. during the first two years of operation. Hurricane Camille, however, did move bedload material up to 25 cm. from the cave itself and bedload up to 45 cm. was moved down the adjacent surface valley. A mean size of 5 cm. was collected in the sediment traps after the storm. None of these figures are large enough to account for the movement and rounding of the massive blocks of Pottsville conglomerate which make up much of the alluvium along the central and basal sections of Basin I.

It can be concluded from these observations that this material is moved only by the greater than one-in-one-hundred-year event, or alternatively, that it is of a periglacial or fossil origin. The latter is considered likely.

Concerning vertical variation of sedimentary characteristics, it can be asserted that all sections of the Grimes-Cassells-Windy network indicate that the regional watertable has been slowly and consistently dropping, as a result of the lowering of valley floors and breaching of lithologic controls. Upper cave levels are drained and although periodic flooding continues for a long time, eventually sediments of the highest levels are abandoned. The caves contain fossil sediment which may be equivalent to those of alluvial terraces in valleys.

There is not a gradual fining upwards in the sedimentary profile from the lower levels to the higher ones. The opposite observation has been made by Collier and Flint (1964, p. 141). This is contrary to the general profile of a single flood event. Boulders are found in the upper levels of some abandoned caves near the upper part of the basin. It appears that:

a) Distance is only a minor factor in explaining variations in sediment size and average water flowthrough time for the caves of Basin I.

b) Gradients are not the main control of sediment size and discharge rates in the caves.

c) The presence of effective sieve deposits or constricted entrances at sinkpoints is a major factor in the control of mean and maximum sediment size.

d) Ponding and syphons cause greater seasonal variations in flowthrough times, but do not necessarily slow the rate of flow during periods of peak discharge.

3. Paleodrainage and Sediments

The modern Basin I for the most part is characterised by active subsurface channels. Only a few cave passages can be considered to be completely "abandoned". These lie in the uppermost levels of the Cassells Cave and in the farthest downstream areas of Cassells-Windy Cave. Table 5.07 illustrates the progressive abandonment of drainage channels. There is an upstream migration of sinkpoints with subsequent subsurface strike-oriented diversions. The length of these diversionary conduits also appears to shorten with time. The most recent diversion through Grimes Cave is the shortest and most direct.

Figure 5.27 illustrates a possible sequence of events which led up to the present drainage conditions of Basin I. Initially, no major karst development occurs. Dendritic and parallel surface runoff patterns are dominant. Headwater areas show evidence of mass wasted material today which was more abundant under these initial conditions. Some of this material was moved across the limestone surface prior to subterranean piracy and diversion.

Progressive upstream diversions of surface runoff via strike oriented underground conduits began with the Windy Cave (Route 1, Figure 5.27). Subsequent diversions developed headwardly along similar strike oriented phreatic conduits in the interfluves of Trout Run and the surrounding surface drainage basins (Routes 2, 3, 4, 5, and 6, Figure 5.27). As the upstream conduits enlarge, downstream diversions are cut off. The subsequent lack of fluvial erosion in these downstream conduits (Route 1, Figure 5.27) may result in their isolation at elevations higher than active headward

Table 5.07

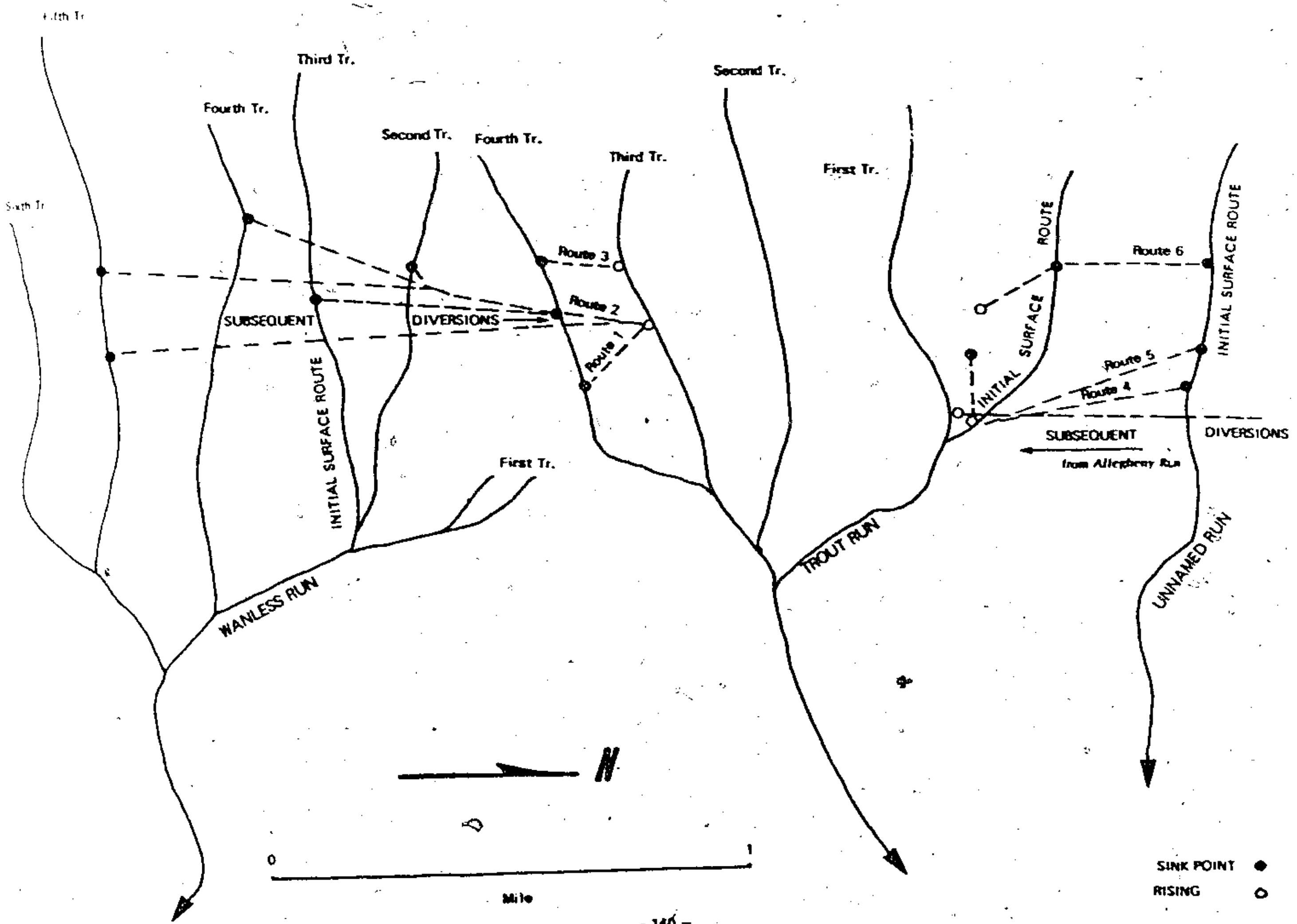
TOPOGRAPHIC AND HYDROGRAPHIC COMPARISONS OF THE FOUR MAJOR CAVE SYSTEMS IN BASIN I

Cave Systems	Elevation Of Upstream Sinkpoint (Feet)	Elevation Of Rising (Feet)	Average Length Of Channel (Feet)	Order Of Drainage Diversion and Condition of Conduit	Characteristics
Grimes Cave					
i) Main Passage	3050	2975*	1000	4th (active)	shows two-phase active development
Cassells Cave					
i) P.S.C. Passage	2990*	2825*	4000	3rd (active in two lowest levels)	dominant vadose characteristics
ii) Main Stream Passage	2975	2825*	5000	2nd (active in two lowest levels)	dominant vadose characteristics
iii) Windy Cave Passage	2910*	2825*	1000	1st (inactive)	phreatic in upper levels with vadose trenching
	Downslope				

*Referred to as "entrance" in the text.

SEQUENTIAL DIVERSIONS OF SURFACE DRAINAGE BY THE UNDERGROUND NETWORK OF BASIN I

Figure 5.27



diversions (Route 2, Figure 5.27). The movement of sediments across the surface is altered by each diversion. Modern sediment transport has by no means reached a condition of "equilibrium". Much coarse material has remained on the surface near the upper clastic/carbonate contact. The loss of stream competence and capacity to underground conduits has greatly reduced the size of bedload below these points and in the surface runoff below the karst basin. Sieving has preserved much of fossil alluvium in the basin head. This development of paleodrainage and sediments is discussed further in Chapter 8.

Chapter 6. BASIN II
THE LOCUST CREEK BASIN

A. The Modern Basin

The second basin chosen for study drains 34.3 square miles along the Allegheny escarpment with a total fall of 2526 feet measured along its maximum trunk channel length of 15.9 miles. Basin II has a geologic and topographic setting similar to Basin I and is approximately 35 miles south of the latter in an area where the limestone outcrop is wider and more karsted than under the very steep gradients of Basin I.

Basin II is defined as the watershed within the maximum runoff perimeter of drainage entering the Greenbrier River at the mouth of Locust Creek.[10] It is a complex basin. The modern watershed includes several surface networks which appear to be topographically separate. These are, however, integrated into one system (Figure 6.01). The active and ephemeral sections of Basin II may be divided into the following areas:

The Modern Basin II

1. The Upper Basin
    a. The Hills Creek network

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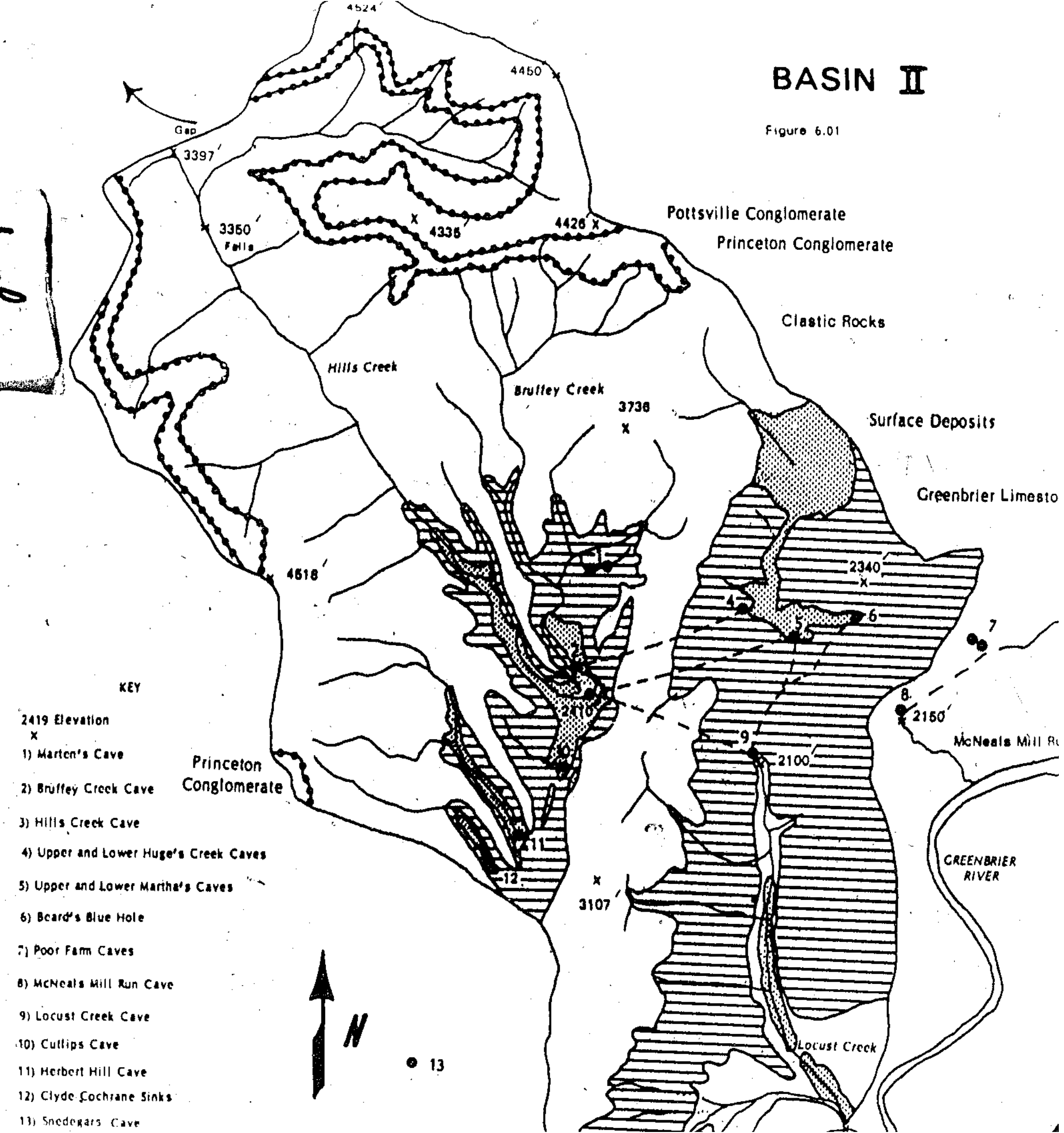
[10] Elevation 1998 feet at Locust Bridge, W. Va., 38° 04'00"N., 80°14'10"W., Marlinton Quadrangle, W. Va., U.S.G.S., 1923.

BASIN II

Figure 6.01



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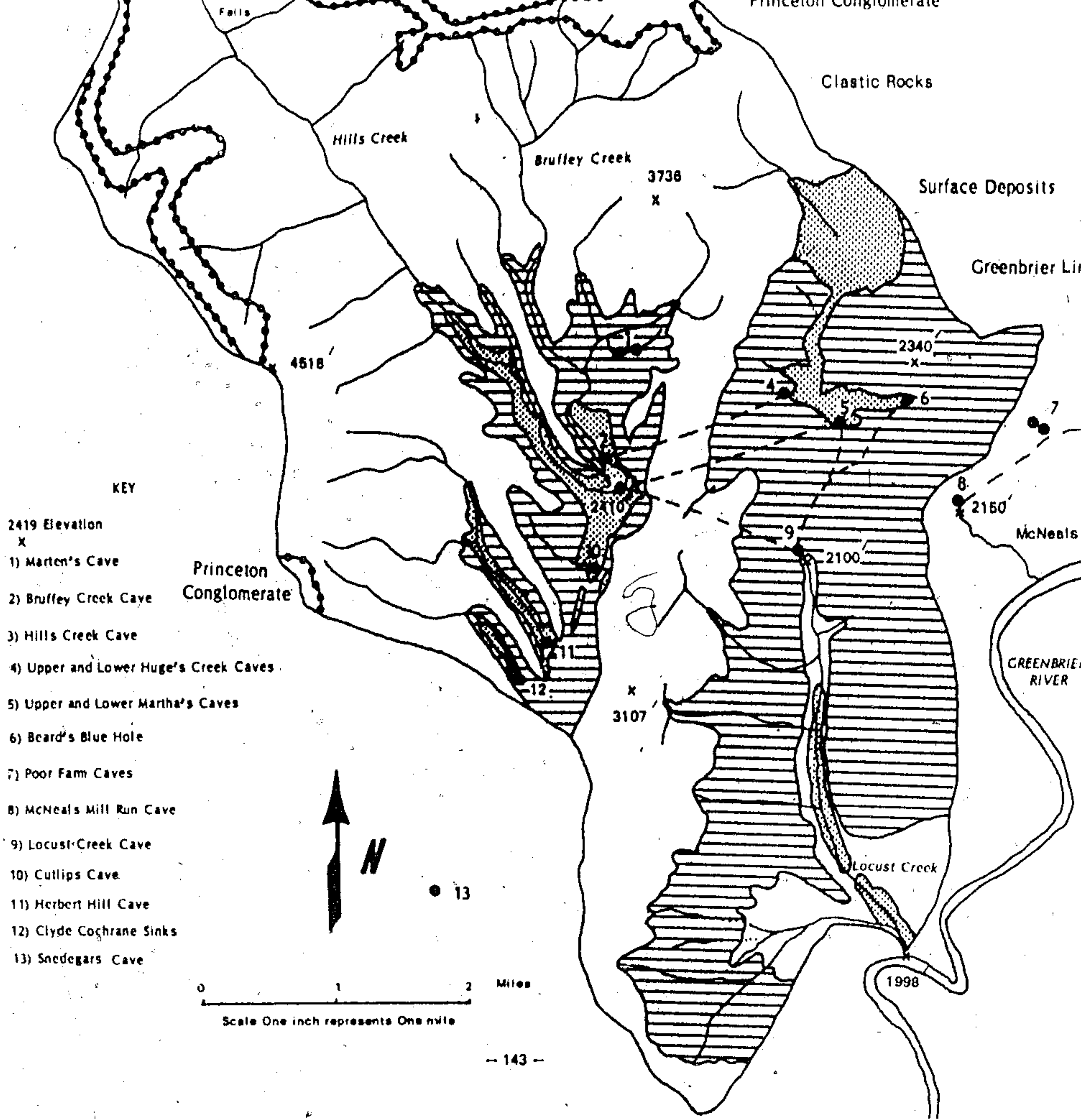

Princeton Conglomerate
Clastic Rocks
Surface Deposits
Greenbrier Li
Falls
Hills Creek
Bruffey Creek
3736
x
4518
2340
x
2410
2100
2150
McNeals
3107
x
GREENBRIE
RIVER
Locust Creek
1998
Princeton
Conglomerate
1
2
3
4
5
6
7
8
9
10
11
12
13
KEY
2419 Elevation
x
1) Marten's Cave
2) Bruffey Creek Cave
3) Hills Creek Cave
4) Upper and Lower Huge's Creek Caves
5) Upper and Lower Martha's Caves
6) Beard's Blue Hole
7) Poor Farm Caves
8) McNeals Mill Run Cave
9) Locust-Creek Cave
10) Cullips Cave
11) Herbert Hill Cave
12) Clyde Cochrane Sinks
13) Snedegars Cave
N
0
1
2
Miles
Scale One inch represents One mile

b. The Bruffey Creek network
c. Martens Cave
d. Rush Run and minor drainage south of Hills Creek

2. The Middle Basin

a. Hills Creek Cave and Bruffey Creek Cave conduits
b. Upper Hughes Creek Cave, lower stream conduits
c. Lower Hughes Creek Cave conduit
d. Lower Martha's Cave
e. Millstone Creek and its related subsurface conduits

3. The Lower Basin

a. Locust Creek and its related subsurface conduit
b. McNeals Mill Run basin

Statistical data are cited in Table 6.01.

1. The Upper Basin

The upper basin is the area isolated by the ridge crest of Droop Mt., Caesars Mt., and Viney Mt. (Figure 6.01). The Hills Creek and Bruffey Creek networks occupy most of the upper basin. Under normal runoff conditions these two networks are not integrated by surface flow, and sink 1500 feet apart. They join underground in the Hill-Bruffey Creek Cave system about 2500 feet downstream from the Bruffey Cave swallow hole. Occasionally during flood and spring runoff, the two networks are joined by surface flow and continue further south to sink at Cutlips Cave as well as at the sinks of Bruffey and Hill Creek. All water from the upper basin eventually rises at the Locust Creek resur-

Table 6.01

HYDROLOGY AND TOPOGRAPHY

SURFACE DRAINAGE	Channel Length (Miles)	Area (Sq. Miles)	Total Fall (Feet)	Mean Gradient	Mean Discharge (cfs.)
Hills Creek	9.4	10.5	2045	40/1000	15
Bruffey Creek	4.6	4.8	2015	80/1000	6
Locust Creek	3.5	10.0	92	5/1000	46
Millstone Creek	1.9	9.0	1575	150/1000	<1
Other drainage	5.5	1.0	N.A.	N.A.	<1

SUBSURFACE DRAINAGE	Conduit Length (Estimated in Miles)	Area (Sq. Miles)	Total Fall	Mean Gradient	Mean Discharge (Estimated cfs.)
*Route 1, Fig. 6.09	3.0	16.3	330	20/1000	22
**Route 2, Fig. 6.09	3.7	24.3	330	15/1000	46
***Route 3, Fig. 6.09	3.5	9.0	200	10/1000	<1
TOTAL OF BASIN II (Surface & Subsurface Drainage)	55.8 (Basin) 15.2 (trunk only)	34.3	2526	34/1000	46

*Route 1....Hills Creek - Bruffey Creek - Martha's Cave to Locust Creek
**Route 2....Hills Creek - Bruffey Creek - Hughes Creek - Martha's Cave to Locust Creek
***Route 3....Millstone Creek - Beard Blue Hole to Locust Creek

gence (Figure 6.01) in the lower basin.

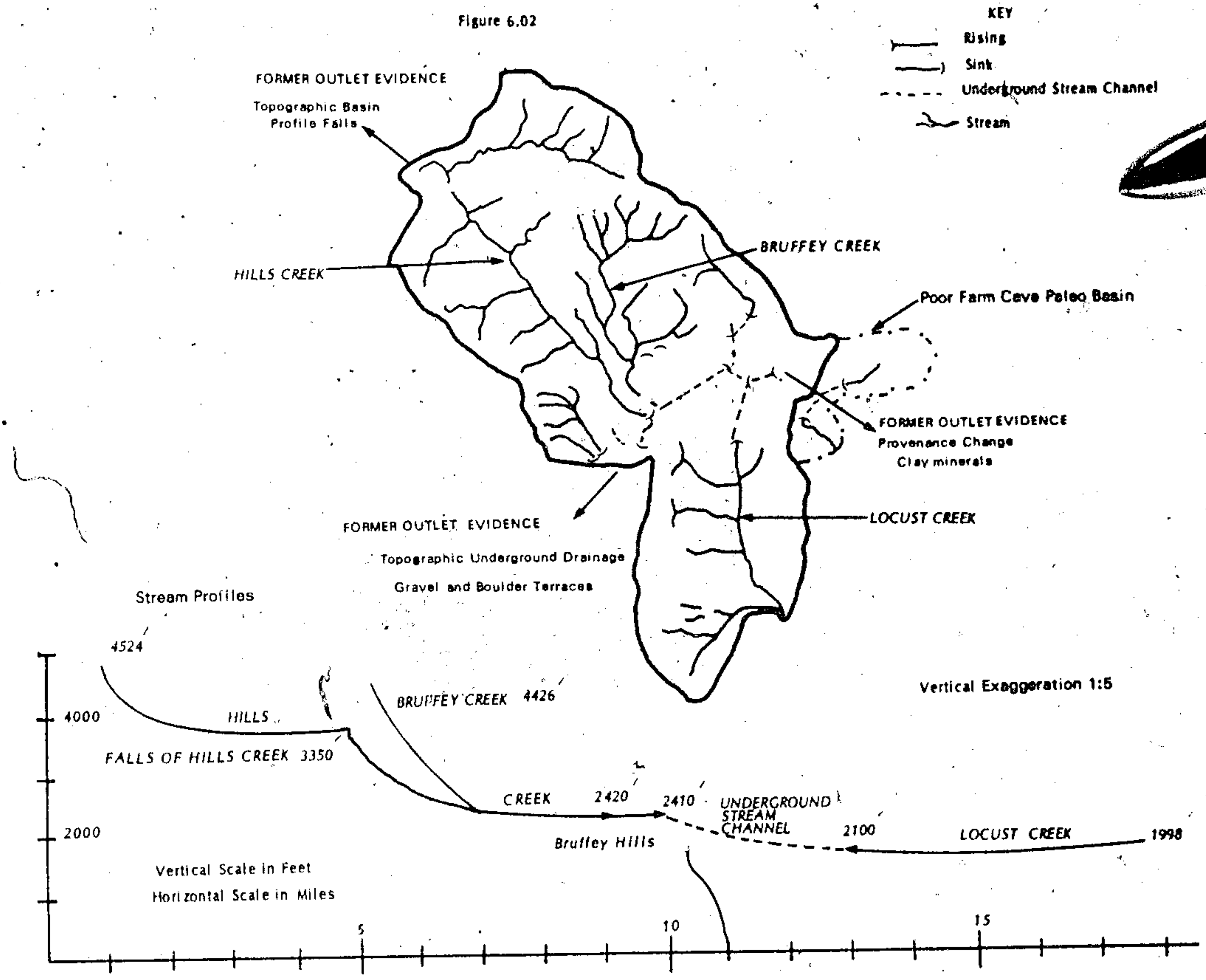
a. Hills Creek Network

Hills Creek is the largest surface stream in the upper basin. It measures 9.4 stream miles in length. The mean gradient for the overall channel is 4/100 , with a total drop of 2045 feet from head to sink. The first mile of channel at the headwaters drops 950 feet and has a gradient of 25/100 . This portion of the basin resembles Trout Run in Basin I. However, an important difference between the two basins is that none of the high gradient portion of Basin II is developed through a karst area, as is the case in Basin I. The total area drained by the modern Hills Creek basin is 10.5 square miles.

In Figure 6.02 two nickpoints appear in the trunk channel profile of Hills Creek. The headward nickpoint is a series of three large falls developed across the Stony Gap sandstone of the Mauch Chunk Series (shown as "falls" at 3350 feet on Figure 6.01). This abrupt drop of 330 feet resulted when drainage was pirated by Hills Creek from the former head of the North Forks of the Cherry River. The overall barbed pattern of the Hills Creek basin is a reflection of this piracy. A small gap at the 3397 feet mark on Figure 6.01 indicates the point of capture. The additional drainage to the Hills Creek system increased the area of the basin by one third and resulted in a new sediment supply from the Pottsville conglomerate outcrops at the

BASIN 2

Figure 6.02



new head of the basin.

The lower nickpoint shown in Figure 6.02 is assumed to be within the underground network of the Hills-Bruffey Cave conduit. The cave is accessible for only short distances at either end, i.e., approximately 2000 feet at the upstream end and 700 feet at the Locust Creek spring. Neither of these sections contain abrupt elevational changes. The nickpoint was probably initiated in Locust Creek by piracy when the upper basin drainage was diverted from its former route west of Droop Mountain. This former route drained south into the next major basin, Spring Creek, which lies to the southwest of Figure 6.01. The route was examined in detail by Coward and this author in 1971. Gravel terraces and sediments are difficult to trace along it, but evidence for its existence can be found in the present topographic configuration and in the occurrence of abundant karst drainage along the assumed route. In 1972 Coward established the southwestern drainage divide of Basin II by stream tracing the drainage of Rush Run and the small tributary immediately south of it shown in Figure 6.01. The stream immediately south of this small tributary (not shown in Figure 6.01) drains southward in a subterranean channel, assumed to flow along the approximate route of the former outlet of Hills and Bruffey Creeks. The latter has been pirated by drainage from Locust Creek. The result of the diversion is modern Basin II as it appears in Figure 6.01.

The position of the lower nickpoint within the Hills-Bruffey conduit is probably stabilised by the Taggard shale which is a strong lithologic control of the local drainage. This shale separates Upper and Lower Hughes Creek caves.

The stratigraphic position of the upstream sinks of Hills and Bruffey Creeks in the Union limestone and the lower rising of Locust Creek in the Hillsdale limestone means that the Taggard formation must be breached by the underground conduit that joins them.[11] During high water a by-pass route over the Taggard shales is afforded by surface crossing of the formation between Hughes Creek upper and lower caves. But only part of the drainage occupies this route (Coward, personal communication).

Both Hills Creek and Bruffey Creek head above the outcrop of the Pottsville conglomerates and the Princeton conglomerate. These supply large amounts of traceable milky quartz pebbles to both streams.[12] Boulder-sized fragments of conglomerates are carried by the streams during times of maximum discharge (Figure 6.03). During Hurricane Camille in 1969, boulders up to 1.5 feet in diameter were moved by Hills Creek. Under normal flow, i.e., 15 cfs. for

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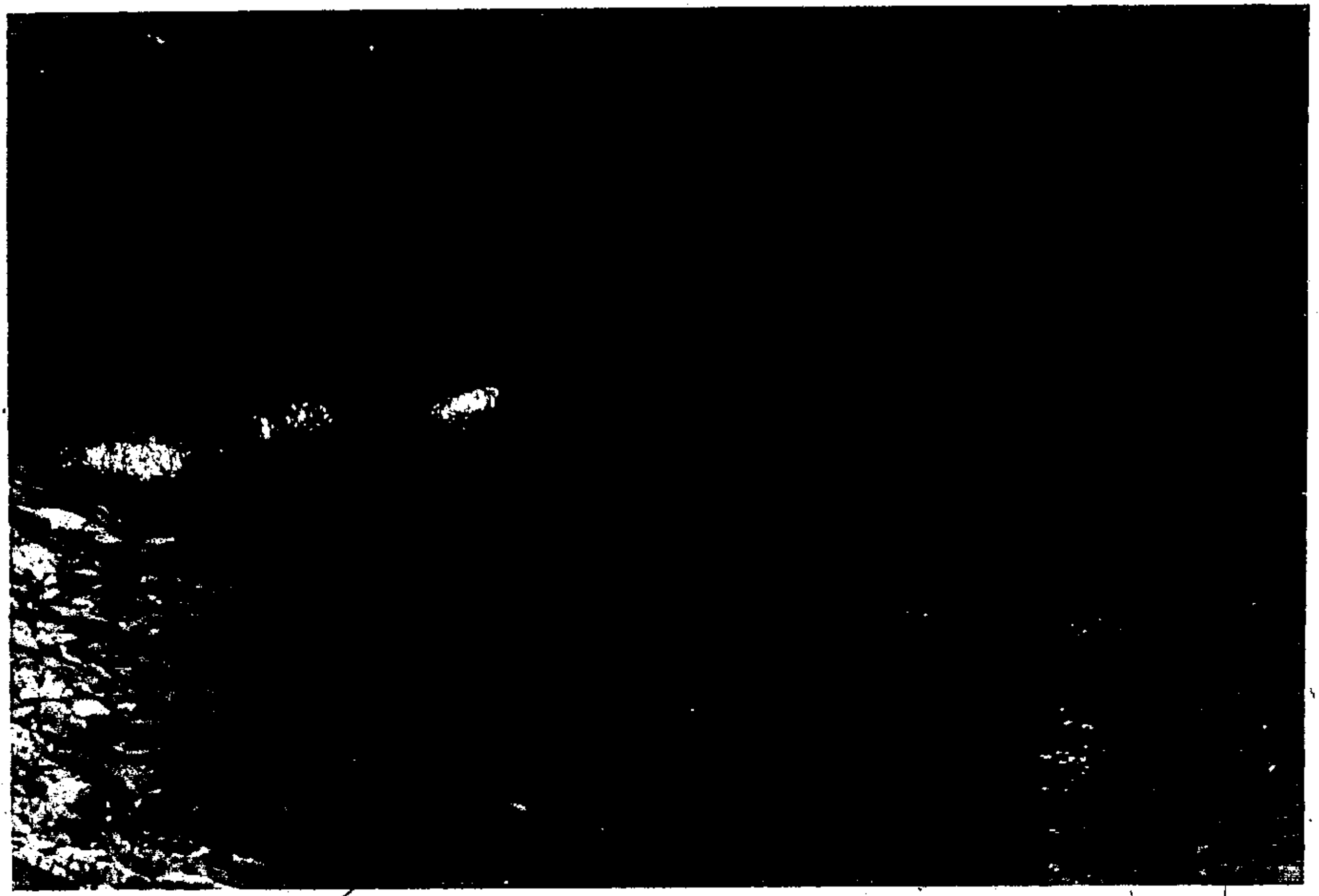
[11] This has never been observed in the cave because of the limit of access from either end of the system, but nevertheless, this must be the case owing to the relative positioning of sinks, rising, and stratigraphy.

[12] Actual amounts of measured bedload quantities in the optimum size range vary downstream from the outcrop from 5% to 35% as far as the rising of Locust Creek.

Figure 6.03

HILLS CREEK FLOWING ON THE MAUCH CHUNK SANDSTONES IN THE UPPER BASIN



Note the large conglomerate boulders in the background. Flow is toward the foreground.

Hills Creek and 6 cfs. for Bruffey Creek, neither stream transports material greater than one millimeter in diameter, as far as their respective sink points at the cave entrance.

The most abundant bedload material is derived from the outcrops of the Stony Gap sandstone of the Mauch Chunk series. At the base of the third falls of Hills Creek, boulders of the sandstone measure over six feet in diameter. At the top of the first waterfall, boulders of Princeton and Pottsville conglomerate are of similar sizes.

Approximately one-half of the total runoff of Hills Creek is diverted underground when the stream reaches the upper contact of the Greenbrier limestone series (Figure 6.04). Under normal runoff conditions, less than one-third of the total discharge of Hills Creek actually enters Hills Creek cave via the entrance of the surface sink. A downstream analysis of maximum particle size of bedload in Hills Creek shows that an increase in grain size occurs at the head of the alluvium. The reasons for this are twofold: (i) a loss of competence of the stream due to a gentler stream gradient in the profile of this portion of the upper basin; (ii) escaping drainage has produced a large karst "sieve-type" deposit.[13]

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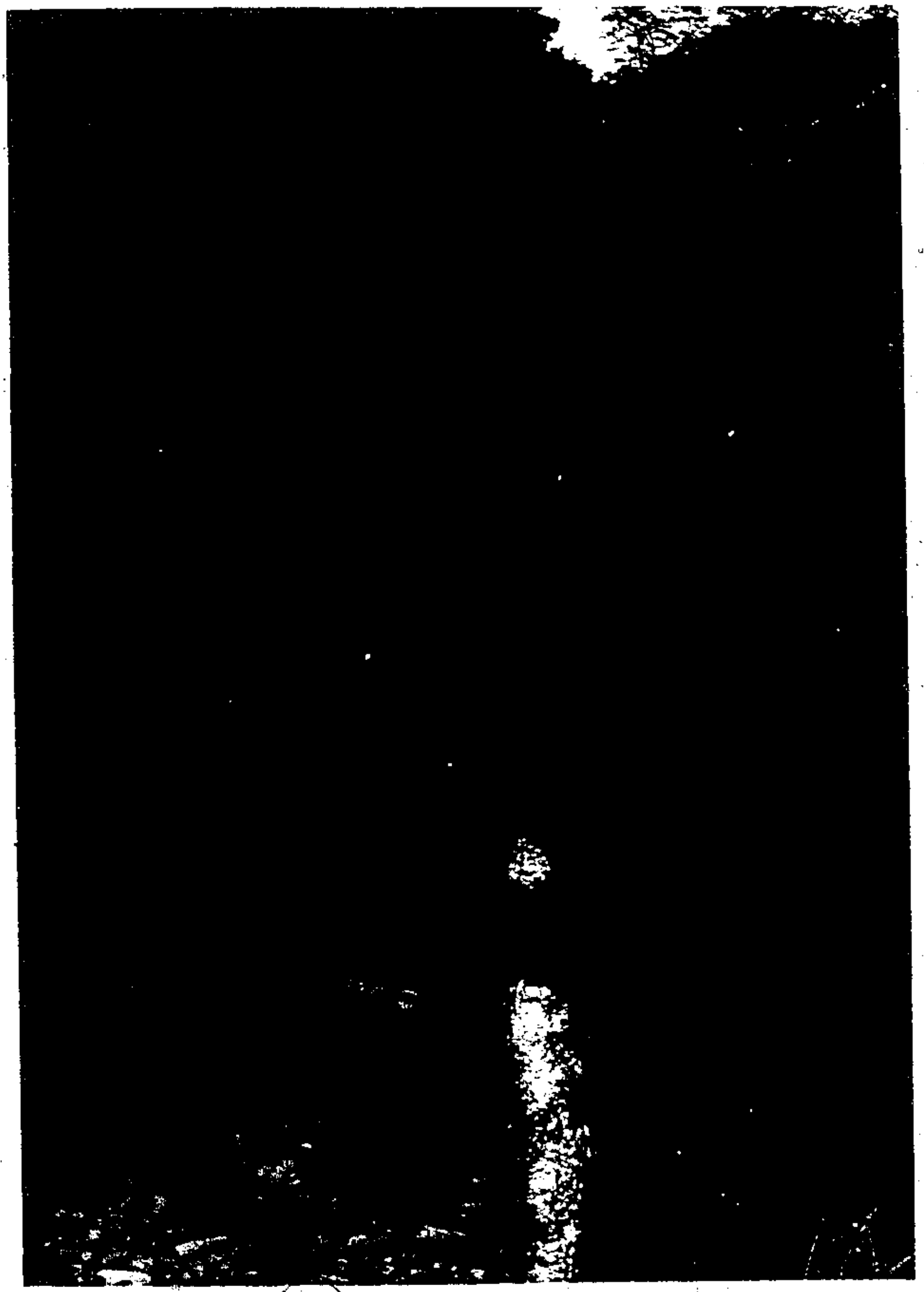
[13] The term "sieve-type" deposit has been used by Hooke (1967) to describe lobate masses of coarse alluvium in arid areas. The process of deposition in karst regions is accelerated by drainage loss underground. Karst "sieve-type" deposits have not been described before in the literature. They are a common feature of medium to large karst networks in areas of high stream gradient where coarse clas-

Figure 6.04

HILLS CREEK AT THE UPPER CLASTIC/CARBONATE CONTACT



The limestone is in the upper right corner (not exposed). The stream is flowing towards the background on alluvium.

In addition to the coarse boulder, gravel and sand deposits, large terraces of sand and silt have accumulated near the toe of the "sieve-type" deposits. These merge to form a continuous alluvial veneer up to 15 feet in depth across the limestone. This covers the lower part of the upper basin adjoining the sink areas of the Hills and Bruffey Creeks (Figure 6.05). This finer material is laid down during periods of excessive runoff when the cave entrances become blocked by debris and are unable to take all of the discharge. Such was the case during Hurricane Camille in 1969.

The total depth of alluvium around the sink points generally exceeds 30 feet. Several large collapse sinks have developed in it. Table 6.02 summarizes the maximum bedload size associated with Hills Creek.

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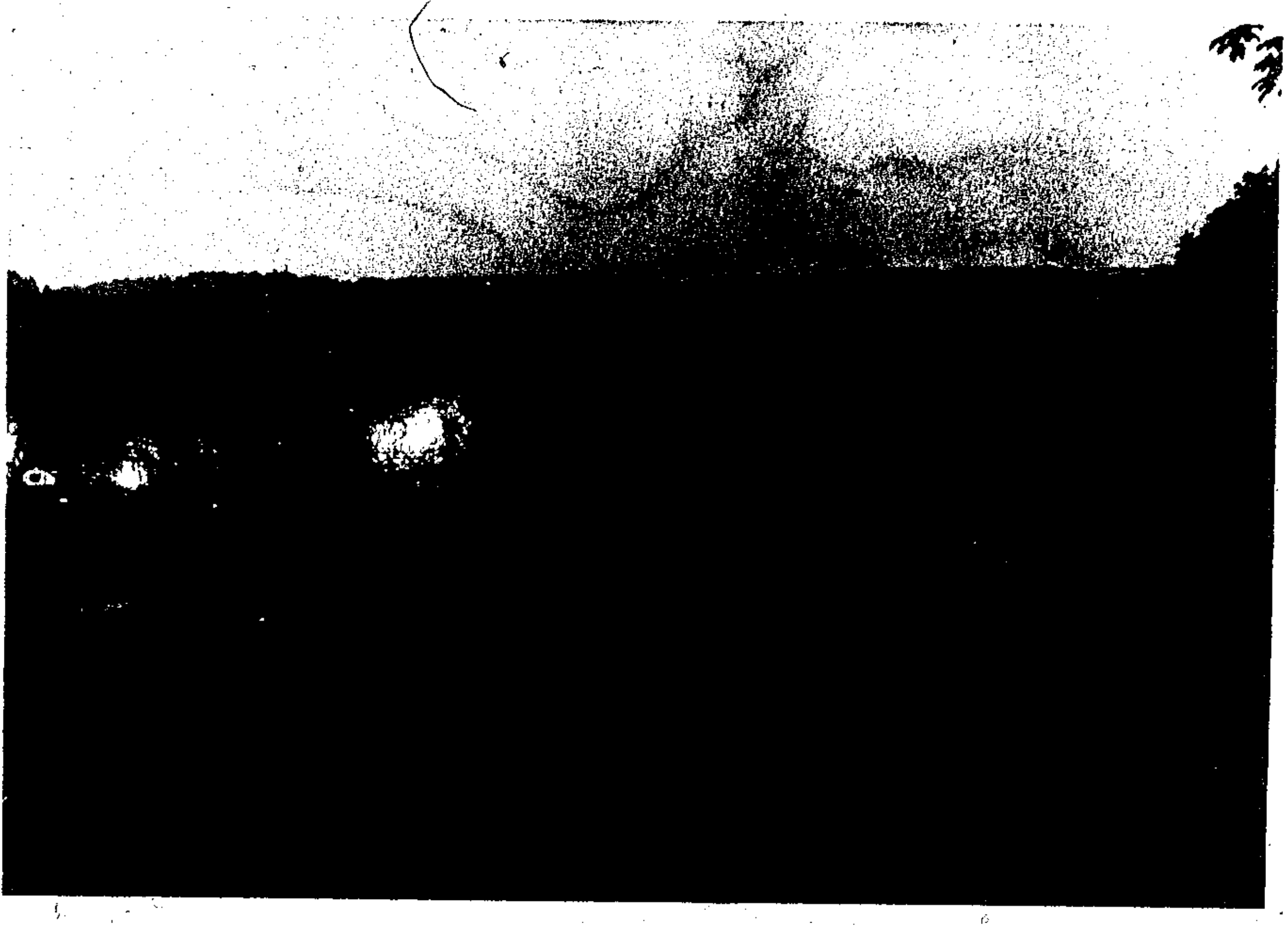
tic bedload is carried across a karsted surface. A larger example of this phenomenon is described in the Roaring Creek channel of Basin III. They are common throughout the Greenbrier karst along the base of the Allegheny Front, and appear to be much less active today than in the past. Forests cover much of the upper areas of these fans. Michalek (1969) has described fanlike features in nearby areas of the Blue Ridge of Virginia and North Carolina, which he attributes to periglacial activity during the Wisconsin. These features of the Greenbrier basin are probably of a similar period, with modification due to karst processes associated with their development. Hack (1965, p. 53) also describes an "alluvial apron" along carbonate-clastic contacts and explains this in terms of hard rock-soft rock "dynamic equilibrium" phenomena.

Figure 6.05

LARGE BLIND VALLEY AT THE SINK OF HILLS CREEK



Droop Mountain is in the background. The stream flows from left to right and sinks on the right. The view is to the east along the underground diversion to Locust Creek.

Table 6.02

HILLS CREEK BEDLOAD[1]

Sample Site Location[2]	Maximum Boulder Size[3]	Lithology
0.0 (head)	5.2 m.[4]	Pottsville conglomerate
1.0 (base of steep curve in gradient)	2.2 m.	Princeton conglomerate
3.0 (falls)	1.0 m.	Stony Gap sandstone
8.0 (head of "sieve-type" alluvium)	1.3 m.	conglomerate
9.4 (sink)	10.0 cm.	conglomerate

[1] The term "bedload" here refers to boulders which are at least "sub-rounded" in appearance and are found lying within the maximum zone of flood along the channel. This includes the fixed bed.

[2] In miles downstream from the head at 4450 feet on Figure 6.01.

[3] Mean size of the five largest fragments in 150 feet of channel.

[4] Hillwaste at the head of the channel (sub-angular).

b. The Bruffey Creek Network

The Bruffey Creek trunk measures 4.6 miles in length, less than one-half that of Hills Creek. The channel has an overall mean gradient of 8/100 , or twice that of Hills Creek. The basin area of Bruffey Creek is 4.8 square miles, or slightly more than one-half that of Hills Creek.

Several features common to these two networks in the upper basin are:

i) Both streams drain across the same stratigraphic outcrops which supply sediments to their respective channels. Thus they have the same lithologic provenance.

ii) Both streams drop about the same elevation (slightly over 2000 feet) in the same physiographic setting along the topographic Allegheny Front.

iii) Although the volume of runoff is less for Bruffey Creek, its steeper gradient provides nearly the same competence as that of Hills Creek. The bedloads measured at the mouths of both streams are very similar in maximum grain size, mean grain size, and volume of material moved. Downstream variations in grain size are summarized in Table 6.03 for the bedload of Bruffey Creek. The major differences in these data appear to be the size and depth of alluvium covering the underlying limestone of the two channels. Alluvial veneer in the Bruffey basin is much finer and lacks the "sieve-type" development of Hills Creek. Hills Creek drains a greater area of conglomerate exposure at a higher

Table 6.03

BRUFFEY CREEK BEDLOAD[1]

Sample Site Location[2]	Maximum Boulder Size[3]	Lithology
0.0 (head)	2.5 m.[4]	Princeton conglomerate
1.2 (base of steep curve in gradient)	2.0 m.	Stoney Gap sandstone
2.5 (at limestone contact)	1.6 m.	Stoney Gap sandstone
4.0 (head of alluvium)	42.0 cm.	conglomerate
4.6 (sink)	10.2 cm.	conglomerate

[1] The term "bedload" is used here as in Table 6.02.

[2] In miles measured downstream from the head near 4426 feet in Figure 6.01.

[3] Mean size of the five largest fragments in 150 feet of channel.

[4] Hillwaste adjacent to the head of the channel (sub-angular).

elevation which may have been subjected to more intense periglacial activity. This is the large area above the assumed point of capture shown in Figure 6.01. A comparison of maximum particle sizes at the respective stream headwaters and head of alluvial veneer in both basins shows the size of material to vary by a factor of at least two.

iv) Clay mineral suites are identical for the finer fraction of the bedload of both streams.

There are, however, some important differences. The Bruffey Creek trunk channel is more typical of "graded" stream profiles described in the Appalachians (Hack, 1957). It does not possess the nickpoints that are found in the Hills Creek channel. It has not grown by piracy in the headward part as in Hills Creek (compare the gradients shown in Figure 6.02). The Bruffey Creek basin is developed to a much greater extent on limestone. Nearly 50% of the drainage area is through or across exposed karsted rock. This is one-half of the total limestone surface of the upper basin. Part of the tributary systems of Bruffey Creek pass through underground channels. This particular drainage can be examined in Martens Cave (p. 159) in this chapter.

The general drainage pattern of the Bruffey Creek basin is dendritic, with a greater surface drainage density in the headwaters than most of the basins along the escarpment. This is due to the outcrop of clastic rocks there.

The lack of surface tributaries in the lower part of the basin is due to the extensive karstification in that area.

It has been suggested by Renault (1965) and others that sediment in limestone caves may act as a shield against further solution of the cave floor, once a stable bed is established. Because the Bruffey Creek basin is well-developed across the limestone, both on the surface and through a tributary cave system, the surface channels and underground conduits of the basin are of particular interest in testing such an hypothesis, as well as in a general study of sedimentation in karst basins. As Figures 6.06 and 6.07 show, there is a considerable loss of drainage through a coarse bedload in a surface stream flowing across limestone. However, where silts and sands predominate, as in both Hills and Bruffey Creeks farther downstream, there is little further loss of drainage underground. Although there is an immediate drop of approximately two-thirds of the discharge in both streams when the streams reach the limestone, as drainage continues across the limestone on finer deposits, little water is lost. Both streams flow nearly two miles on these finer sediments in both to reach their respective sink points.

c. Martens Cave

A study of sediment and drainage movement through a limestone conduit, Martens Cave, was carried out for three

Figure 6.06

BRUFFEY CREEK FLOWING ON THE MAUCH CHUNK SANDSTONE IN THE UPPER BASIN

Flow is toward the foreground.

Figure 6.07

BRUFFEY CREEK FLOWING ON ALLUVIUM

Note the loss of surface drainage. Flow is toward the foreground.

years (#1 on Figure 6.01). The cave lies along Cave Run which supplies about one-tenth of the total discharge of Bruffey Creek. Martens Cave[14] is a natural tunnel containing the underground course of Cave Run for approximately 1000 feet. The south entrance is in a large cliff face 50 feet high and receives the stream draining about one-half a square mile. Figure 6.08 is a map of Martens Cave. The present stream is very much underfit both on the surface and within the cave. The cave itself shows strong evidence of phreatic development. It has an overall oval cross-section, with an elongate horizontal axis. Small scallops produced by modern flow extend only 1.5 feet up from the floor of the stream bed, indicating that modern runoff has not bee responsible for the development of the cave. Large ceiling scallops and solution pockets are preserved above the flood zone of the lower part of the cave. Fine silts and clays are deposited in the higher sections of the side passages. Stalagmites and flowstone has been deposited over some of these fine deposits in the highest parts of the first side passage in the Lapiez Room (Figure 6.08).

Bedload movement into and out of the cave was monitored by sediment traps placed at both ends of it. These

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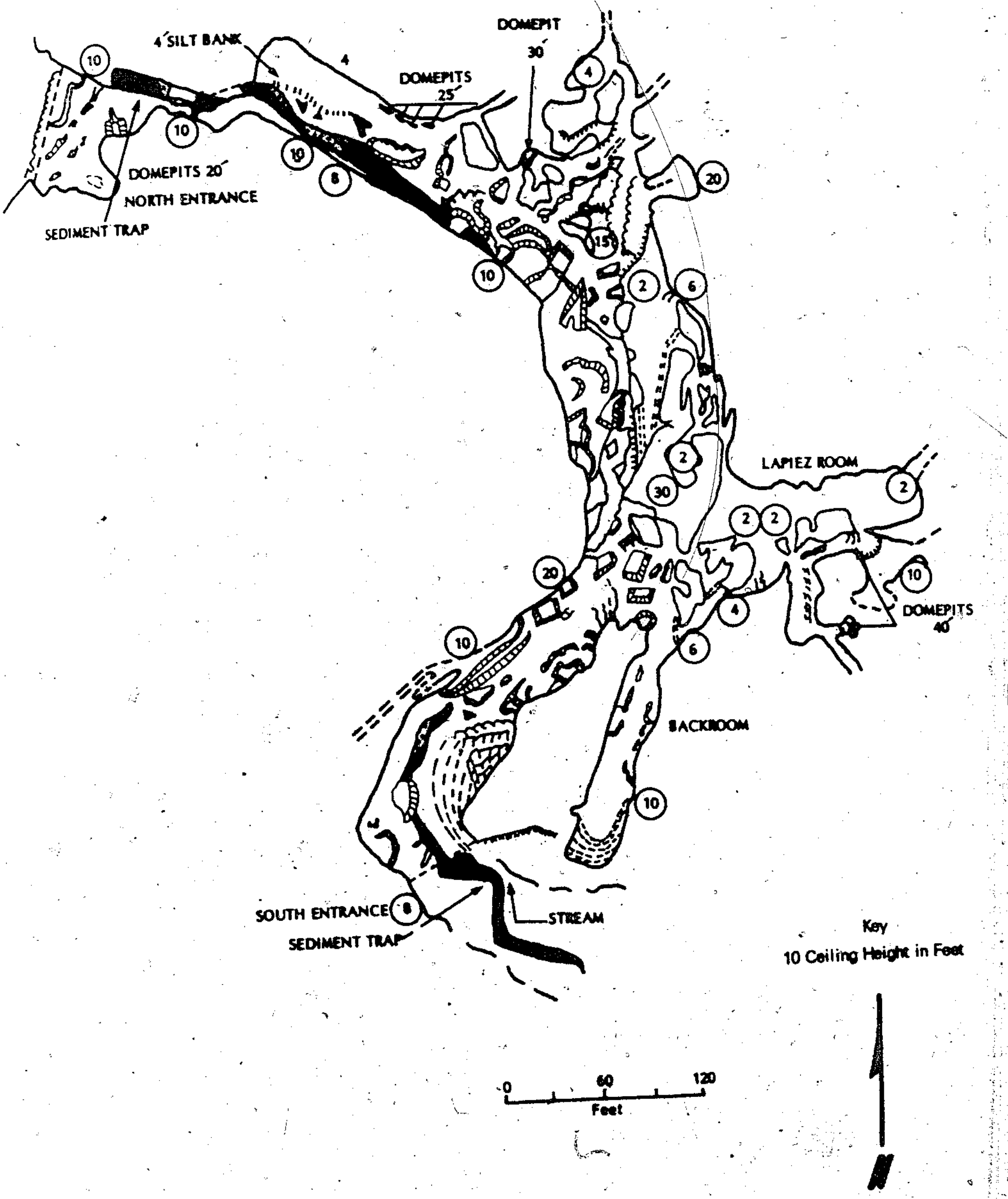
[14] The south entrance is located at 38°08'00"N., 80°16'26"W. and the north entrance at 28°08'05"N., 80°16'35"W., Lobelia Quadrangle, U.S.G.S., 1935.

MARTENS CAVE

Figure 6.08



were checked regularly after any appreciable rainfall during spring and summer, 1968, 1969 and 1970. Measured data are cited in Table 6.04. During this time, sand and silt was transported through the cave. Only on one occasion were gravels deposited. The increase in grain size was due to a particularly large flood caused by Hurricane Camille, 1969. The flood on that occasion removed nearly an equal amount of coarse material from the stream exit of the tunnel. The gradient is only 5/1000 . No major changes in the gradient of Cave Run occur in the cave or above it because much of the drainage is supported on the underlying Greenville shale.

Table 6.04 shows several interesting features about sedimentation in Martens' cave.

1) Most of the time silt-clay grain sizes are all that enter the cave.

2) Hurricane Camille, August 26, 1969 yielded 14 inches of rain and a storm on September 5, 1969 yielded 9 inches of rain while groundwater levels were still high. Together they caused sedimentation to increase by a factor of 15 at the entrance.

3) Removal of sediments at this time was greater than the rate of sediment supply to the cave by a factor of 3 .

4) The sediment removed is finer in grain size than the material entering the cave under all conditions.

Table 6.04

CLASTIC SEDIMENTATION IN MARTEN'S CAVE

	ENTRANCE			EXIT		
Month	Depth in Meters (Mean)	Volume* (Cubic Meters)	Mean Grain Size	Depth in Meters (Mean)	Volume* (Cubic Meters)	Mean Grain Size
1968						
May	0.002	0.02	silt-clay	0.001	0.01	silt-clay
June	0.001	0.01	silt-clay	0.001	0.01	silt-clay
July	0.001	0.01	silt-clay	0.001	0.01	silt-clay
Aug.	0.002	0.02	silt-clay	0.002	0.02	silt-clay
Sept.	0.005	0.05	silt-clay	0.004	0.04	silt-clay
Total	0.011	0.11		0.006	0.09	
1969						
May	0.002	0.02	silt-clay	0.001	0.01	silt-clay
June	0.001	0.01	silt-clay	0.001	0.01	silt-clay
July	0.001	0.01	silt-clay	0.001	0.01	silt-clay
Aug.	0.060	0.60	gravel (1.6 cm)	0.100	1.00	silt-clay
Sept.	0.105	1.05	gravel (2.0 cm)	0.250	1.50	silt-clay
Total	0.169	1.69		0.453	4.53	
1970						
May	0.001	0.01	silt-clay	0.001	0.01	silt-clay
June	0.002	0.02	silt-clay	0.001	0.01	silt-clay
July	0.005	0.05	silt-clay (20% sand)	0.002	0.02	silt-clay
Aug.	0.003	0.03	silt-clay	0.002	0.02	silt-clay
Sept.	0.002	0.02	silt-clay	0.001	0.02	silt-clay
Total	0.013	0.13		0.007	0.07	

*Volume entering and leaving the cave, estimated from new accumulation on ten square meters of plastic sheeting placed at the entrance and exit. The accumulation in these sediment traps was collected each month from May to September.

5) Under low water conditions, more material enters the cave than leaves. The reverse appears to be true during the floods of 1969.

6) During these three years of observation more clastic sediment was removed from the cave than was laid down. These data do not consider dissolved load or suspended load. It is assumed that both of these are nearly the same at entrance and exit to the cave.

The maximum accumulation of transported fills in Martens Cave does not exceed two feet in any location. Sand structures are preserved in point bar accumulations at the inside of meanders in the cave stream. Sedimentary features resemble in every respect those of a small surface stream. The surface deposits above and below the cave are in no way different from those within the cave system itself. The one exception is that cave deposits contain an abundance of infiltrates. Infiltrated silts accumulate inside passages. These deposits, along with ceiling breakdown, make up the bulk of non-transported gravitational fills. The stream channel in the main passage maintains near-equilibrium conditions of deposition, transport and removal of fills. Although breakdown from the ceiling is abundant, removal by solution in the stream appears to keep pace with its deposition. The main factor in preventing removal of material is the restrictive size of the stream exit at the north end of the cave. Here occasional ponding under high water conditions when a higher level water exit is used, has caused sand and silt accumulation near the downstream part of the cave (Figure 6.08).

Martens Cave appears to be typical of low gradient caves with an active stream. As long as the exit of material is possible, a steady state of deposition, transport and removal of sediment is maintained. In Chapter 8, Martens Cave is discussed further in relation to the general sequence of sedimentation development in limestone conduits. The equilibrium state that it appears to have established is considered to be representative of many systems in the late stages of cave sedimentation as interpreted in karst basins of the Appalachians. Vadose cave stream gradients gradually decrease with time as the bedload becomes finer and approaches an equilibrium condition of deposition and removal.

d. Rush Run and Minor Drainage South of Hills Creek

Rush Run sinks at Herbert Hill Cave No. 1 and a small stream immediately south of Rush Run sinks at Clyde Cochrane Sinks. Coward established the connection of the two small streams to the Locust Creek rising (Figure 6.01).

The amount of runoff added to the network is very small[15] and no milky quartz from the Pottsville and Prince-

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[15] Coward estimates less than .5 cfs for the total for both streams (1972, personal communication).

ton outcrops are transported by these streams. The sinks of both streams were examined before and after the large storms associated with Hurricane Camille. The result was two sequences of deposition beginning with leaf litter and floating debris, then silt coarsening upwards to gravels. Each sequence was less than two feet in depth and each was the result of a large thunderstorm. The first storm was recorded at 14 inches, the second occurred a week later and caused 9 inches of precipitation. Overspill flooding from Hills Creek caused coarse gravels, including milky quartz pebbles, to enter the Rush Run sink. No such gravels are actually transported be either of these streams themselves. These networks are not studied in detail; however, their role and that of other small streams draining off the Allegheny Front and into a former network which once flowed southwestward through Friars Hole into the Spring Creek basin has been investigated by Coward (1972, personal communication). A large boulder and gravel terrace near Spring Creek suggests that surface drainage from all streams south of Bruffey Creek once drained along a large channel west of, and parallel to Droop Mountain. This network is discussed in Section B of this chapter.

2. The Middle Basin

The middle basin is the underground portion of the Modern Basin. It extends from the sink points of the upper basin through Droop Mountain to risings at Locust Creek.

An intermediate rising at Hughes Creek acts as an intermittent karst window for part of the drainage during high water. All drainage from both the upper and middle basins eventually rises at the head of Locust Creek. Some additional surface runoff from Caesars Mountain and Little Levels enters the intermittent system associated with Hughes Creek. Because much of the middle basin is inaccessible, the Hughes Creek area is important in an overall study of drainage and sedimentation in Basin II.

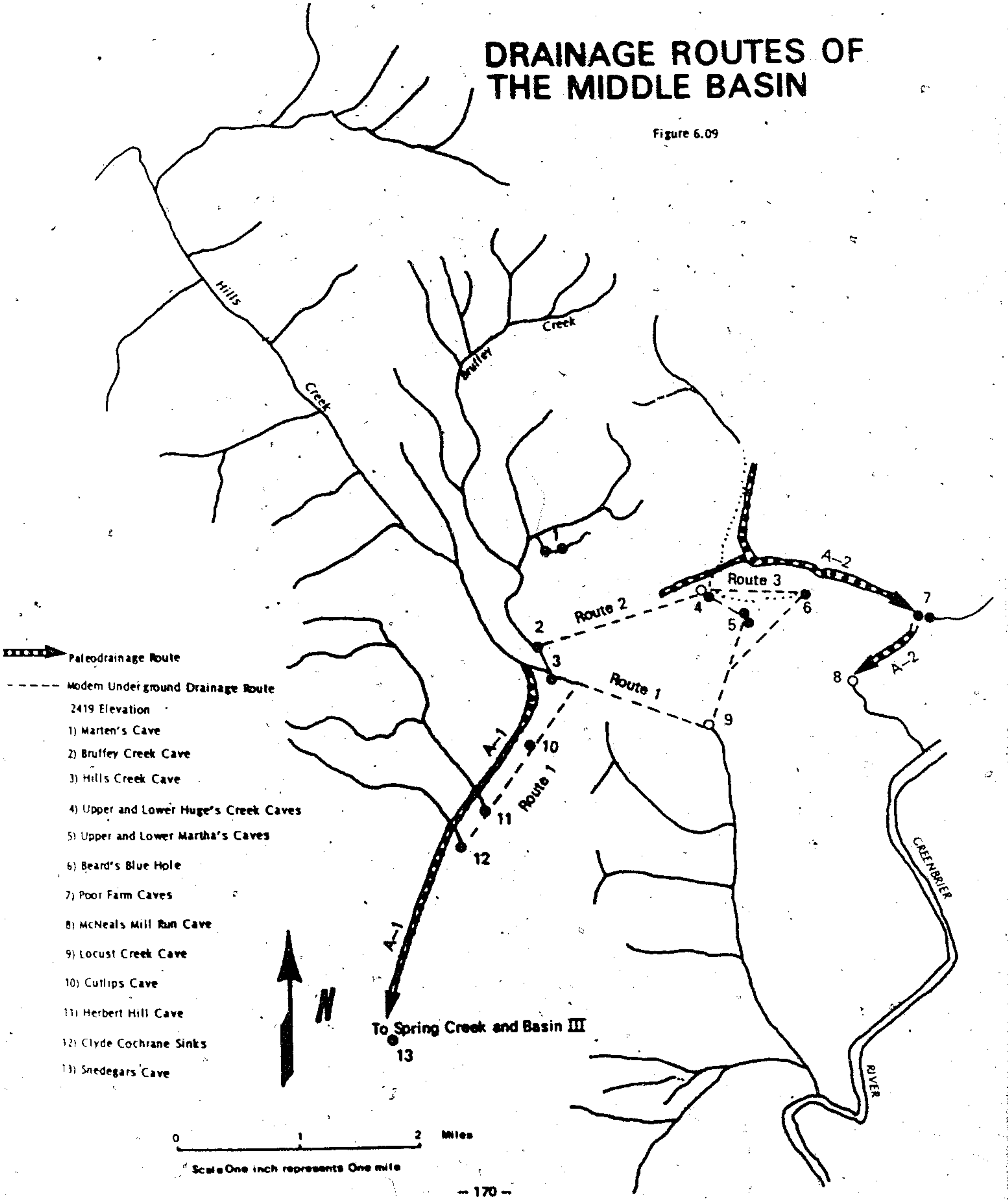
a. Hills Creek Cave and Bruffey Creek Cave Conduits

The general underground network of drainage in the middle basin is shown in Figure 6.09. The movement of water and sediment from the upper basin into and through the middle basin system is not a straight input-output function, as in the simple example of Basin I (Chapter 5).

Under very low water conditions, all water entering the sink points of the upper basin flows through the Bruffey-Hills Creek route to the Locust Creek rising (route 1, Figure 6.09). During normal flow (approximately 15 cfs. for Hills Creek and 6 cfs. for Bruffey Creek) water also moves through route 2, via Hughes Creek Upper and Lower Caves, and Lower Martha's Cave, then rejoins the drainage of route 1. During high water (approximately 5 to 10 times per year) when the Locust Creek rising exceeds approximately 60 cfs., a third route is utilised, via the surface overflow of Millstone Creek (Figure 6.09, route 3). The maximum

DRAINAGE ROUTES OF THE MIDDLE BASIN

Figure 6.09



fall within the middle basin is 330 feet. This is from 2420 feet at Bruffey Creek sink to 2090 feet at the Locust Creek rising. By estimating the underground length at approximately three miles, the average gradient of the middle basin is found to be 2/100 .

The movement of sediment in this system also is more complex than the simple input-output function of Martens Cave in Basin I. All major sinks and risings were monitored for bedload volume, mean grain size, maximum grain size, provenance and clay mineralogy. These data, excluding clay mineral, are summarised for each sample site and shown in Appendix A.

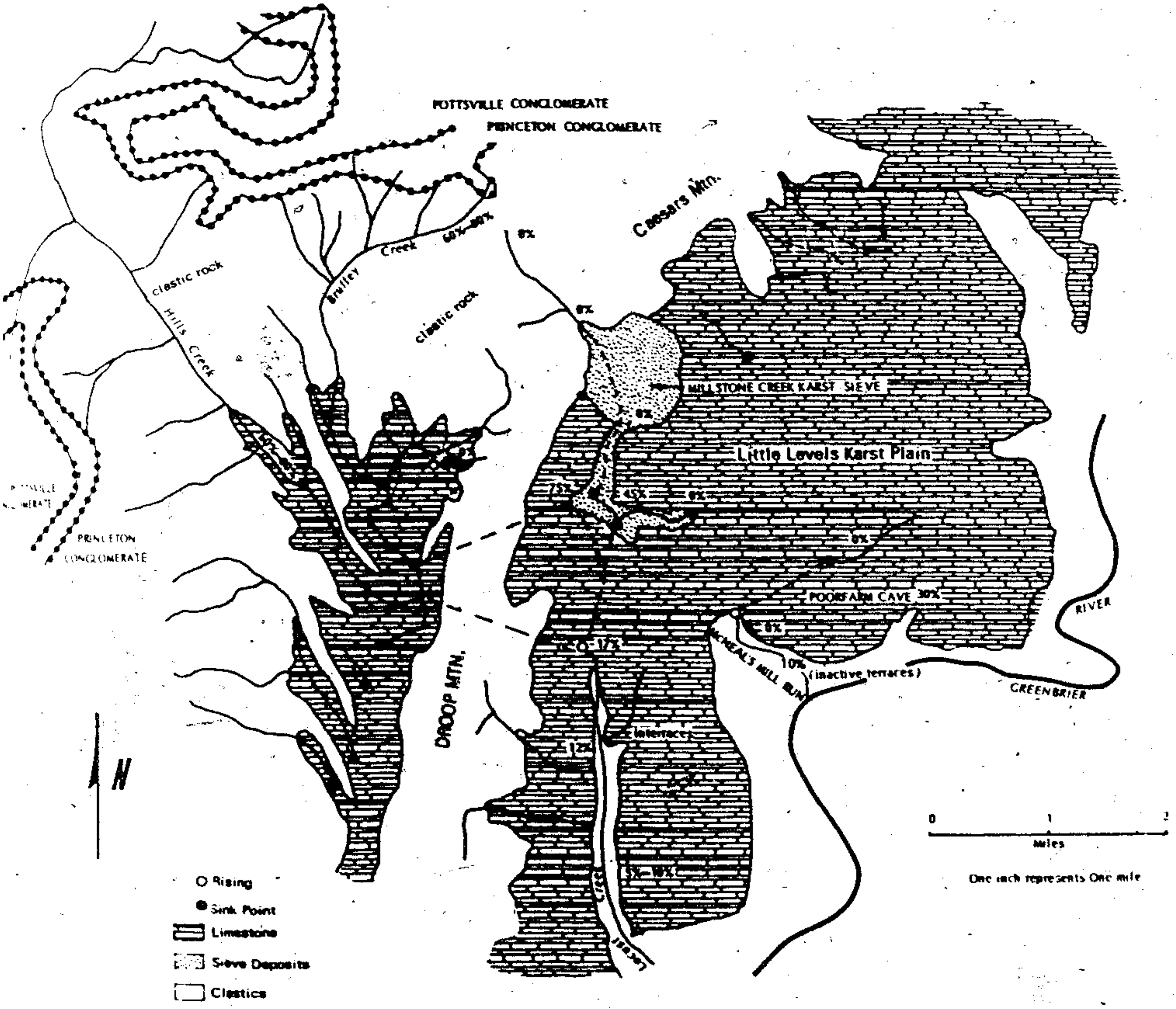
Figure 6.10 shows the distribution of milky quartz pebbles which act as natural tracers in the modern channels of Basin II. The percent of milky quartz pebbles at each site is shown. This figure is derived:

$$\frac{\text{Number of SiO}_2\text{ Pebbles of a Given Size Fraction}}{\text{Total Number of Pebbles at the Same Size Fraction}} \times 100 = \%$$

Figure 6.11 shows the distribution of kaolinite (3.58Å) to illite (10Å) ratios throughout the middle basin. In Chapter 4 it was pointed out why these ratios were more useful and probably more accurate than absolute figures. Appendix B gives all recorded values (peak heights in tenths of inches).

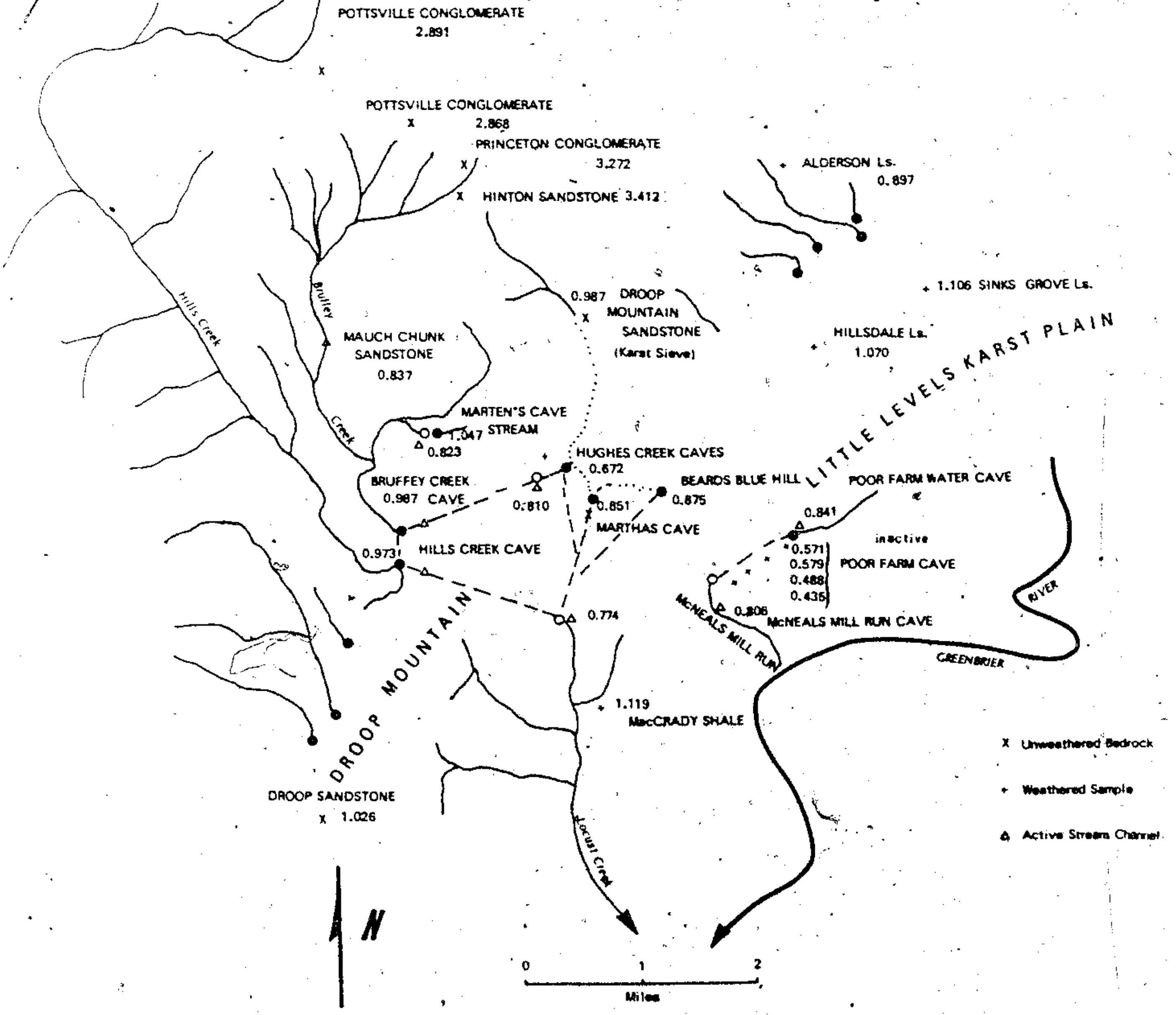
DISTRIBUTION OF QUARTZ PEBBLES IN THE MIDDLE AND LOWER BASIN

Figure 6.10



CLAY MINERAL RATIOS IN THE MIDDLE AND LOWER BASIN

Figure 6.11



b. Upper Hughes Creek Cave, Lower Stream Conduit

Figure 6.12 is a map of the Hughes Creek Caves. "Route 2" shown on Figure 6.09 is the perennial stream which is shown entering the Upper Cave on the left of Figure 6.12. The stream occupies the lowest level of the Upper Cave and usually sinks into limestone cobbles and boulders at the entrance of the Upper Cave. The water reappears in the west side passage of the Lower Cave and sinks at a syphon in the rear of it. During high water a surface overflow route known as Hughes Creek rises at the entrance of the Upper Cave and flows into the Lower Cave. Figure 6.13 shows the overflow from the Upper Cave entering the Lower Cave. The Lower Taggard shale is seen in the centre of the photograph. The observer is standing on the shale directly above the entrance to the Lower Cave. The shale here is two feet thick and has been breached within the entrance of the Upper Cave. When the underground channel fills completely, then the surface overflow channel is utilised.

During Hurricane Camille in 1969, the surface route was flowing at approximately 50 cfs. Water within the Upper Cave reached into the intermediate level of the cave. This is the southwest corner of the cave as shown in Figure 6.12.

The following points concerning modern drainage and sedimentation in Upper Hughes Creek cave can be made.

1) Hurricane Camille and related storms of 1969 caused the highest water since fluvial sedimentation became

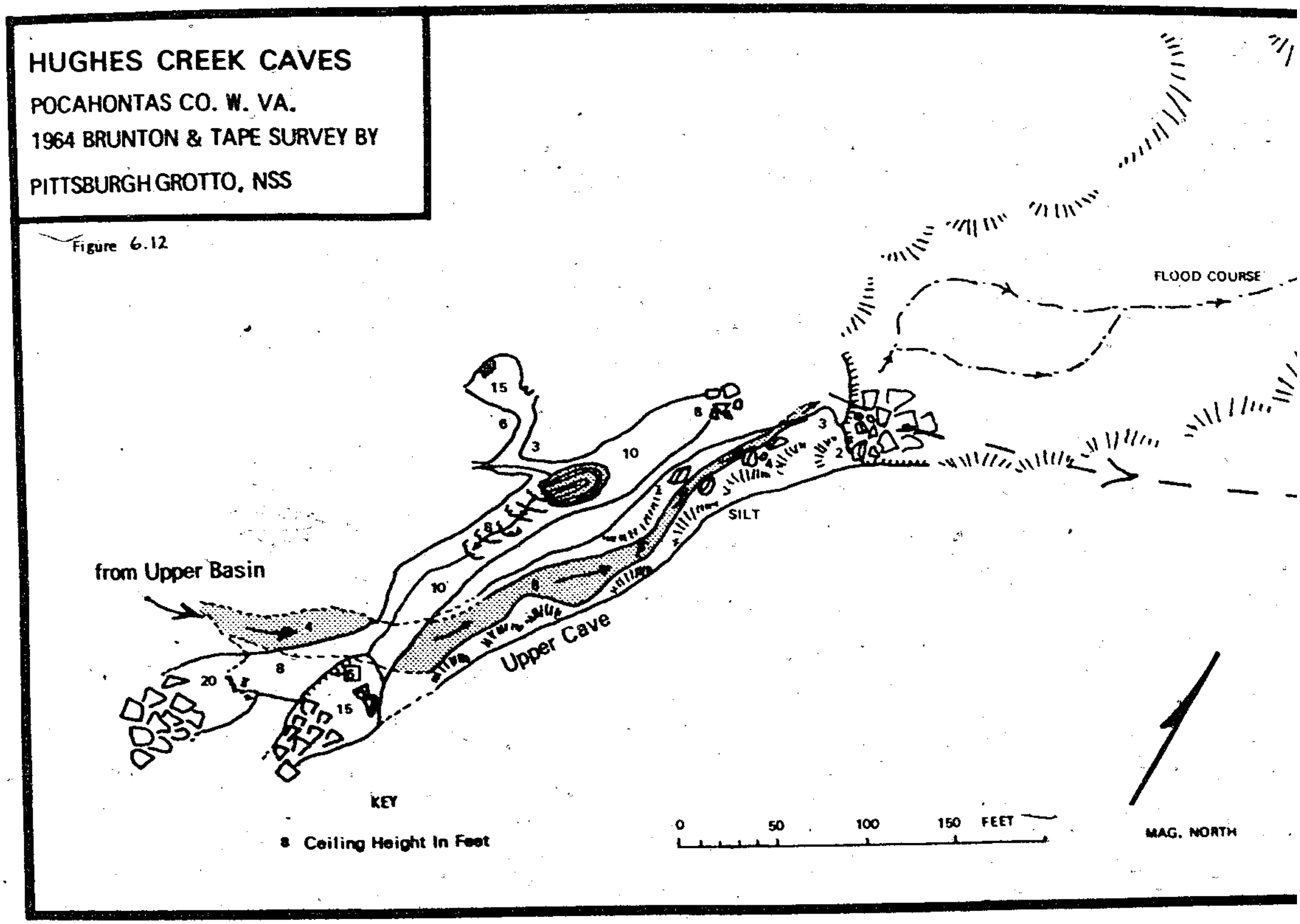
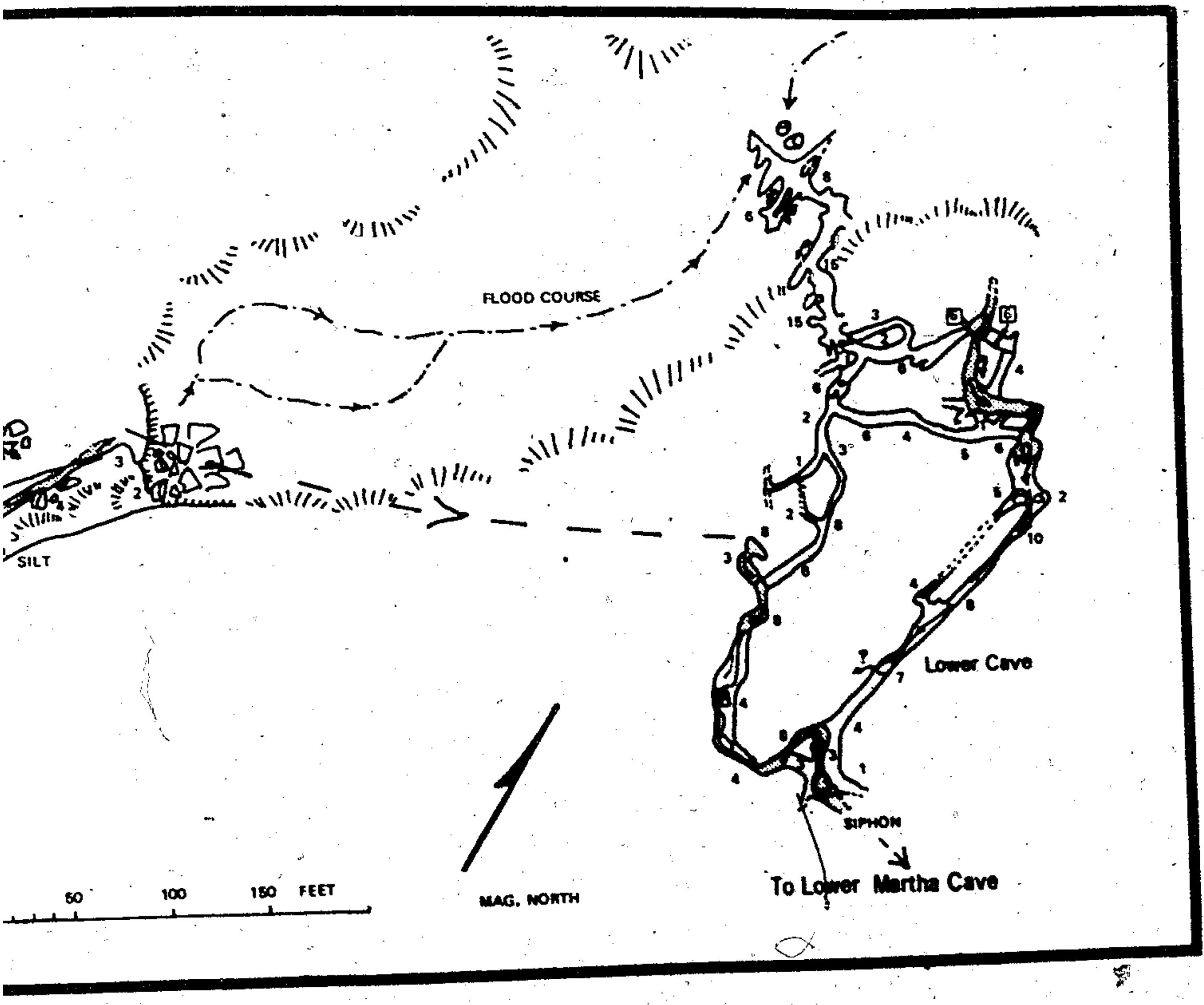


Figure 6.12

1 of


FLOOD COURSE
SILT
Lower Cave
SIPHON
To Lower Martha Cave
MAG. NORTH
50
100
150
FEET

[redacted]

Figure 6.13

ENTRANCE TO LOWER HUGHES CREEK CAVE

The Lower Taggard shale is exposed immediately above the entrance. The short surface route of Hughes Creek flows on this impervious layer between the two Hughes Creek caves during high water conditions.

active in the lowest passage (Figure 6.12). Ceiling breakdown which had never been flooded was buried in several feet of fluvial deposits. This author estimated that at the present rate of accumulation of gravitational deposits, that several thousand years would be necessary for the depth of breakdown to accumulate in the intermediate level of the cave. This is now almost completely buried in sand deposits (Figures 6.14, 6.15 and 6.16). This flood was probably the greatest depositional event in the modern history of the cave. The result was a total of 12 feet of well-sorted deposits with well-developed sedimentary structures from two floods of massive runoff.

2) It appears that the exit of the stream at the mouth of the Upper Cave has become increasingly obstructed by fluvial and gravitational fills during the last several thousand years. This helped to raise the water to the intermediate passage height.

3) Sediments in the upper most passage were not affected by these floods. The flood crest was 15 feet below the floor level of this passage.

4) Quartz pebbles taken from the lower levels are in general accord with an overall downstream decrease in grain size and increase in rounding along routes 1, 2, and 3 in Basin II (Figure 6.09).

5) The height of flood waters above normal stream levels was approximately 18 feet. This represents the

Figure 6.14

POINT BAR IN THE LOWER STREAM PASSAGE, UPPER HUGHES CREEK CAVE

These sands and gravels were deposited as the result of a single flood event during Hurricane Camille, 1969. The scale is one foot.

Figure 6.15

SAND RIPPLES IN THE INTERMEDIATE LEVEL OF UPPER HUGHES CREEK CAVE
(Vertical View)

This deposit covers breakdown which has accumulated slowly over many years and had previously been free of fluvial deposition until Hurricane Camille, 1969.

Figure 6.16

SAND RIPPLES IN THE INTERMEDIATE LEVEL OF UPPER HUGHES CREEK CAVE
(Horizontal View)

range of modern flooding in the cave.

c. Lower Hughes Creek Cave Conduit

The Lower Cave (Figures 6.12 and 6.13) lies 300 feet east of the Upper Cave. Normally the underground stream from the upper cave enters the lower cave 250 feet inside the entrance in the west passage and sinks at the rear of the cave at the syphon (Figure 6.12). During high water, drainage enters the entrance from the upper cave and additional drainage enters from Millstone Creek from the east. The general dimensions and gradient of the passage frequently result in pipe-full hydrostatic flow throughout the cave. Under these conditions velocities exceed three feet per second and small boulders are moved through the cave. Small scallops one to three cms. in length are found on the ceiling, walls and floors of all passages. Much of the lower cave is completely devoid of sediment. Coward (1973, personal communication) estimates the rate of erosion at 1.5 millimeters per year.

The modern drainage of both the upper and lower caves is very much controlled by the size of entrance and exit openings. When runoff exceeds approximately 10 cfs. the underground connection route of the Upper Cave stream to the Lower Cave is inadequate and surface overflow begins. Increased entrance roof-falls and fluvial sediment accumulation of point bar deposits near the entrance of the Upper Cave (Figure 6.14) appear to be partially causing the occasional ponding within the entrance area of the cave. Flooding of the intermediate levels in the Upper Cave, however, is rare, and seems to have been the result of a nearly once-in-a-thousand-years event.

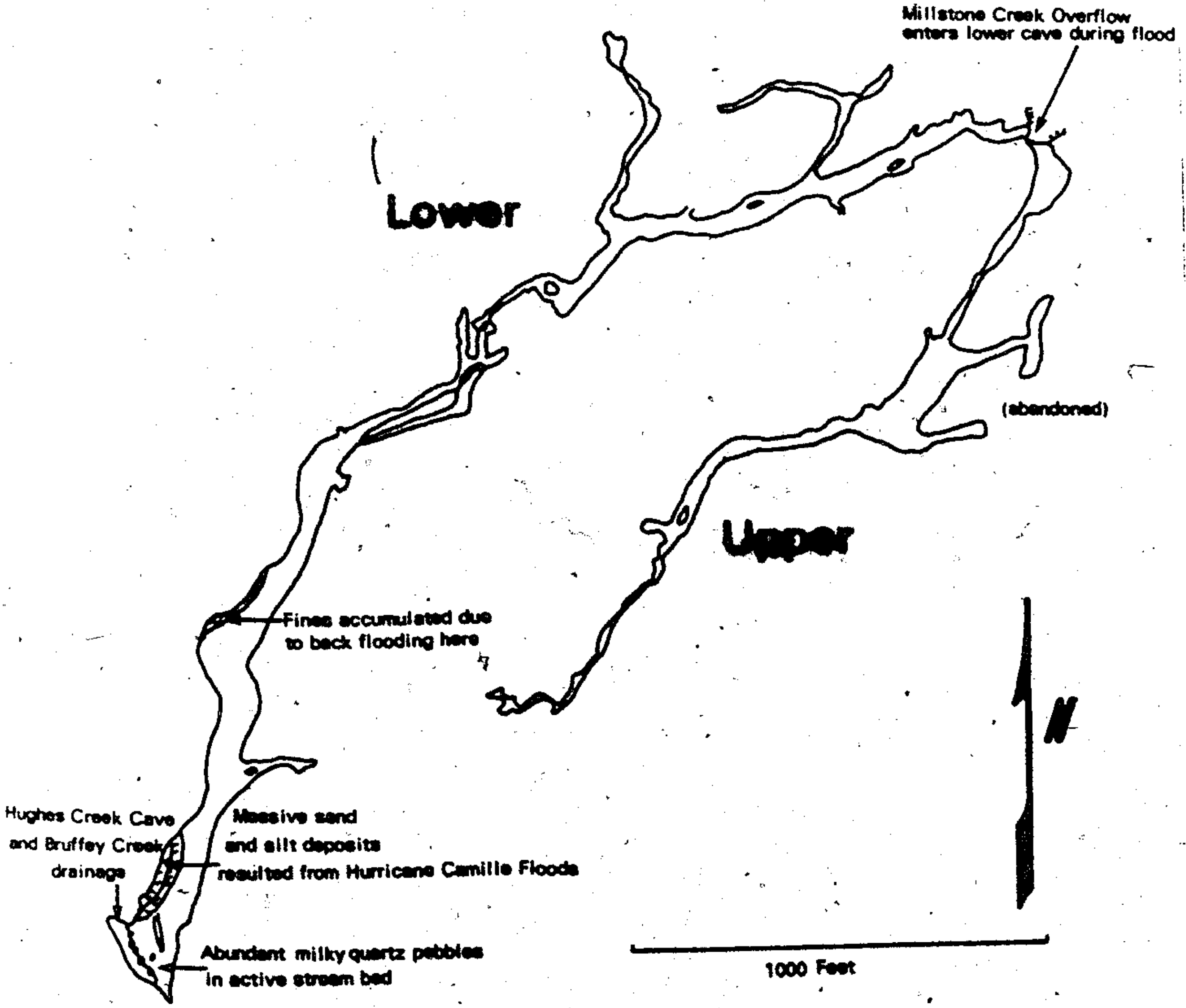
d. Lower Martha's Cave

Figure 6.17 is a general plan of Lower and Upper Martha's Cave. The lower cave contains part of the modern drainage network of Basin II. The upper cave has not been connected by any means to the lower cave. It seems likely that the two caves are related genetically in that they parallel each other and are approximately 30 feet apart vertically. Flood waters occasionally back up within the lower cave flow out of the entrance and across the surface along the dry stream channel of Millstone Creek to Beards Blue Hole (Figure 6.09).

Samples of clay minerals and clastic sediments from Allen's gallery in the rear of the Lower Cave were studied as part of the general network of Basin II, but Lower Martha's Cave as a whole is not a major cave in this investigation. It provides access to part of the drainage net. It is not itself part of the major conduit. Schmidt (1962) estimates that the Martha's Cave stream (route 2 on Figure 6.09) merges with the main Hills Creek drainage (route 1 on Figure 6.09) somewhere within the last 1500 feet of passage. This last 1500 feet is the estimated

.MARTHA'S CAVE

Figure 6.17.



distance to Locust Creek rising from the point where Lower Martha's Cave becomes totally filled with breakdown and ponded sands and silts at the rear of the cave. Positive dye tests from the Hughes Creek Caves have established the drainage association with the stream which enters the west side of Lower Martha's Cave. This is only one-tenth of the volume of water rising at Locust Creek, however. Drainage from Beard's Blue Hole has also been traced to Locust Creek rising (Figure 6.09). It is not known whether or not this passes through the stream in the rear of Martha's Lower Cave.

One week after the major storms of Hurricane Camille, Lower Martha's Cave was examined for alteration in the sediments of the cave. Flooding 30 feet high had occurred where the stream from Hughes Creek enters the cave. Again, as in the case of Hughes Creek Upper Cave, ceiling breakdown and previously bare gravitational fills were buried with six feet of sorted gravels and sands. Silts were laid down by ponding over much of the floor from the entrance into the junction with the Hughes Creek stream. Samples of the Martha's Caves deposits are included in the total basin analysis.

e. Millstone Creek and Its Related Subsurface Conduits

Drainage from Millstone Creek also enters the modern runoff of Basin II. Although the surface drainage includes only 1.9 miles of stream, the area drained is nearly as great as that of Hills Creek. The low drainage density is due to the karstification of 75% of the Millstone Creek basin. Only during flood does runoff from the headwaters reach as far as Beards Blue Hole (Figure 6.01), along with the overflow from Hughes Creek (route 3, Figure 6.09). During low water, Millstone Creek sinks into a large alluvial "sieve-type" deposit at the base of Caesars Mountain. Underground conduits connect this drainage to Beards Blue Hole and eventually to the rising at Locust Creek.

There is abundant sedimentation on Little Levels, the karst plain adjoining the Millstone Creek basin. The large sieve-type deposit contains massive boulders of Droop Mountain sandstone and Pocono series clastics. No quartz fragments or boulders of the Princeton or Pottsville conglomerates are found in it. If a flat-lying bedrock surface is assumed under the sediment, the head of the deposit is deeper than 300 feet. It averages 4.5° in slope. This massive deposit is not being supplied by boulders of the size of which it consists. The largest sizes transported by Millstone Creek during Hurricane Camille did not exceed 32 centimeters. Maximum size measured in the fossil deposit ranged from one meter to six meters.

Extending south from the sieve-type deposit is a dry channel strewn with shale and sandstone gravels and small sandstone boulders up to 32 centimeters in length. This channel was examined for milky quartz; data obtained are summarised in Figure 6.10. There is little doubt that the source of the milky quartz in the lower channel area downstream from the Hughes Creek caves is from the head of the Hills-Bruffey network. The high percentage of these pebbles within fixed size ranges is due to the occasional surface overspills of the Hughes Creek caves into the lower section of the Millstone Creek dry channel. During the course of the investigation the Little Levels karst surface and all related cave systems were closely examined for the distribution of milky quartz. The highest abandoned levels of Upper Hughes Creek Cave and Poor Farm Cave, a fossil remnant of an ancient higher level route in the Basin II network, were also found to contain more than 5% milky quartz pebbles within fixed size ranges. This would suggest this route from Hughes Creek to Locust Creek via the karst plain area has been a continuous route throughout the history of drainage of Basin II. It appears that the modern sedimentation rates and volume of runoff through this area are less today than in former times and that the intermittent use of the channel will become less important as the more direct Hills Creek to Locust Creek route becomes enlarged through solution and erosional processes (route 1, Figure 6.09).

3. The Lower Basin

The lower basin includes all the modern drainage area of Basin II below the Locust Creek rising (Figure 6.01).

This is approximately ten square miles, most of which is over clastic rock or over armoured stream beds of finer than gravel covering the lower members of the Greenbrier series. In contrast to the drainage of the middle basin, the lower basin receives a more nearly constant flow of water and maintains a narrower range of grain size in bedload sediments.

a. Locust Creek and Its Related Subsurface Conduits

Figure 6.18 shows the rising of Locust Creek at the base of the Greenbrier series during average mid-summer runoff conditions. Here can be seen for the first time, the total volume of the modern runoff of Basin II as collected by the various surface and subsurface networks of the system. The flow here is 37 cfs. The stream at the rising is flowing on sediments composed of fine, well-rounded gravel (11% milky quartz in the 2 mm. to 4 mm. size range), sand and silt. Over this material is a layer of angular limestone fragments ranging from pebble to boulder size. These coarser fragments vary from sub-angular to rounded at the entrance and downstream for a distance of 30 feet (Figure 6.19). Further downstream the coarser fragments are less rounded and do not appear to be transported. Figure 6.20 shows these less rounded boulders of Hillsdale limestone. They have been derived from the shattering of the cliff face above the entrance to Locust Creek Cave. Although they are undergoing active solution, these limestone fragments

Figure 6.18

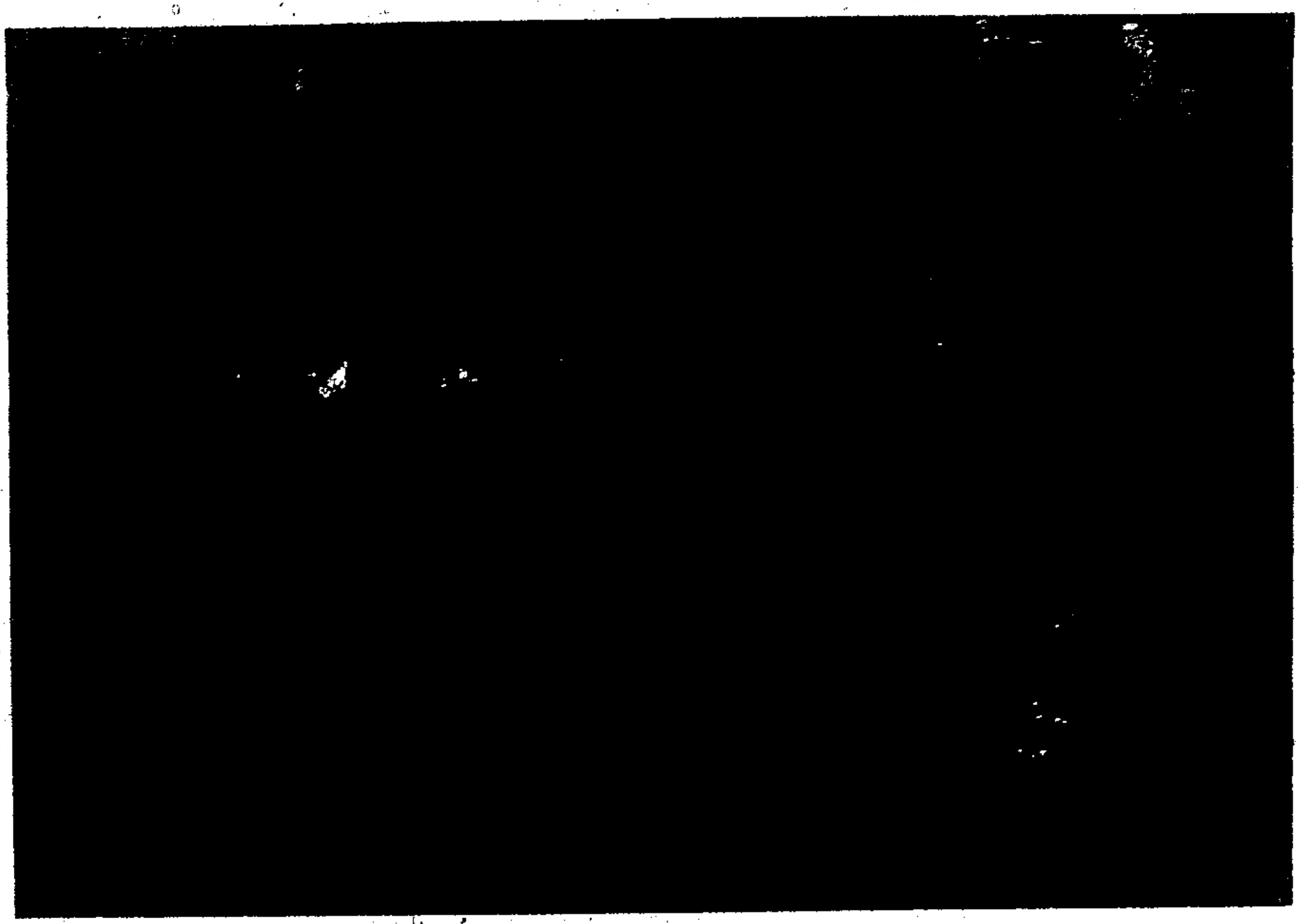
LOCUST CREEK RISING

Figure 6.19

SUB-ROUNDED LIMESTONE FRAGMENTS IN LOCUST CREEK STREAM BED

Figure 6.20

ANGULAR LIMESTONE BLOCKS IN LOCUST CREEK STREAM BED



These blocks are similar to the angular material in Grimes Cave, Basin I.

retain their less than sub-rounded characteristics. This is a process similar to that described in Basin I (Chapter 5) at the entrance to Grimes Cave. The increased rounding of limestone boulders immediately at the entrance to Locust Creek Cave, however, is due to an increase in stream gradient and therefore transport caused by a small nickpoint of four feet at the cave entrance. The downstream increase in limestone boulder angularity is an unusual phenomenon. It could imply greater spalling and increased fragmentation of the limestone in the past. Whether or not this could be related to frost shattering or peri-glacial activity is uncertain.

Three hundred feet below the rising, bedload fragments decrease in mean size to approximately 64 mm. Rounding increases downstream due to transport. Stream competence remains unchanged but the mean bedload size decreases due to solution of the coarser limestone bedload fraction. The transported clastics derived from the upper and middle basin show little change except for shale fragments which increase slightly in roundness downstream.

Silt terraces are common at 3 , 10 , and 30 feet along the Locust Creek channel. These were examined for clay minerals. These data are included in Table 6.06, Figure 6.11 and Appendix B.

The terraces consist of clay and silt size fragments in thick laminar deposits. There are no boulder size fragments and gravels are found only in the lowest terrace level. In contrast, the modern stream carries gravels and limestone boulders. The highest level terrace is the largest. It is 30 feet thick and appears to be mostly silt. This would suggest that the competence of the stream has increased. This may be due to several factors:

i) The cave has enlarged and allows for the passage of larger fragments.

ii) The sinks are less blocked by debris or sediment now than in former times.

iii) There is a greater discharge from the rising today than in former times.

A comparison of clay minerals in the stream bed with those in the terrace suggests that the provenance has not changed. These data and other examples of former drainage are considered in the section of this chapter on paleodrainage.

An additional 10 cfs. of runoff is added to the discharge of Locust Creek between the rising and its mouth at the Greenbrier River. This drainage is derived mainly from the east side of Droop Mountain via short tributaries which flow through the entire Greenbrier series in small sewer-type conduits. They are too small to explore and are in a youthful stage of karst development. They are probably steep gradient, rapid flow-through conduits, whose main sedimentary function is to screen out the coarser fragments of the overlying clastic rocks. Trump Run is the largest of these tributaries, with two miles of drainage. The screening process does not operate in this latter tributary because of blockage. Although underground passages are developed along its route, considerable surface overflow occurs which transports boulders across the limestone and into Locust Creek. The greatest mass of the sediment in this tributary and in the lower portion of Locust Creek is composed of Droop Mountain sandstone. The mean size of bedload in Trump Run at its mouth is 36 centimeters. This is rounded to well-rounded sandstone which is transported only by heavy flood. Hurricane Camille was responsible for transport of the larger fragments which built small fans across the limestone downwards to the Locust Creek valley. The sieve-type deposits which had accumulated at the heads of the tributary valleys were nearly completely removed and spread out down the valley side by the storm. Since then, new material has begun to accumulate. This appears to be the process by which rounded boulders of sandstone are supplied to the lower basin. They definitely do not come through Droop Mountain via the Locust Creek conduit.

b. McNeals Mill Run Basin

McNeals Mill Run is a small stream approximately one mile in length which lies east of Locust Creek outside of the modern drainage of Basin II. It flows directly into the Greenbrier River with no tributaries. The significance of this drainage is that:

i) It lies near to Basin II separated only by a broad limestone divide of low relief.

ii) It is fed by a rising of approximately 2 cfs. which drains the karst plain associated with Millstone Creek.

iii) The upper levels of the major cave system associated with the Mill Run rising, Poor Farm Cave, contain abundant rounded milky quartz pebbles. These are in accord with a downstream decrease in grain size and increase in roundness when plotted with the data from the Hills-Bruffey-Hughes Creek network (route 3, Figure 6.09).

iv) This small neighboring basin is an ideal setting in which to examine the temporal changes in sediment characteristics directly related to the drainage history of Basin II.

v) Inactive terraces along the stream contain 10% quartz pebbles within the 2 millimeters to 10 millimeters range.

The small cave at the head of McNeals Mill Run which supplies the stream with its water was examined for sediments. A sediment trap was constructed and monitored for three years in a manner similar to Martens Cave at the head of Basin II. Although runoff varies from less than 1 cfs. in drought to >10 cfs. during flood, sediment size range remains very constant, with a mean bedload size of 32 millimeters. The bedload is comprised of locally derived shale fragments from the MacCrady series which lies directly below the Hillsdale member of the Greenbrier series. The shale makes up 75% of the bedload. (The modern drainage of McNeals Mill Run Cave is perched on the MacCrady shales.) About 20% of the bedload is comprised of sub-rounded chert fragments which are derived from the overlying Hillsdale member. A remaining 5% is sub-angular pieces of _Lithostrotion canadenses_ corals which have been replaced with silica. These are also derived from within the overlying Hillsdale limestone.

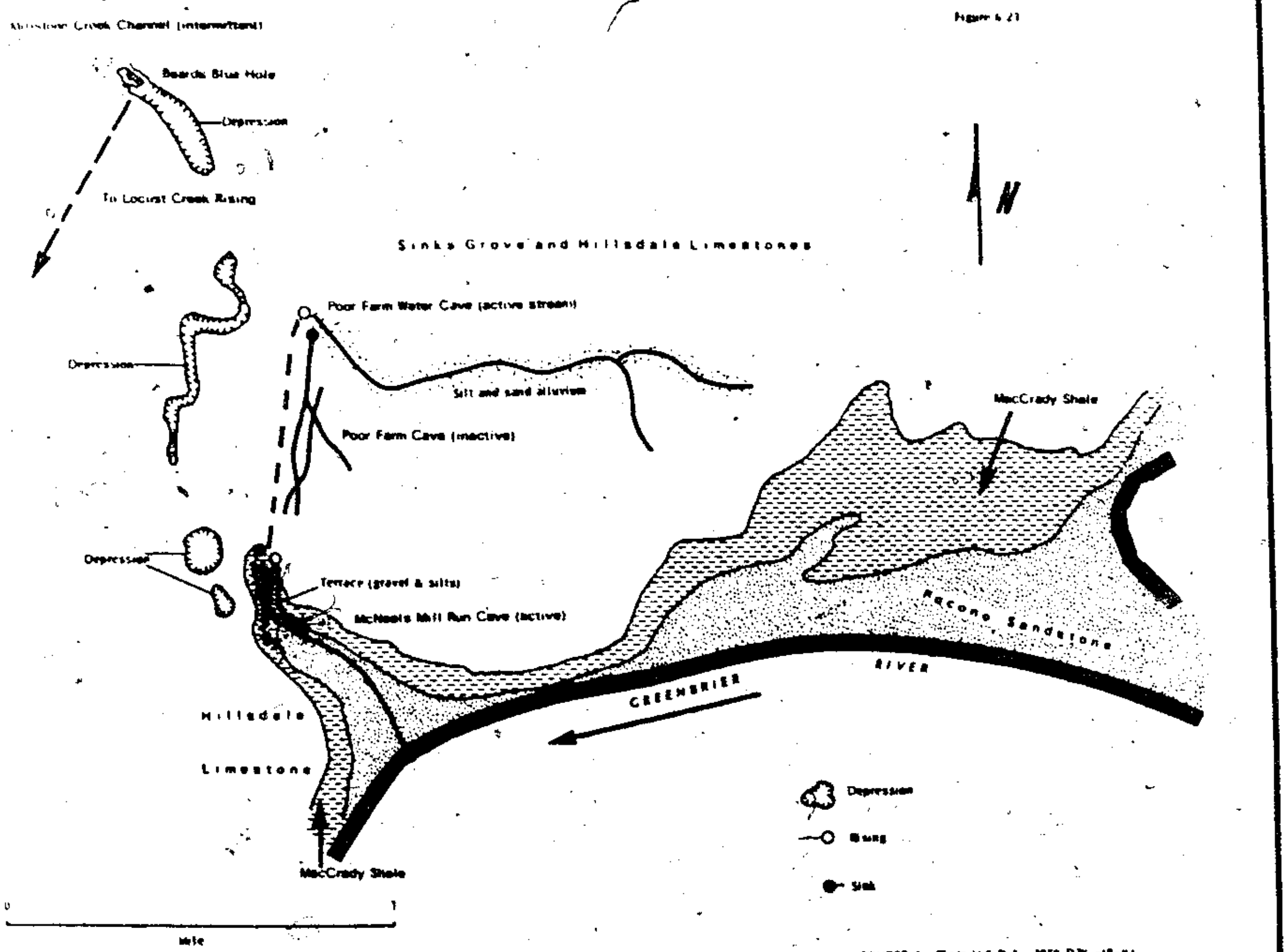
The source of modern runoff for this basin is completely from the Little Levels karst plain, which lies immediately to the east of Basin II and which is also partially drained by Millstone Creek. Drainage which sinks at Poor Farm Water Cave has been traced to the rising at Mill Run. Figure 6.21 shows the McNeals Mill Run drainage.

The area of the modern basin of Mill Run is approximately 3.5 square miles. The modern provenance of the bedload is from the lowest two members of the Greenbrier series and the MacCrady shale. No milky quartz or sandstone fragments are found in the sink, cave, stream, or rising. The surface runoff is channeled along a slow-flowing stream which is perched on shale. Shale fragments and insoluble residue from the overlying limestone make up the bedload throughout the network.

Table 6.05 summarizes the sedimentation for this small modern basin. It is interesting that more sediment is leaving this system than is entering. Bulk loss was

DRAINAGE AND PROVENANCE OF POOR FARM BASIN

Figure 4.21



SOURCE Air Photo U.S.D.A., 1958 DZK –18–61

Table 6.05

SEDIMENTS IN THE MODERN PORTION OF THE POOR FARM PALEO-BASIN[1]

Month	ENTRANCE OF POOR FARM WATER CAVE			RISING OF McNEALS MILL RUN[2]		
	Depth in Meters (Mean)	Volume (Cubic Meters)	Mean Grain Size	Depth in Meters (Mean)	Volume (Cubic Meters	Mean Grain Size (mm.)
1968						
May	0.007	0.07	silt-clay	0.015	0.15	32
June	0.007	0.07	silt-clay	0.018	0.18	32
July	0.005	0.05	silt-clay	0.009	0.09	32
Aug.	0.002	0.02	silt-clay	0.005	0.05	32
Sept.	0.010	0.10	silt-clay	0.020	0.20	32
Total	0.031	0.31	silt-clay	0.067	0.67	32
1969						
May	0.002	0.02	silt-clay	0.005	0.05	32
June	0.001	0.01	silt-clay	0.003	0.03	32
July	0.003	0.03	silt-clay	0.004	0.04	32
Aug.	0.080	0.80	silt (30% gravel)	0.100	1.00	32
Sept.	0.100	1.00	silt (30% gravel)	0.150	1.50	32
Total	0.186	1.86	clay to pebbles	0.262	2.62	32
1970						
May	0.001	0.01	silt-clay	0.001	0.01	32
June	0.005	0.05	silt-clay	0.010	0.10	32
July	0.008	0.08	silt-clay	0.010	0.10	32
Aug.	0.001	0.01	silt-clay	0.002	0.02	32
Sept.	0.009	0.09	silt-clay	0.010	0.10	32
Total	0.024	0.24	silt-clay	0.033	0.33	32

[1] Collected on sediment traps of ten square meters at two locations.

[2] Stream velocity is higher here (3-5 ft/sec) due to the slope of the entrance passage. This compares with less than 0.5 ft/sec at the Poor Farm Water Cave entrance.

greater by twice during the three years of sediment monitoring. The mean grain size of material entering the modern system is smaller by a factor of 10 or more at all times than that which exits. Some possible reasons for this are: additional water added within the underground network; a steeper stream gradient at the exit; and the potential source of bedload from the upper levels of Poor Farm Cave. In comparison with Martens Cave, it appears that in general caves in the karst plain loose more sediment than they accumulate. During the floods of 1969 all observed caves appeared to loose more sediment than they acquired.

B. The Paleodrainage of Basin II

1. Introduction

The general limits of the drainage network which was once active across the area now defined as the modern Basin II are notknown. All that remains of the former basins are abandoned dry valleys and stream terraces on the surface. Underground conduits and fluvial cave deposits of traceable origin and provenance give evidence for the existence of former drainage nets often in direct opposition to modern ones. Indeed, evidence of ancient drainage networks are found in part, here and there, across every basin in the Greenbrier karst.

Structural and lithologic control appears to have been stronger in the early development of surface and subsurface drainage. Consequently sedimentation patterns also reflect this control in the paleobasin area. Figure 6.01 shows the areal bedrock geology of Basin II. The long ridge of sandstone labeled as clastic rocks, extending from Droop Mountain in the south to Little Mountain in the north, still acts as a surface barrier to the surfacial transfer of quartz pebble conglomerate material from the Princeton and Pottsville outcrops. Stream transport of fragments of these formations is restricted to only two systems. These are the underground conduit of Hills Creek and Bruffey Creek to Locust Creek in the south and the intermittent surface channel of Stamping Creek in the north. This latter stream carries only the Princeton conglomerate material. This comprises less than 5% of the gravel fraction as its mouth.

The nature of the drainage, topography and stratigraphic outcrops combine to make the spatial and temporal distribution of quartz pebbles conglomerate fragments useful in interpreting the geomorphic history of this basin. No other streams for a distance of 10 miles north or south of Little Levels carry quartz pebble fragments. They are ideal natural tracers for modern and abandoned drainage in the karst area surrounding Basin II. Ten miles to the south, Spring Creek the outlet for modern drainage from Basin III is the nearest quartz pebble transporting system. Paleodrainage along the slopes of the Allegheny escarpment and across the Little Levels karst plain is traceable from the quartz pebble distribution in surface terraces and subsurface high level dry cave conduits. The modern and abandoned routes are indicated on Figure 6.09. There are several interesting observations concerning these data:

i) The modern active surface channels and subsurface conduits of Basin II carry up to 80% quartz conglomerate material within the pebble size fraction of the bedload, downstream from the outcrops of Princeton conglomerate (Figures 6.09 and 6.10).

ii) Former surface drainage channels and abandoned subsurface conduits which show similar quantities of quartz conglomerate material are considered to have had a similar provenance. These are: (a) the former surface route from Hills Creek and Bruffey Creek southward to Spring Creek (A-1 in Figure 6.09); (b) the former subsurface route through Poor Farm Cave to the former outlet at Mill Run. This is evidenced by the quartz pebble deposits in the upper levels of Poor Farm Cave and in the high level terraces along Mill Run (Route A-2, Figure 6.09).

iii) There have been progressive changes in the surface and subsurface drainage characteristics of Basin II:

a) Initially, runoff from the Allegheny escarpment showed strong structural control. Drainage west of Droop Mountain was channeled on the surface from Bruffey to Hills Creek and flowed southwestward, joined by Rush Run and other small streams to enter the Spring Creek watershed (Route A-1, Figure 6.09). This latter stream is the exit for modern drainage of Basin III (Chapter 7).

b) The headward portion of Basin II, Bruffey Creek, was then pirated by Little Levels Drainage via an underground route through Hughes Creek Upper Cave to Poor Farm Cave, to exit at McNeals Mill Run near the Greenbrier River. These two caves that remain today are only part of a larger network through the Little Levels area, that existed when Bruffey Creek was first diverted. Martha's Upper Cave and Millstone Creek were also part of the underground system.

c) A large karst window developed in the area between Poor Farm Cave and Hughes Creek Upper Cave. Locust Creek then captured drainage from the Bruffey Creek-Hughes Creek-Millstone Creek system. Poor Farm was left isolated in the downstream end of this former network. Drainage of Little Levels in the lower basin continued to exit at Mill Run at a new lower level route. This new route no longer carried the quartz pebbles that were once supplied via Bruffey Creek to Hughes Creek. Provenance is now entirely from the MacCrady and Greenbrier series lying east of the cave.

d) Hills Creek and Bruffey Creek were captured by the Millstone Creek to Locust Creek system and the surface flow across Little Levels became a more direct route to the Greenbrier River. Downstream from the divide (Figure 6.01) this route continued to flow southward to Spring Creek underground through Snedegars Cave and Friars Hole Cave (Davies, 1958).

e) A direct route from Hills Creek and Bruffey Creek to Locust Creek developed by-passing the Hughes Creek Caves, Millstone Creek and Martha's Cave. This is now part of the modern drainage of Basin II. During high water some of the former channels are utilised as overspill for the direct route which is still too small to take all the drainage. This surface portion of the channel is responsible for the removal of some bedload material from the underground system. Pebble terraces composed of 35% milky quartz material in selected size ranges are found along the Millstone Creek channel. These are not deposited in "sieve-type" fans; however, as they are in the upper basin areas. The lack of initial blockage by large boulders does not occur in the middle basin because these are not moved beyond the sieve-type fans of the upper basin.

f) The surface route southwest to Spring Creek and the upper levels of Hughes Creek Upper Cave, Upper Martha's Cave and Poor Farm Cave are never utilised by modern drainage.

These above statements are based primarily on the distribution of bedload material throughout the surface and subsurface conduits of Basin II. An examination of clay mineral ratios also appears to support these hypotheses.

Figure 6.11 shows the distribution of clay mineral ratios throughout Basin II. Table 6.06 is a measured section of the principle rocks which are crossed by the Hills Creek to Locust Creek drainage. It is compiled from field samples and measurements plus measured sections from Briery Knob to Hills Creek and Droop Mountain to the Greenbrier River (Price, 1929, pp. 112-115). This follows a line close to the axis of Basin II.

Clay mineral ratios are shown on Table 6.06. These are for both weathered and unweathered samples. A strong contrast with bedrock samples is shown in the weathered clay mineral distribution.

The very high ratios of the unweathered samples from the overlying clastic rocks reflect a high amount of illites at 10Å. In every case but one, these ratios exceed 1.000 and run as high as 3.412 for the Hinton Group. The exception is a Mauch Chunk sample at 0.837. Some general statements concerning these data can be made:

1) Unweathered clastic bedrock samples all have high $\frac{3.58\text{Å}}{10\text{Å}}$ clay mineral ratios (0.837 to 3.417).

2) Unweathered carbonate bedrock samples have intermediate range ratios (0.500 to 0.679).

3) All surface weathered clay mineral samples taken from active weathering (see 4 and 5) areas have ratios near 1.000, regardless of their parent material (1.000).

Table 6.06

MEASURED SECTION FROM BRIERY KNOB TO LITTLE LEVELS AND THE GREENBRIER RIVER[1]

Stratigraphy	Lithology	Thickness (Feet)	X-Rayed Diffraction Ratios $\frac{3.58\mathring{A}}{10\mathring{A}}$ Unweathered	Weathered
Pottsvilie Series	conglomerates, sandstones, some shale and coal	431		
Guyandot Sandstone	conglomerates	55	2.868	0.973
Upper Raleigh Sand.		105		
Mauch Chunk Series	mostly shales with sandstones and conglomerates	1365		
Princeton Conglom.	massive bedded conglomerate	50	3.272	0.987
Hinton Sandstone	thick bedded sandstone	40	3.412	0.770
Droop Mt. Sandstone (Bluefield Group)	light coloured, massive bedload, weathers easily	40	1.203	0.810
Greenbrier Series	limestones with a few interbedded calcareous shales	605		
Alderson Limestone	crystallin, cross bedded, fossilferous	40	0.550	0.894
Greenville Shale	red and brown shale	30	N.A.	N.A.
Union Limestone & Pickaway Limestone	dark, grey, oolitic	235	0.680	0.993
Taggard Limestone	oolitic, fossilferous	20	0.402	N.A.
Taggard Shale	2 beds of red and green calcareous shales	5	0.568	N.A.
Patton Limestone	dark, grey, hard, oolitic limestones	190	N.A.	N.A.
Sinks Grove Lime.	dark, hard, fossilferous	30	0.679	1.106
Hillsdale Limestone	cherty, dark, contains many Lithostrotion canadense	15	0.568	1.070
MacCrady Series	red shale	66		
MacCrady Shales	red shale	66	0.402	1.119
Pocono Series		210		
Broad Ford Sand.	fine grained, reddish brown, thick bedded	190	N.A.	N.A.

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[1] Based upon Price (1929, pp. 112-115).

4) Clay mineral ratios from carbonate rocks tend to be higher after weathering:

	Unweathered	Weathered
Sinks Grove ls	.679	1.106
Hillsdale ls	.568	1.070
Alderson ls	.500	0.894
MacCrady Shale (70% $CaCO_3$)	.402	1.064

5) Clay mineral ratios for clastic rocks tend to be lower after weathering:

	Unweathered	Weathered
Pottsville SS.	2.868	0.973
Princeton SS.	3.272	0.987
Hinton SS.	3.412	0.770
Droop Mt. SS. (Bluefield G.)	1.203	0.810

6) Clay mineral ratios taken from modern active surface and subsurface channels range from 0.810 to 0.987 . These reflect a mixing of weathered material from both clastic and carbonate sources and are closely grouped in the high intermediate range:

Hills Creek Channel	0.973
Bruffey Creek Channel	0.987
Lower Martha's Cave Conduit	0.851
Poor Farm Water Cave Conduit	0.806
Hughes Creek Lower Cave Conduit	0.810
Locust Creek Terraces	0.875

7) Clay mineral ratios taken from high level abandoned surface and subsurface routes which are not subject to flooding or active modern transport show very low ratios, i.e., they have a higher illite content than kaolinite content. The lowest ratios are found in dry cave passages. The Poor Farm Cave ratios taken from the centre of the upper passage were lowest (0.435 to 0.673). Samples taken nearer the walls showed higher ratios at 0.673 to 0.759 . These latter figures are from what was later proved to be limestone that had become a grey glei like paste due to the constant high humidity of that part of the cave environment. These figures are similar to unweathered carbonate samples from the bedrock.

Such variation in clay mineral ratios in Basin II can be considered as partial evidence for the existence of former surface and particularly subsurface channels. The lowest ratios appear to be associated with the oldest cave levels in the basin. No means of relating ratios to time was attempted. No attempt to relate travertine samples dated by Thompson (1973) to clay mineral ratios of the underlying fills was made. The overall consideration of these data along with information on provenance, lithology, sedimentary structures, rounding and grain size of selected rock types along with gross features of the drainage patterns, modern and inactive surface valleys and subsurface cave conduits provides a basis for modern and paleodrainage interpretation (Figures 6.02, 6.09, 6.10 and 6.11).

2. The Upper Basin

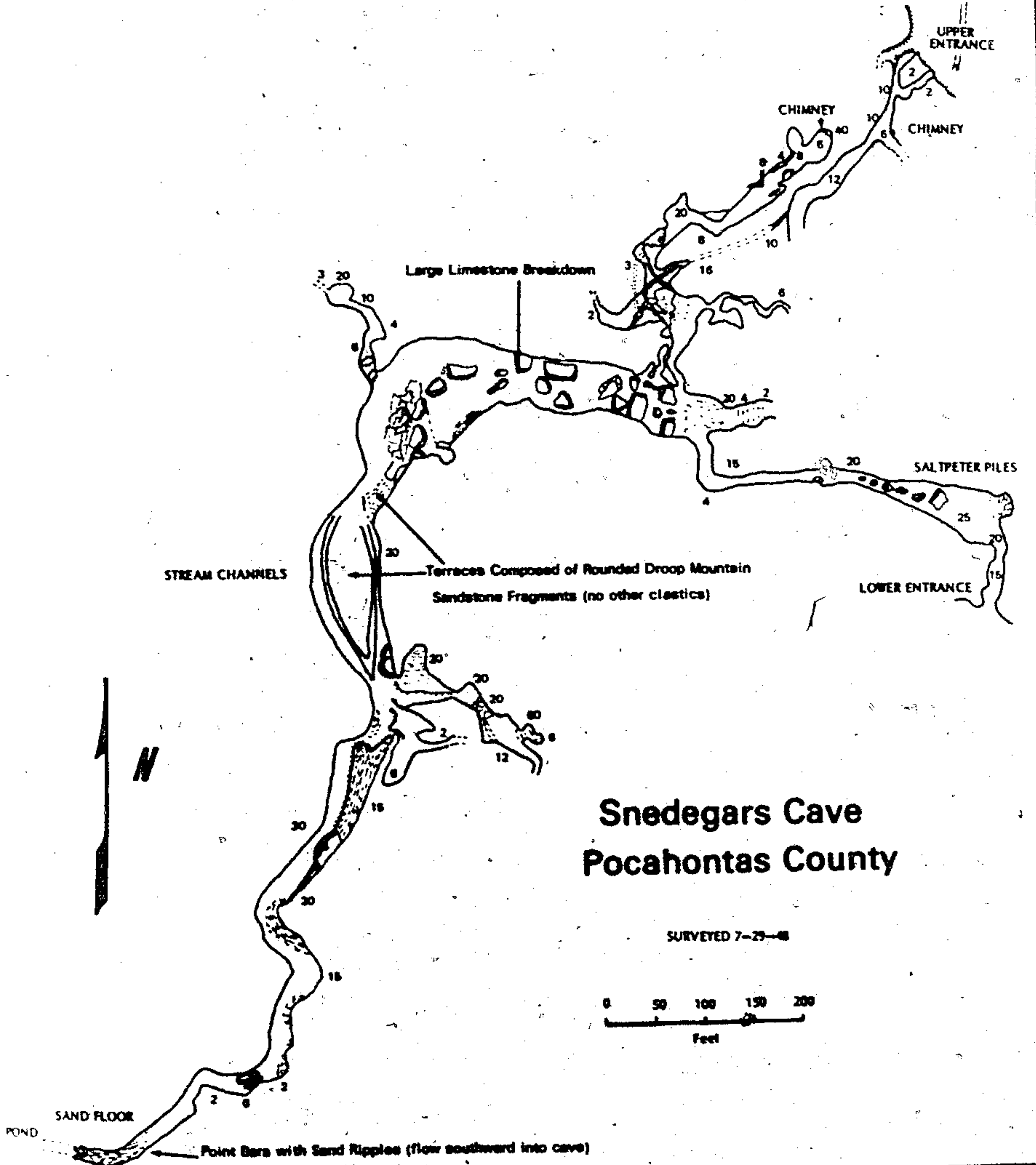
The upper basin area is shown in Figure 6.01. The most outstanding feature of it is the long dry valley that extends southwest from Bruffey Creek past the sinks of Hills Creek and Rush Run and extends 10 miles to Spring Creek in Basin III. The local relief on the floor of this valley is 150 feet. This variation in elevation is due mainly to karstification on the surface. A few terraces remain, but these are relatively rare except for a 75 foot terrace near the end of the valley at Spring Creek outside Basin II. There is little doubt, however, that this large terrace was produced by paleodrainage from Basin II and not Spring Creek. Imbrication, provenance and clay mineralization are in accord with this interpretation. Several cave systems along the dry valley (Route A-1, Figure 6.09) were examined for sediment and scallop origin. Snedegars Cave is located south of the drainage divide at the head of drainage southwest to Spring Creek. No quartz was found in this cave and provenance for bedload material all came from the immediate surrounding outcrops of Droop Mountain sandstone, the Bluefield Group and the upper members of the Greenbrier limestone series. The lack of quartz fragments appears to be due to the fact that the cave is flushed by modern drainage which carries no material of provenance stratigraphically above the Bluefield Group today. The same can be said for other caves downstream from Snedegars Cave along the former surface drainage channel. The fact that this same route is still used underground today may explain the absence of quartz material in these caves. Paleo deposits of quartz have been removed and replaced by modern deposits since provenance changes at the head of the former basin occupied and diverted drainage through Droop Mountain to Locust Creek. Figure 6.22 shows the sediment distribution near the entrances of Snedegars Cave.

All clastic material is rounded to sub-rounded. The maximum size for bedload is one meter. A weathered crust of 45 mm. covers all of the rounded Droop Mountain fragments. A large point bar 300 feet inside the cave contains 24 feet of poorly sorted gravels and boulders. This deposit was excavated. No quartz pebbles or conglomerate boulders were found. Above the deposits small wall scallops in the two to six centimeters range extend to the ceiling. Snedegars Cave can be summarised as having these characteristics:

1) phreatic cross section
2) boulder sized deposits, rounded, poorly sorted, in a gravel matrix
3) no quartz deposits and a narrow local provenance range
4) abundant fine textured scallops indicating high velocity flow (this is in accord with the transport

SEDIMENTS IN SNEDEGARS CAVE

Figure 6.22



velocities of the sediments)

5) evidence for only a few massive sedimentary events rather than many small repeated periods of deposition

6) in contrast to the sediments of the caves in the karst plain, the sediments of Snedegars Cave do not contain fine textured matrices.

3. The Middle Basin

The presence of high level cave passages in the middle basin which show no evidence of modern flooding or sediment movement is of particular interest in the investigation. An hypothesis that a former high level underground drainage system joined the waters of the Upper Hughes Creek upper passage to Poor Farm Cave to enter the Greenbrier River via McNeals Mill Run is based upon: the location of dry valleys; relative passage positions and elevations; a downstream increase in grain size (particularly of milky quartz pebbles); and on the distribution and nature of clay mineral ratios. This area of Basin II is a good one in which to test spatial and temporal variations in sediment and runoff conditions. Several factors make this possible:

1) The increase in limestone thickness in Basin II to 650 feet.

2) The increase in folding southwest along the original Greenbrier limestone basin of Mississippian deposition. This increases the width of the outcrop and reoccurrence of limestone exposures across the modern runoff

areas of Basin II.

3) The entrenchment of the Greenbrier River by 325 feet into karst plain where caves have developed. The subsequent lowering of regional water tables has helped to drain the upper cave levels.

4) The decrease in modern tributary stream gradients southwestwards along the modern Greenbrier River basin. The progressive decrease in the gradients of Basin I, Basin II and Basin III respectively, allows for higher frequency of development of upper cave levels and surface terrace development to the southwest.

The argument that these upper cave levels are truly abandoned by modern drainage is based upon:

1) The presence of travertine deposits on the clastic fills. Some of these fills have been dated by relative means using isotope methods on the overlying travertine.

2) The occurrence of distinctly different clay minerals and ratios in the upper level "abandoned" passages.

3) In some caves a change in the provenance and lithology of the fills can be distinguished between cave levels.

4) An elevation difference between lower active cave streams and the upper abandoned levels of up to 325 feet. This exceeds any observed flood crests or evidence of flooding in modern times.

5) The evidence from Hurricane Camille and its associated storms and floods throughout the caves in August and September, 1969. The results of these floods and storms were closely observed and provided a basis for distinguishing between "active", "ephemeral", and "inactive" cave conduits. Conduits which had been dry under previous flood conditions but which were flooded during 1969 were considered "ephemeral". Those which did not flood at that time were considered to be "inactive".

6) The presence of extinct animal fossils in the upper and intermediate cave levels. In some caves fossils were found to be imbricated with gravels.

7) The change in flow velocities and reversal of cave stream direction as indicated from sedimentary structures, grain size and imbrication between "modern" and "abandoned" cave levels.

Figure 6.09 shows some of the possible changes between paleodrainage and modern drainage in Basin II.

a. Hills Creek and Bruffey Creek Conduits

Little sedimentological evidence for paleodrainage can be found along the present active underground conduits of Hills Creek and Bruffey Creek to the Locust Creek rising. This route appears to be the youngest of the three active connecting channels from the modern upper to lower basins as shown in Figure 6.09. Reworking of sediment by intermittent pipe-full flow occurs several times a year, throughout all accessible portions of this third route. Logs and vegetational debris along with automobile tires and other refuse are lodged in ceiling recesses throughout the conduits. For these reasons this route is eliminated as a possible area of investigation for paleodrainage phenomenon.

b. Upper Hughes Creek Cave, Upper Passage

The second and third routes illustrated in Figure 6.09 contain evidence of paleodrainage and sedimentation, e.g., the uppermost level of Upper Hughes Creek Cave provides an example of paleodrainage along route 2 (Figure 6.09). Although the lower two levels of this cave experience active flooding and sedimentation, the uppermost level does not. It is 32 feet above the main Hughes Creek stream level in the lower passage. Maximum flood level is 19 feet. Active travertine covers the deposits. Figure 6.23 is a typical section. The fills are 9.5 feet to 16 feet in depth and are covered by 2.5 to 7.5 inches of travertine and active rimstone dams. Note that the passage profile has an elongated horizontal axis and large ceiling and wall scallops (45 centimeters to 62 centimeters) which are supposedly typical of slow water movement under phreatic origin.

Flow direction as indicated by the fill imbrication and scallops is in agreement. This is out of the cave at 45° and parallel to modern flow direction in the stream of the active lower passage. Paleoflow velocities as indicated from scallops and from the fills are not in accord

Figure 6.23

UPPER HUGHES CREEK CAVE, UPPER PASSAGE

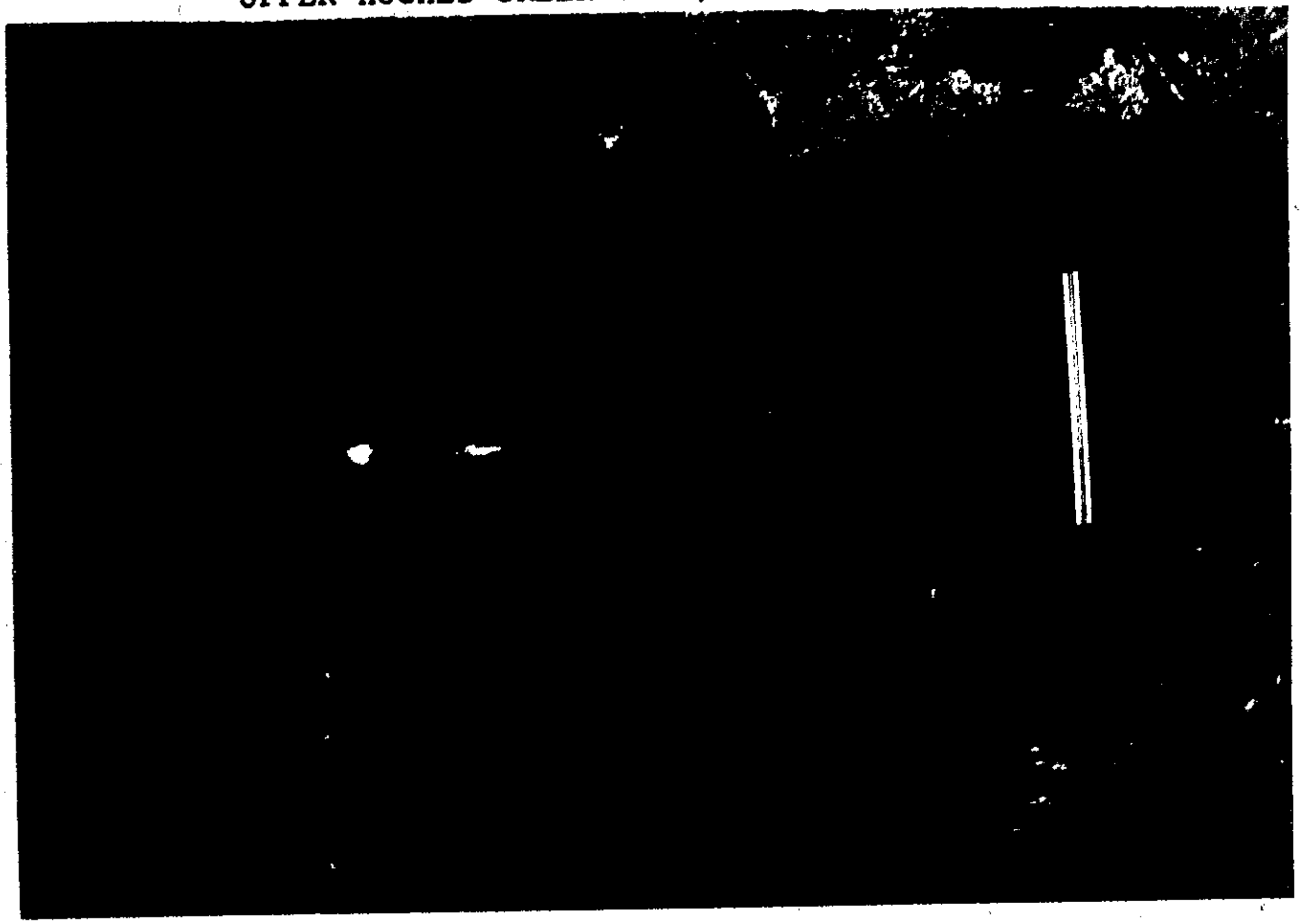
Travertine covers 11 to 12 feet of paleofills. Note the phreatic cross-section and large ceiling and wall scallops (slow flow towards the rear of the cave).

with each other. Fill transport velocities were greater by a factor of 10 at approximately three feet per second. This is similar to the present flood velocities in the lower modern stream channel.

Figure 6.24 shows a section of these paleofills about 163 feet upstream from the photograph in Figure 6.23. The white staining is calcite encrustation. The material is 10 feet in depth. Gravels and sands are generally moderately well-sorted; although silt is found throughout all deposits it may be of secondary origin. Ripples are common in the sand size deposits, indicating flow direction parallel to the direction of the modern drainage in the lower levels. Five to eight per cent of the pebbles in the four to ten millimeters size range are milky quartz derived from the Pottsville or Princeton formations. These are smaller in size than the milky quartz pebbles of the active stream which are from 4 to 32 millimeters with a mean of approximately 12.5 millimeters. Several depositional events are recorded in the deposits of the upper passage. The deposits coarsen upwards in two major phases. Figure 6.24 shows two gravel sections above and below the one foot rule, with a zone of horizontal laminated medium sand between. Sand continues above the site in Figure 6.24 for a distance of three feet. This is capped by silt and six inches of travertine. Figure 6.25 shows a cross-section of all three levels of the cave with the

Figure 6.24

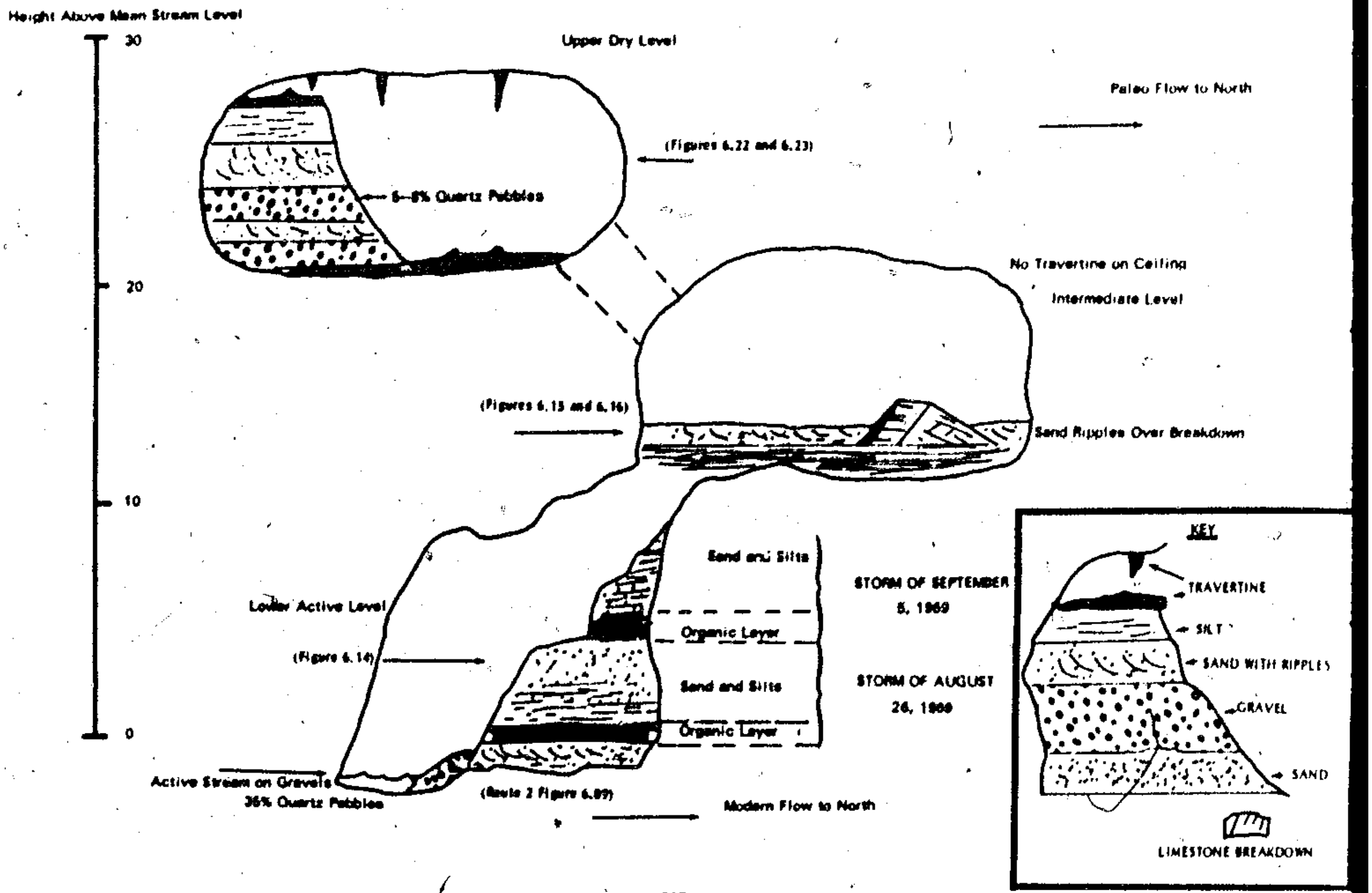
UPPER HUGHES CREEK CAVE, UPPER PASSAGE



Ten feet of moderately well-sorted sands and gravels in the upper level 150 feet upstream from Figure 6.23. While calcite cementation and silt make up most of the matrix material. Flow was to the modern active stream. Grain sizes are finer than in the active stream, but flow velocities as indicated by grain sizes in the same passage are greater by a factor of ten, than those indicated by scallops.

CROSSECTION AND LOCATION OF SAMPLE SECTIONS IN UPPER HUGHES CREEK CAVE

Figure 6.25 (See Figure 6.12)



locations of Figures 6.14, 6.15 and 6.16, 6.23 and 6.24. The sedimentary data for this passage is summarised in Appendix A as Upper Hughes Creek Cave (upper passage).

X-ray diffraction data in the upper passage show rather high $\frac{3.58\text{Å}}{10\text{Å}}$ ratios when compared with other inactive paleofill deposits within Basin II. These higher ratios (in the range of 0.844 to 0.921) are not as great as the ratios of modern channels which generally exceed 1.000, but they are considerably higher than the 0.435 to 0.610 ranges in the oldest passage of Poor Farm Cave. The Poor Farm fills are probably greater than 200,000 years B.P. in age (Thompson, 1972, personal communication). The x-ray diffraction data for this cave is summarised in Appendix B.

c. Upper Martha's Cave

Figure 6.17 shows Upper Martha's Cave. The fills of this cave were not studied in detail. Coarse material is absent in the sediments and maximum grain sizes do not exceed sand size. No milky quartz fragments were found near the surface of the paleofills. It is possible that they do exist in the cave, however, because the genetic relationship between the upper and the lower caves appears to be similar to the upper and lower passages of Upper Hughes Creek Cave.

The importance of Upper Martha's Cave is that it does exist directly above the active channel of the lower cave. The spatial location of this upper cave cannot be ignored in the development of the geomorphology and speleogenesis in the lower basin, even though no paleofills of importance are contained in the passage.

d. Poor Farm Cave

Poor Farm Cave lies entirely outside the modern drainage network of Basin II in the lower portion of the Greenbrier limestone series, at 2325 feet.[16] This is within one mile of the Greenbrier River. The cave is developed within a remnant limestone hill which stands 200 feet above the level of the surrounding sinkhole plain of Little Levels. The cave and the hill are both completely isolated from the modern drainage. Several large uvalas surround the hill. One of these contains a small stream which sinks into a cave 75 feet vertically below the entrance to Poor Farm Cave. This lower stream cave, Poor Farm Water Cave, is the swallow hole for the head of the McNeals Mill Run basin described in the modern drainage section of this chapter.

Figures 6.02 and 6.09 show the location of Poor Farm Cave and Poor Farm Water Cave in relation to the caves and drainage of Basin II. The lower water cave takes all surface drainage in the large uvala east of the hillside where Poor Farm Cave is located. Figure 6.21 shows the

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[16] Lat. 38°07'23"N., Long. 80°13'17"W., Marlinton Quadrangle, West Virginia, U.S.G.S., 1923.

general provenance and geomorphological setting of the small basin and lower water cave. The basin is approximately one square mile in area with a channel 1.1 miles in length. Sediment traps were placed inside the lower cave and at the rising on McNeals Mill Run in the fall of 1968. These remained intact until 1971 and were monitored regularly throughout the spring, summer, and autumn of 1969 and 1970. This included the floods of 1969 associated with Hurricane Camille. These data are summarised in Table 6.05. The outstanding feature of these modern sediments, when compared with the fills of the upper Poor Farm Cave, is their lack of similarity. They are not derived from the overlying clastics of the Allegheny escarpment; they are imbricated from the east to west; they are less rounded; and they are of different lithology and show no clay mineral similarities.

Because of its geomorphic setting and because of the occurrence of abundant isolated, inactive cave fills of a similar provenance and lithology to those of Basin II, Poor Farm Dry Cave was the subject of a detailed sedimentological investigation. The cave was mapped completely. Sediments were examined in situ and mapped on the base map of the cave. Correlation of facies along the main passages was attempted with moderate success. This has proven to be very difficult to do in most of the other caves in the study. Cross-sectional trenches or natural cuts made by invading surface water were examined every 300 feet or less along all passages. Investigation was started as the pilot study for this dissertation and frequent observations were made for five consecutive years.

Figure 6.26 is a map of the cave showing the location of sedimentary profile sites. The wide passage at the top of the figure is the "Main Passage"; the passage extending from the entrance at the north end of the cave to the top of the figure on the right is the "Entrance Passage". These are developed at nearly the same elevation, although they cross near the rear of the cave. The "Main Passage" is approximately 10 feet above the Entrance Passage at this point.

Throughout the two major passages a level floor of laminated silts and clays is common, to a depth of 8 to 15 feet. This thickens to the rear (south) of the cave to nearly 32 feet in depth. Large blocks of breakdown occur in several areas of the cave. Some of these are capped by travertine which dates to approximately 200,000 years B.P. (Thompson, 1972, personal communication).

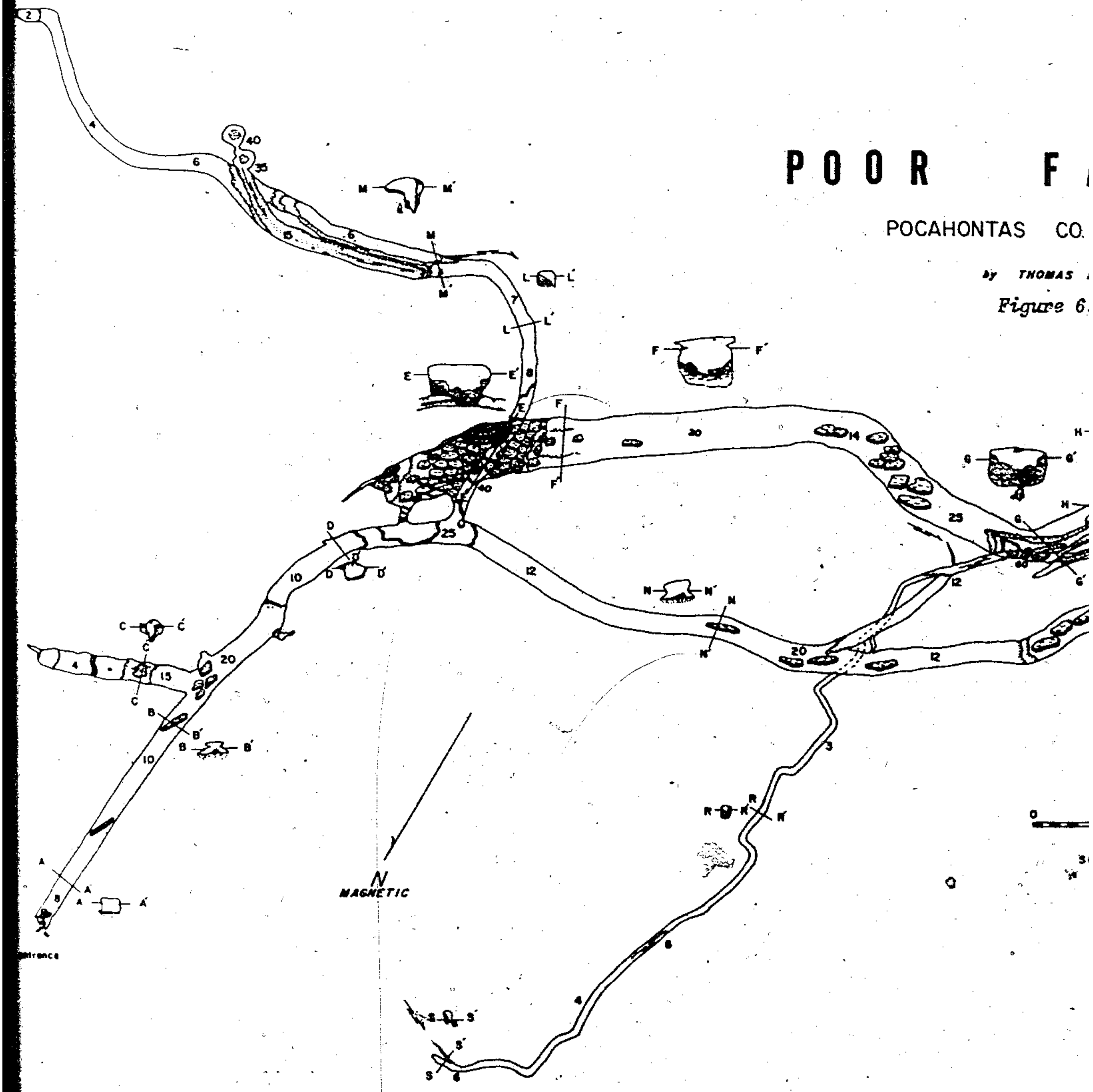
Several small passages are developed at lower levels with small streams flowing southward. Some of the water eventually reaches the stream flowing in Poor Farm Water Cave and rises at McNeals Mill Run. The water for these small streams enters from above via large domes in the northeast part of the cave (upper left of Figure 6.26). The isolated upper molars of several individuals of <u>Platy-</u>

POOR F

POCAHONTAS CO.

by THOMAS

Figure 6.



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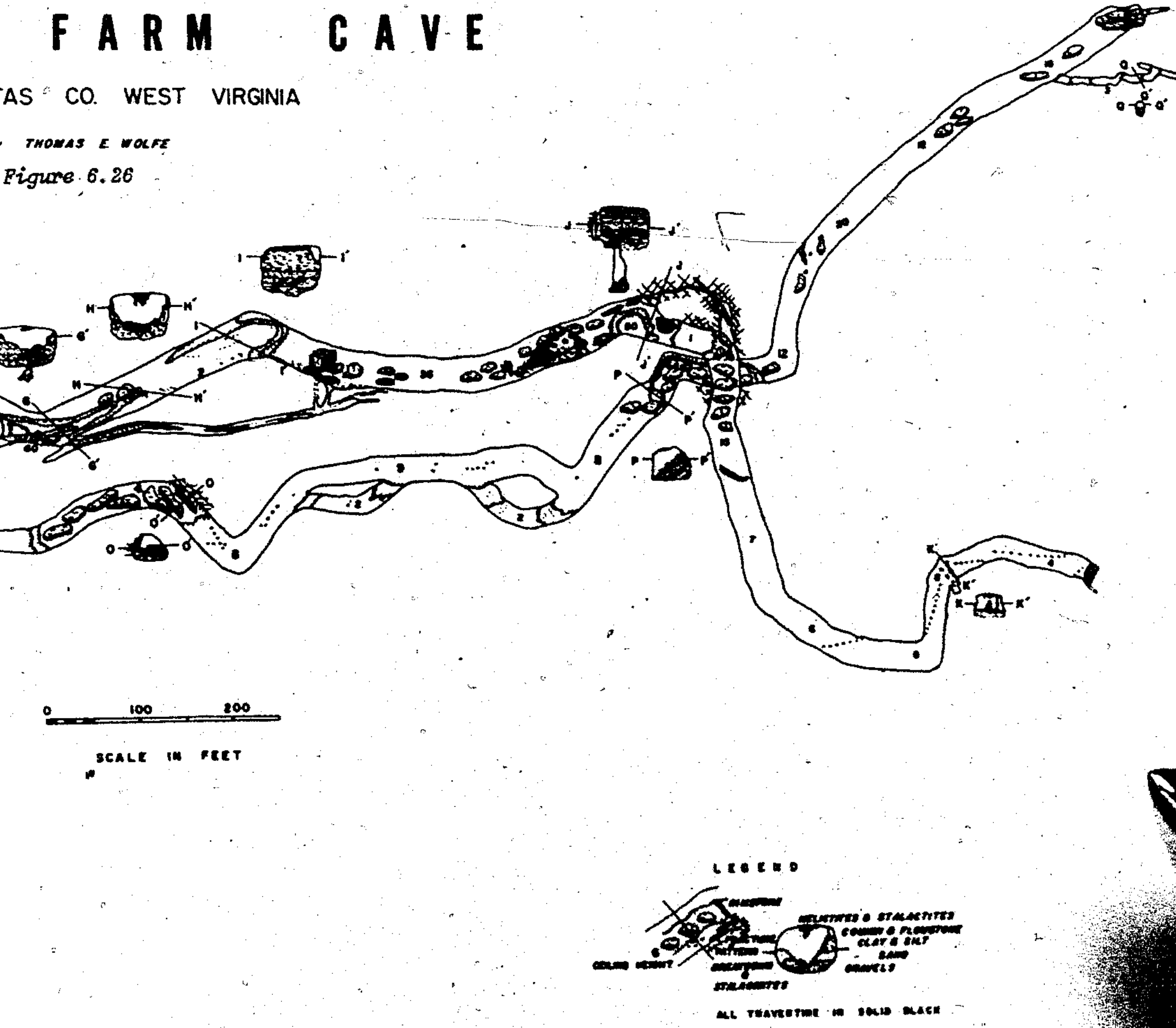
FARM CAVE

TAS CO. WEST VIRGINIA

THOMAS E WOLFE

Figure 6.26



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gonus compressus were found in these lower passages, imbricated with stream gravels of similar size, which were derived from the surface and associated with other modern mammal bones at the base of the domepits. The Platygonus compressus was a Wisconsin peccary, extinct for approximately 10,000 years B.P. (Guilday, 1972, personal communication).

(i) The Entrance Passage

The Entrance Passage is the large straight passage 10 to 25 feet wide and 8 feet high. There is a typically phreatic oval cross-section with horizontal axis extended. Ceiling and wall scallops are large, with a mean long axis of 75 cm., indicating a flow rate of 0.1 feet per second into the cave (south). The passage continues at these general dimensions, meandering in broad curves for 3,000 feet. The curves have a mean amplitude of 100 feet and a wave length of 300 feet. Irregularities in ceiling and floor heights are caused by occasional ceiling collapses and by travertine deposits. The passage terminates in massive breakdown and mud at the opposite end of the limestone hill, close to the valley formed by the headward extension of the rising of McNeals Mill Run Cave.

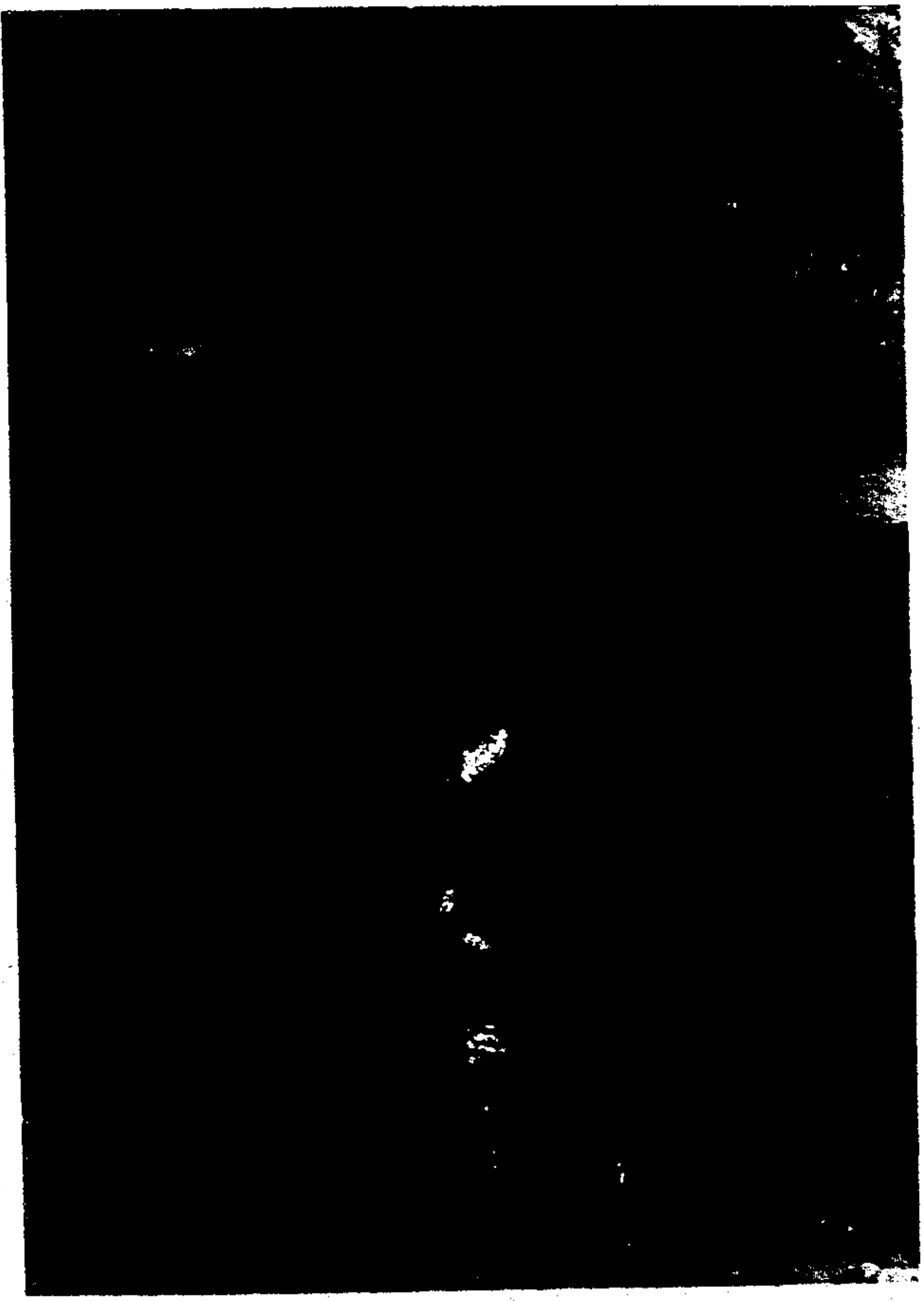
The uppermost layer of sediment is a clay-silt deposit which varies in thickness and extends the entire length of both major passages. The variations in thickness of these upper silts and clays appears to be caused by ponding associated with breakdown in the cave. A maximum thickness of 10.5 feet of silt was measured in the Entrance Passage. A few small channels have been entrenched into these finer deposits, leaving a single layer of large sandstone pebbles. These appear to be reworked material from the Main Passage which is at a slightly higher elevation than this Entrance Passage. Figure 6.27 is at cross-section D-D' (Figure 6.26) where most of the surficial clays have been removed and replaced by coarser fills by stream invasion from the upper Main Passage. Rimstone deposits followed the reworking sequence in this section only. A small pocket in the east wall has preserved a fine-coarse section which may pre-date the removal of fines and coarse deposition on the floor. This is adjacent to the connection with the Main Passage, where large amounts of travertine have been laid down over breakdown and clastic fluvial fills.

(ii) The Main Passage

The Main Passage is shown extending from the large area of ceiling breakdown and travertine in the left centre of Figure 6.26 to the lower right portion of the figure where it terminates in a large flowstone formation which is still active. The general dimensions are 50 feet wide and 32 feet high, where it is not filled with

Figure 6.27

CROSS-SECTION AT D-D' , POOR FARM CAVE



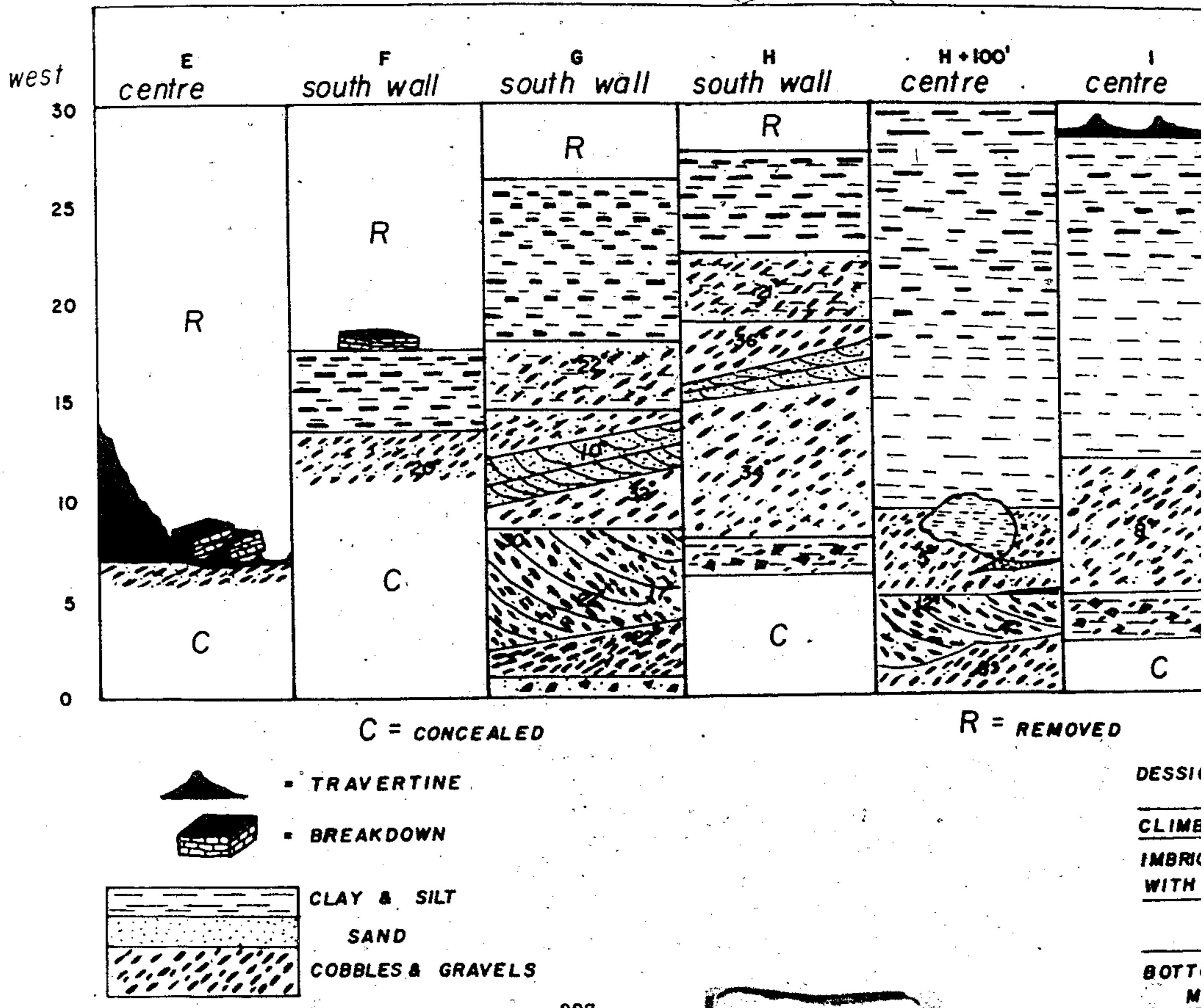
Preserved contact between the upper fines and the lower gravels in a wall pocket.

breakdown, fluvial clastic deposits or travertine. This passage exhibits the same general characteristics as the Entrance Passage, i.e., a phreatic horizontal oval cross-section; large 75 to 100 cm., ceiling and wall scalloping, indicating slow phreatic movement into the cave (southward); and a silt-clay deposit on the floor where this has not been removed by surface invasion from domepits of collapse from beneath.

Figure 6.28 shows the sedimentary section measured along the Main Passage. Here, collapse into a small lower level has produced a deep trench. Further trenches were dug to extend the section to bedrock at G-G' and H-H' to a mean depth of 19 feet. Figures 6.29 and 6.30 are photographs taken at G-G' (Figure 6.26).

The upper part of this section contains four feet of what appears to be dessication wedges. These alternate in a discontinuous blocky pattern of light and dark wedges, which show the same x-ray diffraction pattern and nearly the same silt-clay grain size composition. These brick-like patterns appear to be caused by alternate wet and dry sequences due to periodic ponding extending upstream (towards the entrance) from the large breakdown formation at J-J' (Figure 6.26). Below the dessication wedges are six feet of finely laminated silt and clay. These rest on a section of gravels and coarse sand in a silt matrix. The

VERTICAL SECTIONS EASTWARD ALONG M



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SECTIONS EASTWARD ALONG MAIN PASSAGE

Figure 6.28

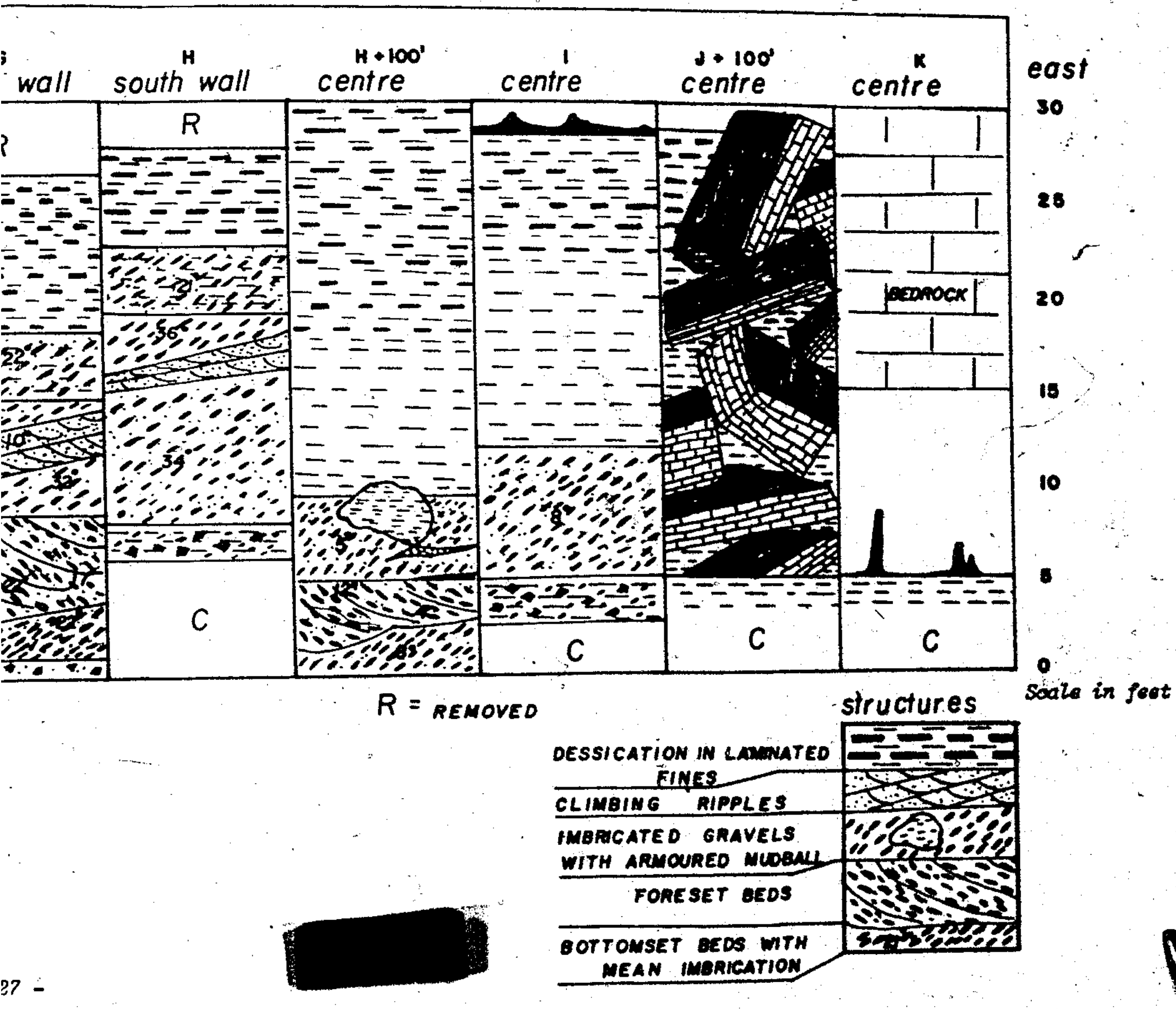
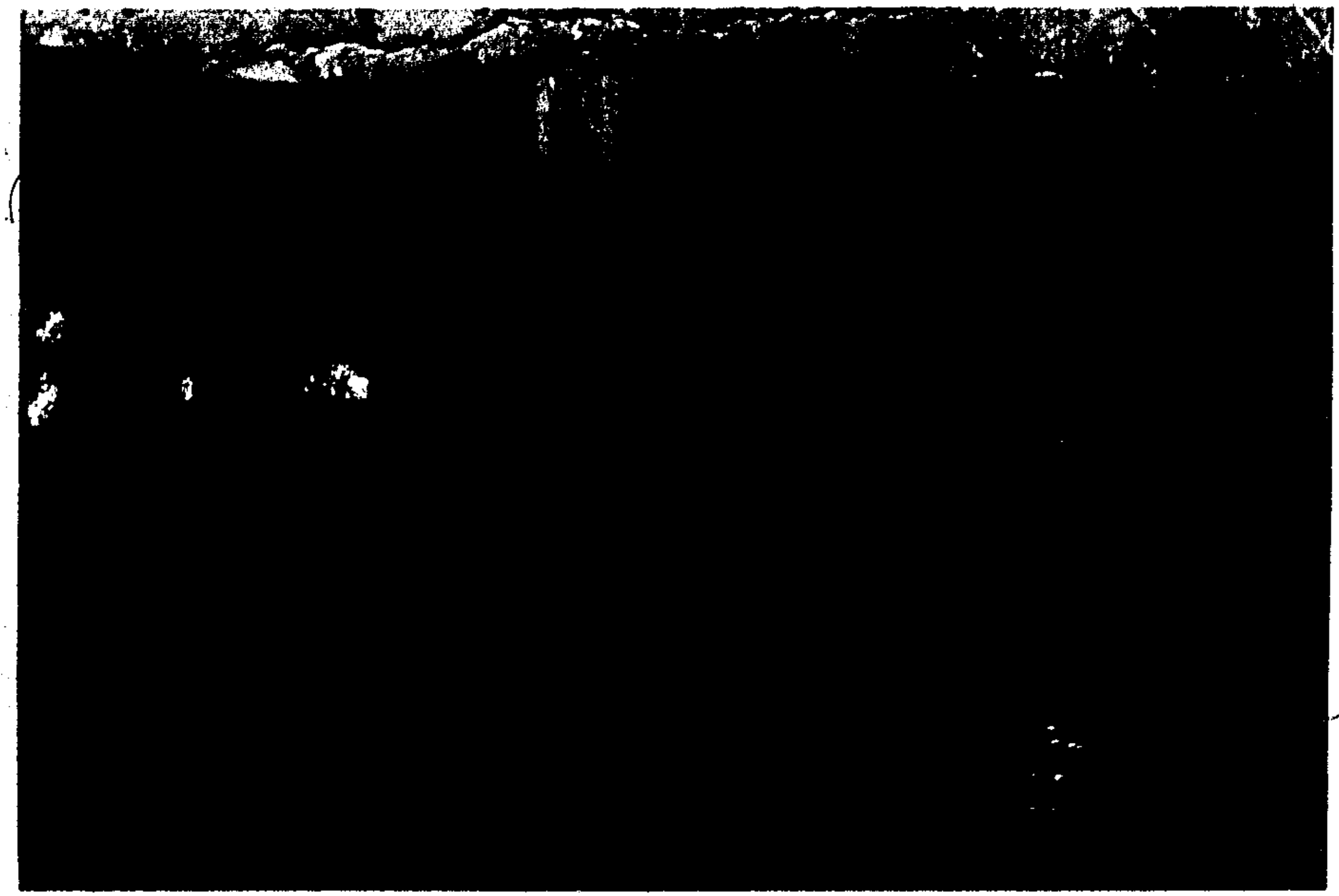


Figure 6.29

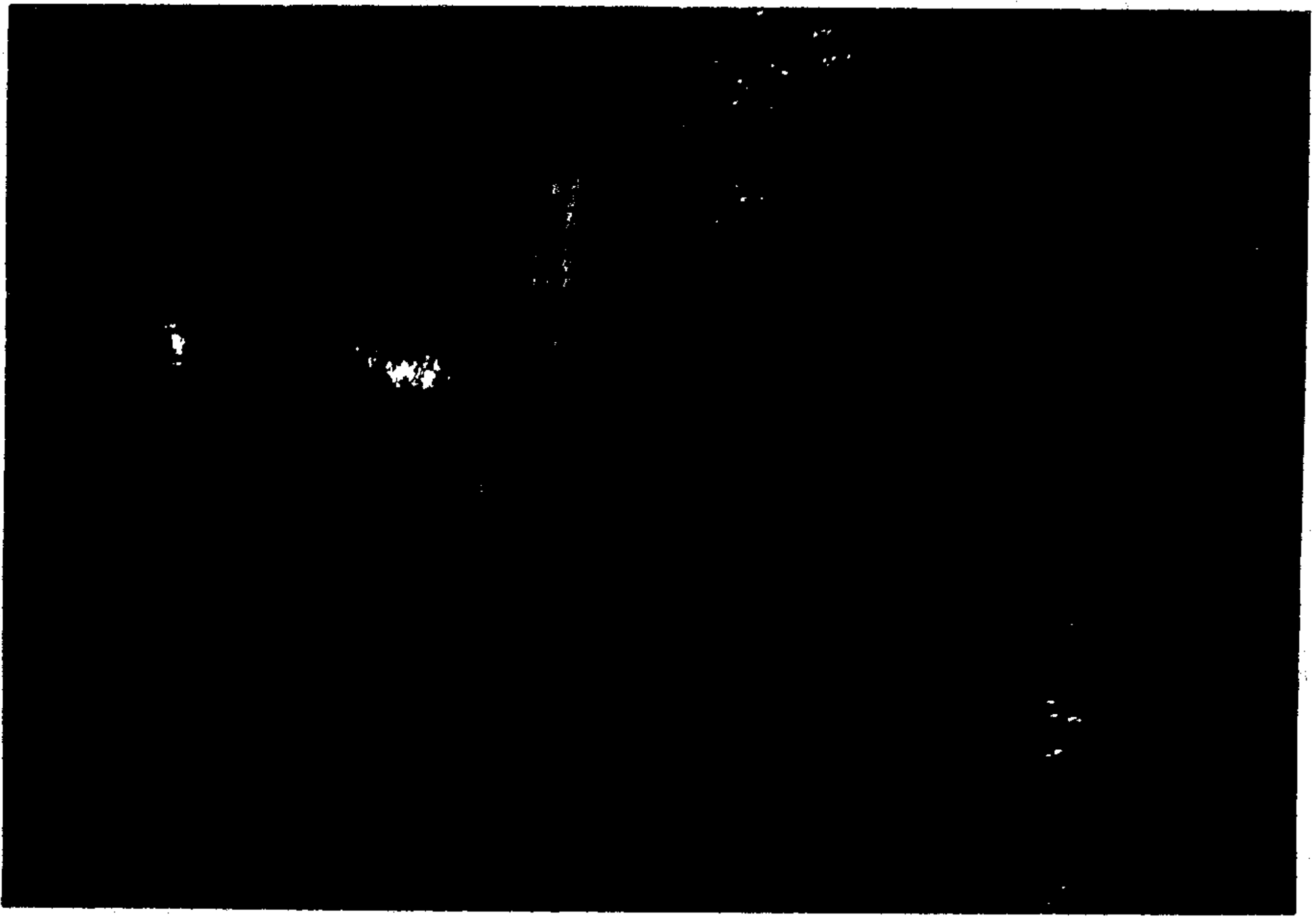
CROSS-SECTION G-G' (UPPER FINES), POOR FARM CAVE



This is the top three feet of column G in Figure 6.28. Dessication features of light and dark clay appear to the left and right of the channel sample box which is one meter in length. The light colour at the top is the bedrock wall of the cave.

Figure 6.30

CROSS-SECTION G-G' (LOWER GRAVELS), POOR FARM CAVE



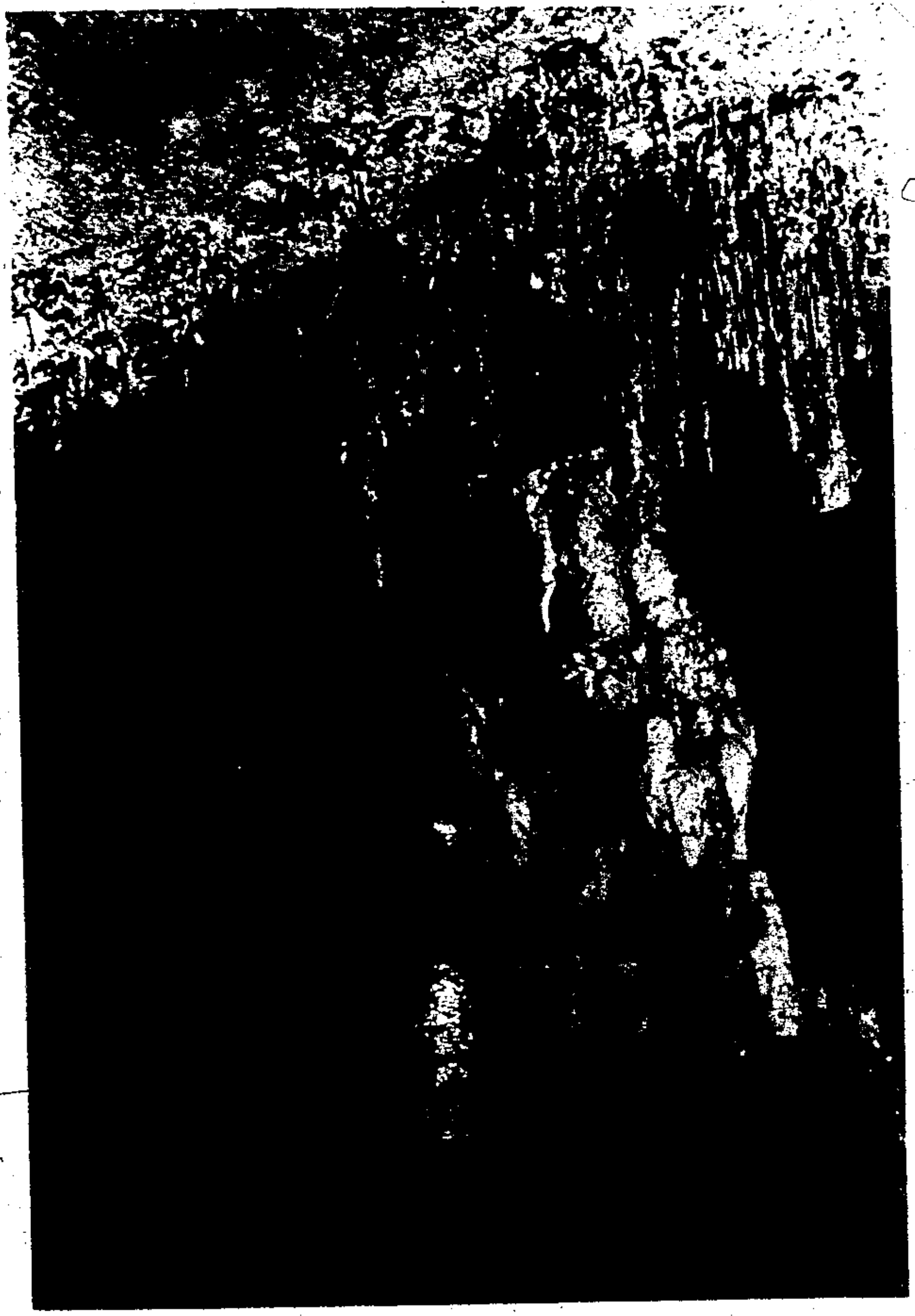
This shows the basal section of column G in Figure 6.28. Paleoflow is to the right. Note delta structures and interbedded sand wedges. The channel sample box is one meter in length. This figure is at the base of the section shown in Figure 6.29.

gravels are imbricated into the cave (south), parallel to flow directions as indicated by the scallop pattern. They also contain abundant well-rounded, milky quartz pebbles (maximum 4.0 mm.). The largest pebbles, however, are composed of Droop Mountain sandstone, which range up to 32 mm. Sedimentary structures are present in the form of delta forests (Figure 6.30). This lower section is nine feet thick and rests on a thin basal layer of silt upon the bedrock floor of Sinks Grove limestone.

Approximately 75 feet farther along the Main Passage at section H-H' (Figure 6.31) travertine deposits in the cave cap and dessication wedges of the upper fine section at G-G' (Figure 6.29). This material has cracked away from the ceiling as the underlying sediments settled. The travertine deposits are approximately 200,000 years B.P., and must post-date the deposition of the underlying fills. The same general sequence of underlying material is found here as in section G-G'. At cross-section I-I' both upper and lower sedimentary sections are present, although the dessication layer is thinner (2.5 feet). The upper fine sequence measures 15 feet and the underlying coarser sequence is thinner (6.5 feet) than in the cross-sections taken at G-G' and H-H'. Figure 6.32 shows the upper fine sequence still capped by travertine, and Figure 6.33 shows the contact with the lower coarse sequence at I-I'.

Figure 6.31

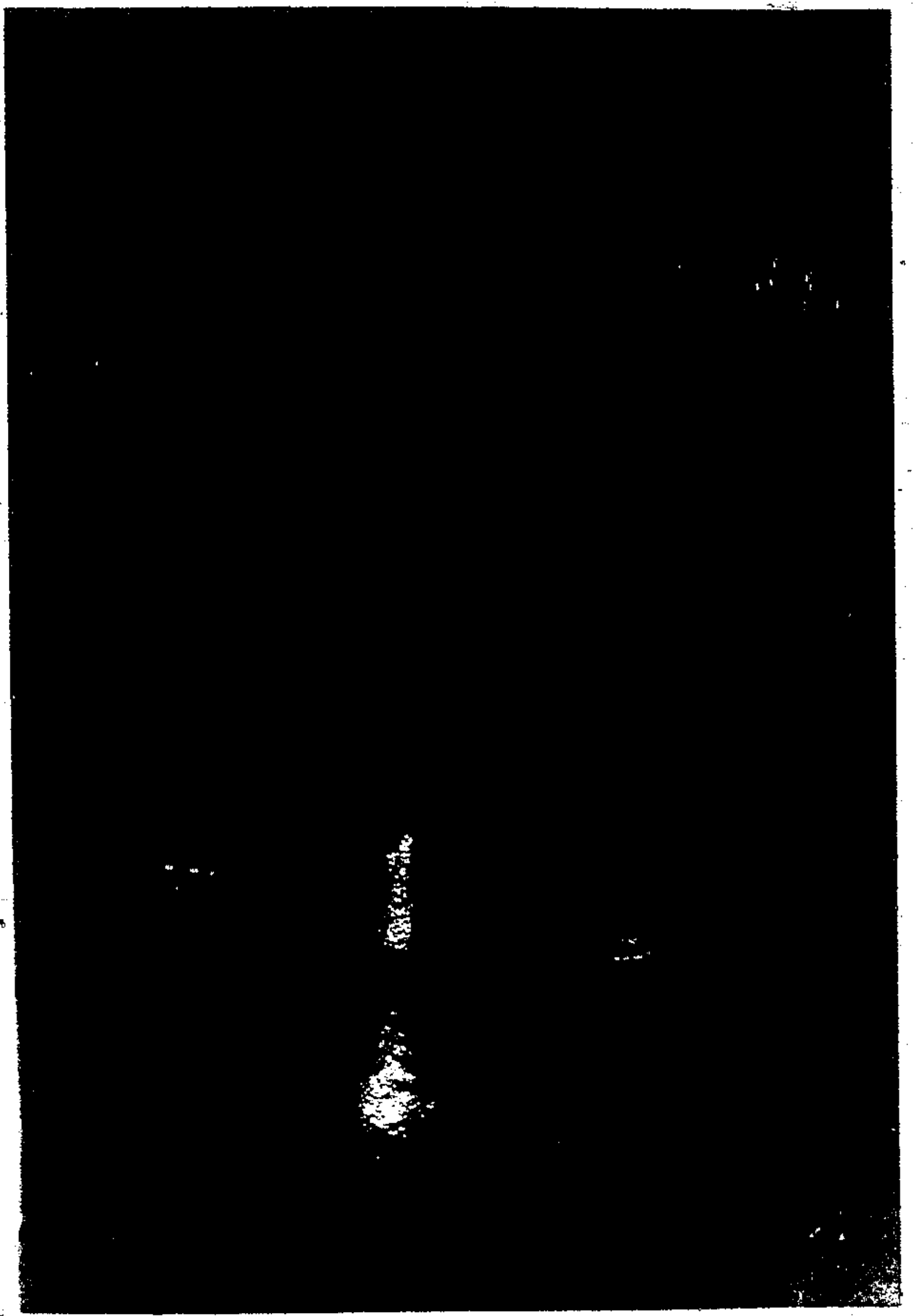
CROSS-SECTION AT H-H' , POOR FARM CAVE



Travertine (dates greater than 200,000 years B.P.) resting on silt-clay laminae with dessication features (see also Section H, Figure 6.28).

Figure 6.32

CROSS-SECTION I-I' (UPPER FINES), POOR FARM CAVE



The upper fine section thickens towards the south. Here it measures 15 feet thick. The upper three feet contain dessication wedges and are capped by a thin layer of travertine which is probably greater than 200,000 years old.

Figure 6.33

CROSS-SECTION I-I' , POOR FARM CAVE

The contact between the upper fines and the lower gravels.

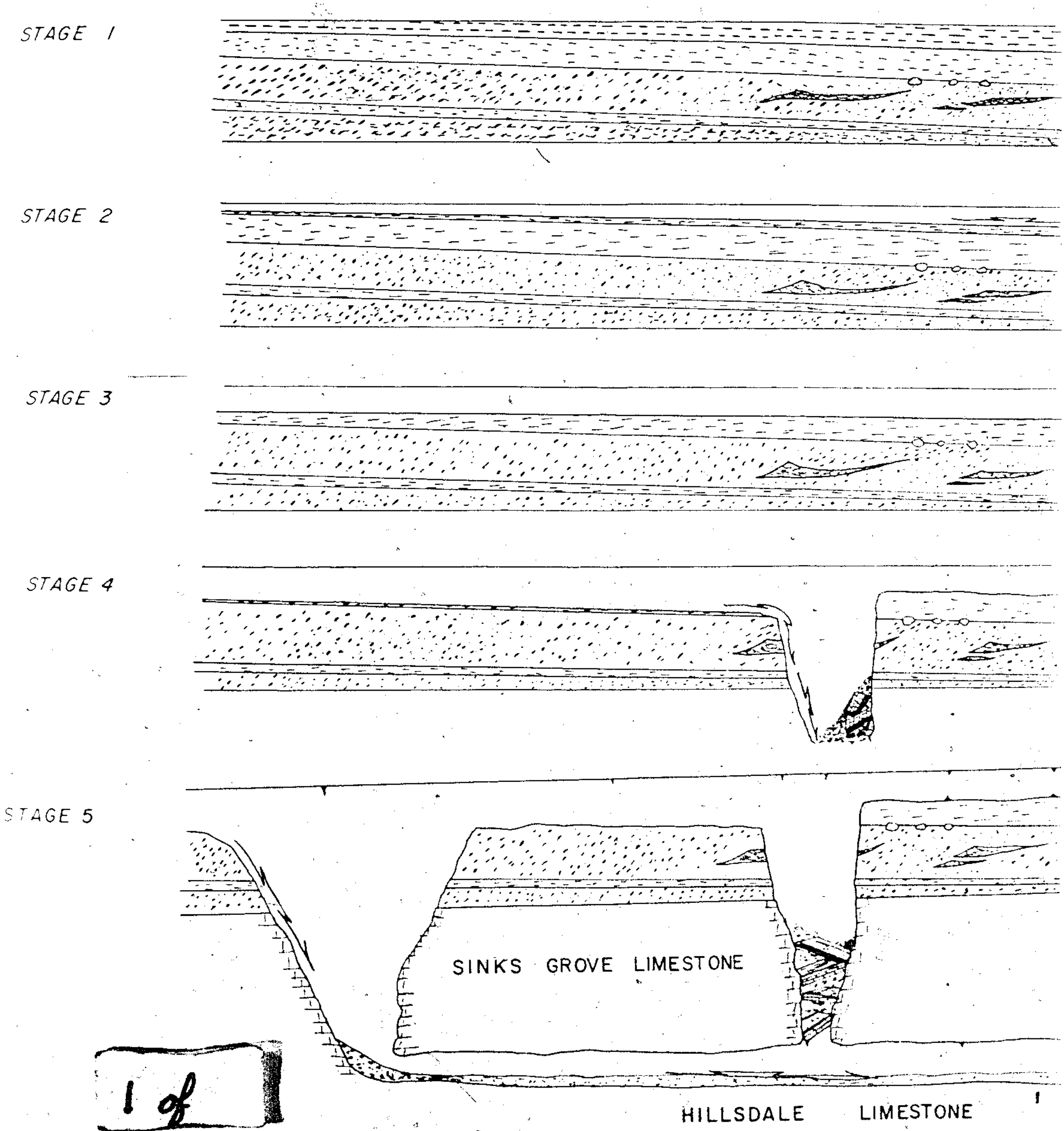
The very flat contact which lacks the even gradation from gravel to silt that might be expected in a gradual cessation of flow is a prominent feature of this sequence, traceable for 1,500 feet (Figure 6.33). Although abundant sand size material is present in the lower sequence there is no sand size fraction in the zone of transition. I attribute this abrupt change in grain size to either of the following hypotheses:

1) A rapid drop in transport velocity due to roof fall in the rear of the passage, 150 feet southwest of cross-section J-J' (Figure 6.26). This produced a dam in the cave stream which later caused wet and dry conditions after surface flooding, resulting in the dessication wedges common to the upper part of the fine sequences at G , H and I (Figure 6.26).

2) A surface change in drainage resulted in the loss of provenance from the Allegheny escarpment. This diverted drainage which formerly supplied the Princeton conglomerates, Mauch Chunk sandstones and Droop Mountain sandstones which make up the coarser lower section. This surface alteration could have been due to the opening up of the Hughes Creek, Martha's Creek to Locust Creek network (route 3, Figure 6.09), or it could have resulted from simple blockage of the former inlet to the cave itself, thus cutting off a source of coarse bedload. There is no material greater than silt size in the upper six feet

CORRELATION OF SEDIMENTARY

Figure 6.34



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NTARY STRATIGRAPHY

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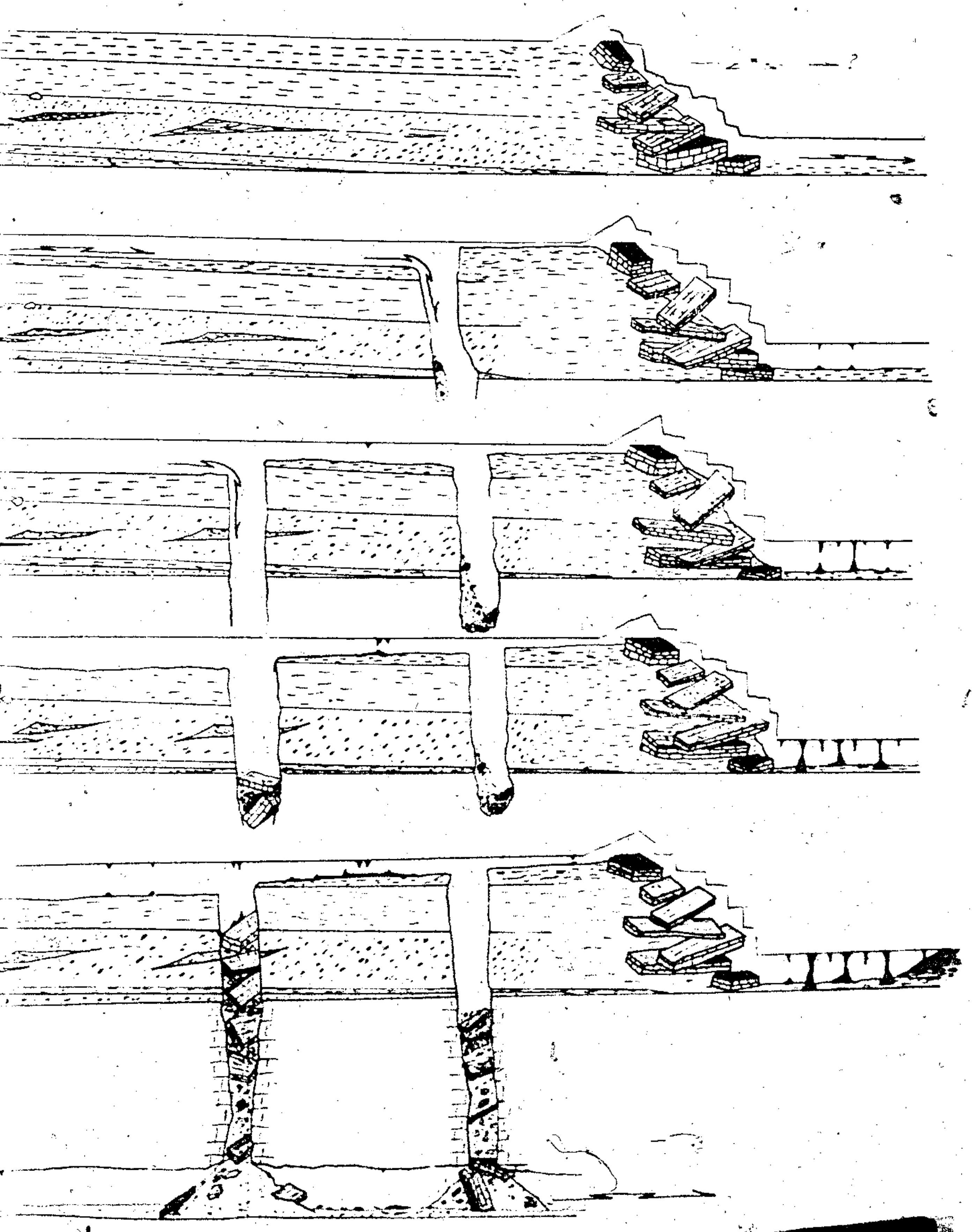

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4) The filling of the upper passage, combined with a general lowering of the regional water table, initiated the lower vadose passages (Stages 2 to 5, Figure 6.34).

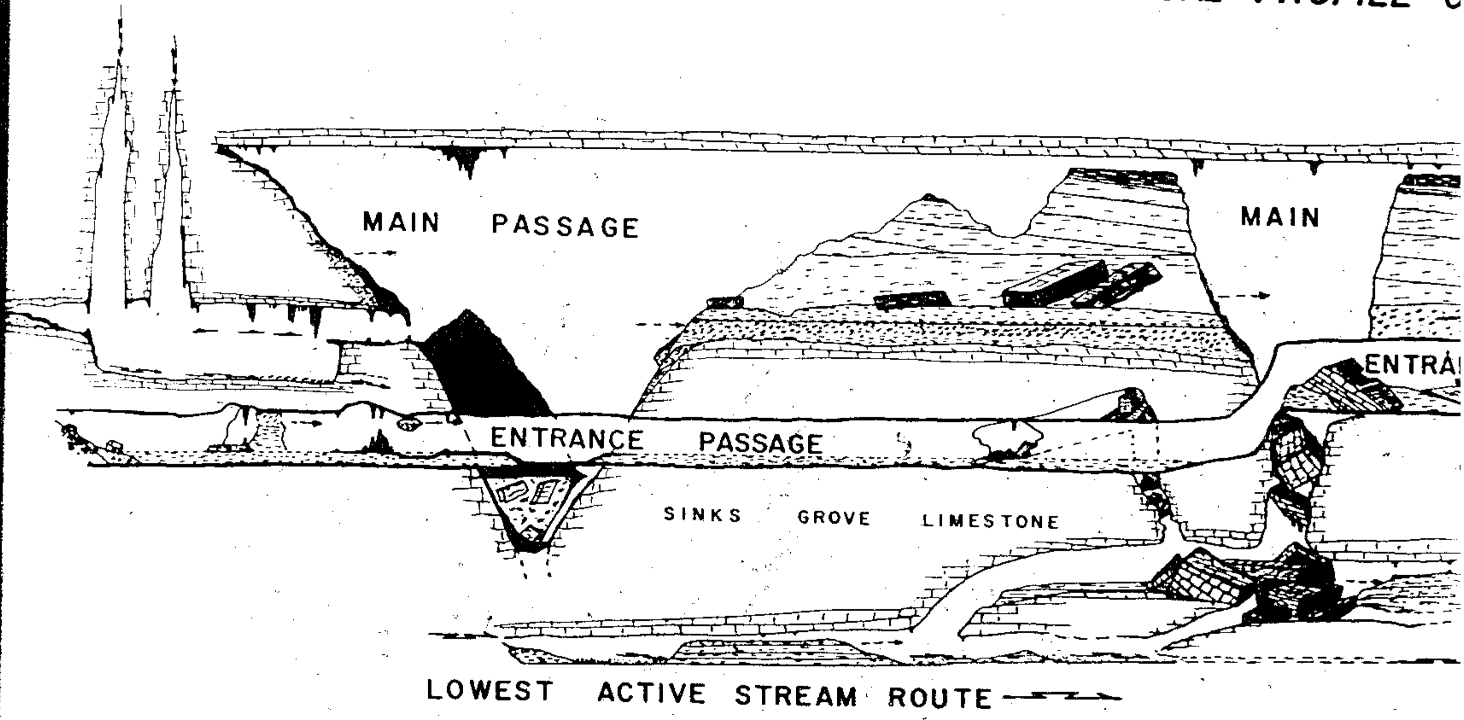
Sediment sizes and scallop sizes are in general agreement with the present flow velocities in the lower passage (20 cm/sec. approximately) and probably have evolved simultaneously under vadose conditions.

Studies of provenance show a complete change of source area between the upper and lower passages. The upper level contains Pottsville, Princeton and Mauch Chunk material including quartz pebbles and groups of clay minerals similar to those found in the weathered regolith derived from these rocks. The lower passage material was derived mainly from insoluble residues within the Greenbrier limestone, or from reworked upper level sediments near the base of domepits. Figure 6.35 shows the cave profile as it is today.

4. The Lower Basin

The Lower Basin area was not part of the early drainage network in Basin II. It is likely, however, that drainage existed independently along the area now drained by Locust Creek. Without the runoff from the upper basin (Hills and Bruffey Creeks) and from the middle basin (Millstone to Beards Blue Hole to Poor Farm to McNeals Mill Run) the discharge from the lower basin was probably under 10

GENERALISED SEDIMENTOLOGICAL PROFILE



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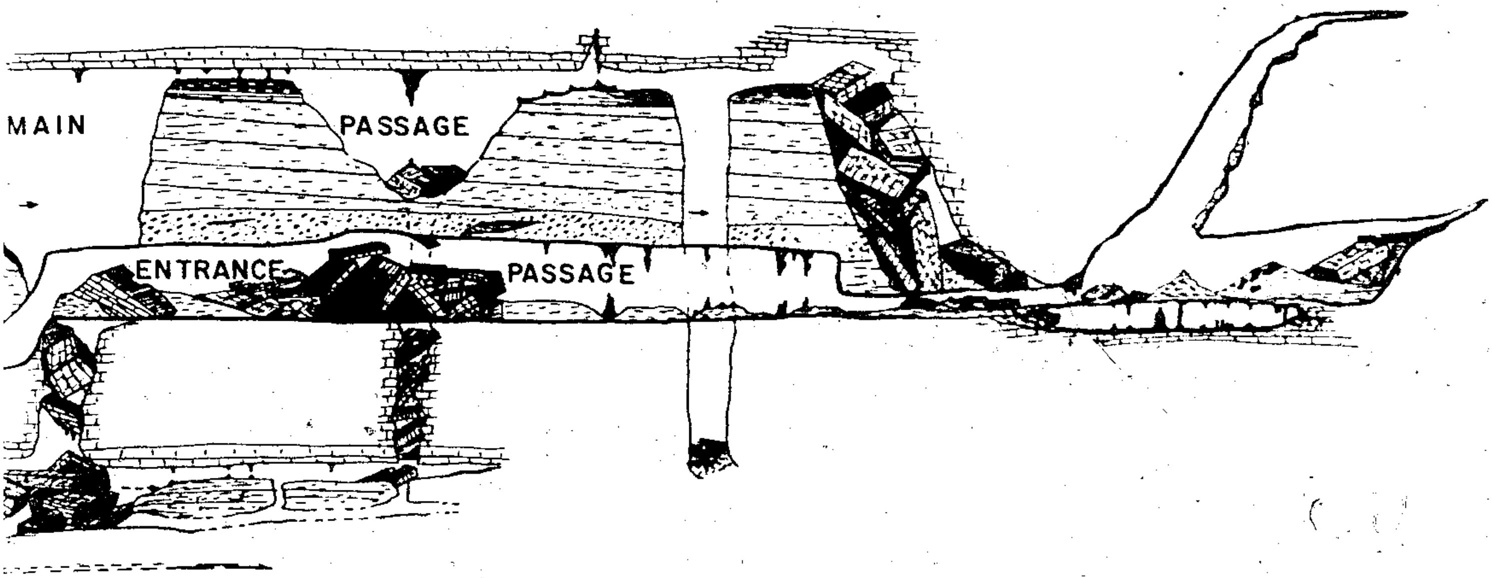
PROFILE OF POOR FARM CAVE WEST VIRGINIA

Figure 6.35



cfs. at maximum. The terraces at 3 , 10 and 30 feet, described earlier in the modern basin, are probably the result of deposition since the integration of upper and middle basin drainage. They show an increase in grain size downwards from silt to gravels in the lowest terrace. This is probably due to enlargement of the underground conduit and increase in runoff via the modern network. The silts of the upper terrace show x-ray diffraction patterns similar to those in the upper basin area. All terraces and surface alluvium along the Locust Creek channel appear to have been derived from the modern basin.

C. Conclusions

The development of the present drainage network and accumulation of sedimentary deposits in Basin II has resulted from the interaction of climatic and geomorphic processes. The result is a complex system of removal, transport and deposition of weathered and mass wasted materials from the clastic outcrops along this portion of the Allegheny escarpment. Karstification is more intensive here than in Basin I. Basin II is more typical of the Greenbrier limestone as a whole.

The following outline is drawn from the information gained through the study of surface and subsurface drainage and sediments in Basin II.

1. Surface Evolution

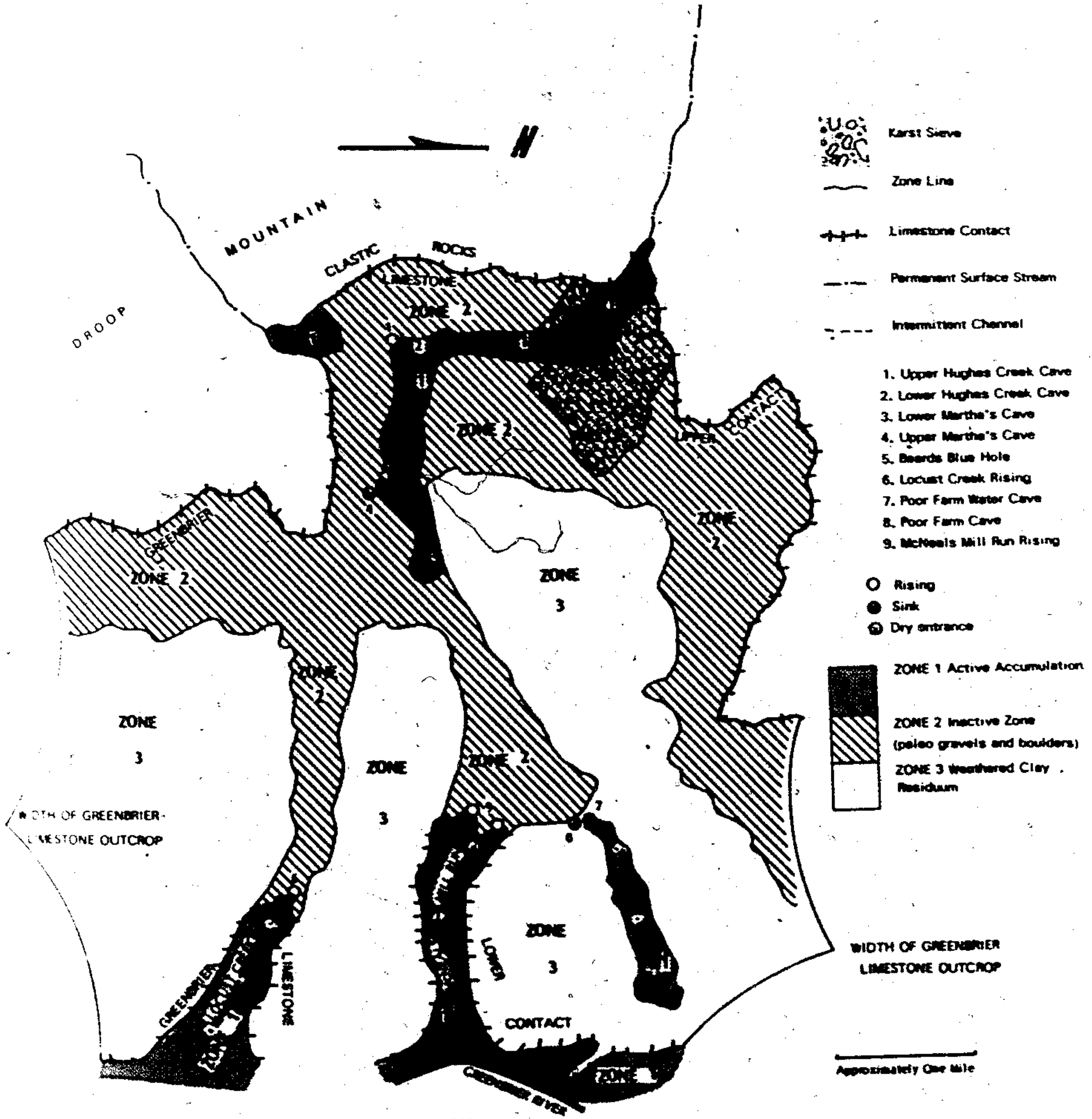
Three distinct zones of surface accumulation of mass wasted and stream transported material are distinguishable on the basis of clay mineral distribution, provenance, lithology, and from the vertical and downstream variations in particle and structural characteristics of the deposits (Figure 6.36).

a. Zone 1: Active Accumulation Zone

This is the zone of modern accretion. The main cause of deposition is stream action, although occasional gravitational transfer of hillwaste occurs in the form of landslides triggered by heavy precipitation. This fluvial accumulation is most common on the alluvial flood plains along Hills Creek and Bruffey Creek in the upper basin and immediately below the mouth of Hughes Creek Upper Cave as far west as the ephemeral sink at Beards Blue Hole (route 3, Figure 6.09). Modern surface accumulation of sediments occurs several times each year when local karst water tables are high and surface flow is possible. Coarser sedimentation in this zone is characterised by sand ripples and gravel deltas which remain in the dry channels after

SURFICIAL DISTRIBUTION OF SEDIMENTS IN THE MIDDLE AND LOWER BASINS

Figure 6.36



each major flood. Widespread deposition of fines also occurs when ponding occurs at blocked sink entrances.

The modern accretion is most common in two areas: where drainage leaves the overlying clastic rocks and crosses the upper portion of the Greenbrier series; or where surface streams are temporarily carried on armoured stream beds across the limestone. The Hills and Bruffey Creek accumulations are examples of clastic/carbonate contact deposition; the alluvium extending west of Hughes Creek along the Millstone Creek channel is an example of armouring over limestone surfaces (Figure 6.37). The development of modern alluvial terraces along Locust Creek (Figure 6.36) can be considered as typical fluvial accumulation without the influence of karst processes, except that materials greater than fine gravel have been screened out in the alluvial deposits of the upper and middle basin areas or within syphons in the underground conduit of Locust Creek Cave.

b. Zone 2: Inactive Zone of Paleogravels and Boulders

Zone 2 includes all inactive coarse material underlying Zone 1 and extending eastwards across the limestone surface in the middle basin and southward along the dry valley of the upper basin (Figure 6.36). Part of the large karst sieve-type deposit near the head of Millstone Creek (Figure 6.36) is included in this zone. This type of deposit has not been described in the sedimentological literature. Basin III contains a large deposit of similar

Figure 6.37

MILLSTONE CREEK STREAM BED

Eight feet of surficial alluvium is exposed in a sink in the intermittent Millstone Creek bed one-half mile east of the Hughes Creek Caves. Note the upper zone of surface alluvium (Zone 1, Figure 6.36) which supports surface flow across the underlying limestone. The coarse gravels at the bottom are considered part of Zone 2 (Figure 6.36) that is, paleo-gravels and boulders. Bedrock is exposed at the bottom centre.

characteristics in Trout Valley. These features are common where streams flow from clastic rocks on to the karsted limestone. They result from the loss of surface water to underground channels. This causes loss of stream competence and capacity; then surface accumulation of bedload material results. Although this occurs today it is not depositing boulders of the size found in many of these deposits. In the case of the Millstone Creek deposit (Figure 6.36) a large fan-shaped feature has formed from boulders up to six meters across (Droop sandstone) in a matrix of smaller boulders and gravels. Its depth is estimated to be about 300 feet. Although additional material is added to the deposit in the form of gravel, the overall budget of the feature appears to be negative, with a loss of sediment during floods, which carry coarse material into the active area of Zone 1. This was noted during the heavy floods of 1969, when surface alluvium was carried as far as the sink at Beards Blue Hole (Figure 6.09). A large stand of mature hardwoods now covers all the sieve-type deposits. I consider such deposits to be no longer accumulating large boulders; such accumulation occurred under periglacial conditions during ice advance periods. Information from Darlington (1943), Guilday (1971), Clark (1969) and sedimentological evidence in the caves of the karst plain east of these deposits supports this hypothesis.

Zone 2 also includes the large alluvial deposits which cover one-third of all exposed karst in the area of

Basin II. Table 6.07 is a sample collected at random from the Moffat McNeal property over a distance of one mile southward from the toe of the sieve deposit. This is typical of Zone 2 beyond the contact zone with the overlying clastic rocks. Figure 6.37 shows some of the coarser material underlying the finer material of Zone 1 in the dry stream bed of Millstone Creek, about one mile east of the Hughes Creek risings.

c. Zone 3: Zone of Weathered Clay Residuum

Zone 3 is the widest in the middle basin and extends across the lower part of the Greenbrier series and MacCrady shale outcrops. It is comprised principally of deeply weathered red and orange clay and silt. X-ray diffraction of this material shows similar clay minerals regardless of the color or underlying lithology. The kaolinite (3.58Å)/illite (10Å) ratios are consistently over 1.000 . Samples taken in this zone from three different bedrock zones are shown in Table 6.08.

In housing foundation and road excavations these same clays are found in joints in the bedrock. The absence of laminae and the presence of interspersed angular blocks of the underlying bedrock material would suggest that the <u>in situ</u> decomposition of the underlying parent material is the source of most of the material in Zone 3. These clays differ from the paleofills in the abandoned upper levels of the caves in this area. They are also different from

Table 6.07

SUMMARY OF MEAN BOULDER DATA ON MILLSTONE CREEK ALLUVIUM[1]

Station	Length[2]	Width[2]	Height[2]	Lithology[3]
1	1.4	.6	.5	Droop Mt. Sandstone
2	1.0	.9	.3	"
3	1.3	.7	.5	"
4	1.1	.4	.3	"
5	1.4	.7	.5	"
6	.3	.3	.3	"
7	.4	.3	.2	"
8	.4	.3	.1	"
9	.5	.3	.2	"
10	.4	.4	.2	"

[1] Mean of 10 largest boulders in a radius of 10 feet at each station spaced 100 feet along the dry channel commencing at the toe of the alluvial karst "sieve-type" deposit and continuing downstream across the karst surface (see Figure 6.36).

[2] Recorded in meters.

[3] No conglomerates were found.

Table 6.08

CLAY MINERAL RATIOS IN ZONE 3

(Figure 6.36)

Number of Samples	Bedrock	Depth of Residuum (In Feet)	3.58Å/10Å Mean Ratio
(3)	Sinks Grove limestone	5	1.106
(4)	Hillsdale limestone	8	1.070
(3)	MacCrady shale	8	1.119
	Mean for Zone 3	7	1.098

the clays of the active surface channels in Zone 1 (Figure 6.36).

2. Subsurface Development

Some general statements about the subsurface development of karst and accumulation of sediments can be made:

1) Initial cave development appears to be parallel to the regional strike, i.e., N. or NW. to S. or SE. The main upper passages of abandoned conduits conform to these general directions in Upper Hughes Creek upper passage, Poor Farm Cave, Upper Martha's Cave, and Snedegars Cave.

2) Surface orientation of abandoned dry valleys also conforms to the regional strike. The large abandoned outlet to Spring Creek in the upper basin shows this very clearly.

3) Locally, the ultimate control over subsurface

drainage is the level of the Greenbrier River, or the base of the limestone series, if the latter is higher. As this drainage cuts below the limestone surface, all caves become subject to vadose entrenchment and the invasion of fluvially transported clastic fills from the outcrops of overlying sedimentary rocks.

4) As Figures 6.09 and 6.36 have shown, subsurface conduits become more direct as time progresses. The first diversions of upper basin drainage to the lower basin were in large loops which still showed strong strike control. Later these became more direct from basin head to river outlet. Table 6.09 summarises these diversions through time ending in predictable changes (Number 5).

3. Subsurface-Surface Relationships

The geomorphic significance of the paleo and modern fills in the caves of Basin II is that they provide a means of comparison between paleo processes and landscape evolution associated with the abandoned cave fills. Table 6.10 is an attempt to summarise some of these relationships. The general character of modern surface deposits and associated modern cave fills is the dominance of fluvial sedimentation. The modern deposits are better sorted, more rounded, and generally finer textured than the paleo deposits. In general, running water appears to be of greater influence through time than any other geomorphic process.

Table 6.09

SUMMARY OF THE ROUTES FROM THE UPPER BASIN TO THE GREENBRIER RIVER

(See Figure 6.09)

Route	Control
1. Hills-Bruffey-Rush Run to Spring Creek via Friars Hole	Strike oriented, initiated an overlying clastic rocks
2. Hills Creek and Bruffey Creek to Upper Hughes Upper Passage to Poor Farm to Mills Run	Karst diversion through Droop Mountain to Hughes Creek
3. Hills-Bruffey, Upper Hughes Upper Passage to Martha's Lower Cave to Locust Creek (Poor Farm Cave then isolated)	Karst diversion to Locust Creek due to headward growth on clastic rock
4. Hills-Bruffey to Locust Creek (caused intermittent use of Millstone Creek surface channel)	Continued downcutting of base level
5. Predicted abandonment of the Little Levels drainage area as the direct route (number 4) becomes enlarged by solution. The general sediment budget seems to have less material entering the upper basin now than in peri-glacial times. Sedimentation should decrease as fills are removed and travertine deposition in upper levels should increase.	Dominance of regional base level

Table 6.10

ASSOCIATIONS OF SURFACE AND SUBSURFACE DEPOSITS

Type Examples	Deposits	Variables	Landscape Processes
A. Modern Deposits and Related Landscapes			
Hills-Bruffey to Locust Creek	Well-sorted silts, sands and some gravels. Generally similar in caves and in surface channels.	Surface "sieve" deposits. Syphons in cave conduits. Floods.	Youthful surface streams developed on alluvium and overlying clastics. Stream piracy results from sudden downcutting accelerated by karstification in lower basin.
Hills-Bruffey to Hughes Creek Cave and Martha's Cave	Sand, gravels and boulders. Coarser material due to occasional overspill flooding of above channel	Floods are the major variable.	Surface alluvium across the karst plain provides thick veneer of insoluble clastic residuum on limestone
Millstone Creek to Beards Blue Hole to Locust Creek	Sand, gravel and reworked boulders	Surface karst "sieve" deposits. Floods.	Surface alluvium over limestone. Veneer at heads of karst sieve deposits, removal of sediments from sieve deposits and distribution on karst plain. Terraces, solution of angular bedrock limestone fragments.
B. Paleo Deposits and Related Landscapes			
Paleo surface channels parallel to strike developed in upper basin southeast to Spring Creek conduit	Poorly sorted massive deposits of large angular boulders in matrix of gravels and sand		Steep, poorly vegetated slopes with rapid downslope movement during melt conditions, result in massive karst sieve deposits and rapid

It has already been observed that strike control becomes less important as kartification increases. Major trunk channels on the surface, as well as subsurface conduits, ignore underlying structure. Modern tributaries to these surface channels still show strike orientation (Figure 6.01). Modern active vadose cave conduits, on the other hand, are less strike oriented than the upper level phreatic conduits, which were generated under slow velocities with gentler gradients than their modern equivalents.

It would appear that during former times of abundant clastic infilling and reworking, that stalactite and stalagmite deposition is near minimal activity. Conversely, it would appear from the evidence gathered in Basin II that during times of active carbonate deposition that clastic fluvial deposition is less. Thompson (1973, personal communication) concurs in these observations.

Chapter 7. BASIN III
THE CULVERSON CREEK SYSTEM

A. Introduction

Basin III is the largest and most complex basin considered because here the limestone outcrop is widest and thickest. The basin has three parts:

1) an upper basin composed of surficial Culverson Creek and its tributaries plus a well-marked paleodrainage channel, the "Great Banana" valley;

2) a middle basin comprising the underground (and diversion) course of Culverson Creek to Spring Creek. Above the conduit are other caves which drain to other district springs on Spring Creek, or to Fort Spring, a major spring many miles to the south;

3) a lower basin draining to other springs on the south bank of Spring Creek. Drainage is from the north part of the most extensive karst surface in West Virginia (the Great Savanna) where drainage divides are poorly established and probably unstable. To adequately investigate characteristics of cave sediments in this problem area, a sample of four caves was investigated in detail, two of which are known not to drain to Spring Creek risings today but which may have done so in the past.

The area investigated in this chapter, is therefore, somewhat greater than the single drainage basin. This was also the case in Basin II where Poor Farm Cave now lies outside of the Locust Creek catchment, and is considered permissible practice in such areas of complex holokarst drainage (Jennings, 1971, p. 200).

Basin III is located in the lower portion of the Greenbrier River system, where the limestone outcrop reaches its widest exposure. The maximum width is ten miles. This is due to the downstream widening of the Greenbrier floodplain. There is also an increase in folded strata to the west of the river, and a thickening of the Greenbrier limestone series in the southwest of the Greenbrier basin. The thickness of the Greenbrier series increases from 450 feet in Basin II to 900 feet in Basin III. Karstification in the south is intense. Local relief features exceed 700 feet on the karst plain. Several uvalas are greater than three miles in length.

Figure 7.01 shows the karsted area in the lower portion of the Greenbrier River basin which contains Basin III. Spring Creek, in the north, is the only surface channel cut across the full width of the Greenbrier series. It was once the recipient of paleodrainage from the upper portion of Basin II and is now the modern outlet for drainage from Basin III.

BASIN III and SURROUNDING KARST DRAINAGE of the LOWER GREENBRIER VALLEY

Figure 7.01

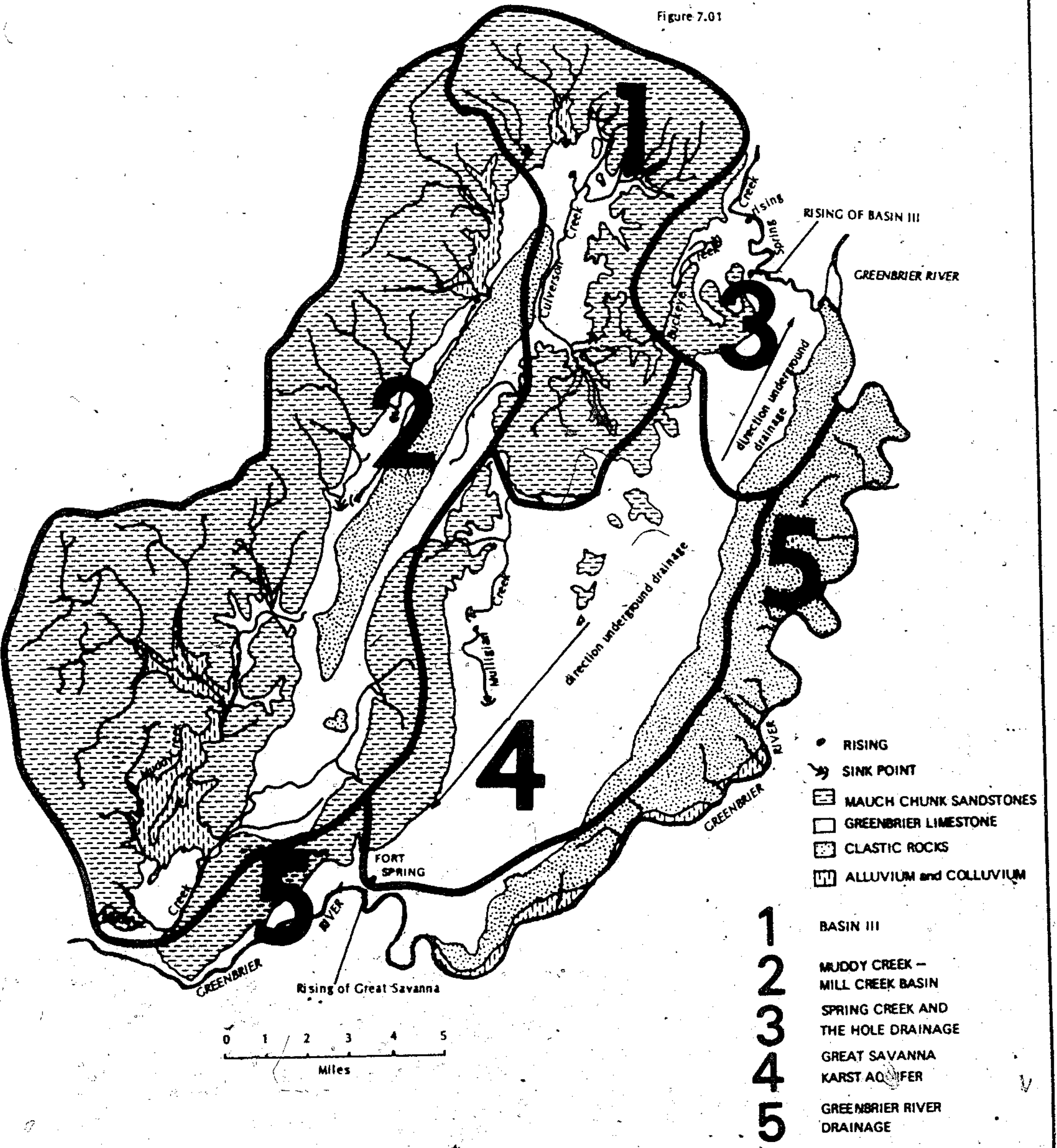


Figure 7.02 is an oblique aerial view of a large meander cutoff a few hundred yards upstream from the rising of the Great Savanna aquifer at Fort Spring. The top of the photograph shows the surface of the surrounding limestone karst plain. The forested slope of the scar represents 200 feet of pre-cutoff entrenchment by the Greenbrier River. The bench to the left of the railroad on the right of the photograph represents an additional 50 feet of post-cutoff downcutting by the modern channel. Figure 7.03 shows the surrounding karst plain surface with its general lack of surface runoff. The role of underground conduits in regional drainage and sedimentation in such an area is of great importance.

The former outlet for drainage from Basin III was along the east flank of the Williamsburg Anticline (Brushy Ridge). This dry stream channel is shown on Figure 7.01 as the "Great Banana River". Paleodrainage from Basin III flowed southwest along it into Mill Run and thence to Muddy Creek to joint the Greenbrier River at the extreme southwestern corner of the figure. The modern diversion now enters the river 69 miles north of its former outlet at Muddy Creek. The modern Muddy Creek drainage basin occupies the western third of Figure 7.01. It includes nearly 200 square miles of drainage. The drainage from the Allegheny Escarpment, confined to the west of the Williamsburg Anticline (Brushy Ridge), is forced to flow southwest along the strike and into the Muddy Creek basin. To the

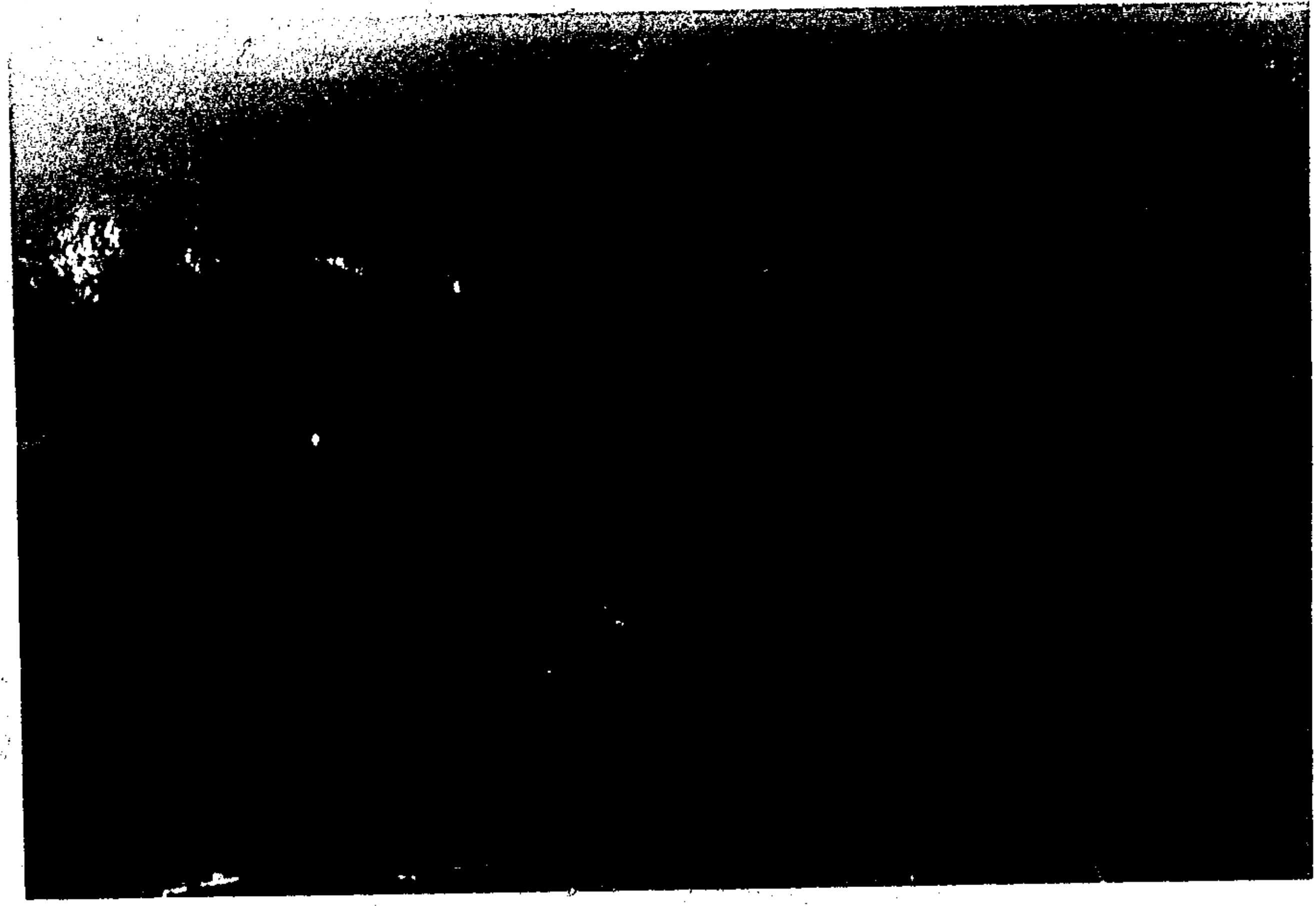
Figure 7.02

THE GREENBRIER RIVER AT FORT SPRING, WEST VIRGINIA

The Greenbrier karst plain is seen behind the meander scar in the background.

Figure 7.03

THE GREENBRIER KARST PLAIN



east, two nearly wholly karst aquifers[17] have developed large underground systems. These are the Great Savanna aquifer which rises at Fort Spring, in the south (Figure 7.01), and the drainage associated with The Hole, which flows northward into Spring Creek. Both of these networks are extremely complex and the actual drainage divides are only estimated from limited dye testing and cave stream data. Only a few surface streams are found on the limestone. These are supported on alluvium.

The fourth largest cave system in the world is developed within the Great Savanna aquifer (Fairbridge, 1968, p. 1037). This is Greenbrier Caverns, which acts as a major conduit southwest along the strike for drainage similar to the strike-controlled drainage of the major Muddy Creek channel. Table 7.01 lists the drainage basins and their tributaries surrounding Basin III. These are shown on Figure 7.01.

Basin III is defined as the watershed within the maximum runoff perimeter of modern drainage entering Spring Creek via a series of risings approximately 2.4 miles upstream from the confluence of Spring Creek and the Greenbrier River.[18] Figure 7.04 shows the surface drainage network of Basin III. The basin lies in a similar topograph-

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[17] The term "autochthonous" karst basins has been used by Jennings, 1971 to refer to this type of drainage.

[18] Elevation 1900 feet at Matt Batts Black Cave rising along Spring Creek, White Sulphur Springs, Quadrangle, West Virginia, U.S.G.S.

Table 7.01

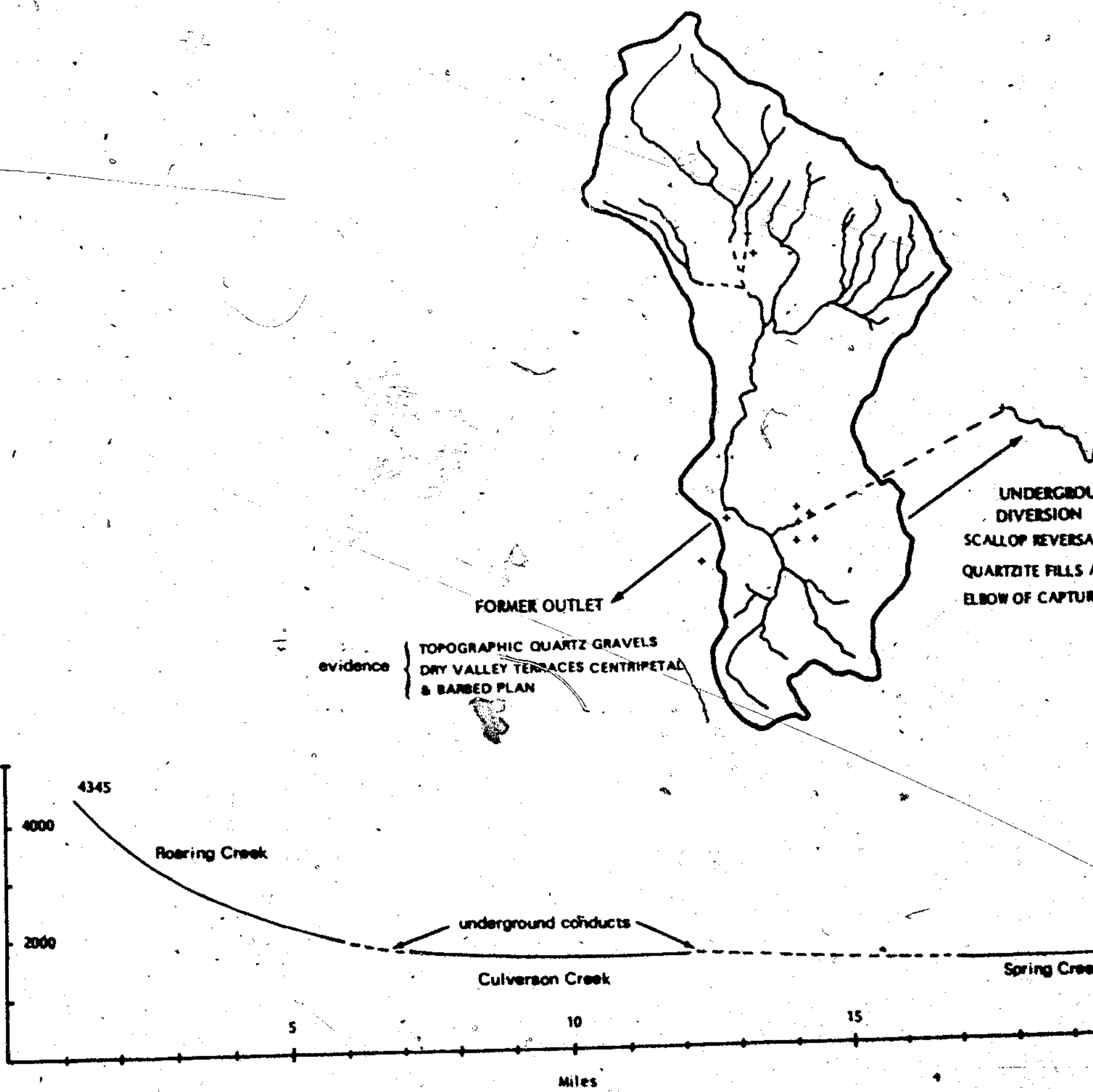
HYDROLOGY AND TOPOGRAPHY OF BASIN III AND SURROUNDING AREAS

Surface and Subsurface Drainage	Trunk Channel Length (Miles)	Area (Sq. Mi.)	Total Fall (Feet)	Mean Gradient	Estimated Mean Discharge (cfs.)
Upper Basin Area					
Little Roaring Creek	2.9	2.8	1400	90/1000	9
Roaring Creek	5.2	7.9	1715	60/1000	9
Charley Run & Related Drainage	4.2	2.6	1550	70/1000	5
Indian Creek	3.5	2.6	810	40/1000	N.A.
Subsurface Channel	1.0	N.A.	50	11/1000	N.A.
Middle Basin Area					
Culverson Creek (surface only)	6.5	35.0	400	8/1000	30
Spice Run	2.8	2.4	600	30/1000	N.A.
Burns Run	4.0	2.8	210	10/1000	N.A.
Culverson Creek Cave Conduit	4.7	N.A.	150	7/1000	40
Lower Basin Area					
Spring Creek (to Greenbrier River)	2.4	2.8	45	3/1000	100
Total for Basin III	19.8	53.2	2445	25/1000	40
Surrounding Karst Drainage					
(North) Spring Creek	21.3	76.3	1675	14/1000	100
(East) "Great Savanna" Aquifer	17.2[1]	100 (est.)	878	10/1000	100
(South) Muddy Creek	35.0	100 (est.)	750	2/1000	75

[1] **Straight line distance.**

DRAINAGE OF BASIN III

Figure 7.04



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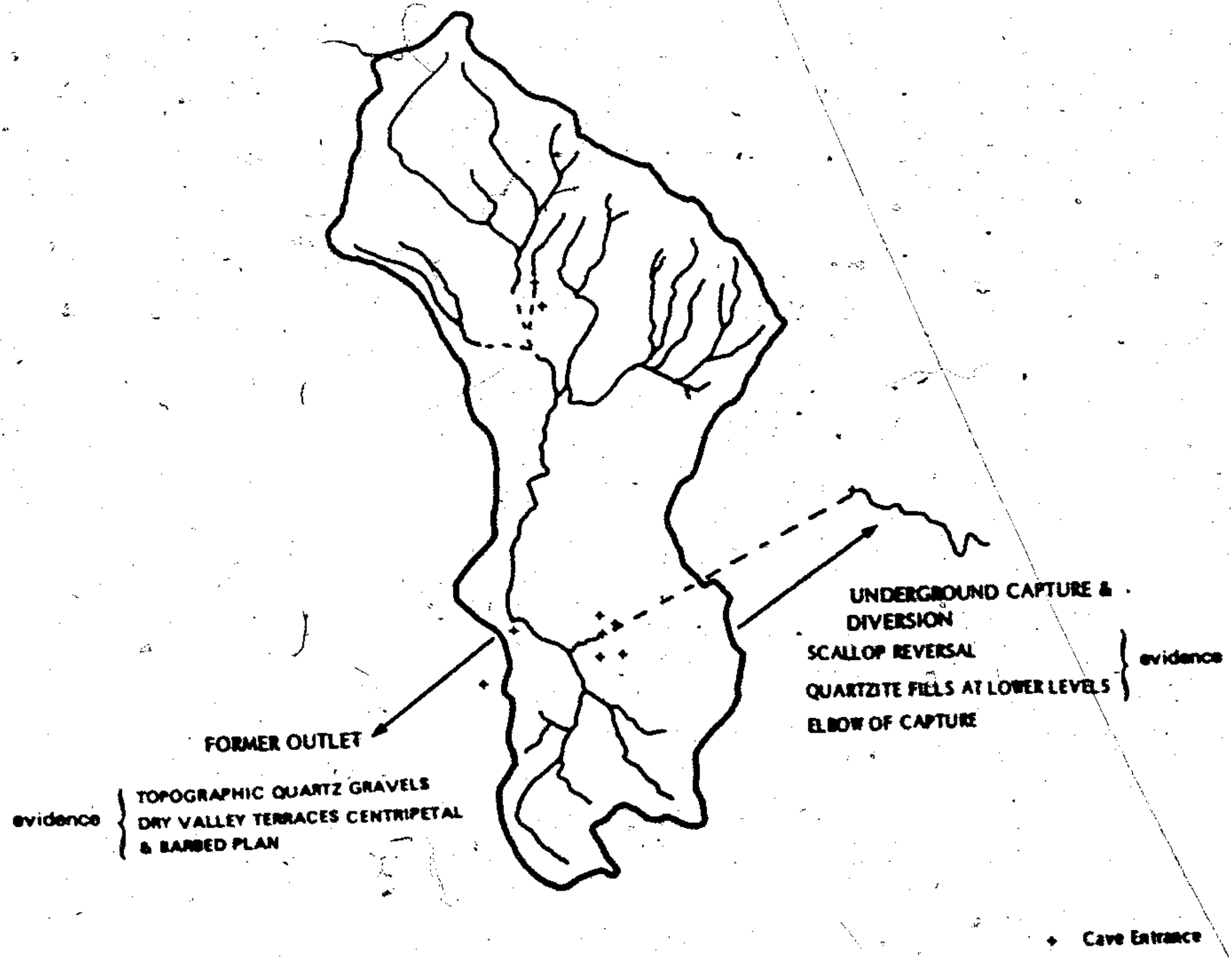
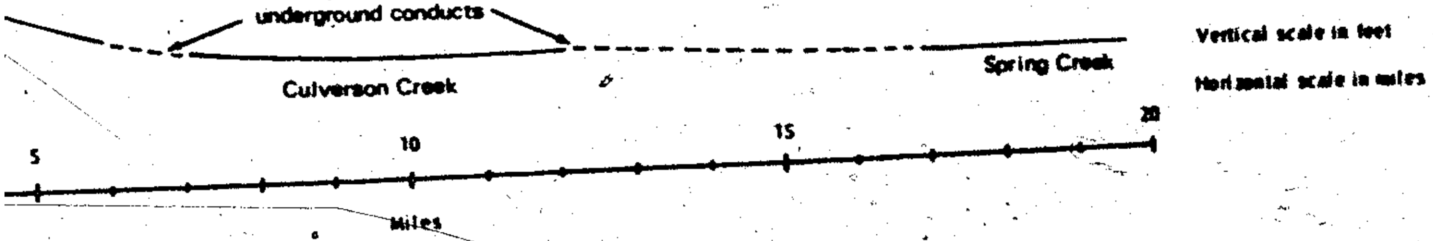
DRAINAGE OF BASIN III

Figure 7.04





[redacted]

ic, lithologic and stratigraph setting to the two previously described basins. However, the function of the basin in relation to the general geologic and hydrologic setting is very much more complex. It crosses over, or flows through 13 miles of highly karsted limestone before reaching the Greenbrier River. It contains 53.2 square miles of drainage, 25 square miles of which is developed within a limestone terrain. The entire Greenbrier series is crossed by the trunk channel of the basin. This is due to the gentle anticlinal fold developed at right angles to the general trend of the basin (Figure 7.01).

It is a distance of 17.4 stream miles from the head of the basin to the rising along Spring Creek (Figure 7.04). Seventy percent of this route is through or across the highly karsted Greenbrier limestone. An additional 2.4 stream miles is added to reach the Greenbrier River via Spring Creek, 1.2 miles of which is through limestone terrain. The surface trunk channel of Basin III is intermittent throughout its course across the carbonate rock, and flows on a bed of alluvial veneer.[19] The trunk stream flows directly on bed rock near the headwaters of Roaring Creek where it crosses clastic exposures and for part of its underground course where it is actively removing limestone from the floor and walls of the cave conduit. The general pattern of drainage is centripetal, with an extension of the basin

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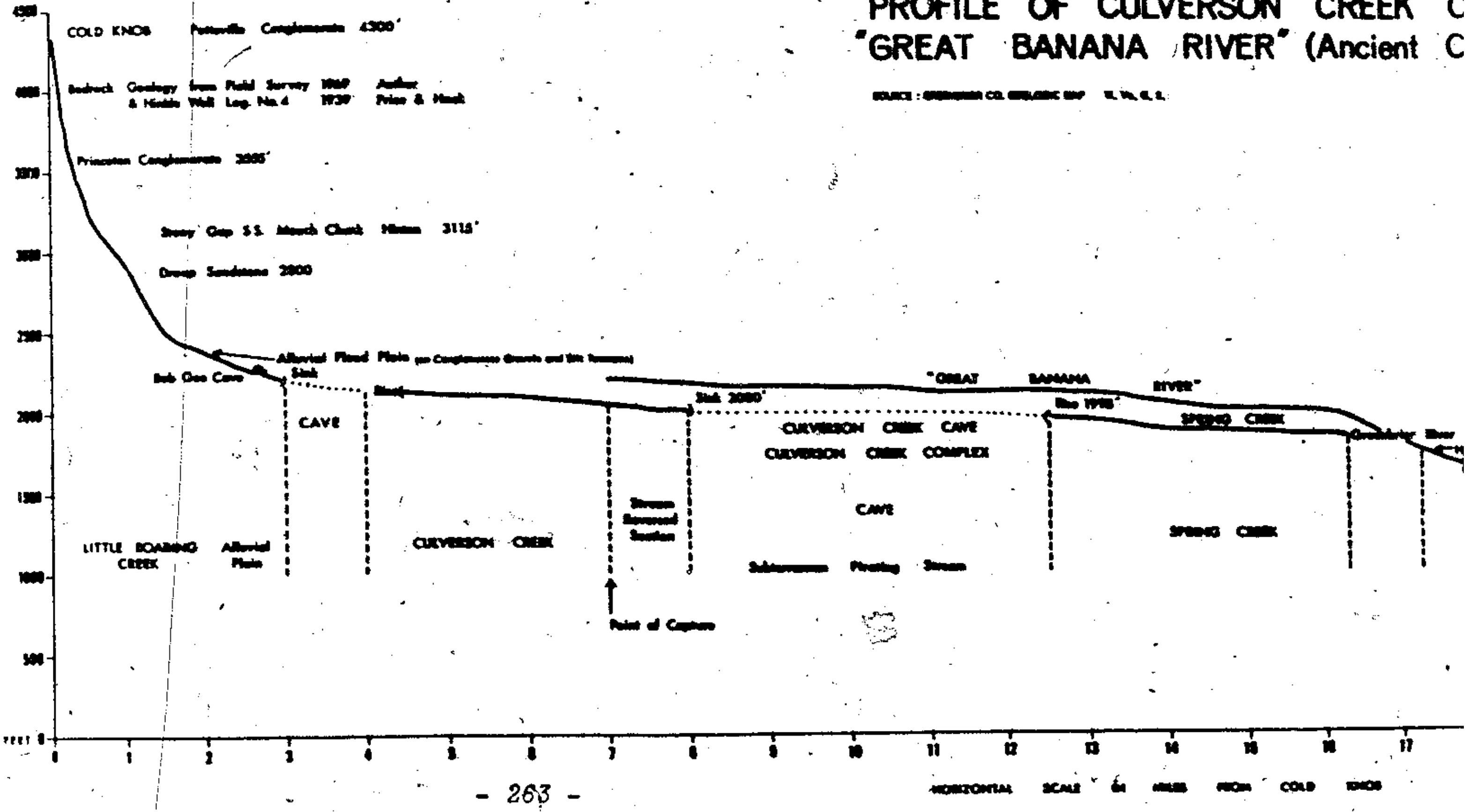
[19] This is estimated to be 8 feet to 12 feet in depth, based upon bedrock areas exposed after the Camille floods in 1969.

axis along the strike. Table 7.01 summarises some of the drainage characteristics of the components of Basin III.

Figure 7.04 (bottom) shows the profile of the trunk channel. The structural influence of an anticline, a syncline and a monocline from west to east along the channel is important. These structures isolate sections of drainage and karst topography completely from one another and exert strong strike orientation on drainage (Figure 3.06). Despite the influence of structure, the ultimate control of drainage is the position of the regional base level. This is, of course, the Greenbrier River which lies east of the limestone. Drainage from the Allegheny escarpment must flow updip and across the strike through three repeated exposures of the Greenbrier limestone in order to reach the lowest elevation. This is a total fall of 2445 feet in a distance of 19.8 miles measured along the trunk channel. Even so, Basin III has the gentlest gradient on the three basins considered in this study: Basin I, 133/1000 ; Basin II, 34/1000 ; Basin III , 25/1000 . Figure 7.05 is measured along the maximum length of the trunk channel extending from the headwaters of Roaring Creek on the Pottsville outcrop near Cold Knob (elevation 4345 feet) to the sink of Roaring Creek into the karst "sieve-type" deposits in Trout Valley (Figure 7.06, Numbers 1 and 2). After an unexplored course through deposits and bedrock of one mile, this drainage, combined

PROFILE OF CULVERSON CREEK C
"GREAT BANANA RIVER" (Ancient C

SOURCE : GREENBRIER CO. GEOLOGIC MAP W. Va. G. S.



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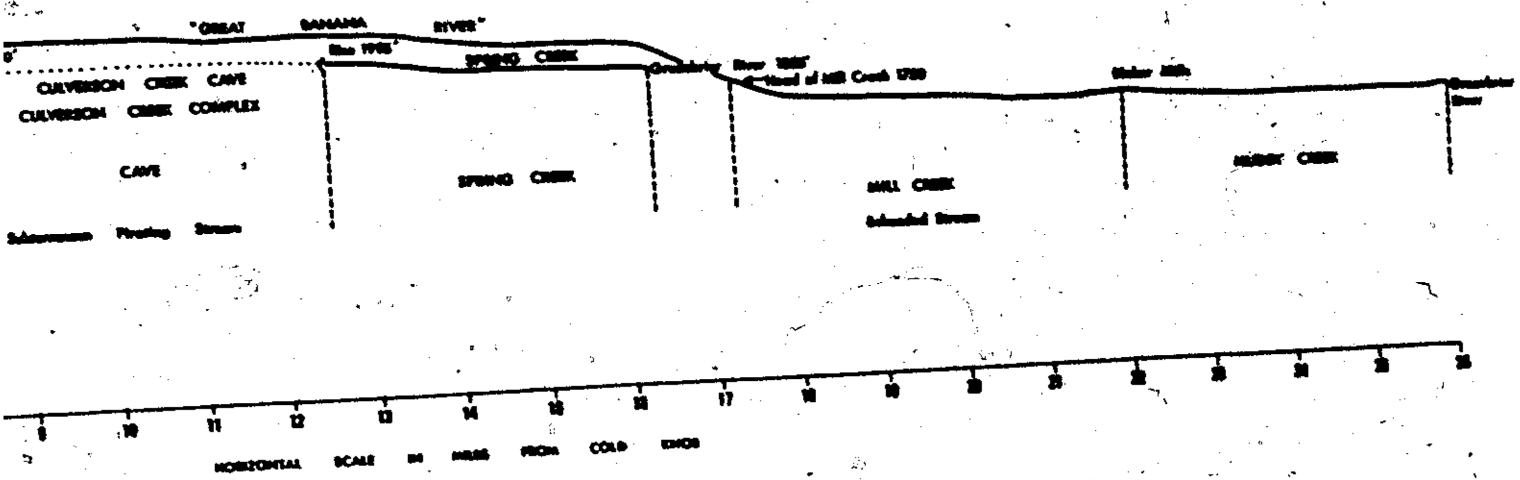
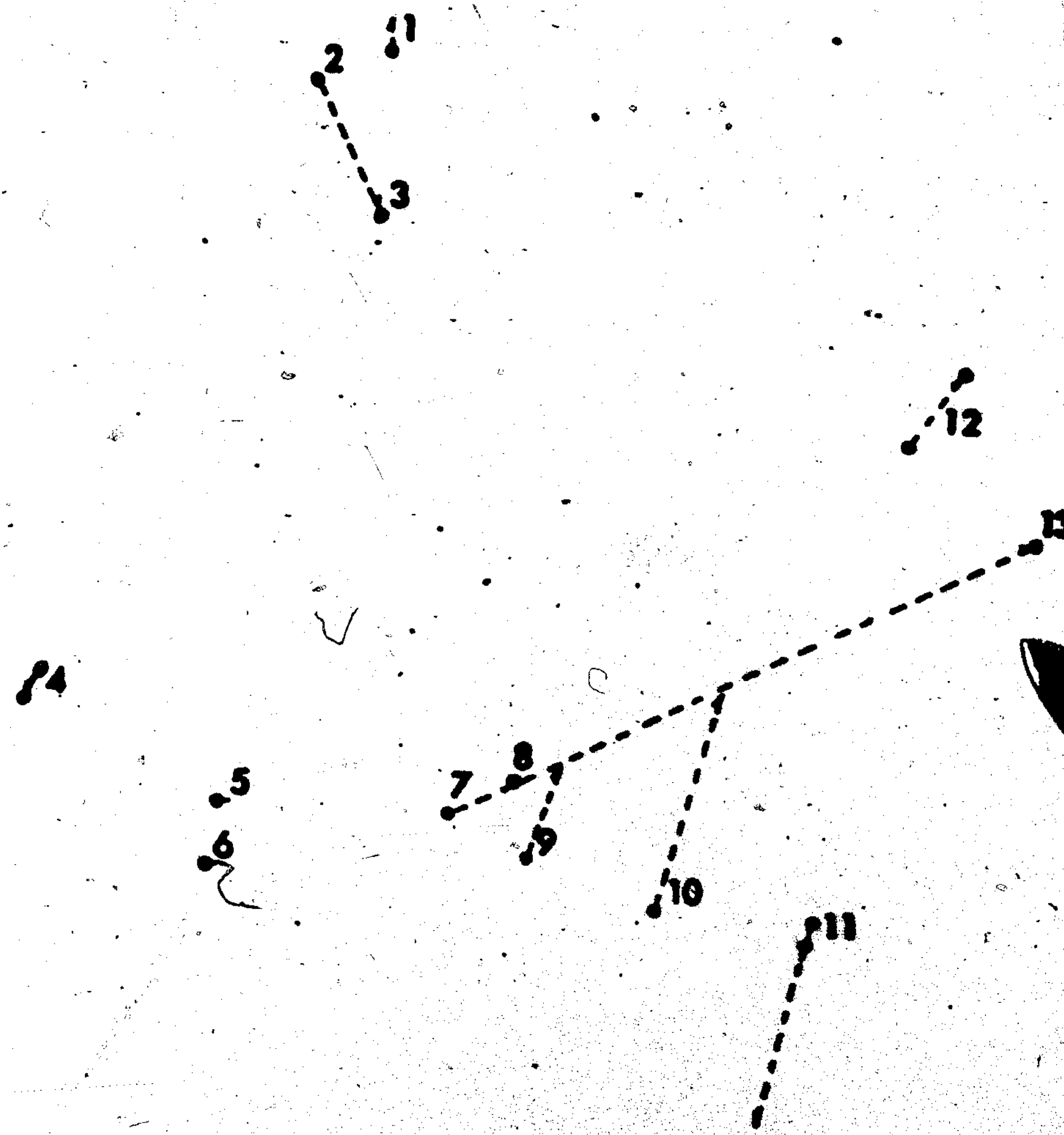
PROFILE OF CULVERSON CREEK CAVE SYSTEM AND "GREAT BANANA RIVER" (Ancient Culverson Stream Bed)

Figure 7.05

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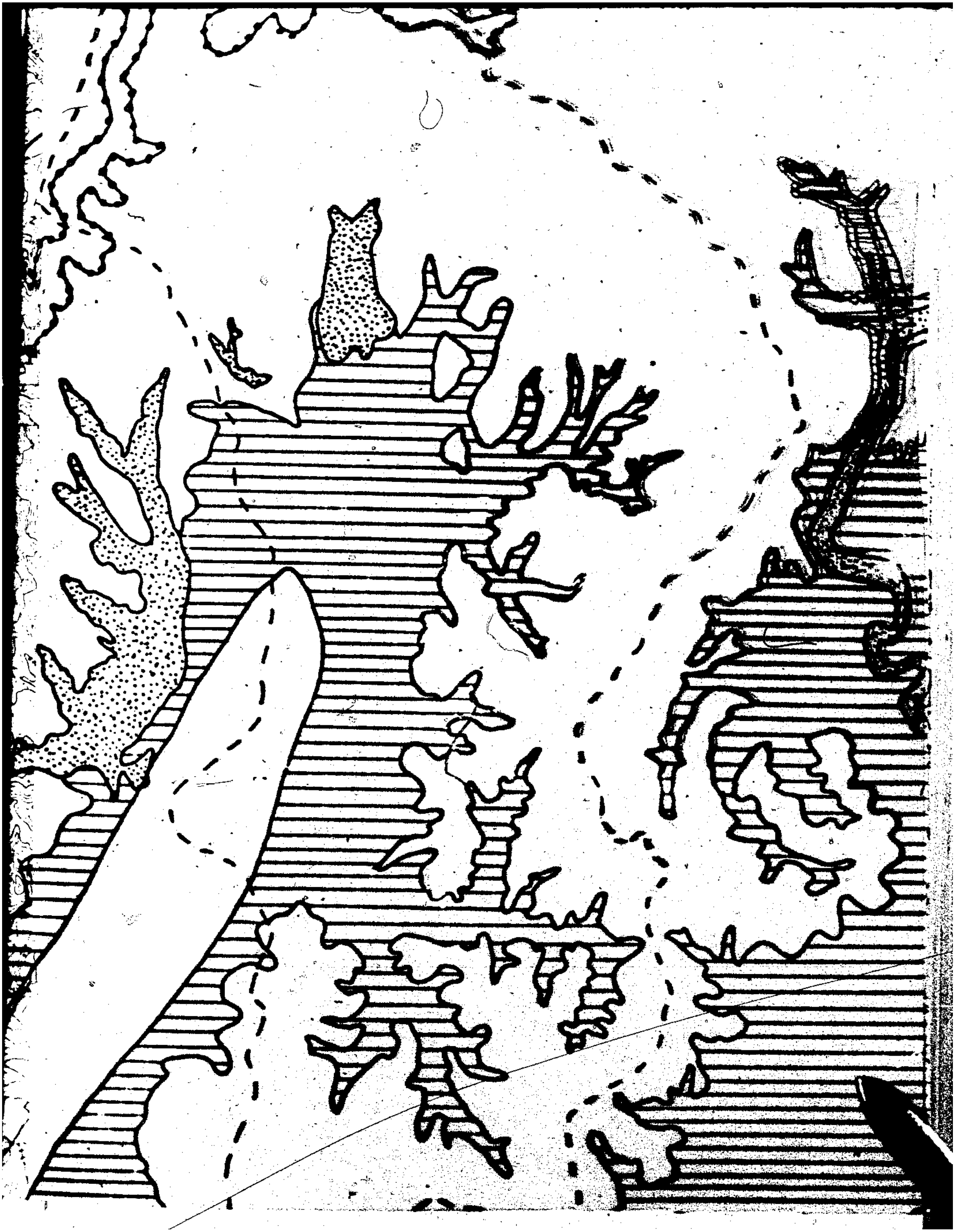

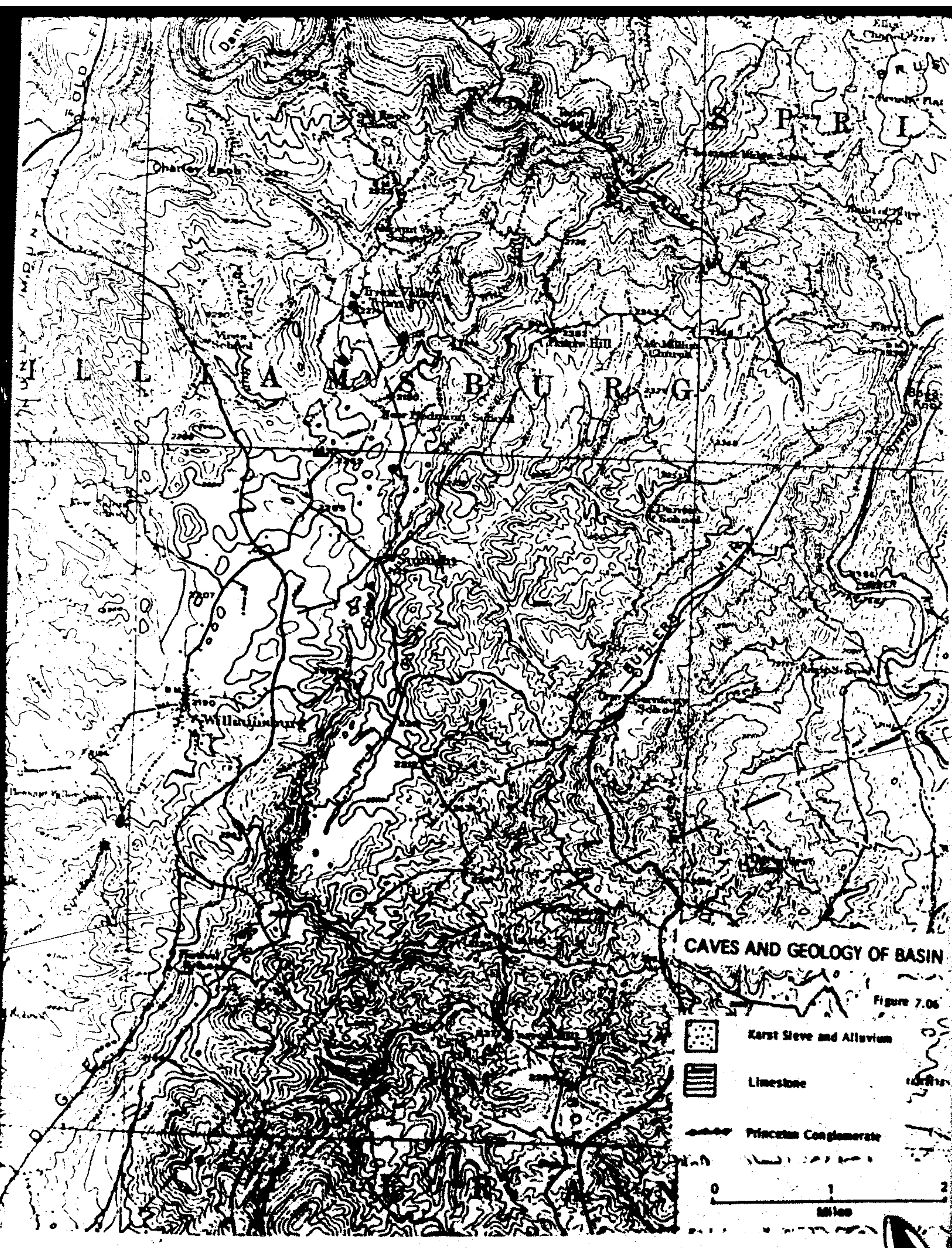

CAVES AND GEOLOGY OF BASIN

Figure 7.06

with Charley Run and Little Roaring Creek, rises on limestone to join Culverson Creek and Indian Creek drainage. This then parallels to axis of Muddy Creek Mountain Syncline and the axis of the Williamsburg Anticline (Brushy Ridge). A sharp turn eastward occurs in the last 2.5 miles of the Culverson Creek surface channel and the drainage flows downdip toward the axis of the Muddy Creek Mountain Syncline. Drainage from the clastic cap rock of the syncline joins the Culverson Creek trunk approximately one mile upstream from its main sink near Unus. This surface drainage from Spice Run and Burns Run enters the trunk channel at an acute angle pointing downstream (Figure 7.04). This strongly suggests a reversal of flow for this portion of the Culverson Creek channel at some time in the past. From its sink point near Unus Culverson Creek flows underground through the lower levels of the Culverson Creek Cave complex for a distance of 4.7 miles to resurge at Spring Creek (Figure 7.06, Number 13).

Modern Basin III contains several strong indications that it is only part of a much greater drainage network which once flowed to the southwest, parallel to the axes of the Williamsburg Anticline and Muddy Creek Mountain Syncline to joint the Greenbrier River via the Muddy Creek channel.[20] The evidence for the existence of this former

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[20] This paleosystem is referred to as the "Great Banana River".

basin and the subsequent subterranean piracy to Spring Creek may be summarised as follows:

1) The centripetal drainage pattern of Modern Basin III.

2) The sharp eastward bend at elbow of capture in the Culverson Creek channel 2.5 miles upstream from the main sink at Unus.

3) The acute downstream-facing angle formed at the confluence of Spice Run and Culverson Creek.

4) The existence of a high level, dry channel, 50 feet above and continuing downstream from the bend (referred to in point 2) parallel to the axis of the Williamsburg anticline.

5) The presence of rounded quartz pebbles in terraces downstream along this ancient channel. Pebbles were collected and analysed for mean size and roundness properties in a downstream direction along the assumed former drainage route. This was also done for samples collected downstream along the modern channel, its associated high level terraces and randomly chosen sites surrounding Basin III.

6) The presence of scallop reversals in the uppermost level, i.e., the "Echo Gallery", of the main Culverson Creek Cave channel approximately 1.5 miles downstream from the modern sink of Culverson Creek. This scallop reversal suggests that former underground drainage

near the sink of Culverson Creek flowed westward to join the drainage net of the "Great Banana River". Lower level scallops are in accordance with modern directional flow towards Spring Creek and the east.

It would appear that the last 2.5 miles of surface drainage of Culverson Creek has since reversedits flow from the bend (referred to in 2 above) and has been pirated by Spring Creek drainage. This concept of reversal is also supported by the unusual angle of confluence (referred to in 3 above). There is a clear change in provenance of the sediment source for the upper and lower passages of Culverson Creek Cave to support this concept of drainage reversal in the cave.

Since the surface capture of Culverson Creek, 150 feet of downcutting and removal of bedrock has taken place at the point of capture. The breaching of the semi-impervious Greenville shale may have been the impetus for the initiation of this piracy. This would then permit the two independent networks of drainage above and below the shale to integrate at the breaching point which has since migrated two miles upstream along Culverson Creek trunk channel.

The surface network of Buckeye Creek (Figure 7.06, Number 12) still maintains a completely separate drainage basin above the underground channel of Culverson Creek. These are separated by two impervious shale layers within the Greenbrier limestone series.

Figure 7.05 shows a comparison of profiles of the modern and ancient channels of Culverson Creek. These are measured in horizontal miles downstream from Cold Knob along Little Roaring Creek. No major nickpoints appear in the modern channel which is typical of the graded surface basins in this area of the Appalachians. The ancient stream bed shows a large nickpoint at the head of Mill Creek. This is due to the fact that the modern drainage of Mill Creek (the downstream remnant of the former basin) is still actively downcutting in the lower channel of the "Great Banana River". This has also removed any former terraces below the head of Mill Creek. Terraces were found to contain quartz pebbles along the ancient channel from mile 7.0 to 16.0 (Figure 7.05). The source of this material can only be from the headwaters of Charley Run, Roaring Creek or Little Roaring Creek (Figure 7.06). Brushy Ridge provides an effective barrier to drainage and sediment transfer from the west flank of the anticline. This separates the modern channel of Sinking Creek from the ancient channel of Culverson Creek. The former still maintains strike oriented flow for 35 miles along the west flank. This drainage has cut to nearly the same depth as the modern drainage in a similar position in Culverson Creek.

B. Subdivisions of the Modern Basin

Because of the large size and increased complexity in Basin III description emphasizes the major drainage conduits. Some minor tributary systems are not considered. The basin may be subdivided as follows:

1. **The Upper Basin**
    - a. Roaring Creek, Little Roaring Creek and the Trout Valley System
    - b. Other Headwater Drainage from Clastic Sources
2. **The Middle Basin**
    - a. Culverson Creek
    - b. The Culverson Creek Cave Conduit
3. **The Lower Basin**
    - a. The Culverson Creek Rising
    - b. The Spring Creek System

1. The Upper Basin

a. Roaring Creek, Little Roaring Creek, and the Trout Valley System

The headwaters of Basin III are characterised by steep gradients, rapid flow and massive bedload movements during times of high flood. For example, Roaring Creek falls 1300 feet in the first stream mile of the channel. The first four miles of its course are entirely across clastic rock. This is mainly the sandstones and shales of the Bluefield Group of the Mauch Chunk series. At their headwaters Roaring Creek and Little Roaring Creek flow on the Pottsville series conglomerate. Large boulders of conglomerate and sandstones, mainly Pottsville conglomerate, Princeton conglomerate, Stony Gap sandstone and Droop sandstone are carried out onto the limestone surface and deposited in Trout Valley in a large alluvial-colluvial deposit. This deposit, which extends over one square mile of limestone terrain and reaches to 190 feet in depth[21] in the centre of the valley, is similar to the karst "sieve-type" deposit described in Basin II. Figure 7.07 is an oblique air photograph showing the southwest side of it. The village of Trout is situated at the lower centre of the photograph. This is the location of the deepest part of the deposit. Roaring Creek and Little Roaring Creek join near the head of the deposit and depending upon the volume of runoff, sink at various points downstream across the valley. Figure 7.08 shows three major zones of accumulation across the valley. In zone I large angular boulders with a mean length of 2.5 meters are found in a matrix of rounded smaller boulders and gravels. No limestone outcrops in this zone and all material is clastic sandstone, shale or conglomerate. During extremely low water, drainage sinks just beyond the margin of this zone and zone II. Water supply for the few hundred inhabitants of the valley is obtained from drainage entering the valley head in zone I. Throughout most of the year, however, water flows on to zone II and sinks at two major swallows where bedrock limestone is exposed. Approximately 9 cfs. was observed entering each of these

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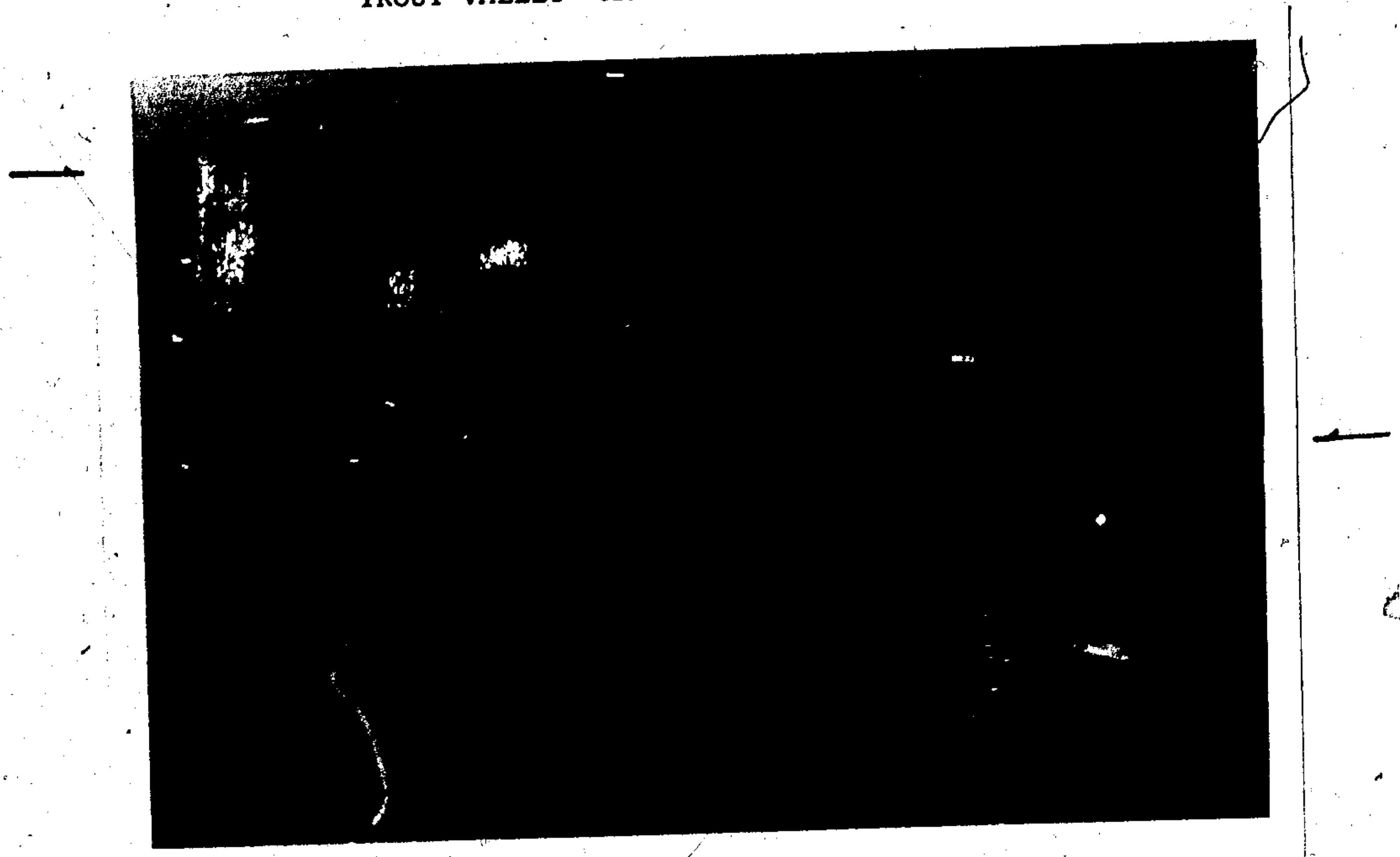
[21] Based upon well log data in Trout Valley.

Figure 7.07

TROUT VALLEY "KARST SIEVE" DEPOSIT



The village of Trout, West Virginia lies in the centre of a large karst sieve-type deposit. The main Roaring Creek channel enters at the bottom of the photograph and sinks at the top centre. The arrows indicate the extent of the deposit.

ALLUVIAL AND COLLUVIAL DISTRIBUTION ON THE KARST SIEVE

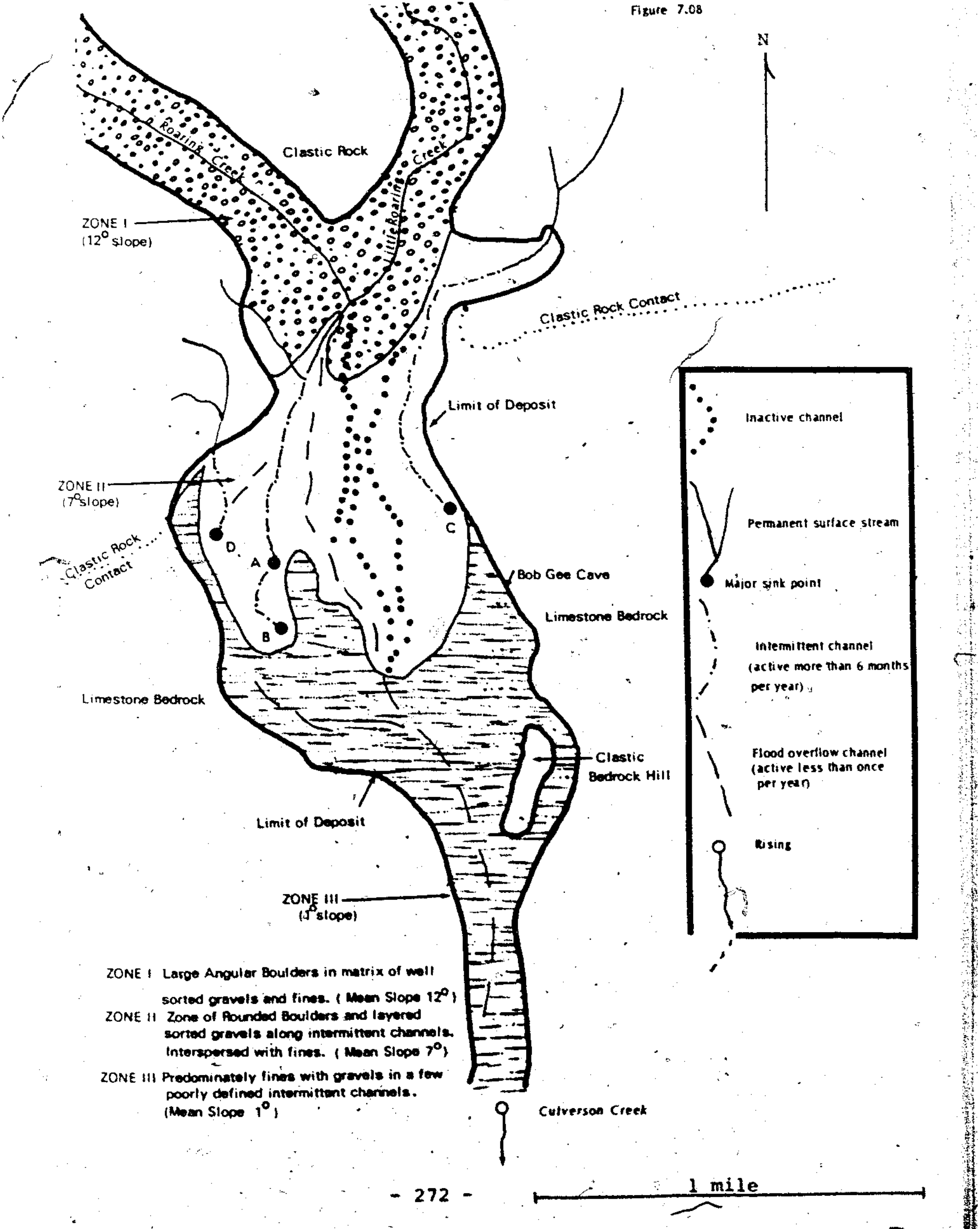


Figure 7.08

ZONE I Large Angular Boulders in matrix of well sorted gravels and fines. (Mean Slope 12°)

ZONE II Zone of Rounded Boulders and layered sorted gravels along intermittent channels. Interspersed with fines. (Mean Slope 7°)

ZONE III Predominately fines with gravels in a few poorly defined intermittent channels. (Mean Slope 1°)

swallows on several occasions during mean runoff conditions. These are shown as points A and B on Figure 7.08. Two smaller streams sink at points C and D during higher than average runoff conditions. No bedrock is exposed at these latter sinks. Zone II is comprised mainly of well sorted layers of gravels and silts. Figure 7.09 is a profile dug in zone II near the zone III contact. A soil profile is buried under coarser rounded boulders and gravels imbricated down the slope of the deposit. At several places across zone II, channels have been cut and larger boulders are common. Figure 7.10 shows an air view of the main channel of Roaring Creek above point A (Figure 7.08). The straight part of the channel has been widened by earth-moving machinery. After the storms of 1969 it was completely filled with large rounded bolders which appear in the photograph. A paleochannel is outlined by small trees and shrubs (Figure 7.07). Zone III is in the background and zone II is outlined by trees. The arrows in the margin indicate the limit of the coarser "sieve type" deposition of zone II.

Zone III (Figure 7.08) is composed of fines. A few surface gravels exist in poorly defined channels along the right of the deposit. During Hurricane Camille, drainage flowed across the zone. Boulders were carried across the upper one-third of it. This was a rare event. Much of zone III is classed as "sandy loam" and "silt loam" by the United States Department of Agriculture. This is considered to be well drained and not subject to flooding. A paleochannel

SEDIMENT PROFILE IN ZONE II

Figure 7.09

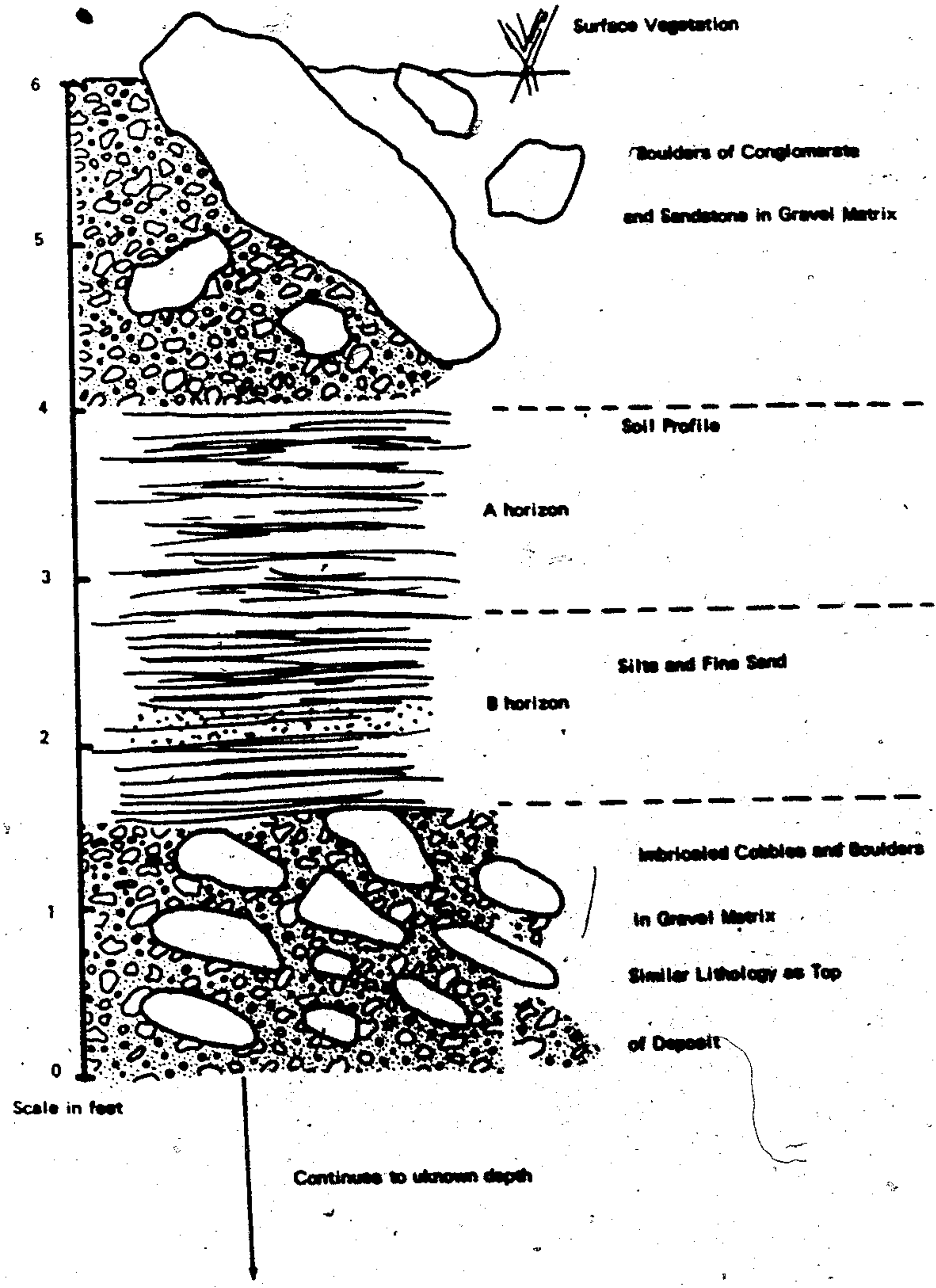


Figure 7.10

ROARING CREEK CHANNEL AT TROUT

outlined in gravels is traceable all the way to the toe of the deposit at the rising of Culverson Creek (Figure 7.08).

Karst sieve deposits, such as described above, are frequently found along the clastic/carbonate bedrock contact. They result from the deposition of surface stream bedload when surface drainage is filtered through the alluvial veneer of the surface stream to underground conduits developed in the underlying carbonate bedrock. The stream profile shows no major alteration at the contact (Figure 7.05). The deposition of at least 165 feet of material has occurred in zone II (Figure 7.08). Throughout the Greenbrier karst such "sieve-type" deposits are commonly developed along the western margins of the limestone. There appear to be several reasons for the western clastic/carbonate contact occurrence. These are:

1) The abundance of well-consolidated, massive bedded, clastic sedimentary rock in the headwaters of the western contact streams. These rocks include the Pottsville and Princeton conglomerates and the massive Hinton and Droop sandstones. The only such source of clastic material is the Droop sandstone to the east. The bulk of the clastic outcrops to the east are shales in the Bluefield formation.

2) The length of tributaries and size of catchment is greater for the western margin streams.

3) The influence of frost action and possible peri-glacial activity in the past due to higher elevation

along the western margins which provided a greater source of material from the west along the Allegheny escarpment. Elevations here exceed 4500 feet. Peaks along the eastern contact do not exceed 2800 feet.

In general, the deposits on the limestone from eastern contact streams are composed of well-sorted sands and abundant silt and clay terraces. Such streams as Spice Run, Burns Run and the headwaters of Indian Creek are supported on massive deposits of clay and silts. The term "sieve-type" deposits is reserved for the coarser deposits of the western margin streams.

It seems probable that the greater bulk of these deposits was accelerated by peri-glacial mass movement during colder periods recorded in this region 10,000 years B.P.[22] Zone I (Figure 7.08) is comprised mainly of coarse material which does not show evidence of rounding and stream transport. This is a mass wasted deposit. The reworking and removal of material from zone I results in the supply of progressively finer and better rounded material in zones II and III. The loss of drainage into the karst beneath produces a net accumulation at the limestone contact. The observations and analysis of the inactive entrance facies of Bob Gee Cave, which lies immediately along the east side

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[22] Studies by Clark (1968), Craig (1969), Darlington (1943), and Guilday (1971) show evidence for a periglacial environment from patterned ground, pollen analysis and plant and animal distribution, respectively.

of the Trout Valley sieve deposits, support the hypothesis of peri-glacial surface deposition. Further studies are needed to make more positive conclusions.

b. Other Headwater Drainage from Clastic Sources

After sinking at the head of the Trout Valley "sieve-type" deposit, Roaring Creek drainage rises at Bransford Cave and Marshall rising below zone III (Figure 7.08) and flows on surface alluvium to join the ephemeral waters of Culverson Creek and the intermittent drainage of Indian Creek (Figure 7.07). This additional surface water drains from the clastic outcrops of the Mauch Chunk series preserved upon Muddy Creek Mountain syncline. The syncline lies to the east of Trout Valley and trunk channel of Basin III. The bedload of this eastern tributary contains only shale and sandstone detritus which quickly breaks down into clastic component particles. As a result, the surface alluvium is not a coarse "sieve-type" variety, but of a fine textured silt and sand. Much of this material forms surface terraces which are of a fluvial origin. These surface deposits were not investigated in detail.

2. The Middle Basin

a. Culverson Creek

From the Marshall rising below the Trout Valley deposit to its major sink point, Culverson Creek is supported on the surface entirely by thick, fine textured deposits and gravel veneer, which "shield" it from the underlying limestone bedrock. There may also be some lithologic control in maintaining surface flow caused by presence of interbedded carbonate shale members in the underlying bedrock. These are not exposed, however, due to the thickness of the surface alluvium. This is estimated from terrace and river cuts to exceed 10 feet along much of the middle section of Culverson Creek. Well-rounded boulders up to 25 cms. derived from the Pottsville or Princeton conglomerate and deposited in a matrix of coarse stream gravels, comprise the stream bed of Culverson Creek from its source downstream from Trout Valley to its main sink point near Unus.

Figure 7.11 is an oblique air view of the centre of this portion of the basin. In the lower left, an alluvial terrace 30 feet high corresponds to a similar feature on the opposite bank. Boulders in a matrix of gravels make up 75% of material in the terraces. The point bar along the main channel is comprised of gravels and sand. The area void of vegetation on the downstream side of the point bar is the remains of surface veneer deposited by the Hurricane Camille flood two years before this photograph was taken.

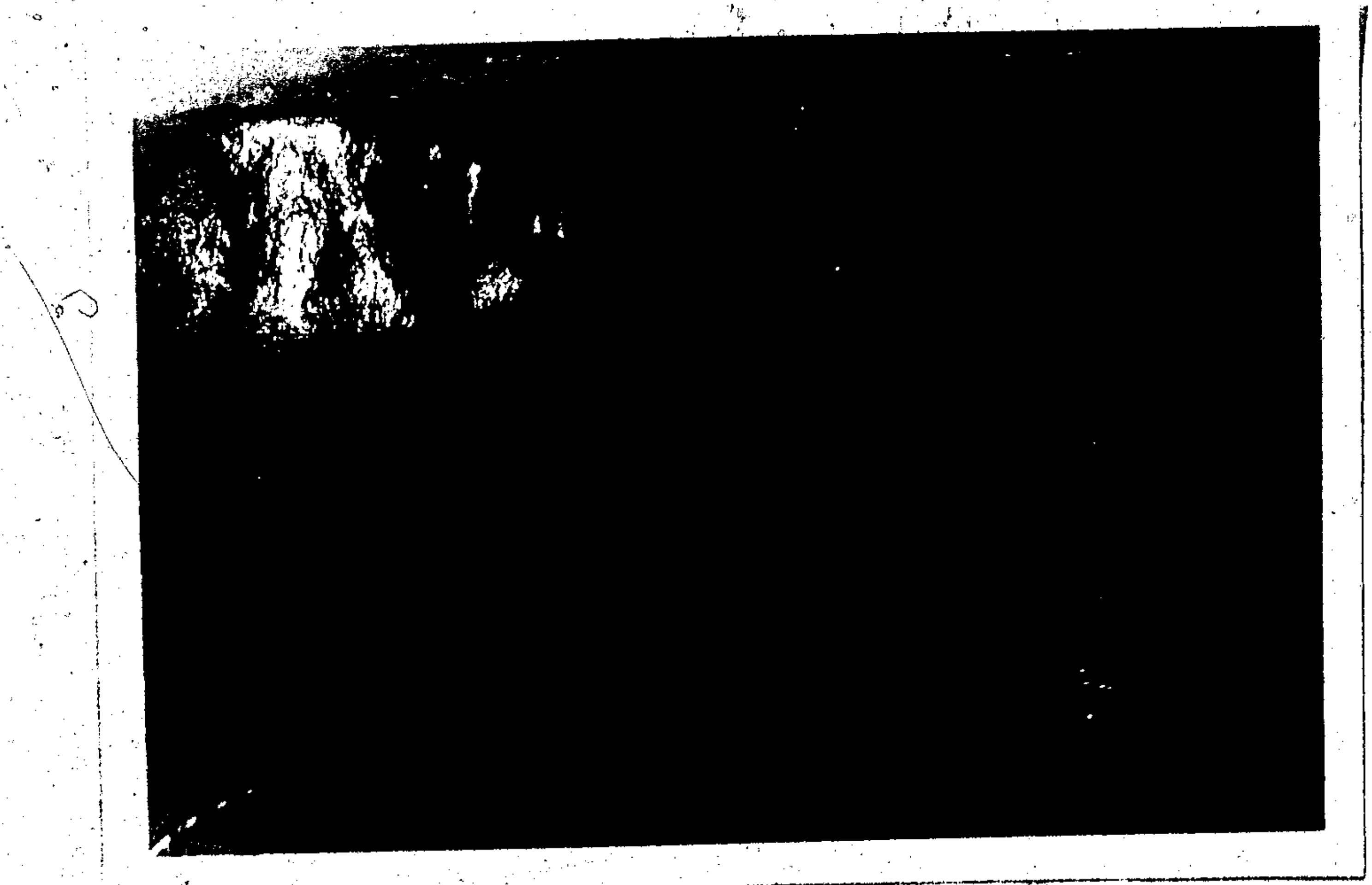
Figure 7.12 is an aerial view of the lower section of the middle basin. At the top of the photograph is the forested Williamsburg anticline (Brushy Ridge). Culverson

Figure 7.11

CULVERSON CREEK VALLEY AND TERRACE

Figure 7.12

THE PRESENT HEAD OF THE "GREAT BANANA" VALLEY



The Williamsburg (Brushy Ridge) Anticline is seen in the upper "treed" section of the photograph. Note the highly karsted portion of the paleodrainage channel in the lower left (C). Drainage enters at A, and flows out at B. The former paleochannel entered at A and flowed out at C along the strike of the anticline.

Creek flows down the valley from the top right, and makes a sharp turn to lower right at the centre of the picture. This turn is the point of capture and diversion of the former drainage of Culverson Creek from the "Great Banana River" outlet which flowed toward the lower left of the photograph (Chapter 7, A. Introduction).

Figure 7.13 shows the sink of Culverson Creek. The stream flows from the bottom centre of the photograph into the cliff face in the centre of the photograph. Within the cave, the meander bend of the surface channel is continued underground to the centre right of the photograph. The local relief of the limestone surface is greater than 300 feet in this photograph. An additional 600 feet of limestone remain beneath the elevation of the sink entrance, in which subterranean conduits are extensively developed. on fine silt and clay alluvium which has accumulated during occasional ponding at the entrance site after very heavy flooding as from the Camille storms of 1969.

Figure 7.14 is an oblique air photograph taken approximately one-half mile due east of Figure 7.13, directly above the underground conduit of Culverson Creek. The small village of Unus is seen in the centre of the photograph. A centripetal pattern of five dry valleys converges at the barn in right centre. Three dry entrances to the Culverson Creek Cave system lie within the area shown in the photograph: Wildcat Cave (A), Fuller's Cave (B), and Hinkel's Cave (C). None of these open directly into the main

Figure 7.13

THE SINK OF CULVERSON CREEK

Figure 7.14

THE DRY VALLEY ABOVE THE UNDERGROUND CONDUIT OF CULVERSON CREEK CAVE

A......Wildcat Cave B......Fullers Cave C......Hinkel's Unus Cave

Culverson Creek conduit, but are entrances to smaller tributary caves which act as intermittent wet-weather feeder channels to the main active stream conduit.

b. The Culverson Creek Cave Conduit

Figure 7.15 is a generalised plan of the Culverson Creek Cave system. A total of 10.73 miles (56,675 feet) has been mapped in it.[23] This total includes extensive upper levels and small connecting tributary conduits from the five entrances (Figure 7.14). The straight line distance from sink point to rising is 4.6 miles. The total length of this conduit has never been explored or mapped, but it is estimated from the two miles of main trunk conduit already known that the actual distance in stream miles is close to seven miles.

The main stream passage is linear in pattern and trends north 50° to 80° east. This is across the regional strike and updip. The mean gradient for the main stream conduit is approximately 3/1000 . In several places along the stream route, meander cutoffs and lower level diversions are occurring. These tend to straighten the channel and alter previously established joint or strike controlled orientation. Upper levels are developed along the strike and are usually connected by vertical drops to the main conduit. McLaughlin's Unus Cave, Hinkel's Unus

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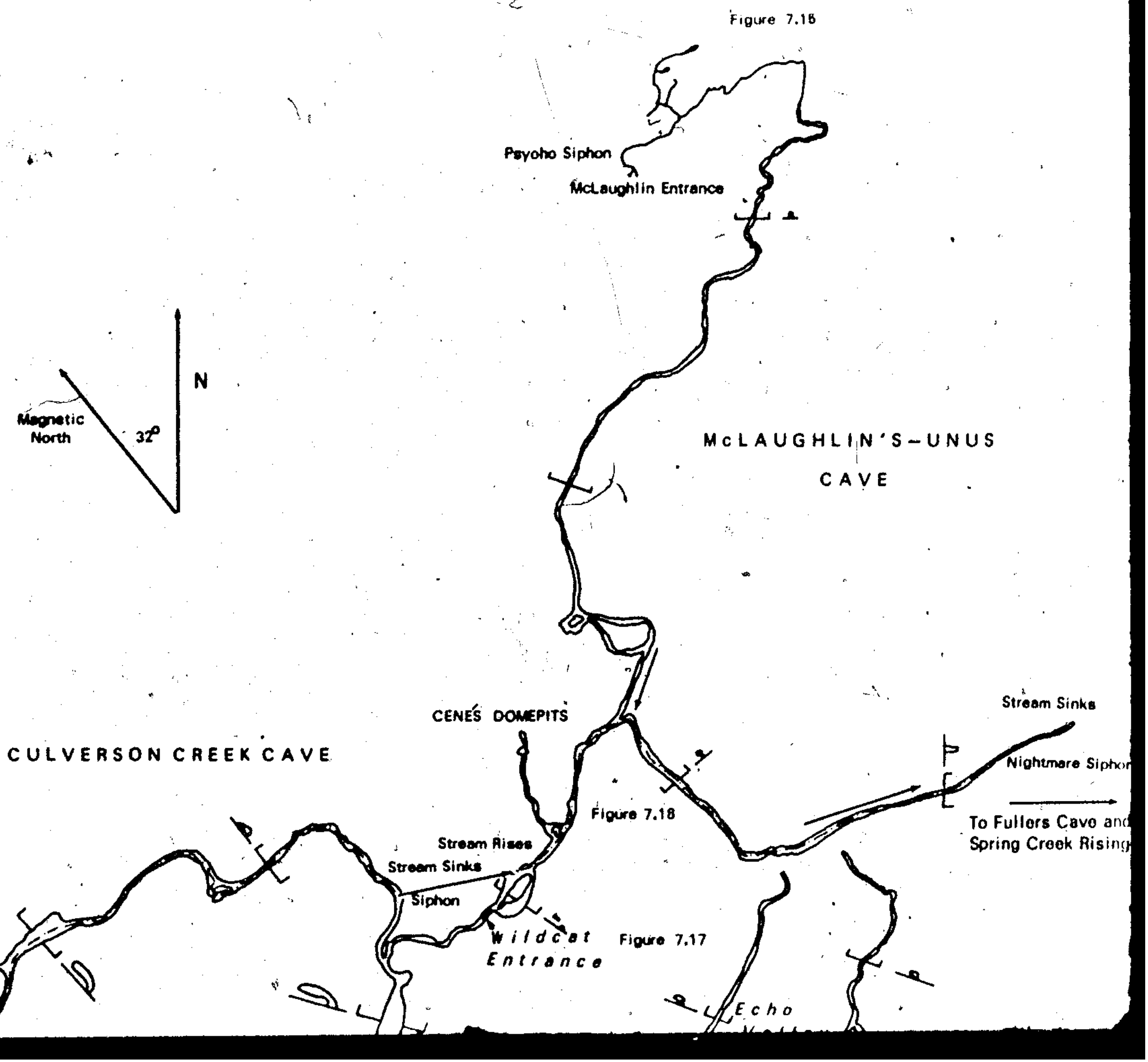
[23] Based upon figures in the secretaries report of the West Virginia Association for Cave Studies, January, 1971.

CULVERSON CREEK CAVE SYSTEM



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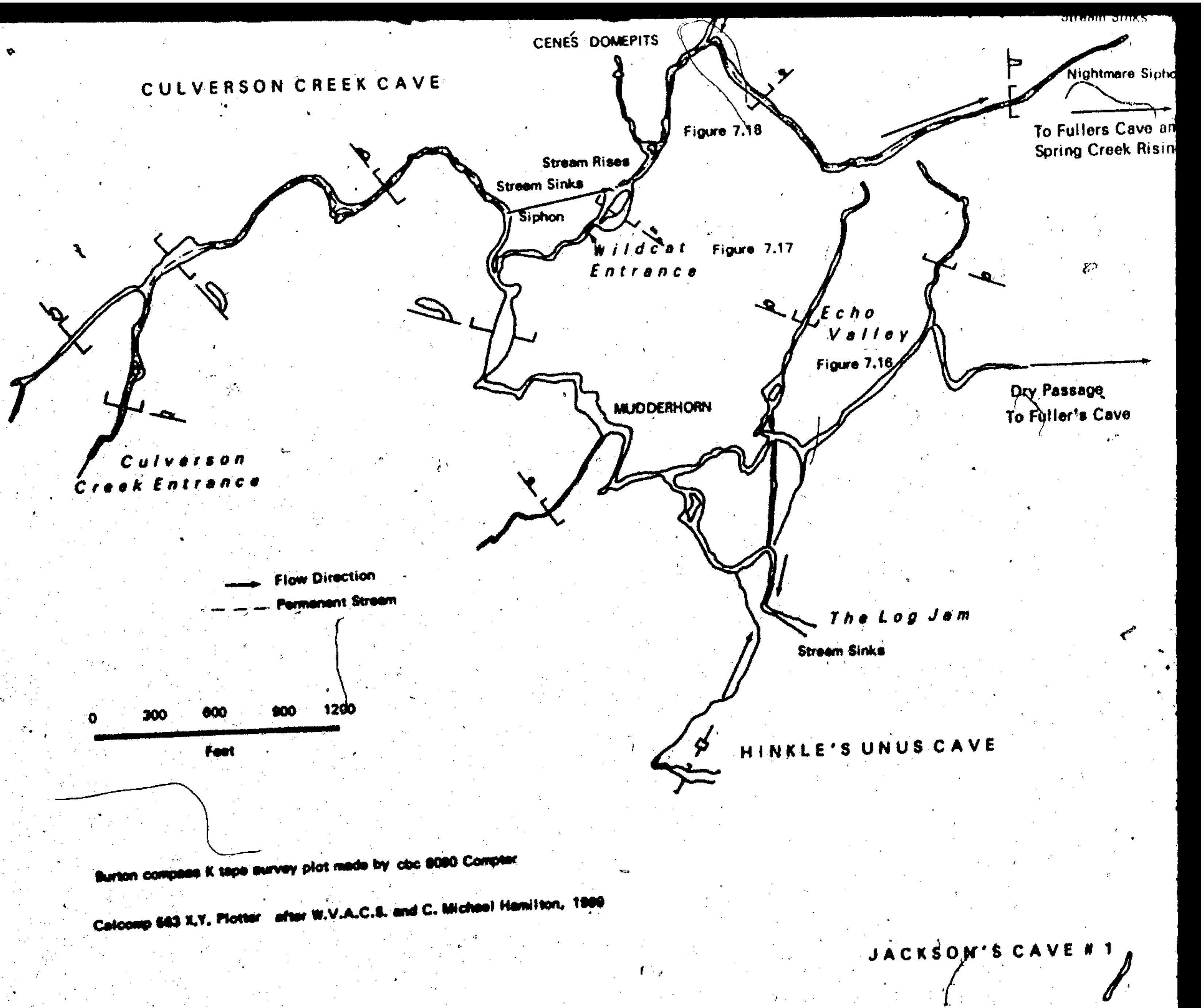


Burton compass K tape survey plot made by cdc 6600 Compter

Calcomp 563 X,Y. Plotter after W.V.A.C.S. and C. Michael Hamilton, 1969

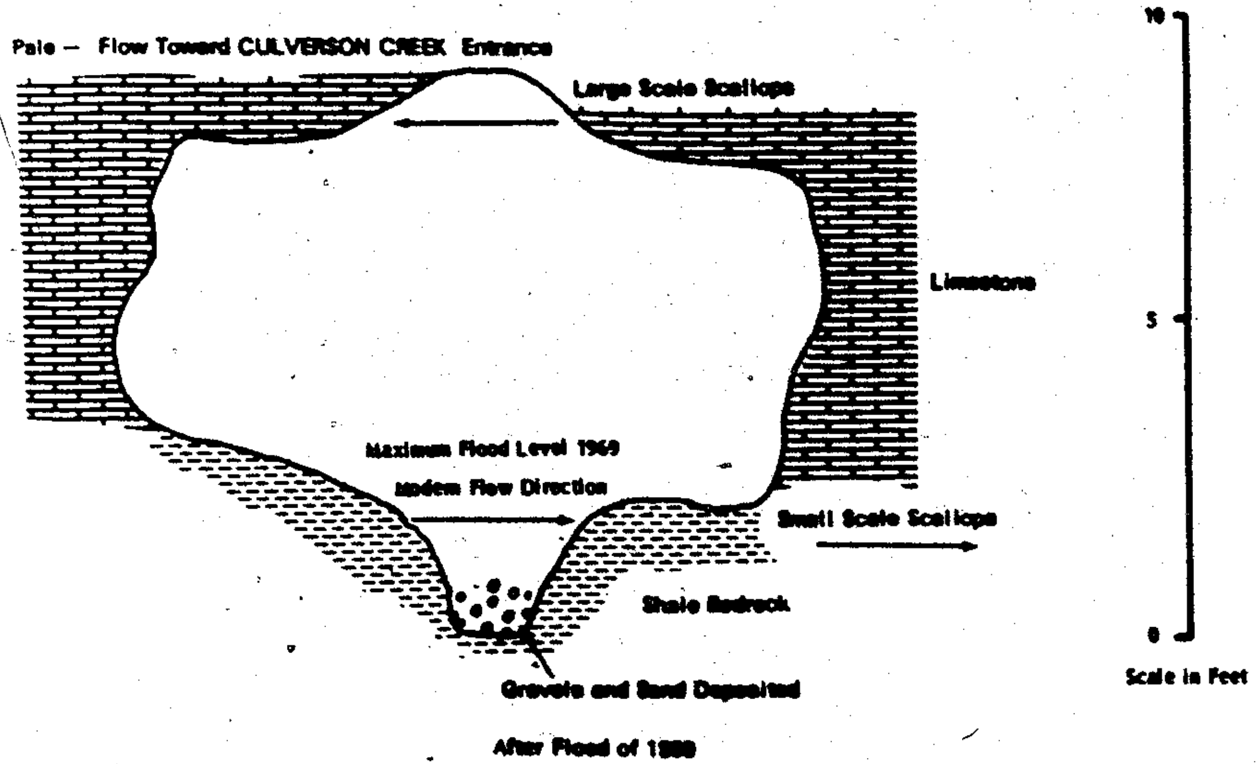
Cave, Fuller's Cave, and Wildcat Cave (Figure 7.15) make up the upper level system, each with its own extrance. These passages are smaller and typically vadose in character, with little sediment accumulation.

During flood conditions these upper levels receive overspill from the main conduit below. The only known area of the cave not reached by the high waters of the Hurricane Camille flood was the "Echo Gallery". The ceiling of this passage is 55 feet above the mean stream level in the active conduit. Recent deposits from the hurricane occurred as high as 45 feet above the stream. The cross-section shows a phreatic solution tube developed above a shale bed which contains a small vadose trench three feet deep. The cross-section in Figures 7.16, 7.17 and 7.18 are typical of the main conduit. The position of these cross-sections is indicated on the map in Figure 7.15. There is little doubt that more than 90% of the volume of this cave fills with water during flood. This occurs several times a year. Modern active flooding and associated ponding behind the syphons are the main source of sediments in the cave. The bulk of the deposits throughout the cave are finer than one millimeter in grain size.

Stream flow measurements in the main conduit one mile downstream of the sink were monitored by Coward from the spring of 1970 to the summer of 1972. He estimates a mean flow of approximately 30 cfs. (Coward, 1972, personal

CROSSECTION IN 'ECHO GALLERY', CULVERSON CREEK CAVE

Figure 7.16



GENERALISED CROSSECTION AT WILDCAT ENTRANCE, CULVERSON CREEK CAVE

Figure 7,17

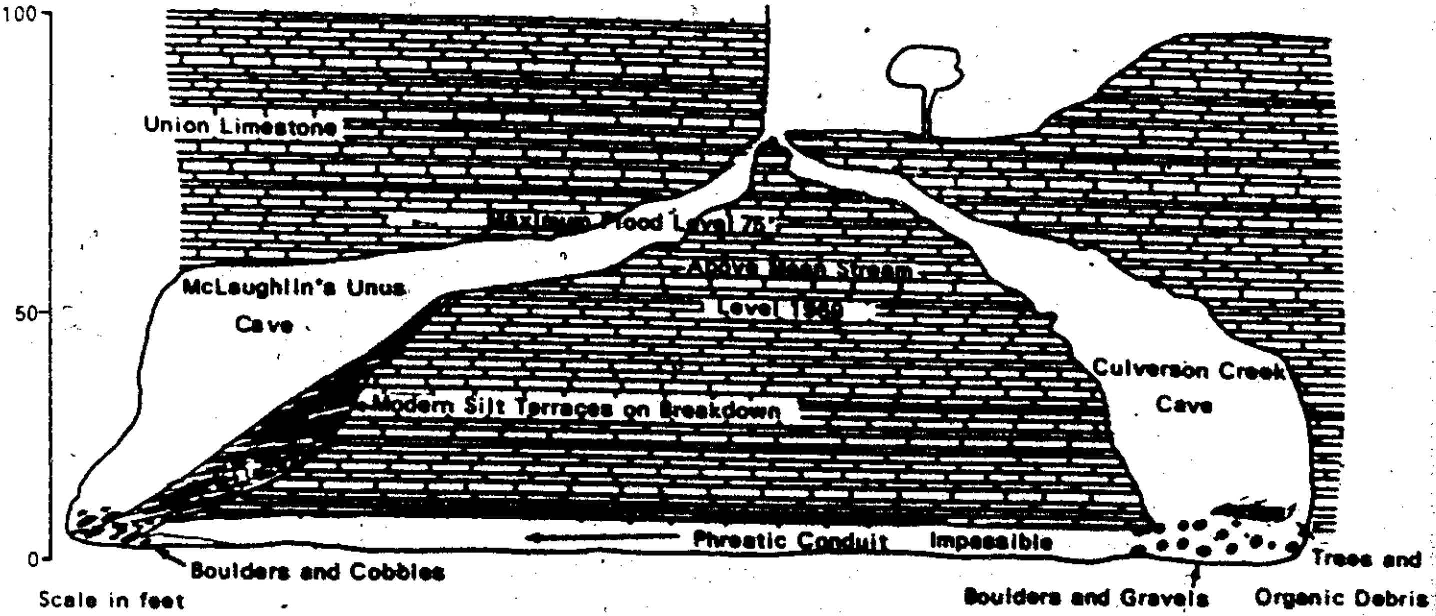
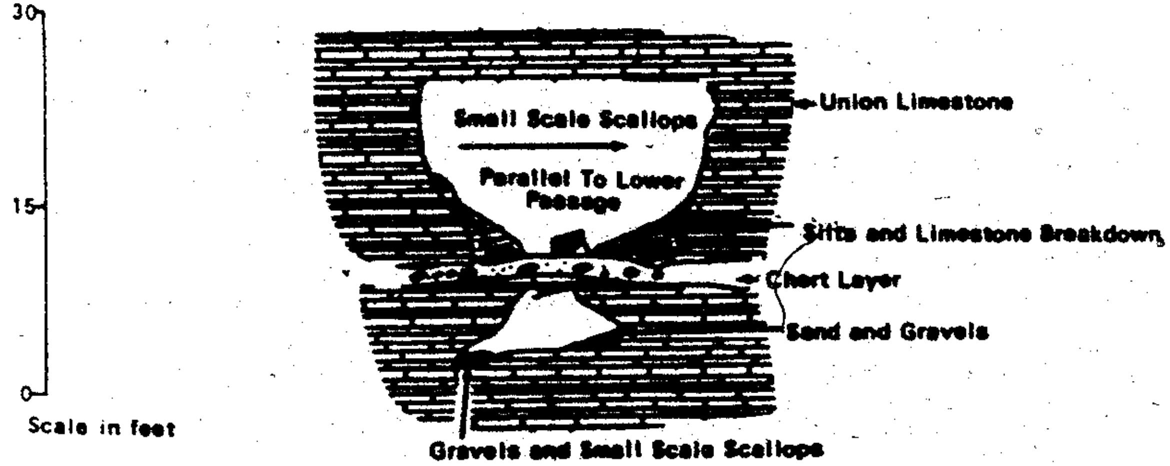


Figure 7.18



communication). Figure 7.19 shows this portion of the main stream near the Wildcat entrance (Figure 7.15). Here flow velocity is approximately three feet per second, and small irregular scallops are being generated on the cave floor by active bedrock solution. This photograph was taken during moderate runoff conditions. Estimated stream flow fluctuates greatly, from 20 to over 500 cfs.

The solution of the bedrock floor is very noticeable throughout the lower levels. Figure 7.20 shows scallops of a mean long axis of 3.2 cm. forming in association with the transport and deposition of bedload material ranging from coarse sand to cobbles. This is mainly derived from the Droop sandstone and other massive bedded sandstones. Up to 35% milky quartz gravels were found in point bars within the range of 10 mm. to 28 mm. deposited after Hurricane Camille.

Further evidence of active bedrock solution is seen in Figure 7.21. Here a rock span of 30 feet bridges the main active channel. The soluble Union limestone member has dissolved away, leaving behind a less soluble bed of chert. What would normally be a vadose trench cut into a larger, initially phreatic tube, is a two section passage; the larger passage being above the small vadose conduit. Note the abundant medium to small size scallops. The larger ones are formed during paraphreatic pipe-full flow of the lower tube. These are developed on the ceiling

Figure 7.19

SCALLOPS IN CULVERSON CREEK CAVE STREAM BED

Figure 7.20

SCALLOPS AND SEDIMENTS, CULVERSON CREEK CAVE

Small scallops and coarse sands in a contemproaneous situation. Gravels are deposited in flood conditions. This photograph was taken during mean water conditions. Small pools occupy each scallop in the foreground, some of which contain coarse sand. Note the ripples in the sand.

Figure 7.21

INSOLUBLE CHERT LAYER IN CULVERSON CREEK CAVE

and upper walls. Below on the floor, small (2.5 to 5.0 cm.) scallops (at the feet of the lower observer) develop under variable vadose flow. Flow direction as indicated by all scalloping in both levels shown in Figure 7.21, is toward the rear of the photograph.

Although some coarse bedload enters the cave, the great bulk of sediments are finer than sand size. Boulders and pebbles make up the bedload of the active channel only as far as the first syphon near the Wildcat entrance (Figure 7.15). Beyond this point the gentle stream gradient and frequent ponding produce the deposition of fines. During flood, vegetational debris and mud block the lowest levels, thus causing a drop in stream velocities which dams up a high volume of water and floods most of the upper levels. A rise of more than 100 feet took place during Hurricane Camille. The result was the deposition of silt within a few feet of the otherwise dry and inactive Wildcat entrance.

Figure 7.22 shows some of the massive fine deposits in this passage (note the observer for size comparison). Limestone breakdown comprises the bulk of the coarse material. Ponding within the lower passage occurs several times a year when the marrower syphons become clogged with large trees and debris. At these times discharge exceeds the volume of the passage at these constricting points. Both cave explorers and flood waters must seek higher by-pass levels in order to continue along the general route from sink point to rising.

Figure 7.22

MASSIVE DEPOSIT OF FINES NEAR THE WILDCAT ENTRANCE TO THE MAIN STREAM CONDUIT, CULVERSON CREEK CAVE

The arrows in Figure 7.15 show the general flow direction of permanent and intermittent flow channels. The "Mudderhorn" is a 45 foot high accumulation of silt and clay deposited in an intermittent passage near the Wildcat entrance (Figure 7.15). This material accumulates as the result of ponding in the active channel during flood.

The upper levels of Culverson Creek Cave which flood on the average of twice per year, contain more sand size material than the lower clay-silt containing passages of the main active channel. This may be due in part to the winnowing of fines from these upper level deposits. Mean grain sizes range from .00049 mm. to 2.38 mm. The bulk of the material (over 75%) is in the sand size ranges. Gravels are not generally found in the upper levels except where constriction of lower active conduits occurs, as in the upper "Echo Gallery" passage (Figure 7.15 and 7.16).

The major difference between this cave and most of the others studied is that it undergoes active flooding throughout the vertical range of all levels. No passage is free of invading waters from lower levels during high water. In order to study paleoflow conditions it is necessary to examine other cave systems at higher elevations in the basin and surrounding area. The only example of paleoflow in Culverson Creek Cave appears to be in the ceiling of "Echo Gallery".

3. The Lower Basin

a. The Culverson Creek Rising

4.6 miles northeast of the sink of Culverson Creek it rises again and flows directly into Spring Creek. The risings are 30 feet above the stratigraphic base of the Greenbrier series. Figure 7.23 shows one of the four resurgences which are on the south bank of Spring Creek. Because of a lumber-railway embankment built along the south bank during the last century, access to the downstream end of Culverson Creek Cave is closed. The dumping of rubble has prevented exploration of the lower half of the cave system. It may also have prevented the complete flow through of coarse bedload material, although syphons within the cave are also capable of restricting the sediment movement. Non-carbonate rock fragments at the risings do not exceed .25 mm., fine sand size. No quartz gravels emerge via these springs. Spring Creek itself, however, contains abundant stream gravels, including quartz, derived from the Pottsville and Princeton formations at its headwaters. The greatest bulk of sediment discharged is as suspended load. This occurs during high water, when particles as large as fine sand are carried from the stream rising. Total mean discharge for the four Culverson Creek risings in the summer is approximately 40 cfs. This means that approximately 10 cfs. of drainage is added to the underground conduit of Culverson Creek between its sink point and its rising.

Figure 7.23

SPRING CREEK, ONE RISING OF THE CULVERSON CREEK CAVE SYSTEM

The additional drainage comes from the smaller high level entrances in the area around Unus.

b. Spring Creek

Figure 7.24 shows Spring Creek at the site of one of the risings of Culverson Creek. Note the presence of massive silt, sand and gravel terraces on the opposite bank (north) of Spring Creek. The stream here is perched on a veneer of gravels and cobbles which shield it from the underlying limestone bedrock.

Coward (1973, personal communication) estimates the mean Spring Creek runoff at approximately 100 cfs. The role that Spring Creek has played in the drainage nets of Basins II and III is that it has served as a direct outlet to the Greenbrier River at one time or another for both basins. A permanent channel has developed across the limestone despite repeated tributary system changes in its headwaters, i.e., Basin II and Basin III. Although much of its drainage is underground, the surface and subsurface routes of the major network have maintained relatively the same course throughout its history of development.

Spring Creek is unique in that it has not developed an extensive deep underground network as have the major streams in Basins I, II and III. The reasons for this are not fully understood. It appears that a major factor, however, is that it is developed parallel to the regional strike and only in the last few miles of channel does it cut across

Figure 7.24

SPRING CREEK TERRACES

the limestone. This supplies the stream with a greater percentage of clastic fills than comparable basins. Over 75% of its drainage is developed on the upper clastic rocks. This assures it of an abundant supply of perennial runoff and sediments. Nowhere along its channel on the limestone is bedrock exposed. Sediment shielding is complete and drainage is maintained at or near the surface at all times.

C. Paleodrainage Networks of Basin III

1. Introduction

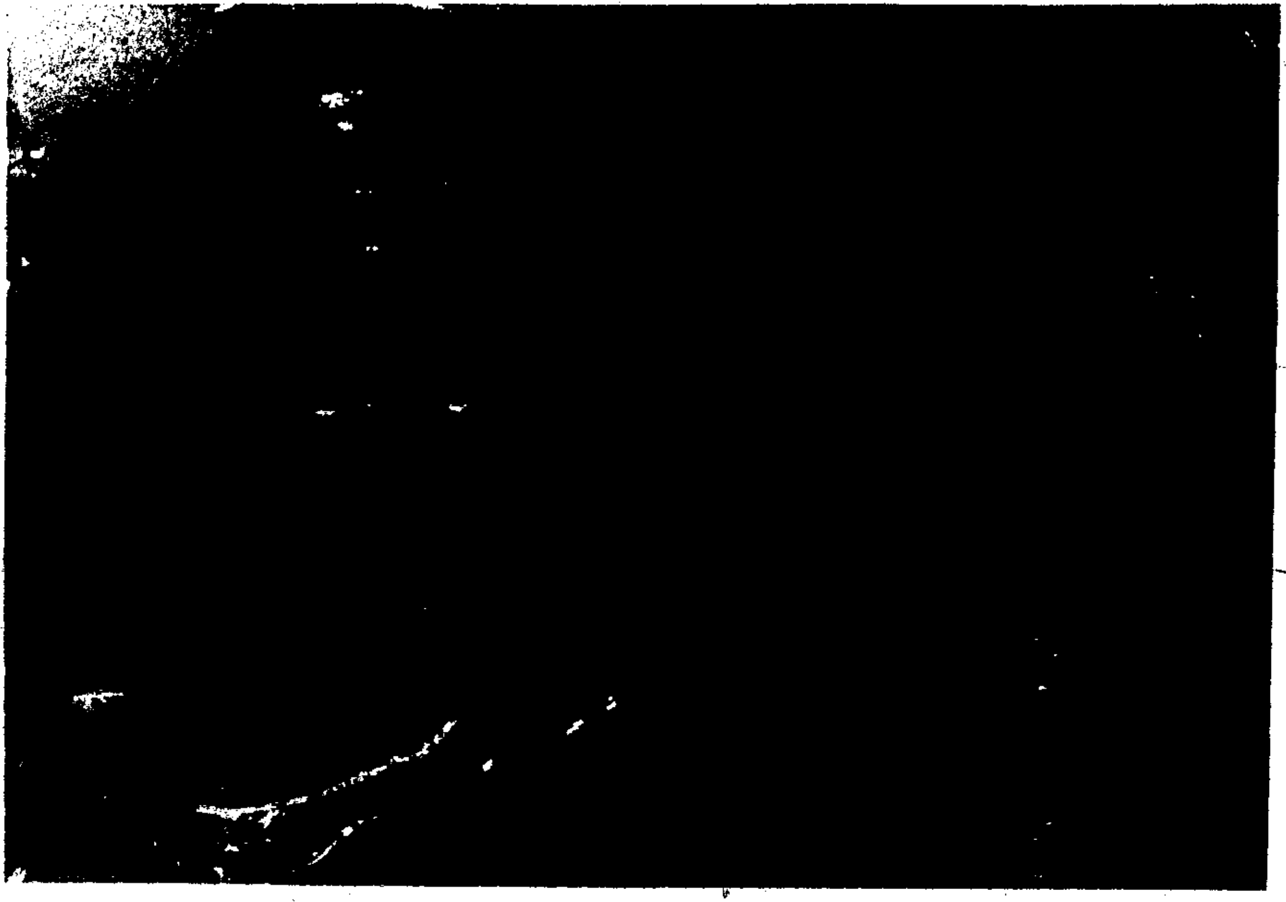
The ability to make temporal and spatial comparisons of drainage conditions now with those in the past may reflect climatic and/or geomorphic change, rests on the presence of preserved erosional and sedimentary features of the former drainage networks. Considerable evidence for the existence of former surface and subsurface drainage can be found in the area now occupied by modern Basin III. Remnants of drainage channels and depositional features include the following features.

a. Erosional Evidence

1) Surface meander scars preserved in isolated surroundings on the karst plain. Figure 7.25 is a photograph taken south of the underground channel of Culverson Creek on the "Great Savanna" aquifer (Figure 7.02). The

Figure 7.25

MULLIGAN CREEK ABANDONED MEANDER SCAR



scar is cut 100 feet into the Union limestone. The stream which cut the channel appears to have been of similar discharge characteristics to modern Culverson Creek and may have been supported on the limestone by sediment shielding. This channel never carries water under modern conditions and did not during the Hurricane Camille floods.

2) Long strike-oriented valleys. Figure 7.26 is an oblique air photograph taken south of the Culverson Creek surface channel. This valley extends southwestwards along the east flank of the Williamsburg anticline. Brushy Ridge, seen on the right, is developed along the axis of the anticline. The Greenbrier limestone is exposed along the deforested strip in the centre of the photograph. This is the route of the "Great Banana" river (Figure 7.01). Although relief along the modern dry valley floor now exceeds 100 feet, this channel once carried Culverson Creek drainage southwards to Muddy Creek (Figure 7.06). Modern drainage has cut down more than 150 feet since the Creek has abandoned this route. Post-fluvial erosion by solution and collapse is responsible for the relatively uneven floor of the valley. In addition to the topographic expression of the long unbroken valley floor, depositional evidence in the form of terraces and quartz gravels support the hypothesis that this valley is the former outlet of the drainage now occupying modern Basin III.

Figure 7.26

THE "GREAT BANANA" VALLEY

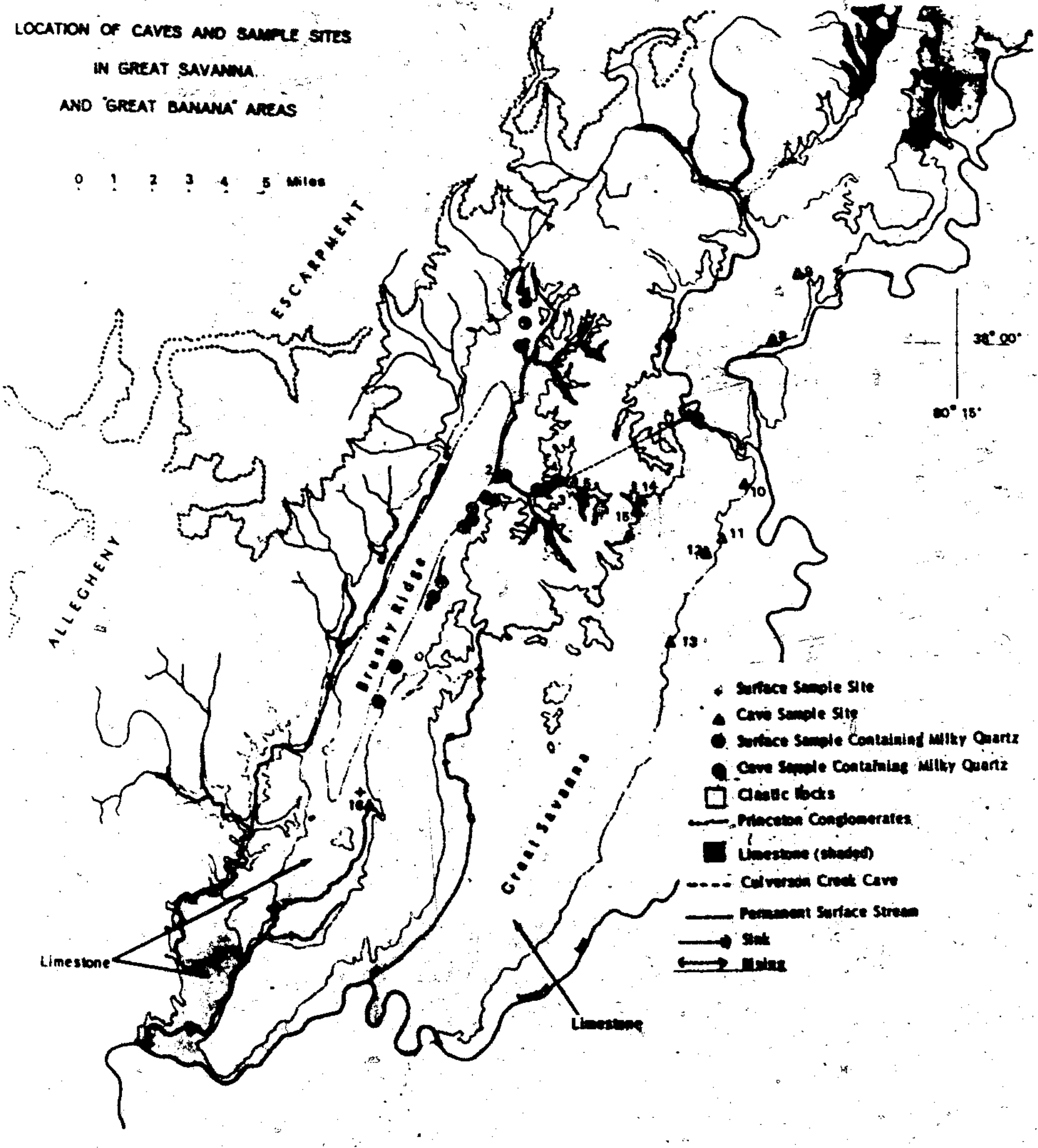
3) High level caves and upper level cave passages associated with former surface drainage indicated by scallop size variation and reversal of direction. The scallop reversals found in the "Echo Gallery" of Culverson Creek have been described (Figure 7.16). These may have been the result of subsurface diversion and capture of Culverson Creek. The upper level flow was toward the west and into the "Great Banana" outlet. The lower level flow is now toward the east and into the Spring Creek outlet. Further examples are illustrated in Bob Gee Cave and in caves of the karst plain. These show the value of detailed study of high level cave passages.

b. Depositional Evidence

1) The transport and deposition of identifiable rocks and minerals. Provenance studies on the material found in abandoned caves and terraces suggest that paleo-drainage conditions have varied in direction, quantity and origin of drainage and sediment. Figure 7.27 shows the location of sample sites in and surrounding modern Basin III. These data are described in this chapter.

2) The presence of karst "sieve-type" deposits. The abundance of clastic source rocks on the karst in greater quantities than might be expected under present climatic conditions, as well as greater angularity than might have been expected to result from the present conditions of fluvial transport alone. Much of this material

Figure 7.27


LOCATION OF CAVES AND SAMPLE SITES
IN GREAT SAVANNA
AND 'GREAT BANANA' AREAS
0 1 2 3 4 5 Miles
ESCARPMENT
ALLEGHENY
Brushy Ridge
Great Savanna
38° 00'
80° 15'
2
3
7
9
10
11
12
13
14
15
16
Limestone
Limestone
Surface Sample Site
Cave Sample Site
Surface Sample Containing Milky Quartz
Cave Sample Containing Milky Quartz
Clastic Rocks
Princeton Conglomerates
Limestone (shaded)
Culverson Creek Cave
Permanent Surface Stream
Sink
Rising

appears to have been transported by mass movement and gravitational processes no longer operative on these "sieve-type" features.

3) Systematic variations in grain size and particle properties along the assumed paleochannels.

2. The Upper Basin Area

a. The Brushy Ridge Drainage Systems

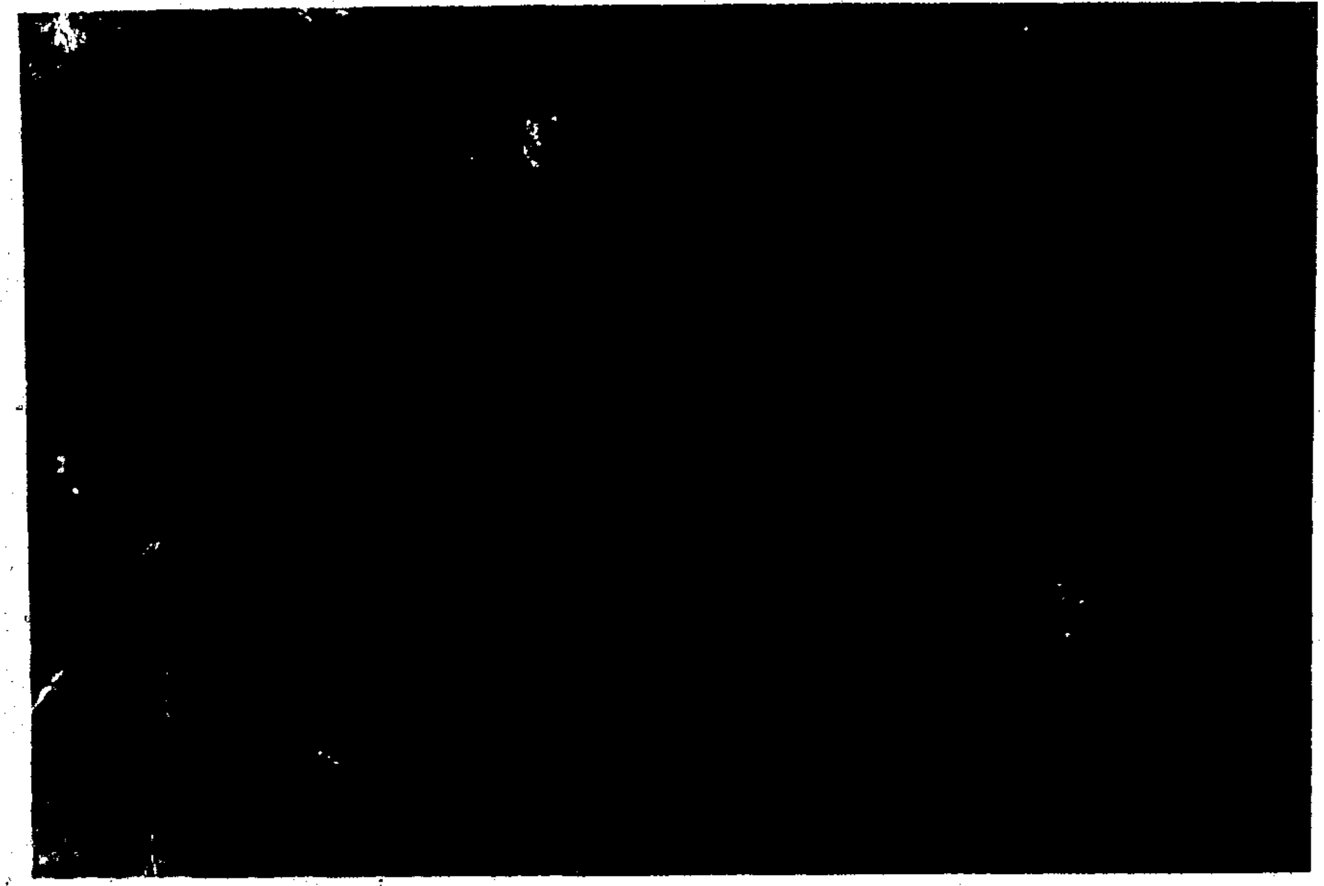
The present drainage along Brushy Ridge (Figure 7.01) provides an interesting comparison between modern and paleodrainage conditions.

(i) Drainage Along the West Flank

All runoff from the Allegheny escarpment south Charley Run (part of modern Basin III) flows southwestward along the Greenbrier limestone outcrops along the west flank of Brushy Ridge (Figure 7.01). The relief of this valley exceeds 300 feet. This is more than twice the relief of paleo "Great Banana" channel. Fluvial action has caused the development of several large karst windows and tunnels (Figure 7.28). This valley has undergone intense karstification and fluvial action during the time that modern and paleodevelopment has taken place in Basin III. This greater concentration of solutional and fluvial processes along the west flank of the anticline is due mainly to lithologic isolation and its resulting hydrological con-

Figure 7.28

NORTH ENTRANCE TO SINKING CREEK NATURAL TUNNEL (STREAM GOING IN)



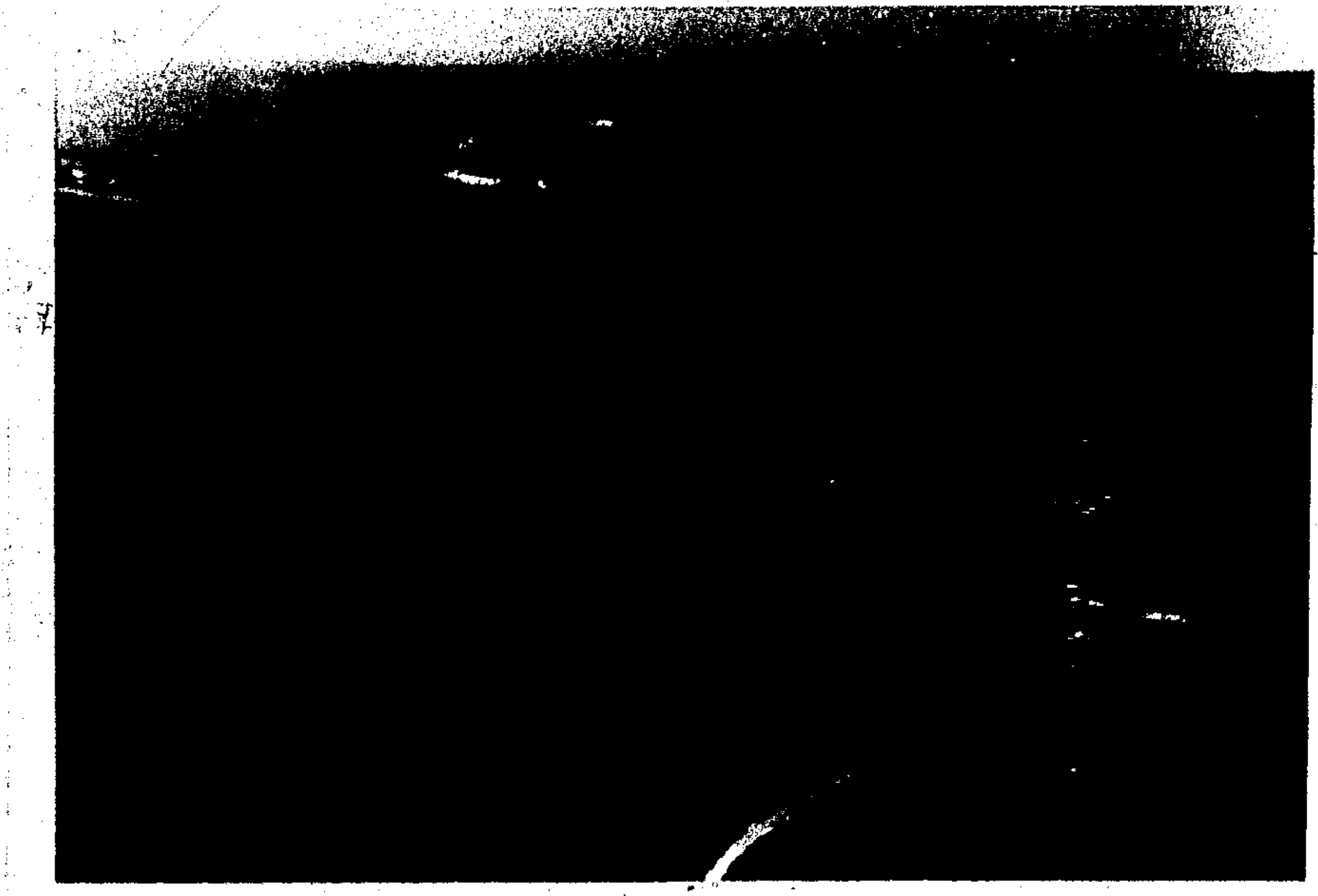
finement. Brushy Ridge, developed along the axis of the Williamsburg anticline, provides an effective barrier for drainage flowing to the east and the Greenbrier River. Drainage is forced to flow southwest to connect with Muddy Creek via a series of underground channels (Figure 7.01). The latter is a much less direct route to the regional base level, the Greenbrier River system. This structural and lithological isolation has created a deeply entrenched active channel confined to the narrow limestone exposure west of Brushy Ridge. The movement of sediments along this route is interrupted by several constricting cave entrances; large spreads of surface alluvium occur at these points. A detailed study of sediment and drainage along this route was not carried out. More work does need to be done in this valley.

(ii) Drainage Along the East Flank of Brushy Ridge

The east flank of Brushy Ridge contains no known modern continuous surface or subsurface stream. This is the location of the former outlet of Basin III, the "Great Banana River". The valley floor is 150 feet higher in elevation than the valley developed in the limestone on the west side of the ridge, even though the latter valley is further from the Greenbrier River. This is due to the lack of active fluvial erosion along the abandoned "Great Banana" course, which is now 150 feet above the active channel of Culverson Creek (Figure 7.29).

Figure 7.29

THE GREAT BANANA VALLEY, EIGHT MILES SOUTH OF CULVERSON CREEK DIVERSION



A detailed study of the drainage and sediments of this dry valley was carried out over three summers, from 1968 to 1970. This included the period of record runoff associated with Hurricane Camille in 1969. No surface runoff occurred anywhere along this channel other than from local valley slopes downward to sinks in the valley floor. Dye tests were carried out in small sinking streams in an attempt to link the drainage to springs in adjoining areas but no links were established. It is suspected that cave development is comparatively primitive and inefficient, a product of the lack of water supplied by a beheaded valley.

Figure 7.27 shows the location of sediment sampling sites at three caves and nine terrace exposures along the "Great Banana" valley. Sites 2, 7 and 16 are the caves. A circle around the site indicates that rounded milky quartz pebbles were found there. In the northern part of the abandoned valley site 2 (Brushy Ridge Cave) and seven terrace sites directly south for a distance of six miles contain well-rounded milky quartz. This showed a decrease downstream in mean long axis of 30 pebbles at each site from 1.60 cm. to 0.70 cm. This mineral is not available from the surrounding shale and sandstone outcrops in this form and can only have been transported via a former stream carrying gravels down from the Pittsville and Princeton conglomerates exposed at the head of Basin III. It is significant that modern Mill Creek terraces (the two unnumbered sites in the extreme southwestern portion of Figure 7.27) do not contain milky quartz fragments. No quartz pebbles were found at site number 7 (McFerrins Cave) which is located in the valley side 200 feet above the assumed "Great Banana" river level.

Sample sites in the southern part of the valley were found not to contain quartz pebbles. It was assumed that these were removed by subsequent drainage which is still active in the lower valley area, or that they were reduced below pebble size at this distance from the source (greater than 15 miles). This lower portion of the valley is shown in Figure 7.29.

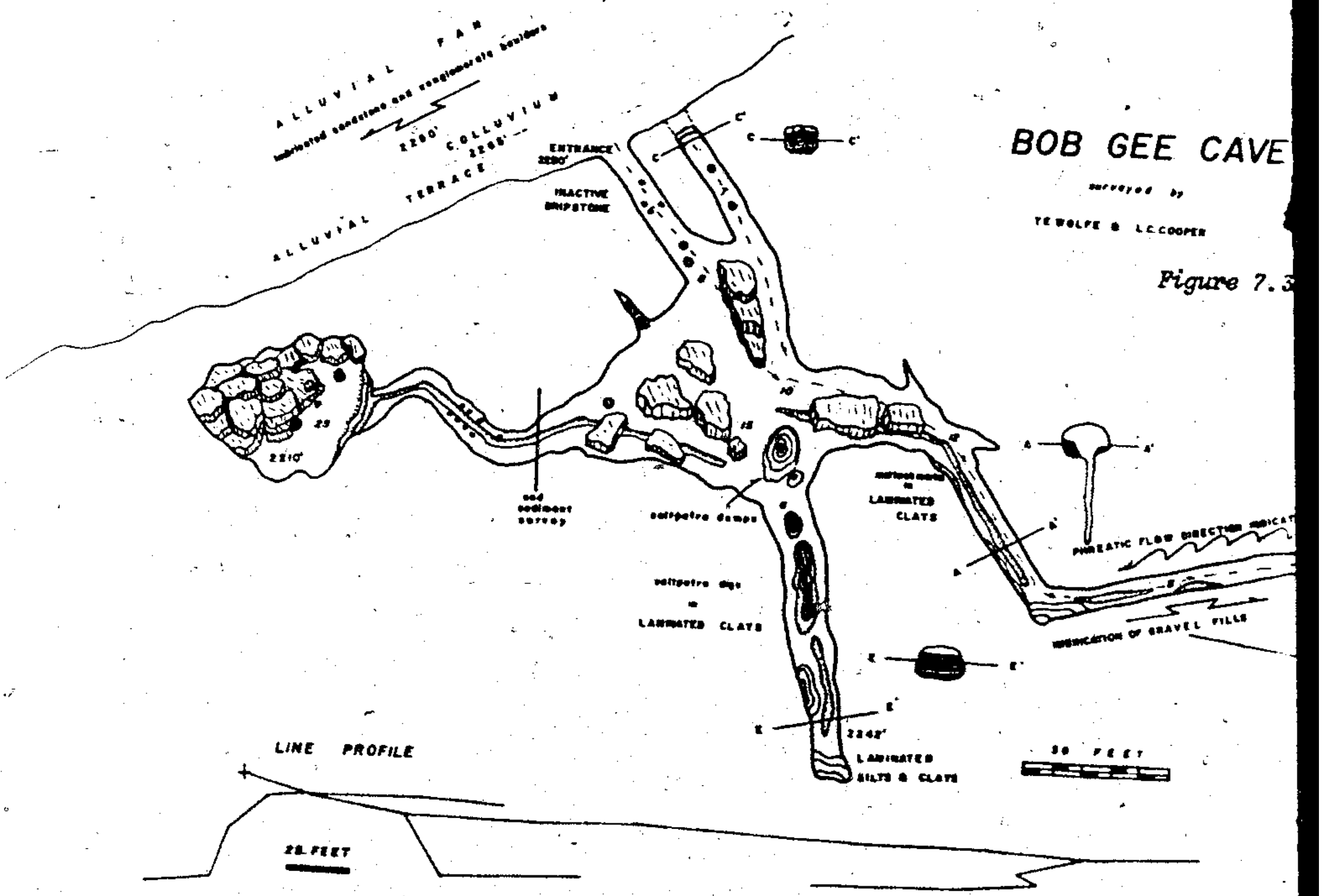
Clay mineral analysis was carried out on samples from three caves and nine terrace sites. Kaolinite (3.58Å)/ illite (10.0Å) ratios along the valley floor are close to 0.900 , suggesting a single source of provenance. Modern channels in Basin III are greater than 1.000 , while ratios for McFerrin Cave (high above the valley floor) are 0.639 . This lower ratio is typical of isolated cave deposits which are not subjected to modern surface weathering. These data are shown in Appendix A and Appendix B.

b. Bob Gee Cave

Bob Gee Cave (Figure 7.27, number 1) is located in a small remnant limestone ridge at the north side of the karst sieve deposit in Trout Valley. The entrance is at 2250 feet in elevation. Approximately 75 feet of relief in the cave lies at the same level or below the entrance elevation. Figure 7.30 is a plan of the cave and its surroundings. The cave contains approximately 2000 feet of passage. At the entrance there is a parallel passage blocked by colluvium and travertine (cross-section C-C'). This presumably also provided access to the cave. Elevations on the sieve deposit outside the entrance vary slightly due to paleochannels across the surface, but are still within a few feet of the elevation of the main passage of the cave.

Much of the cave appears to be phreatic in origin. It is developed along the strike in a linear, meandering pattern. Two large interior galleries extend from the entrance. One of these is completely blocked with fine fill. The other extends north for approximately 1000 feet and is joined on the west to a series of rectangular joint controlled passages. Throughout the upper levels, large phreatic scallops (62 cm. to 90 cm.) predominate. Paleocurrents in these upper levels flowed outward toward the valley at a slight upward gradient (1° to 3°) at a few centimeters per second. Past phreatic development was followed by sedimentation and vadose trenching. These latter events occurred in opposite directions to the phreatic flow (Figure 7.31).

The lowest levels of the cave slope southward are 2° to 4° in opposition to the slope of the upper levels. Small scale scallops (2 cm. to 4 cm.) are developed on the trenches, indicating rapid flow outwards toward the valley



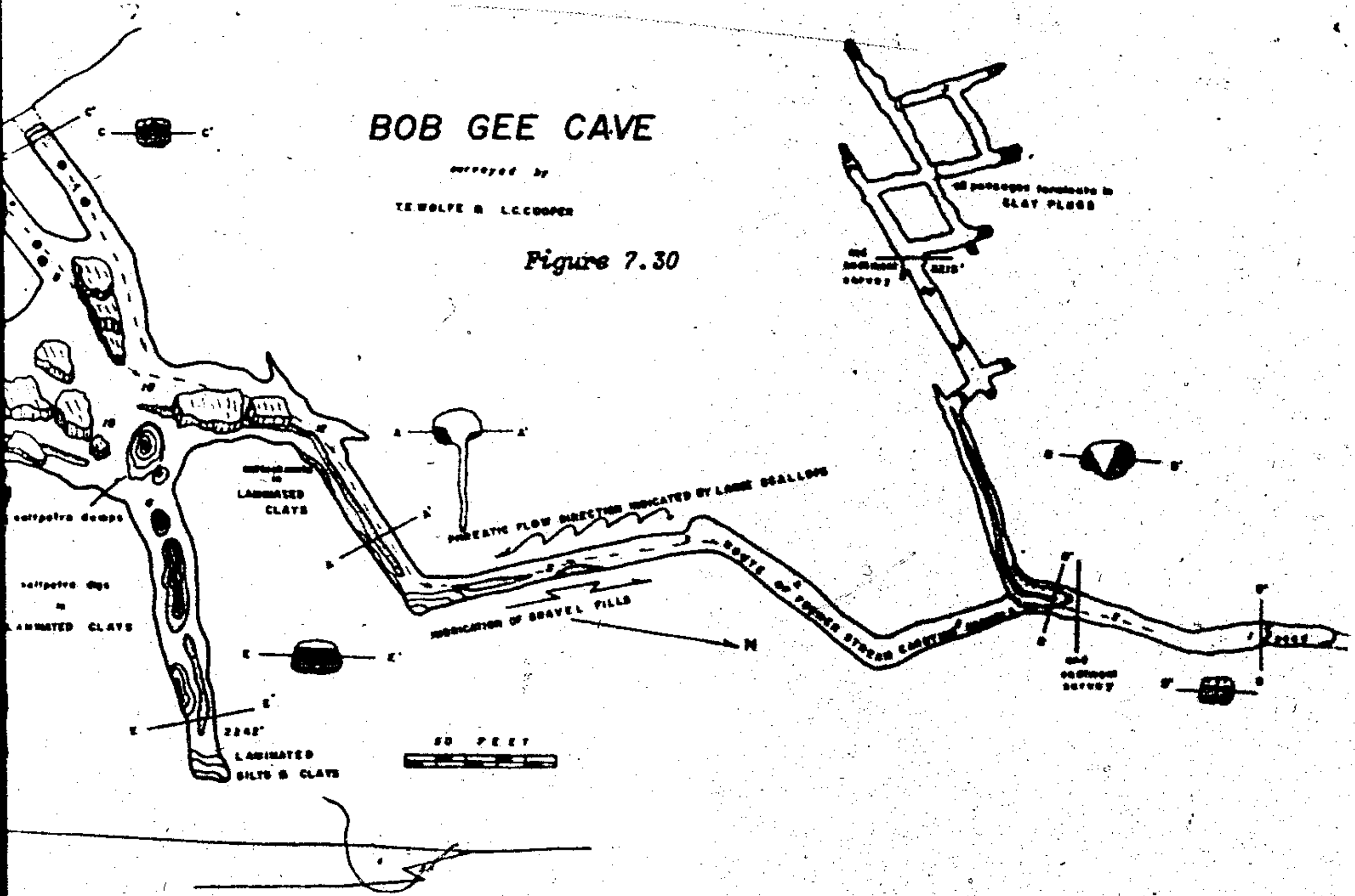
BOB GEE CAVE

surveyed by

T.E. WOLFE & L.C. COOPER

Figure 7.3

1 of



BOB GEE CAVE

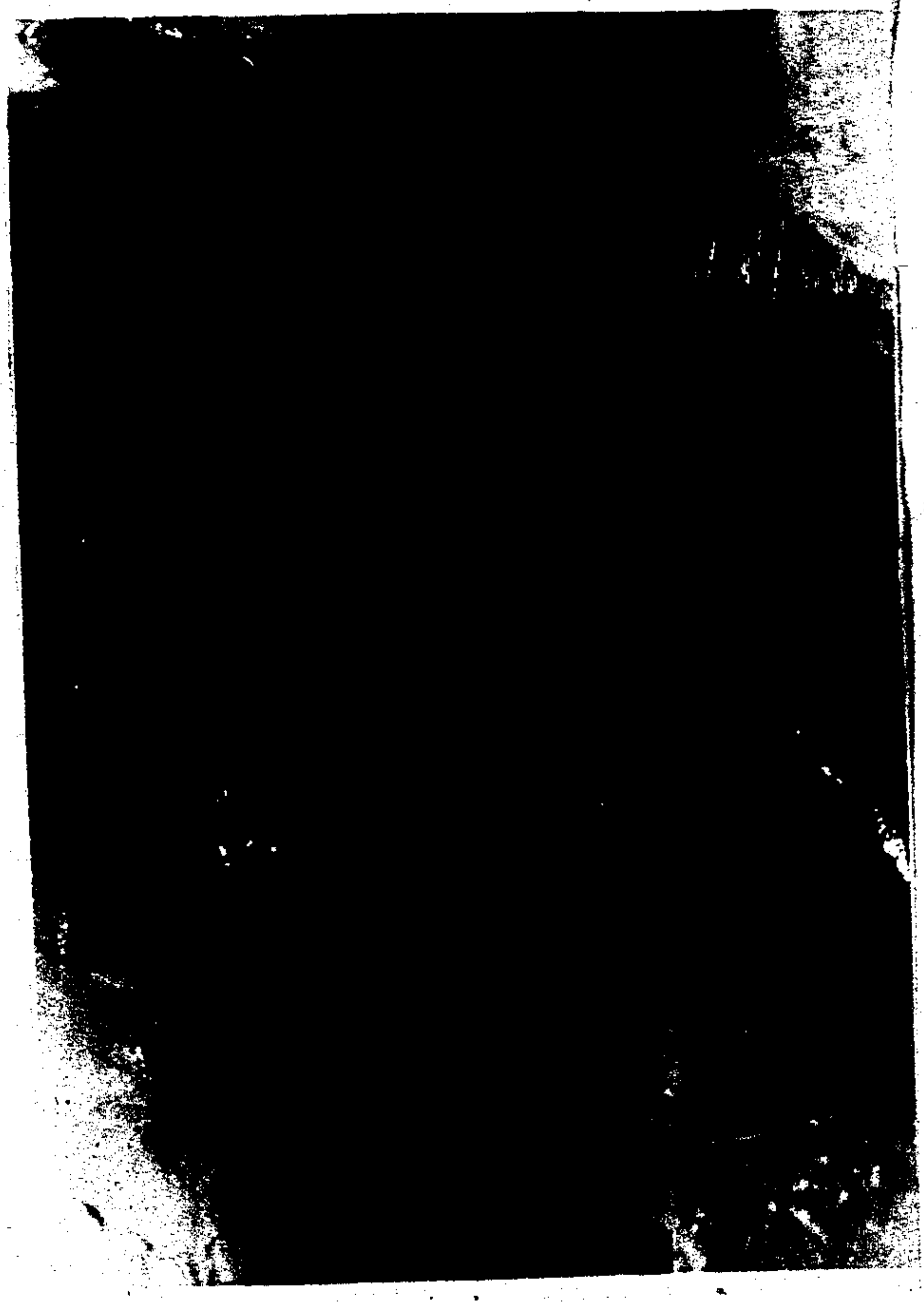
surveyed by

T.E. WOLFE & L.C. COOPER

Figure 7.30

Figure 7.31

VADOSE TRENCHING INTO UPPER PHREATIC TUBE AND FILLS, BOB GEE CAVE



at velocities near one meter per second. Figure 7.32 illustrates some passage cross-sections shown on Figure 7.30. The vadose trench shown at A-A' in both figures is typical of the two-phase solutional sequence found along the main north passage. The trench does not extend the full length of the cave. Sections B-B' and D-D' illustrate the continuation of the upper level along the same passage. Gravel fills in this phreatic passage are imbricated in opposition to flow directions indicated by the scallops. This would suggest an invasion of surface water carrying gravels and flowing into the cave at about one meter per second. Figure 7.33 and 7.34 are photographs taken near cross-section B-B'. Figure 7.34 is taken directly below Figure 7.33, and shows the sedimentary sequence. A few inches of clay cap sand and fine gravels with foresets. Six to eight inches of these are covering several feet of imbricated gravels and pebbles. These in turn rest on finer material. Figures 7.35 and 7.36 show this fining downwards section near cross-section A-A' (Figure 7.32). Figure 7.37 summarises the sedimentary sequence along the main upper level passage. The provenance of the material is from the Mauch Chunk sandstones and Pottsville/Princeton conglomerate. Quartz pebbles comprise 5 to 15 percent of the material in selected size ranges. Imbrication is into the cave (northwards).

Figure 7.32

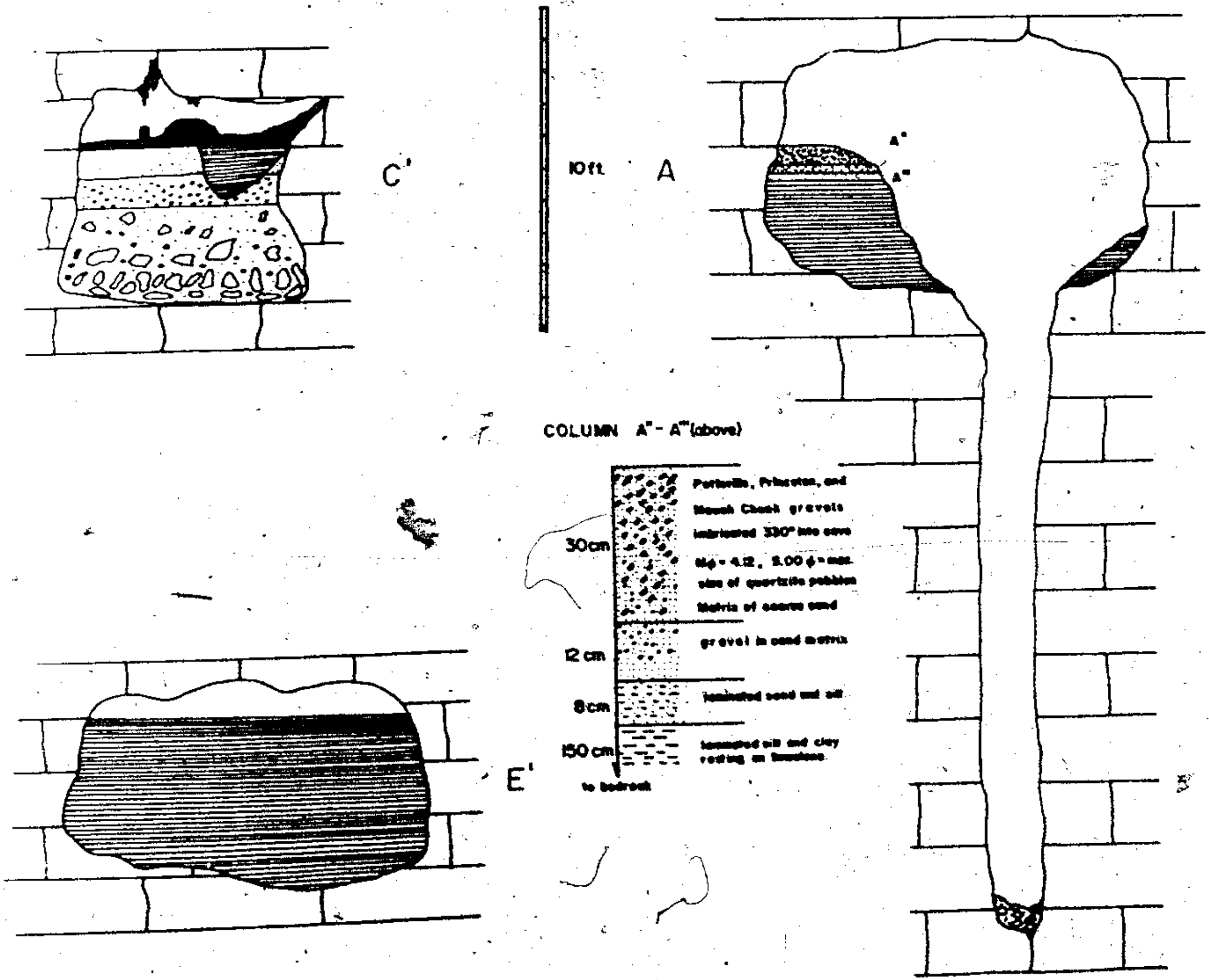


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Figure 7.32

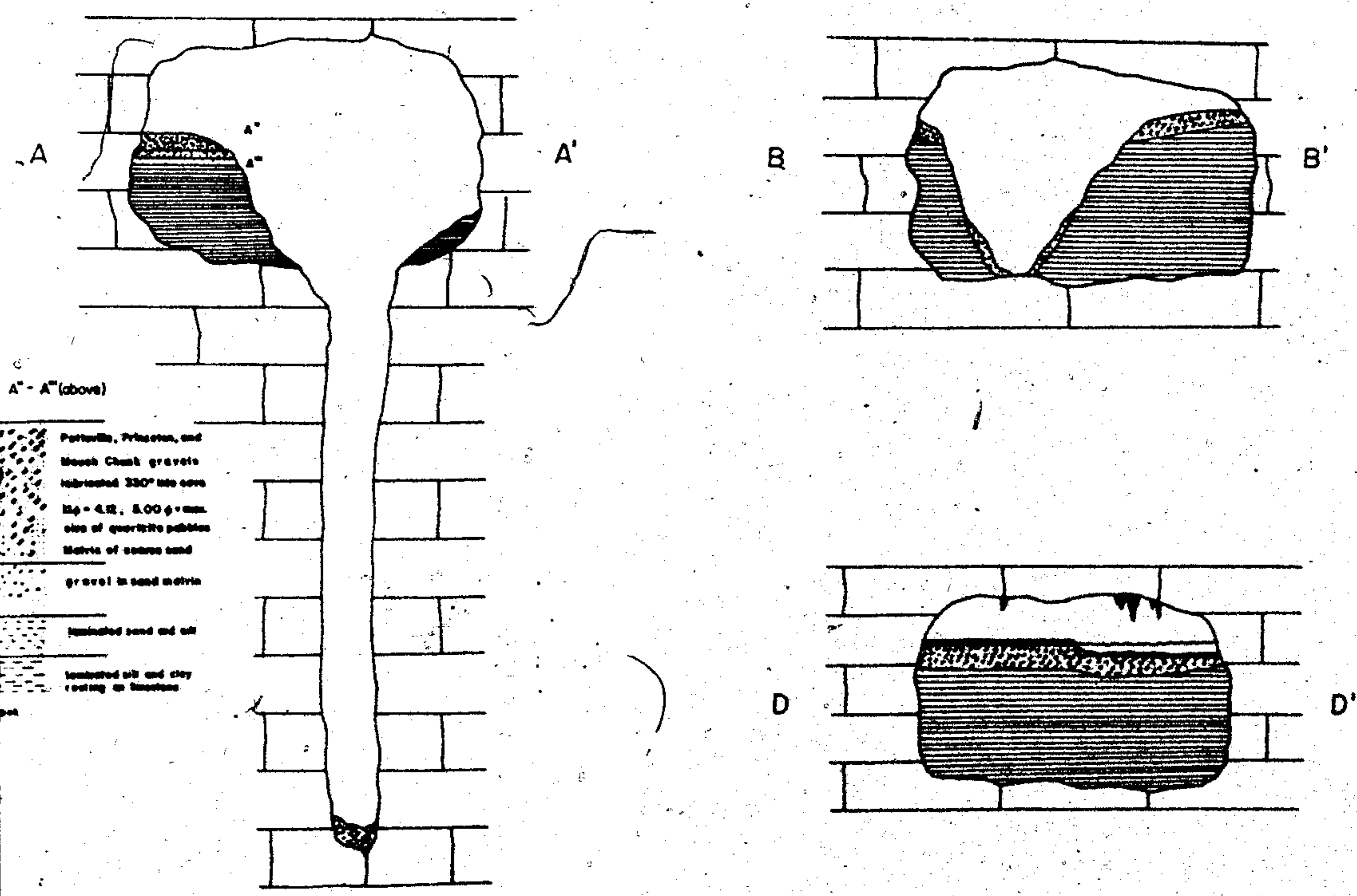

A
A''
A'''
A'
B
B'
D
D'
A'' - A''' (above)
Pottsville, Princeton, and Mauch Chunk gravels imbricated 330° into cave
Mφ = 4.12, 5.00 φ = mm.
size of quartzite pebbles
Matrix of coarse sand
gravel in sand matrix
laminated sand and silt
laminated silt and clay coating on limestone
pot

Figure 7.33

PHREATIC CEILING SCALLOPS, BOB GEE CAVE

Paleoflow from left to right. Height is 3 feet.

Figure 7.34

COARSE VADOSE FILLS (IMMEDIATELY BELOW THE LOCATION OF FIGURE 7.33), BOB GEE CAVE

Paleoflow from right to left. Height is 30 inches.

Figure 7.35

SEDIMENTS NEAR CROSS-SECTION A-A' , BOB GEE CAVE

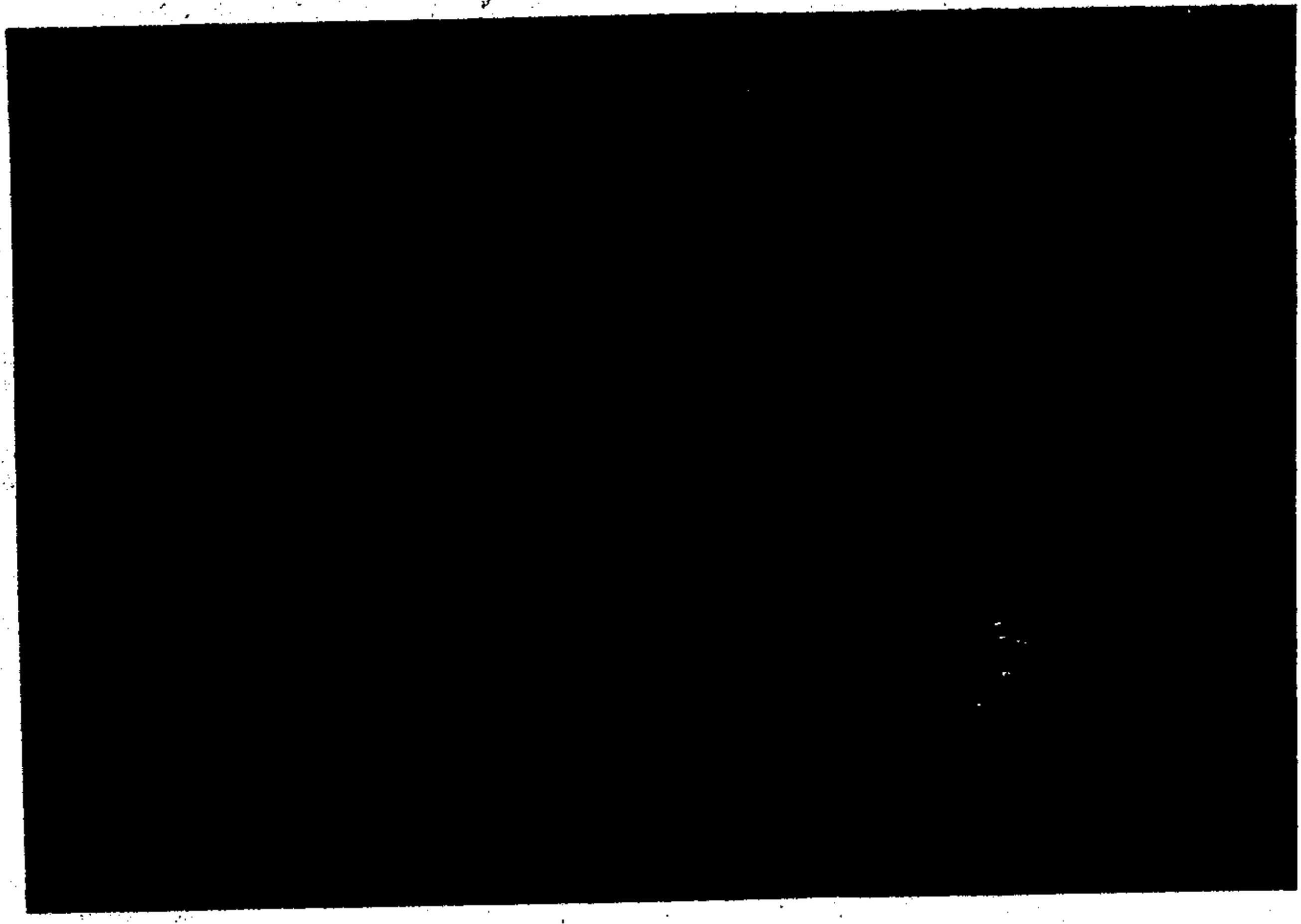
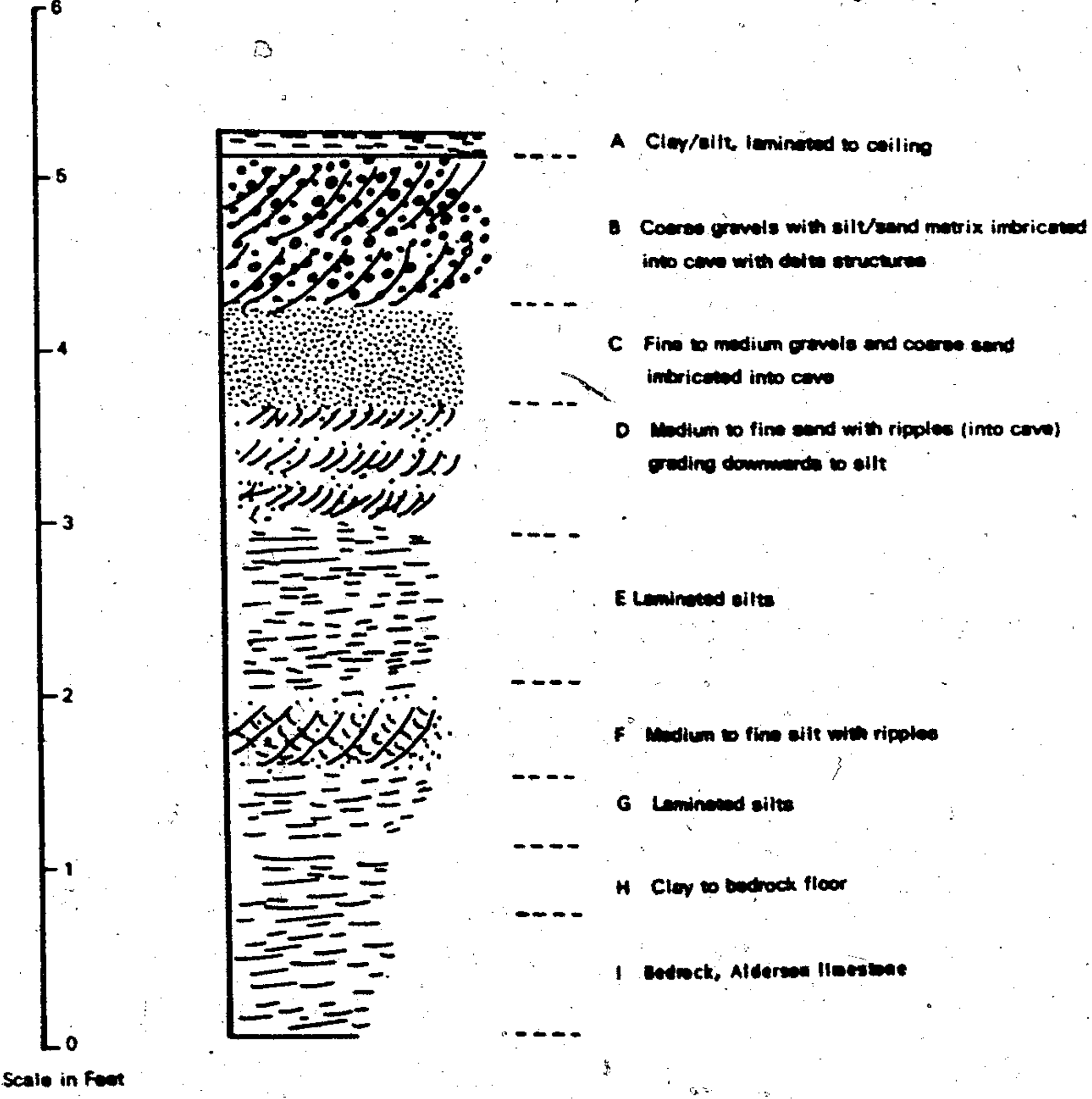


Figure 7.36

DETAIL OF SEDIMENT TRANSITION ZONE (FROM FINE TO COARSE)
NEAR CROSS-SECTION A-A' , BOB GEE CAVE

GENERALISED SEQUENCE OF SEDIMENTS IN THE MAIN PASSAGE FROM A–A' TO D–D' IN FIGURE 7.30, BOB GEE CAVE

Figure 7.37



In the lower levels small scale scallops indicate relatively high velocities flowing out of the cave (southwards), parallel to the flow directions in the upper phreatic levels. Little sediment is found here. It is assumed that waters derived from within the cave carried less sediment and therefore trenching readily took place. Some reworked gravels and pebbles remain in a few areas. These appear to be carried by the same flow responsible for the vadose trenching.

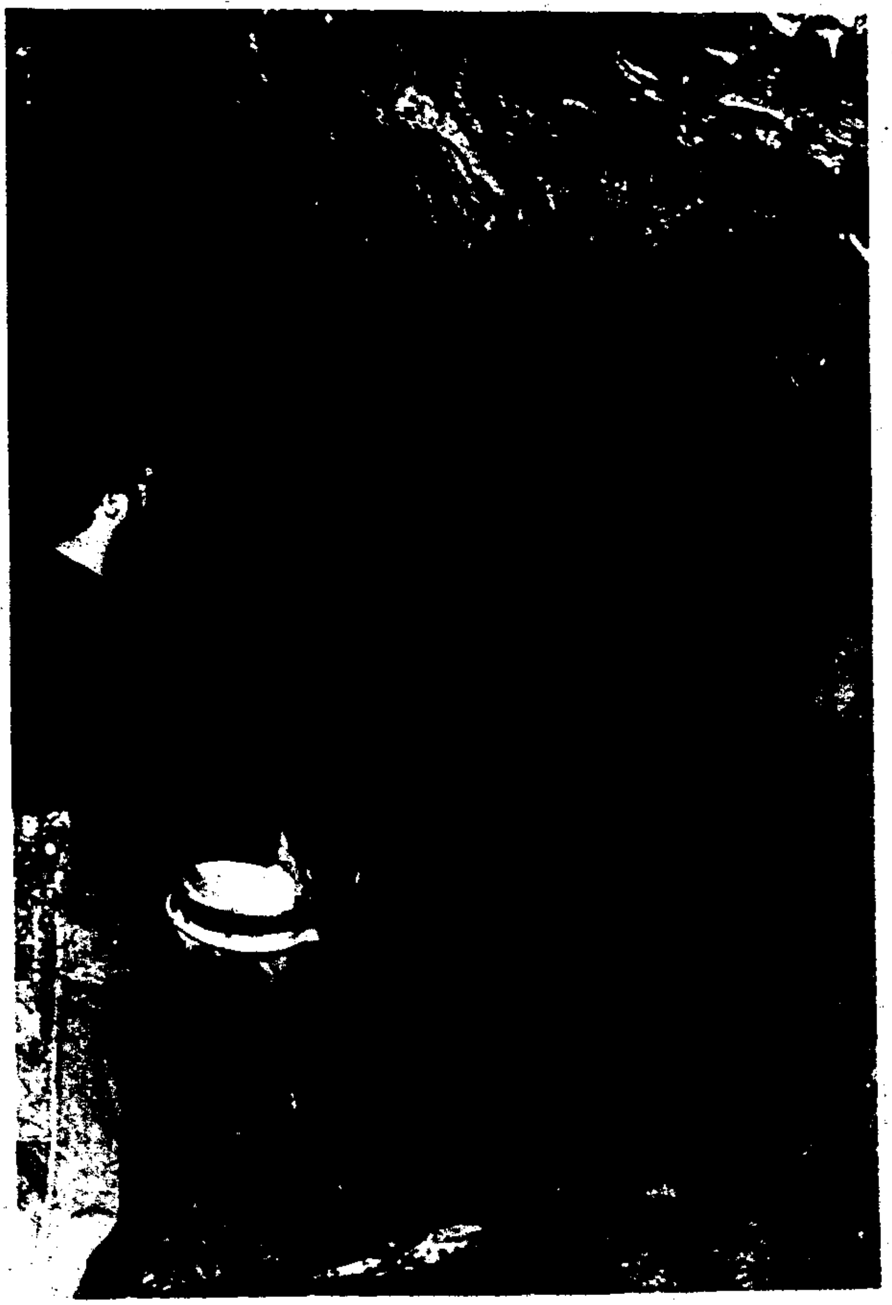
The entrance facies vary in several respects from the upper phreatic passage fills. They are found at nearly the same elevation, but contain angular blocks of limestone at the base and are capped with travertine (Figure 7.38). The gravel and pebble sequence is still preserved, however, in a channel cut in the lower right section of the fills. The travertine is inactive and no surface drainage ever enters this cave through either of the entrance passages.

The sequence of erosional and sedimentary events in Bob Gee Cave can be summarised as follows (and as illustrated in Figure 7.39, numbers 1, 2, 3 and 4):

1 - Phreatic origin with flow outwards (south) towards the valley floor with the limestone surface higher than at present by at least 200 feet. The clay-silt sequence at the base of the gravel fills may have been deposited at this time.

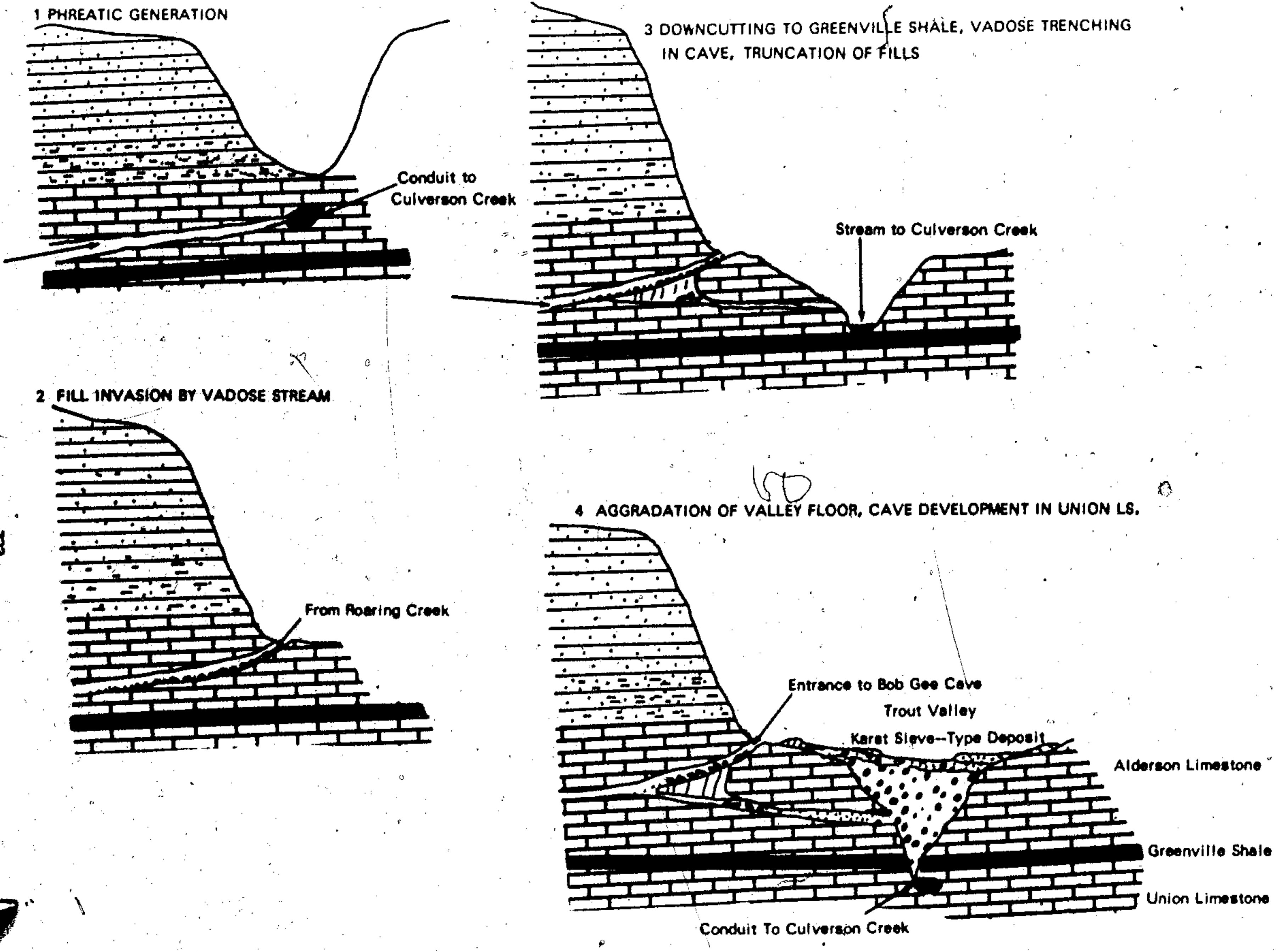
Figure 7.38

BLOCKED ENTRANCE PASSAGE AT C-C' IN FIGURE 7.30, BOB GEE CAVE



SEQUENCE OF EROSIONAL AND DEPOSITIONAL EVENTS IN BOB GEE CAVE

Figure 7,39



1 PHREATIC GENERATION

2 FILL INVASION BY VADOSE STREAM

3 DOWNCUTTING TO GREENVILLE SHALE, VADOSE TRENCHING IN CAVE, TRUNCATION OF FILLS

4 AGGRADATION OF VALLEY FLOOR, CAVE DEVELOPMENT IN UNION LS.

2 - Downcutting of the surface valley exposed the entrance and allowed clastic fills to enter from the Roaring Creek surface runoff. Provenance was the same as today in the area. The larger fragments at the sealed entrance may indicate a cold climatic phase prior to this second stage.

3 - Downcutting of the surface valley and breaching of the underlying Greenville shale. This is also the probable stage during which the underground Culverson Creek Cave diversion captured strike oriented surface flow from the "Great Banana" valley. Flow into the cave was outwards (south) toward the valley again and vadose trenching occurred due to the steeper gradient and lack of invading surface fills.

4 - Reworking of surface gravitational fills at the base of the retreating Allegheny Front now extended well across the limestone. The Trout Valley karst sieve became extensively developed. This process of winnowing of fines from the head continues, and surface drainage is lost completely to underground streams which now drain to Spring Creek via the modern Culverson Creek Cave.

c. Discussion of the Upper Basin Area

Table 7.02 summarises the gravel sediment data from the sites associated with paleodrainage in the upper basin area. Bob Gee Cave fills fit into a general continuum that extends down the "Great Banana" valley. The per-

Table 7.02

COMPARISON OF GRAVELS DOWNSTREAM ALONG THE MODERN AND ABANDONED CHANNEL OF BASIN III

Condition of Site	Distance from Sample*	Number of Pebbles	% of Broken Rounds	Comparisons of Long (A) to Short (C) Axes in Phi Units & Mm.	Description of Site	Comments
Modern	#1 0.0	47	10	-4.59/-3.86 $\frac{24.5}{15.0}$	Source - all samples from the Princeton conglomerate	Very little Pottsville S.S. available
Modern	#2 3.5	22	84	-4.27/-3.34 $\frac{19.5}{10.2}$	Recent flood alluvium at upper portion of fan along Culverson Creek	Conglomerate boulders present at this site
Abandoned	#3 3.5	56	48.5	-3.46/-2.77 $\frac{11.1}{7.0}$	Upper level of Bob Gee Cave (gravels on laminated clay) not affected by flooding	Inactive samples, does not fit downstream size decrease
Abandoned	#4 5.3	8	N.A.	-4.06/-3.37 $\frac{16.1}{10.5}$	Terrace on DePreist Farm 50' above Culverson Creek Bed	Inactive deposits
Modern	#5 9.5	28	52.6	-4.14/-3.32 $\frac{17.0}{10.0}$	In Culverson Creek Bed just below Great Banana Capture	Small conglomerate cobbles present
Abandoned	#6 9.2	6	N.A.	-4.00/-3.25 $\frac{16.0}{9.5}$	At head of Great Banana R. 150' above Culverson Creek Bed	Two samples from inside a small cave (Brushy Ridge Cave)
Modern	#7 10.7	26	30	-3.73/-3.07 $\frac{14.0}{8.1}$	In Culverson Creek Cave in stream bed	Active transport sample
Abandoned	#8 12.4	22	N.A.	-2.95/-2.31 $\frac{7.8}{5.0}$	In terrace along Great Banana Route	5.4 miles from head of G.B.
Abandoned	#9 14.9	25	23	-2.77/-1.86 $\frac{7.0}{3.8}$	In terrace along Great Banana Route (along U.S. 60 Highway	5.4 miles from head of G.B.

*In miles.

centage of broken rounds was examined in a manner similar to Pittman and Ovenshine (1968). Broken round percentages on the surface sieve outside the cave are almost twice as great as those of the fills inside the cave. This breaking suggests a high gradient and efficient disintegration of boulder fragments consequent upon rapid production of escarpment debris. This accelerated production is interpreted as further evidence for one or more recent cold phases, the remains of which are being scavenged today at the base by streams building karst sieves along the contact. Clay mineral analysis from the upper basin shows some interesting comparisons (Table 7.03). The lower ratios are associated with paleodrainage sequences in Bob Gee Cave, McFerrin Cave and the "Great Banana" valley. The highest ratios are found in active or exposed surface areas along the present drainage route. This is similar to the pattern observed in Basin II.

3. The Middle and Lower Basin Areas and Adjacent Parts of the Great Savanna

a. Introduction

Approximately 10 cfs. of discharge is acquired by the main Culverson Creek conduit between its major sink near Unus and the risings along Spring Creek. Several tributary streams from Hinkel's Unus Cave, Fullers Cave, McLaughlin's Unus Cave and possibly the Jackson Caves may account

Table 7.03

CLAY MINERAL ANALYSIS FROM THE UPPER BASIN

Site	Kaolinite (3.58Å)/Illite (10.0Å)
Phreatic fills of Bob Gee Cave	0.540
Great Banana high level terrace	0.424
Great Banana valley floor	0.900
McFerrin Cave in the Great Banana Valley	0.639
Modern Roaring Creek stream bed	1.273
Modern Culverson Creek Cave stream	0.933
Parent rock from Pottsville Conglomerate at the basin head	2.868

for all or part of this additional water (Figure 7.04, numbers 8, 9 and 10). These are the result of recent surface diversion toward Spring Creek and are not a reflection of the paleodrainage pattern toward the Great Banana valley which is outlined by the surface topography and geology (Figure 7.04, first overlay).

There is a poorly defined divide between Spring Creek drainage in the north and the Great Savanna aquifer draining to Fort Spring (Figure 7.01). The underground diversion of Basin III is very close to this poorly defined divide. Caves at the upstream end of the diversion show different sedimentary, provenance and drainage characteristics from those near the lower carbonate/clastic contact.

Evidence of paleodrainage in Culverson Creek Cave is extremely limited. All passages are subject to modern floodwater invasion. The only evidence of former drainage is in the ceiling scallop pattern at the high level "Echo Gallery", which suggests an early and slow phreatic flow towards the "Great Banana" outlet.

In order to establish the character of drainage and sediment patterns of the paleodrainage network, all major caves and dry surface channels of the middle and lower part of modern Basin III were examined. Figure 7.27 shows the location of the sample sites where detailed analysis was undertaken. The Great Savanna aquifer is shown on Figure 7.01. This includes all underground drainage which rises at Fort Spring. This system is fed almost entirely by karst drainage and some minor drainage east off the narrow exposure of the MacCrady and Pocono series immediately west of the Greenbrier River. The aquifer is an area greater than 150 square miles which contains only ten stream miles of surface drainage. Much of this appears to be supported upon silts and alluvium, for example Mulligan Creek. The rising at Fort Spring has a mean discharge of 75 cfs., that is, more than twice the mean discharge of the Culverson Creek springs.

Most caves within the Great Savanna are entered at the lower Greenbrier limestone contact with the underlying MacCrady shales. These are small vadose channels developed downdip on the shales which continue westward until they reach large, more complex channels along the strike, which carry the drainage southwestward to Fort Spring. The larger southwest trunk channels have phreatic upper sections. These are often subject to enlargement by collapse. Large surface sinks and uvalas have resulted from this process. Vadose trenching deep into the underlying shales is presently very active along these southwest routes.

b. Caves of the Middle Basin Area (West of the Karst Plain)

Several small caves are found above the Culverson Creek conduit which are not connected. Of these Buckeye Creek Cave (Figure 7.04, number 12) and Higginbothams Caves

(Figure 7.04, number 11) were studied in detail. Both caves display similar provenance and grain size distributions. Modern drainage, however, is north to Spring Creek in the case of Buckeye Creek Cave and southward to Fort Spring risings in the case of Higginbothams Caves.

(i) Buckeye Creek Cave

Today some runoff is carried directly over the Culverson Creek cave conduit without being integrated into the underground system. This is the water of Buckeye Creek (south of number 12, Figure 7.06). No quartz gravels or sediments derived from the clastic outcrop of the Allegheny escarpment are found in the sediments of this small network.

It contains Buckeye Creek Cave (Figure 7.06, number 12). The cave is 3000 feet in length. Its drainage joins Spring Creek two miles upstream from the Culverson Creek rising. It is approximately 200 feet above the Culverson Creek channel in elevation. Buckeye Creek Cave is developed in the uppermost member of the Greenbrier series, the Alderson limestone. Its channel is composed of silts and clays and may be perched upon the underlying Greenville shale. X-ray diffraction of samples taken from the surrounding regolith compare closely with the samples of silts and clays found inside the cave. This would suggest a modern and local origin for the cave sediment. There appear to be drainage associations with the modern or paleodrainage of Basin III.

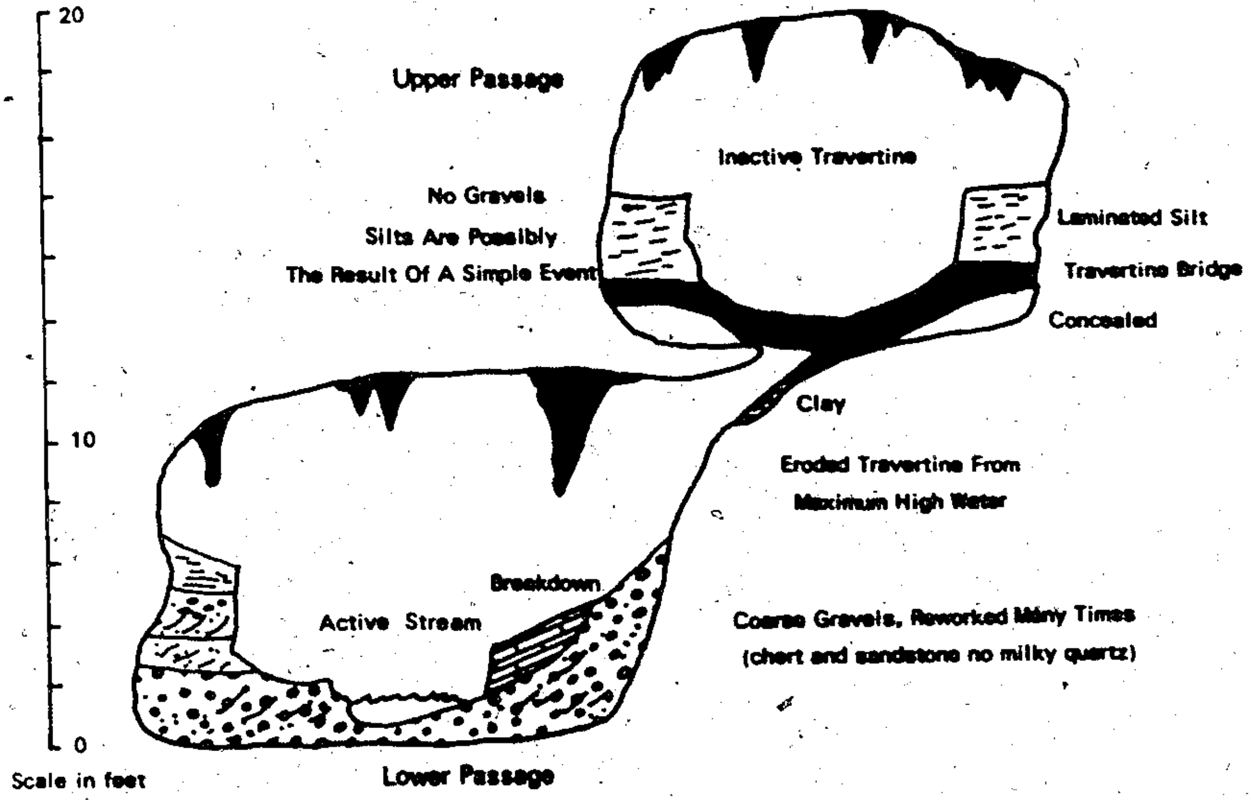
(ii) Higginbothams Caves

The entrance to the two Higginbothams Caves are shown as number 11 on Figure 7.06. There are three other entrances. All lie very close to the Culverson Creek Cave conduit, but as in the case of Buckeye Creek Cave, drainage in these caves does not join the underground trunk of Basin III. The small stream there (about 1 cfs.) has been traced southwest to Coffman Cave and thence to Fort Spring. This is a straight line distance of 14.5 miles with a vertical drop of 650 feet. Higginbothams Caves lie above the Greenville shale in the Alderson limestone and the stream flows on a bed of gravels and silt. These factors are responsible for the hydrologic separation of this system from the underlying Culverson Creek Cave network.

Figure 7.40 shows a typical passage cross-section 500 feet inside the entrance of Higginbothams Cave number 1. The upper level shows no evidence of modern flooding. Abundant inactive travertine covers the ceiling of the lower level and the floor, ceiling and walls of the upper level. Erosion of the longer stalactites on the ceiling of the lower level indicates maximum stream height at about six feet in depth since the stalactites were formed. There are four feet of silt deposited over the travertine on the floor of the upper level. Hurricane Camille caused the stream to rise only 1.5 feet. An examination of the coarse fill

CROSSECTION OF MAIN STREAM PASSAGE, HIGGINBOTHAM'S CAVE

Figure 7.40



Modern Provenance Includes DROOP MOUNTAIN Sandstone
But No POTTSVILLE or PRINCETON Conglomerates

composition in the lower level of the cave is shown in Table 7.04. The significance of the sediment distribution is as follows:

1) The total absence of milky quartz or rock fragments from sources stratigraphically higher than the Droop sandstone of the Bluefield formation. Thus there is no material derived from the Allegheny Front now or in the past. Paleodrainage along the strike was carried southward along the Great Banana route. This appears to be the same with sediments of Buckeye Creek Cave.

2) All travertine is inactive and appears to be greater than 10,000 years in age. This is due to the very thin cap of limestone above the cave roof today. Less than ten feet of limestone overlie much of the cave, and the roof has completely fallen in in several places. The removal of the overlying limestone has interrupted the steady downward percolation of saturated water necessary for travertine formation. Although no travertine isotope dating was done in this cave, it seems likely that the thick, inactive layer of travertine in the upper level is much older than 10,000 years and could be up to 250,000 years B.P.

3) There is ample evidence of reworking of fills in the lower passage. The coarse gravels have been cut and alternate layers of silts and fine gravels have been deposited. The modern bedload appears to contain nothing larger than fine gravels. The coarse gravels and cobbles which underlie

Table 7.04

COMPOSITION OF COARSE FILL IN THE LOWER LEVEL OF HIGGINBOTHAMS CAVES

Lithology	Proportion (Percentage)	Provenance	Approx. Mean Grain Size	Approx. Minimum Grain Size
Alderson limestone	10	*in situ* breakdown	28 mm.	1.5 meters
Chert	15	from Alderson limestone in the cave	32 mm.	68 mm.
Sandstone	60	from Droop sandstone from hillside to west of cave	24 mm.	68 mm.
Shale	15	from Lillydale shales on hill	24 mm.	24 mm.

the fines are not typical of the modern bedload of caves on the karst plain. However, boulder-size sediments do appear to have been deposited in karst plain caves at an early date throughout the Great Savanna aquifer. It has been suggested that recent colder climates during the late Pleistocene are responsible for the production of coarse, angular material of the colluvial type found in Trout Valley. These larger blocks were not produced on the relatively steep slopes of the Droop sandstone hills around Higginbothams and Buckeye Creek Caves. Lower elevations by nearly 2000 feet may account for this lack of colder climate coarse debris locally. It is clear also that different provenance and lithology may account for the contrast in bedload size between the Trout Valley area and the caves of the karst plain. Both Buckeye Creek Cave and Higginbothams Caves contain well-rounded fine grained deposits of local derivation. In contrast, the caves of the lower carbonate/clastic contact show angular, coarse material which is very poorly sorted. It appears that both eastern and western margins of the limestone exposure receive highly angular debris which may have been the product of colder climatic conditions. This was not the case in Buckeye Creek Cave nor in Higginbothams Caves.

c. Caves of the Lower Basin Area (East of the Karst Plain)

A narrow band of MacCrady shale and Pocono sandstone outcrops immediately to the east of the Greenbrier limestone and west of the Greenbrier River (Figure 3.01). Relief across this clastic exposure is no greater than that of the limestone. However, short westward flowing streams with small catchments of less than a square mile rise along the outcrop, flow away from the river, and sink into some of the largest caves systems in the world. The major strike oriented conduits of these systems appear to be phreatically developed. Short tributaries flowing off the surface clastic rocks flow downdip along the contact. These vadose passages are often entrenched 30 feet into the underlying MacCrady shales which are roofed by the Hillsdale limestone. The Hole and McClungs Cave are representative of these lower contact caves.

(i) The Hole (Modern Drainage)

The largest modern drainage basin between modern Basin III and the Greenbrier River is that of the Hole. This cave has three entrances (Figure 7.27, numbers 10, 11 and 12) each of which receive intermittent surface runoff from the karst plain and the narrow outcrop of MacCrady shale lying west of the limestone and west of the River (Figure 7.01). The system flows northward to join Spring Creek in a series of risings downstream from the Culverson Creek resurgences. This drainage system is developed almost entirely within the Greenbrier series and has very little clastic sediment supply. As a result, the sediments are mainly the insoluble residue of limestone solution. Up to 96% of the Hillsdale and Sinks Grove limestone in which the cave is developed, are soluble. Sediments in the upper abandoned levels of this cave are very similar to those in the lower level which carried intermittent drainage today. Table 7.05 shows the means of some grain sizes randomly sampled in the main dry levels of the cave. Detailed sampling was not carried out in the Hole. The main source of insoluble material are the chert nodules found abundantly in the Hillsdale member of the Greenbrier series. This produces coarse sub-angular gravels. Although sand occurs in selected areas of the cave it is not commonly found. A red clay-silt is derived mainly from a breakdown of the MacCrady shales which outcrop in the lower passages. Vadose streams have entrenched as much as 25 feet into the MacCrady shale. The upper levels are filled with abundant chert gravels averaging two feet in depth, with a mean grain size of 32 mm. In contrast to caves in Basin III, the sediments are not indurated and are rarely compacted. They are poorly sorted at most sites and often appear to be completely reworked as a result of flood events. X-ray diffraction of fines shows no marked contrasts in kaolinite/illite ratios between the upper and lower cave levels. These lie well within the range for weathered limestones of this area (0.780 to 0.692).

Table 7.05

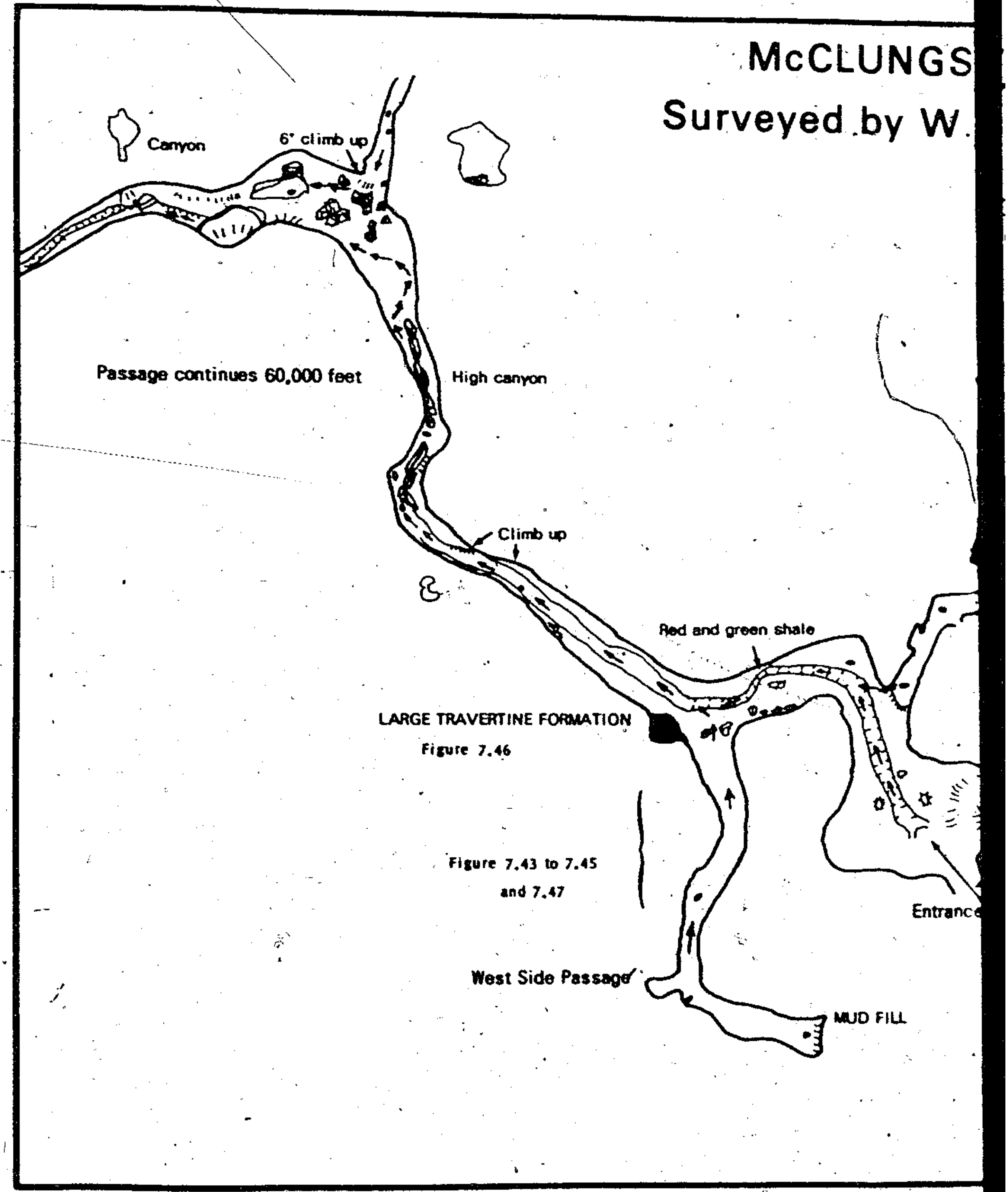
COMPOSITION OF COARSE FILL IN THE HOLE
(BOGGS ENTRANCE)

Grain Size	Proportion	Mean Grain Size
Silt and finer	10%	0.015 mm.
Sand	5%	0.5 mm.
Gravel and coarser	75%	32.0 mm.

(ii) McClungs Cave (Figure 7.27, Number 13)

McClungs Cave lies at the Greenbrier-MacCrady contact within the Great Savanna aquifer. There is no topographic or sedimentary evidence for its association with modern or paleodrainage of Basin III. Nevertheless, a detailed examination of the fills in McClungs Cave is considered to be of value in this study because of the vertical cave development and excellent preservation of fills in all levels. These were examined in the main entrance passage and two side passages (Figure 7.41). The sediments are found throughout 35 feet of range of relief. In addition, a vadose entrenchment into the MacCrady series allows for an additional 50 feet of vertical range for sediment and drainage variation in the first 3000 feet along the main passage. More than 62,000 feet of passage are developed in this typical lower contact karst plain cave.

The cave is developed in both the Hillsdale limestone and the MacCrady shale. This is a setting similar to the Hole and many other caves at this contact. A typical cross-section contains an upper phreatic channel oriented along the strike, with a deep vadose, V-shaped trench cut into underlying shales. The upper part of the MacCrady has been described as "non-calcareous" and "very porous" (Price and Heck, 1939, p. 714). It weathers out in angular prisms, rather than in thin friable plates. The prisms are easily rounded into small egg-shaped pebbles after a

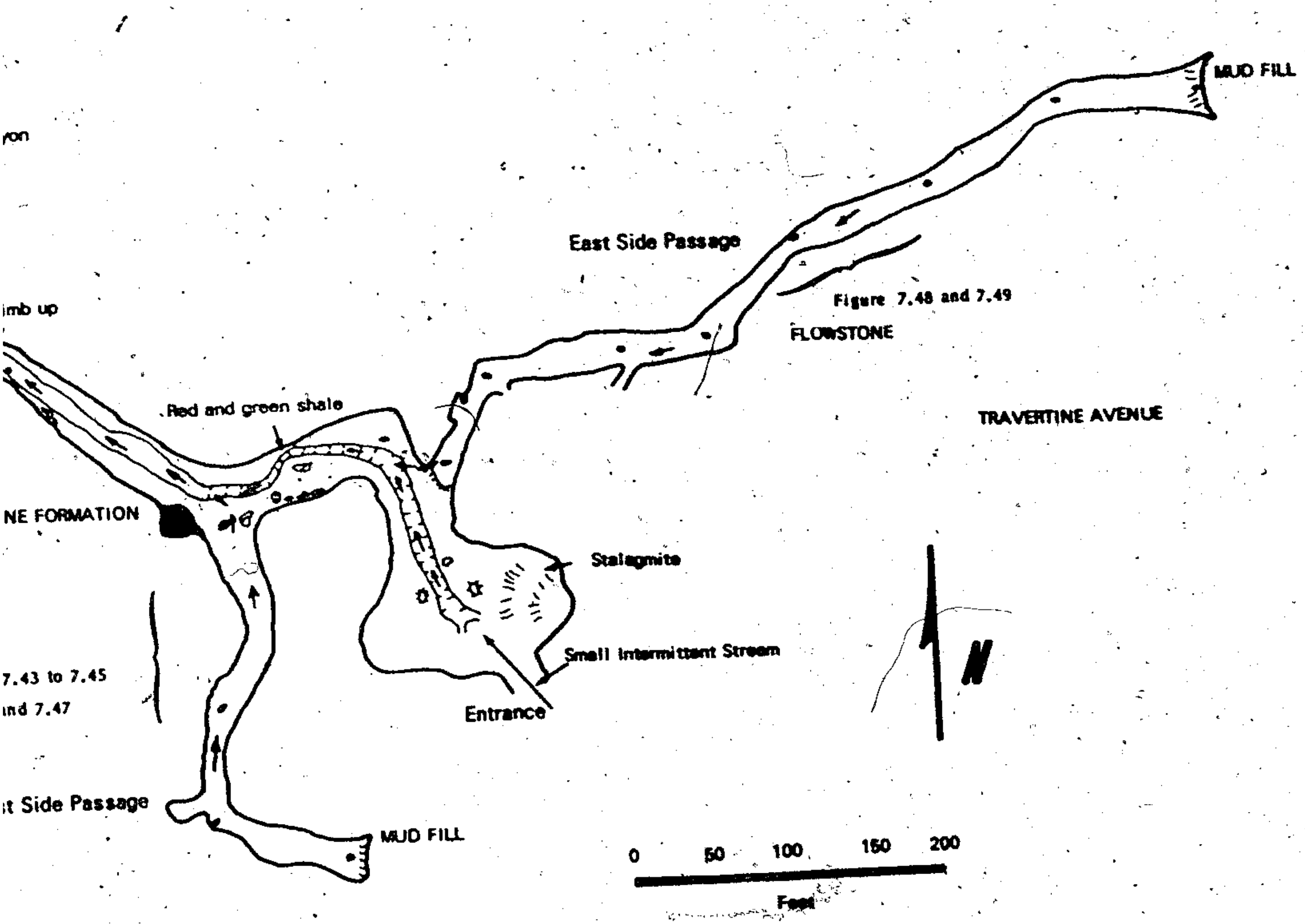

McCLUNGS
Surveyed by W.
Canyon
6" climb up
Passage continues 60,000 feet
High canyon
Climb up
Red and green shale
LARGE TRAVERTINE FORMATION
Figure 7.46
Figure 7.43 to 7.45
and 7.47
Entranc
West Side Passage
MUD FILL

1 of

McCLUNGS CAVE

Surveyed by W.V.A.C.S.

Figure 7.41



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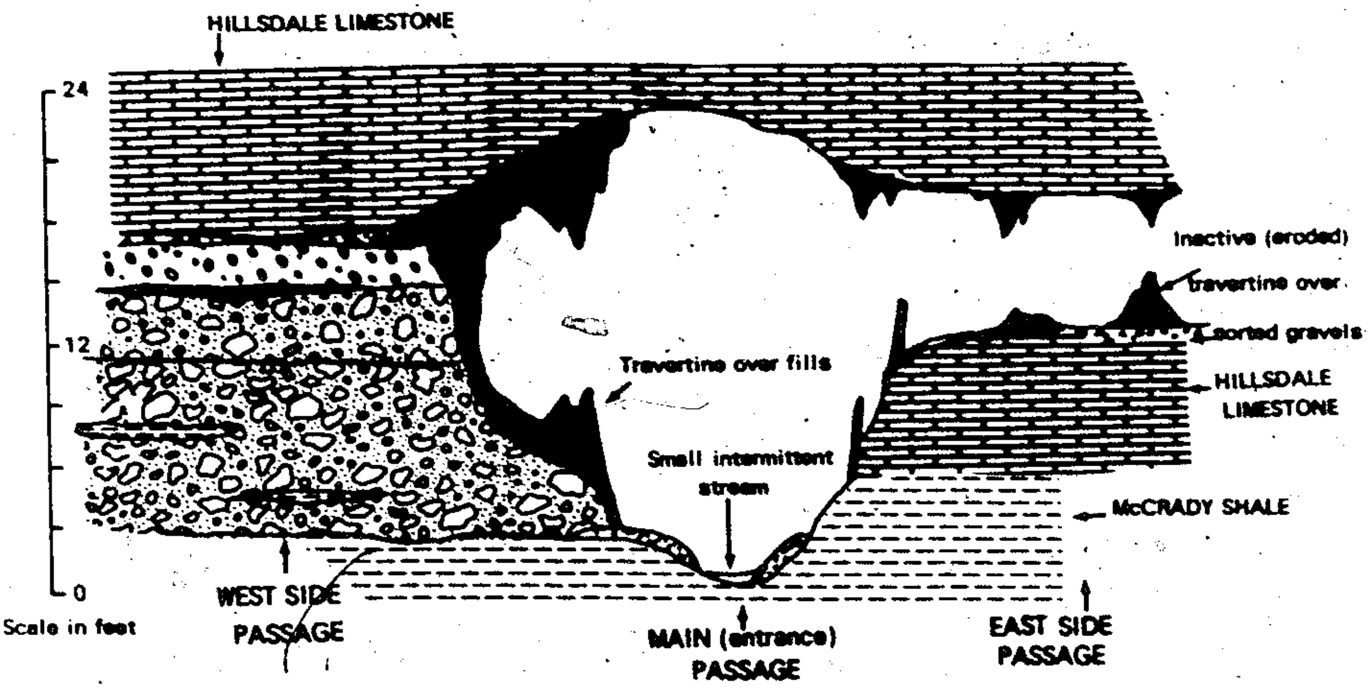
short distance of stream transport in the cave. They then break down into finer particles, and after a very short distance become silt. The rounded shale pebbles and red silt derived from the MacCrady shale comprise 75% of the modern bedload and suspended load of a small stream which flows intermittently down the trench of the main entrance passage. The remaining 25% of the clastic load is derived from surface silts and clays which wash into the cave during storms. The modern catchment area for the main passage is less than .5 square miles. The small valley outside the entrance is covered with vegetation (mainly grass and weeds). This prevents the invasion of coarse bedload entirely. During Hurricane Camille less than six inches of water filled the deep trench cut into the centre of the entrance passage. No drainage was observed in the two side passages.

Figure 7.42 is a cross-section of the entrance passage showing the relation of sediments to the two side passages which enter, one from the west and the other from the east, 100 feet inside the entrance. The side passages are of particular interest because they contain massive fills which have not been removed by active intermittent erosion. The stream activity in the main passage has removed any evidence of fluvial deposition there except where travertine covers it.

The west side passage joins the main passage at a right angle on the southwest (Figure 7.41).* Dimensions

CROSSECTION IN MAIN PASSAGE OF McCLUNGS CAVE

Figure 7.42



Coarse angular poorly sorted gravels, cobbles, and boulders with silt/clay matrix and lenses which predate inactive travertine cap.

of the passage vary because of sediments and travertine, but these are approximately 12 feet to 15 feet in height, by similar widths. No active drainage is present in the passage. Both walls and part of the floor are covered with massive bedded deposits of boulders, cobbles and gravels, with large lenses of silt and clay. Table 7.06 gives a breakdown of this material in the gravel and larger size fractions, which comprise 80% of the mass of these deposits.

The most interesting component of these fills is the Pocono sandstone. It is larger than the other grain sizes and has travelled the greatest distance from known outcrops. The outcrop lies one mile to the east and extends along both sides of the Greenbrier River. The distance from the original provenance to the cave was probably somewhat less than the present outcrop. The former Pocono exposure was probably higher and wider than the present narrow outcrop on the west side of the river. This is now less than a mile wide and at maximum only 100 feet above the entrance to McClungs Cave. Greater relief and a larger catchment would be necessary to provide the large angular blocks of Pocono sandstone found in the side passages of McClungs Cave. The nearness to the Greenbrier River of the outcrop may explain the low relief which has been described as the "Harrisburg" erosion surface (Fenneman, 1938). Constant erosion by small tributaries draining east to the river is a probably cause for the loss of catchment

Table 7.06

COMPOSITION OF COARSE FILL IN McCLUNGS CAVE

Lithology	Proportion (Percentage)	Source	Approx. Mean Grain Size
Chert and limestone	50	Hillsdale limestone	65 mm.
Sandstone	25	Pocono sandstone	25 cm.
Shale, siltstone	25	MacCrady shale	28 mm.

area immediately to the east of the cave. The fills are imbricated into the main passage toward the northwest.

The finer fraction, comprising 20% of the under 2 mm. material is over 80% silt and clay. There is a noticeable lack of sand-sized material, which comprises less than 4% of the total mass of the deposits. This is true despite the abundance of sandstone cobbles and boulders.

It appears that the finer fraction was deposited simultaneously along with the coarser fraction. Evidence for this is the lensing nature of the fines. They are not found in continuous beds for more than 30 feet, and are usually tapered at both ends in long lenses (Figure 7.43). X-ray diffraction of these fines yielded the lowest kaolinite/illite ratios of any cave deposits in Basin III. A ratio of 0.505 was obtained for one deposit in this side passage. This contrasts with much higher ratios in the range of 0.800 to 1.000 for the surface clays immediately above the cave. Active cave streams like Culverson Creek and Buckeye Creek caves were higher at 0.933 and 0.962 respectively. The paleofills in Bob Gee Cave gave ratios that were very close to the ratios of the deposits of McClungs Cave. The McClungs fills, however, are noticeably different from the paleofills of Bob Gee Cave in the following respects:

1) They are of a different provenance, being derived from the east near the Greenbrier River and not from

Figure 7.13

WEST (LEFT) SIDE PASSAGE, CLAY LENSES IN POORLY SORTED FILLS, McCLUNGS CAVE

the younger Pennsylvanian outcrops to the west along the Allegheny Front.

2) They contain no milky quartz pebbles.

3) They are very poorly sorted and occur in massive beds. The Bob Gee Cave sediments are moderately-to-well sorted and thinly bedded.

4) They are of greater angularity than the Bob Gee deposits. They have been transported no more than two miles from the outcrop source.

5) They are of a larger grain size and of great bulk.

6) Whereas some coarse angular fills were found near the entrance of Bob Gee Cave, the McClung fills have been deposited several hundred feet into the cave. These may have extended much farther, but have been removed from the main passage except in one place.

7) No karst "sieve-type" deposits are associated with the McClungs deposits on the surface. Nor do these deposits occur anywhere on the associated karst plain area.

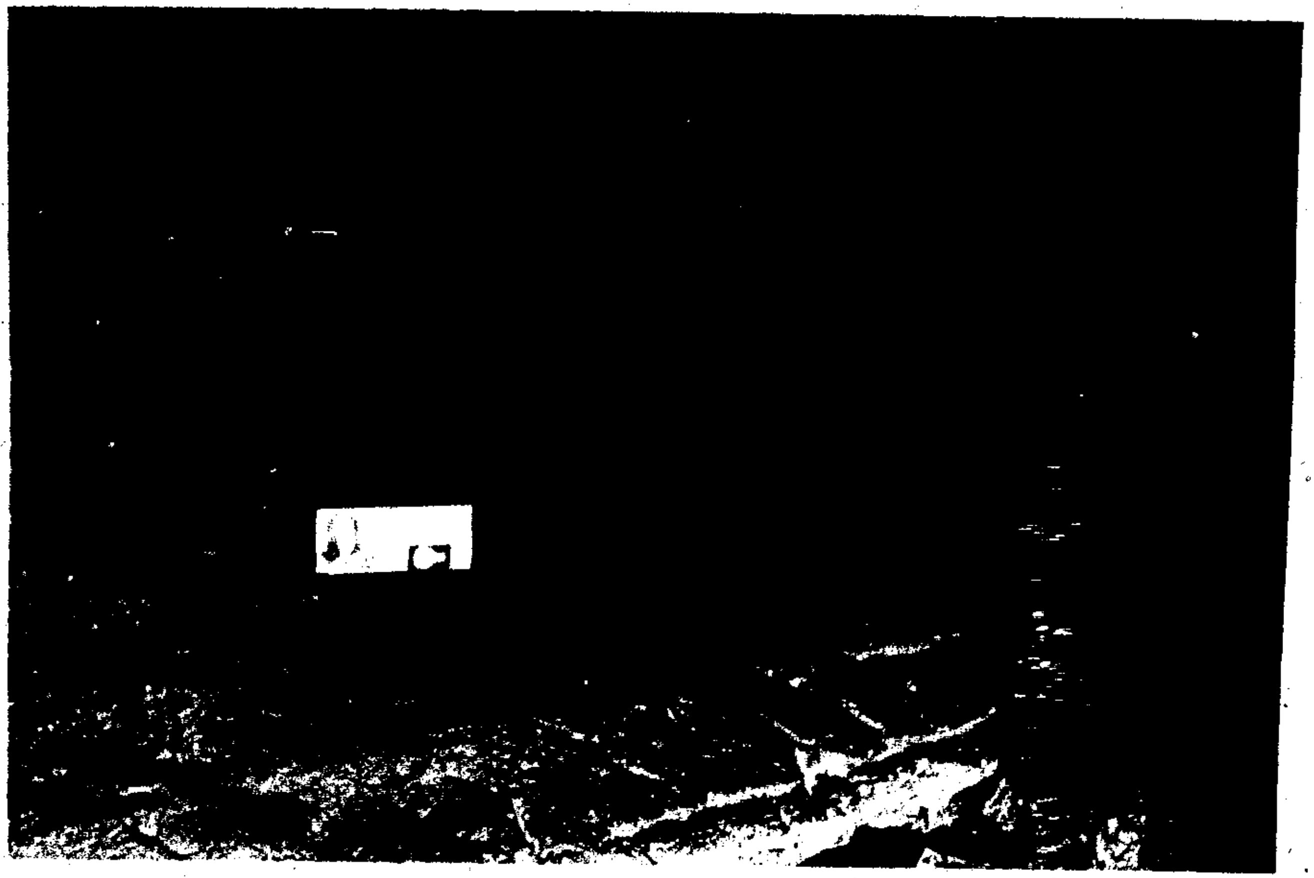
Figure 7.43 shows the north wall of the west side passage. Two thick silt-clay lenses are seen at the top of the photograph. Figure 7.44 is a close-up of the contact between the lower silt-clay lense and the underlying gravels. Note the poor sorting, high angularity, and massive bedding in the underlying gravels. Figure 7.45 is to the immediate right (downstream) at a distance of 100 feet from the

Figure 7.44

WEST (LEFT) SIDE PASSAGE, COARSE FILLS, McCLUNGS CAVE

Figure 7.45

WEST (LEFT) AIDE PASSAGE, COARSE FILLS AT CEILING LEVEL, McCLUNGS CAVE



junction with the main passage (Figure 7.42). Here coarse, angular, poorly sorted fills are capped with silts and clays. There is no graduation through fine gravels and sand-sized particles. The ceiling fines are probably the result of ponding when the passage became completely filled with sediments. The ledge at the bottom of the photograph is bedrock limestone which has defended the upper fills from later removal. The sediments in the upper right (background) can be traced to the main passage junction where they have become covered with massive travertine (Figure 7.46).

Figure 7.47 shows the opposite wall of the west side passage. Here more fills have been removed than on the opposite side, although they are nearly continuous along both walls of the passage. It appears that after deposition which completely filled the passage, a vadose stream removed 80% of the deposits down the centre of the passage. This stream appears to have meandered in a different pattern from the initial passage meander pattern. The result was the further erosion of the limestone wall shown in Figure 7.47. The small size scalloping in the upper right corner of the photograph is an indication of this post-depositional erosion of the formerly phreatically scalloped limestone wall.

The main entrance passage lacks clastic fluvial sediments except in the first 300 feet of passage. Some silt accumulation is found inside the entrance of the cave

Figure 7.46

MAIN PASSAGE, TRAVERTINE COVERING COARSE ANGULAR
FILLS FROM WEST (LEFT) SIDE PASSAGE, McCLUNGS CAVE

Figure 7.47

WEST (LEFT) SIDE PASSAGE, EROSION OF MASSIVE FILLS, McCLUNGS CAVE

but this is less than one foot in depth and is of recent origin. Where the west side passage joins the main passage from the left, the coarse fills of the side passage are found preserved beneath a thick flowstone deposit (Figures 7.42 and 7.46). The coarse fills are below the travertine ledge (at the hand of the observer) and can be seen in the opening on the right. The side passage joins the main passage 30 feet to the left of this photograph. These fills are traceable back into the west side passage, but do not continue along the main passage.

The east side passage joins the main passage from the right (Figure 7.41). It is approximately 15 feet higher in elevation than the left side passage, and lacks the massive fills of a predominantly coarse nature. Inactive travertine of an apparently similar age to that in the main passage fills much of this west passage. Two hundred feet from the junction a massive stalagmite is being eroded (Figures 7.48 and 7.49).

Beneath the travertine is a moderately sorted deposit of rounded stream gravels. This material is less than two feet in depth where it is protected by flowstone. Elsewhere it has been completely removed by post-depositional erosion. It contains abundant chert nodules, no milky quartz, no shale fragments, and a small percentage of sandstone. The finer grain size, better sorting and rounding of this deposit suggests a greater distance of transport than the

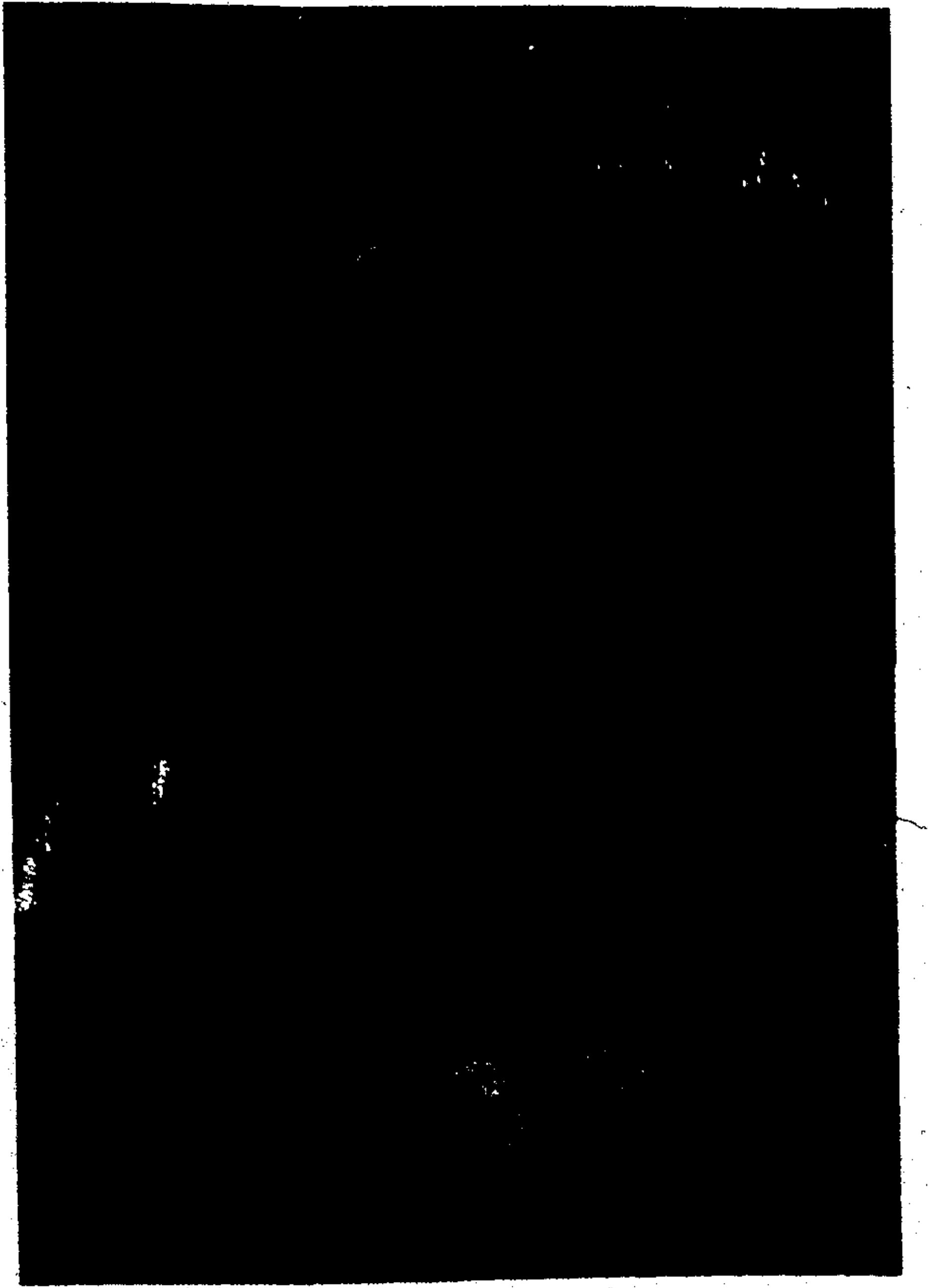
Figure 7.48

EAST (RIGHT) SIDE PASSAGE, ERODED TRAVERTINE, McCLUNGS CAVE

Eroded column in the east side passage of McClungs Cave. This deposit once measured eight feet in diameter. "Aggressive" water which may have resulted from deforestation of the limestone surface above, has removed 90% of the deposit. No travertine deposition occurs today in this passage.

Figure 7.49

EAST (RIGHT) SIDE PASSAGE, FILLS BENEATH ERODED TRAVERTINE, McCLUNGS CAVE



material in the east passage. However, the very small amount which remains makes an accurate interpretation impossible. It is not traceable for more than 30 feet along the passage floor and may have entered from a sink above the passage which is now blocked with residuum.

Both side passages and the upper portion of the main passage cross-section appear to be of phreatic origin, with post fill deposition entrenched by vadose invasion (Figure 7.42). The following interpretation of the development of McClungs Cave is based upon the foregoing description of its sedimentary and drainage characteristics:

1) The main entrance passage of McClungs Cave was generated by phreatic movement of ground water downdip from the east and north toward the "Great Savanna" aquifer trunk conduit. This occurred above the underlying shales entirely within the Hillsdale limestone as a perched aquifer.

2) Fills of a coarse grain size were deposited rapidly by invading surface flooding. This material remains only in the west side passage today, but some evidence suggests that this material may have completely filled the main passage as well. This may have occurred as the result of a single flood event. However, this does not seem possible under the present type of climatic regime for the following reasons:

a) the size of the catchment is very small

b) provenance and rounding suggest a very short distance of transport for all fills (less than two miles distance)

c) modern vegetation restricts sediment removal and transport of material greater than sand-size particles

d) the age of these deposits is clearly greater than the period of historical settlement and land use in the area. Agricultural activity is therefore ruled out as a cause for these poorly sorted, massive fills

e) observations during and after the floods of Hurricane Camille showed that only a small amount of fines entered the cave. This single flood is considered to be a once-in-a-hundred year or rarer event, but it in no way resulted in the type of sediment transport necessary to deposit the massive fills in the west passage. For these reasons this author suggests that the massive deposits in the left side passage were caused by periglacial activity in a poorly vegetated small karst basin of greater relief than at present, feeding from the east into this passage. Rapid melting and movement of surface layers of ice fractured material accelerated by flooding due to spring thaw and summer rain could have produced such deposits. Their provenance area lay to the east along the Greenbrier River in the outcrops of Pocono sandstone which formed a sharp divide between this basin and the river at that time. The lack of animal fossils in the deposits also tends to support the periglacial hypothesis.

3) Travertine was later deposited over some of this material in the main passage and over fills in the east

side passage, probably at the same period of active calcite deposition. This could have occurred during a warm interglacial period when forest cover allowed for slow percolation of water and stalactite development in the right passage. This buried the fills in the main passage with three feet of travertine.

4) Vadose entrenchment into the fills and travertine eventually reached the base of the carbonate rocks of the Greenbrier series. This entrenchment continues today at a moderate rate and has cut into the underlying non-calcareous, porous MacCrady shale to a depth of 30 feet. The preservation of the fills in the side passages has been due mainly to downcutting in the main passage by vadose invasion and to travertine deposits in the past.

D. Conclusions on Basin III

Basin III shows the greatest complexity of the three basins chosen for this study. Many drainage and sedimentary alterations of considerable consequence and magnitude have taken place since the limestones were first exposed to karstification. The downcutting of at least 250 feet by the modern channel of the Greenbrier River below the karsted limestone surface has been the main cause for acceleration of many of these drainage and sedimentary changes. In summary, the following statements concerning the erosional and depositional development of Basin III can be made:

1) Modern and paleodrainage shows a strong structural and lithological control. The same can be said for vadose drainage in caves. The Sinking Creek to Muddy Creek network and the entrenchment of cave floors by invading surface waters show a similar strike oriented pattern.

2) The continued erosion and removal of clastic material from the upper Mississippian and Pennsylvanian outcrops of the Allegheny escarpment have left behind sedimentary evidence on the surface and in the caves across the ten mile wide karsted surface between the escarpment and the Greenbrier River, which has yielded valuable information about the sequence of geomorphic events during the past several hundred thousand years.

3) The particular cave clastic assemblages reflect the position of caves with reference to the clastic strata which outcrop at the margins and elsewhere. Thus, Bob Gee Cave, Higginbothams and McClungs contain coarse debris injected at different stages in their history, but reflecting local supplies of sandstones. The Hole and Buckeye Caves are also inlet caves which channelled local waters, but they lack abundant coarse fill because their basins are limited to limestones and shales. Culverson Creek system stands at the centre of Basin III. It has the largest catchment, as is fully indicated by its very large passage dimensions, but it is remote from the clastic margins and it is a cave dominated by the transport and deposition of fines.

4) Evidence for climatic changes is present in the deposits of Basin III. The surface karst "sieve-type" deposits and the massive, poorly sorted, angular cave fills suggest a past colder periglacial environment.

5) Comparison between modern and paleo evidence for deposition and removal of fills across Basin III would suggest:

a) a greater amount of deposition and removal of fills has occurred during the past than is presently going on. This includes infrequent events such as the once-in-one-hundred years floods caused by Hurricane Camille in 1969

b) caves nearest to the Allegheny escarpment at stream level, such as Culverson Creek Cave, experience the greatest amount of modern deposition. This is still less than 1/100th the rate indicated by paleo deposition in some caves of the karst plain and elsewhere

c) once a cave has been cut off from the active supply of fills either by surface stream diversion or downcutting of a cave stream to a lower level, the removal of sediments in the upper levels ceases

d) acidic waters draining from the non-carbonate rocks along the forested slops of the Allegheny escarpment appear to be presently capable of maintaining and enlarging cave systems at a general rate which is greater than the overall rate of deposition of clastics and carbonates; otherwise these caves would have become completely filled with sediments as they have at times in the past. The overall volume of open space in the cave conduits appears to be increasing, despite the occasional blockage of passages and deposition of cave fills.

e) the deposition events during the Pleistocene still account for the greatest volume of material found in present day caves of the Greenbrier karst

f) very few modern cave streams are flowing directly upon limestone, but the veneer or armour of clastic sediment is rarely thicker than three feet.

5) Surface drainage only exists on the karst plain where fine sediments have accumulated to a depth of at least five feet. Coarse "sieve-type" deposits result where the limestone is in contact with clastic rocks of high relief along the western margin of the karst plain. Streams rise on the limestone below these deposits supported on winnowed fines from the "sieve-type" deposits. Along the eastern margin of the karst plain "sieve-type" deposits do not accumulate. This may be the result of:

a) a lack of boulder-sized material from the lithologies available

b) a lack of a large catchment

c) a lack of high elevations now or in the past which would have been subject to greater periglacial activity

d) the presence of large cave openings which are capable of receiving all the sediment supplied by these smaller basins now and in the past. The coarse angular fills of McClungs Cave would have accumulated on the surface if the cave opening were not so large.

Chapter 8. ANALYSIS AND CONCLUSIONS

A. Introduction

Basins I, II and III represent the variety of drainage and sediment properties characteristic of the larger Greenbrier River drainage network. Basin I and Basin III are representative of the extremes in karst drainage development and clastic sediment properties across the karst of the Greenbrier limestone. Basin II is intermediate and thus more likely to characterise the majority of karstic tributaries (Tables 8.01 through 8.05). The variables of each basin are summarised in Table 8.06. This developmental sequence of karst aquifers in a downstream direction along the main trunk may also represent temporal variations within the same basin. A comparison of the alterations of these tributary basins is, therefore, considered to be the model for drainage and sediment changes in the Greenbrier limestone karst.

Basin I is typical of the steep gradient networks in the upper one-third of the Greenbrier River basin. It has not yet attained maximum relief as in Basin II. It has the largest number of profile nickpoints, indicating that lithologic control over the drainage is still strong. Coarse, boulder-size bedload moves completely through the system to

Table 8.01

CHARACTERISTICS OF THE MODERN DRAINAGE BASINS

Basin	Perimeter of Basin (Miles)	Maximum Area (Sq. Mi.)	Drainage Density L/A	Total Length of Streams (Miles)	Basin Ruggedness H/D	% of Area on Limestone	% of Area on Clastics	% of Area Alluvium
Basin I	13.5	4.8	2.38	11.4	.164	41.5	48.5	0.0
Basin II	28.5	34.3	1.63	55.8	.296	30.0	65.0	5.0
Basin III	42.0	53.2	1.12	59.5	.420	22.5	74.0	3.5

Table 8.02

CHARACTERISTICS OF MAIN TRUNK CHANNELS

Basin	Surface Length (Miles)	Subsurface Length (Miles)	Total Length	% on Carbonate Rock	% on Overlying Clastic Rock	% on Underlying Clastic Rock	% on Sediment Armour on Limestone	Gradient	Total Relief (Feet)
Basin I	1.5	1.0	2.5	40.0	20.0	40.0	0.0	133/1000	2285
Basin II	12.9	3.0	15.8	19.0	47.5	21.0	12.5	33/1000	2526
Basin III	14.1	5.7	19.8	34.0	21.0	6.0	39.0	25/1000	2490

Table 8.03

CHARACTERISTICS OF MAJOR CAVE CONDUITS IN BASINS

Basin	Position in Basin*	Mean Grain Size of Bedload	Maximum Grain Size Entering Conduit	Maximum Grain Size Leaving Conduit
Basin I	.4	62 mm.	4 m**	140 mm.
Basin II	.66	8 mm.	1 m**	10 mm.
Basin III	.7	5 mm.	1 m**	under 1 mm.

*Fraction of Major Trunk from Head 1 = mouth , 0 = head

**not undergoing active transport

Table 8.04

GENERAL SEDIMENT CHARACTERISTICS OF BASINS

Basin	Provenance	% Milky Quartz	Mean Ratios of Kaolinite 3.58Å/Illite 10.0Å		Mean Active Bedload	Maximum Modern Bedload
Basin I	Mississippian and Pennsylvanian sandstones, shales and conglomerates	15-20	Active channel* Mean Ratio	= .890	62 mm.	4 m.
			Inactive conduits** Mean Ratio	= .540		
Basin II	As above.	5-8	Active channel* Mean Ratio	= 1.019	8 mm.	1 m.
			Inactive conduits** Mean Ratio	= .488		
Basin III	As above.	5	Active channel* Mean Ratio	= .930	less than 1 mm.	370 cm.
			Inactive conduits** Mean Ratio	= .424		

*Active surface and subsurface channels.

**Inactive conduits in caves

Table 8.05

CHARACTERISTICS OF BASIN PROFILES

Basin	Total Gradient	Gradient of First Mile of Upper Basin on Clastics	Mean Gradient on Limestone	Number of Nickpoints	Location of Nickpoints
Basin I	133/1000	350/1000	76/1000	3	Near upper and lower limestone contacts and over Taggard shale
Basin II	33/1000	200/1000	28/1000	2	Point of capture in upper basin and in cave (Taggard shale)
Basin III	25/1000	160/1000	4/1000	0	Smoothed profile

Table 8.06

SUMMARY OF BASIN DATA, SHOWING THE RANK OF EACH BASIN FOR EACH CATEGORY

	Perimeter P	Area A	Drainage Density L/A	Total Stream Length L	Basin Ruggedness H/D	Percent of Basin Area on			Gradient	Basin Relief	Number of Nickpoints
						Carbonate Rocks	Clastic Rocks	Alluvium			
Highest	III	III	I	III	III	I	III	II	I	II	I
	II	II	II	II	II	II	II	III	II	III	II
Lowest	I	I	III	I	I	III	I	I	III	I	III

I = Basin I
II = Basin II
III = Basin III

the river. Headward growth on the clastics of the upper basin continues, while downstream alterations are minimal. The narrow width of exposed limestone does not yet allow for shifting of risings and piracy in the lower basin. The middle portion of Basin I is beginning to undergo integrational processes between the surface and subsurface networks as surrounding drainage is captured. This is the most active part of the basin.

Basin II has attained maximum basin relief and also has the highest percentage of its drainage over clastic sediments upon the limestone. Piracy has occurred in the upper basin drainage by capture of westward flowing drainage on the Plateau. Alteration within the middle basin is mainly due to the loss of lithologic control at the expense of the hydrological gradient toward the base level trunk. High water overflow still utilises the intermittent strike-oriented subsurface conduits. Surface and subsurface divides are more accordant than in Basin I. These, however, never reach complete coincidence. The location of the major rising of the system is fixed. Alternative surface overflow routes exist and are in the process of becoming abandoned as local base level drops below the limestone outcrop.

Basin III has passed the maximum basin relief. It lies between Basin I and Basin II in this respect (Table 8.06). It has the most graded overall trunk profile. The underground trunk has become an integrated part of the basin profile. Drainage density is low. However, across the limestone it is greater than for Basin II, but less than for Basin I. This is due in part to the accumulation of fines along the trunk channel. This armours the surface stream bed and shields it from the underlying limestone. There is now only one outlet in the lower basin area, and lithologic controls are minimal. Drainage is across the stike. Surface and subsurface strike-oriented channels and conduits have been completely abandoned. Flooding does not utilise surface overflow routes as these are now too far above the level of the sinkpoint. Upper level cave conduits provide the only overflow paths. Sediments are sieved in the upper contact area of the limestone and only the fines are able to pass completely along the trunk conduit. Enlargement of the lowest level in the cave continues. This appears to be more by collapse than by solution, as its stream bed is also shielded from the floor of the limestone cave. This shielding prevents continuous downward vadose trenching in the system. New low level routes develop below the active one, and periodic lowering of the drainage occurs via these new conduits.

B. Drainage Development

From the observations in the three basins it is suggested that the characteristic Allegheny Front karst drainage pattern develops as follows.

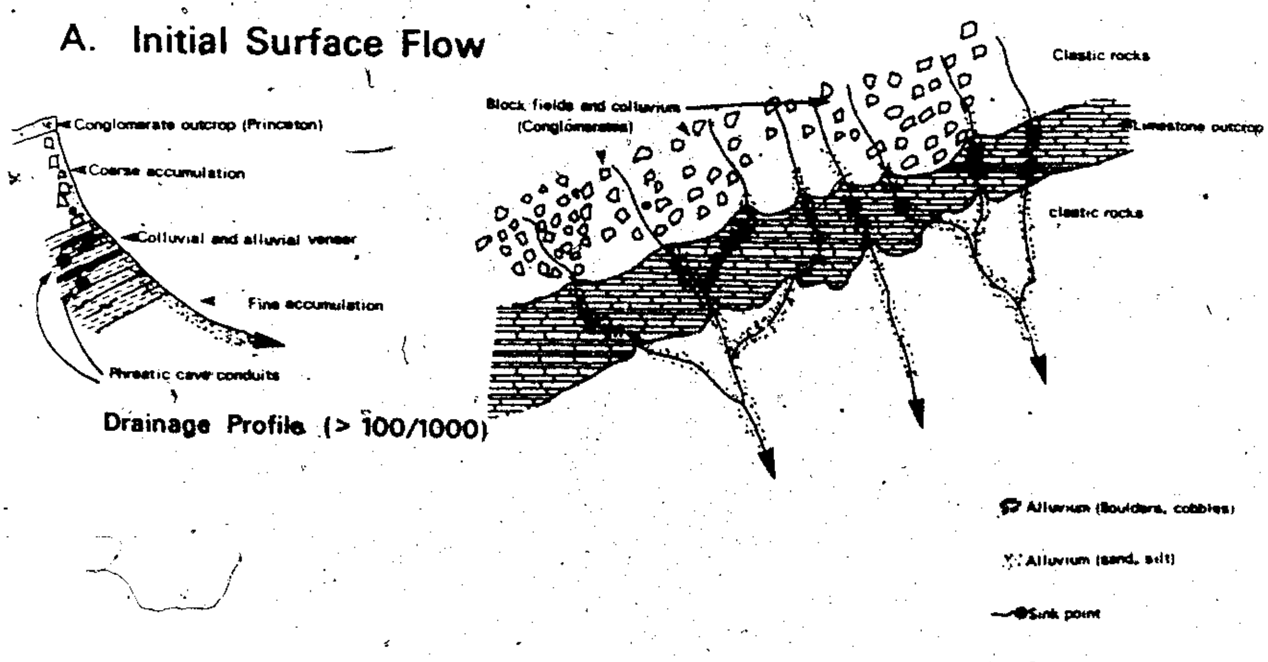
1. Initial Surface Flow (Figure 8.01A)

Along the Allegheny Front, steep gradient, rapid intermittent runoff is initiated in parallel channels. Deep deposits of surface colluvium cover the limestone and lower clastic rocks. Evidence for mass movement down the escarpment has previously been cited by this author and others. The activity of these streams is mainly in the transport, reworking and removal of fines from the surface veneer. Modern streams are not capable of moving the larger boulders which exceed eight meters in length. Rounding of large boulders in the active channel occurs as the finer fragments are removed. Eventually bedrock is reached. Surface flow continues, and under steep gradients and high velocity runoff, a channel is often cut into the limestone surface. This may be 15 feet deep and extend across the full width of the outcrop to the lower clastic rocks. Interbedded shales within the limestone create small nickpoints. Gradients of these small First and Second Order surface channels are in excess of 300/1000 in the upper basin areas (above the limestone). The average gradient across the limestone is greater than 75/1000 and overall basin gradients are greater than 125/1000.

DRAINAGE DEVELOPMENT ACROSS THE GREENBRIER KARST

Figure 8.01

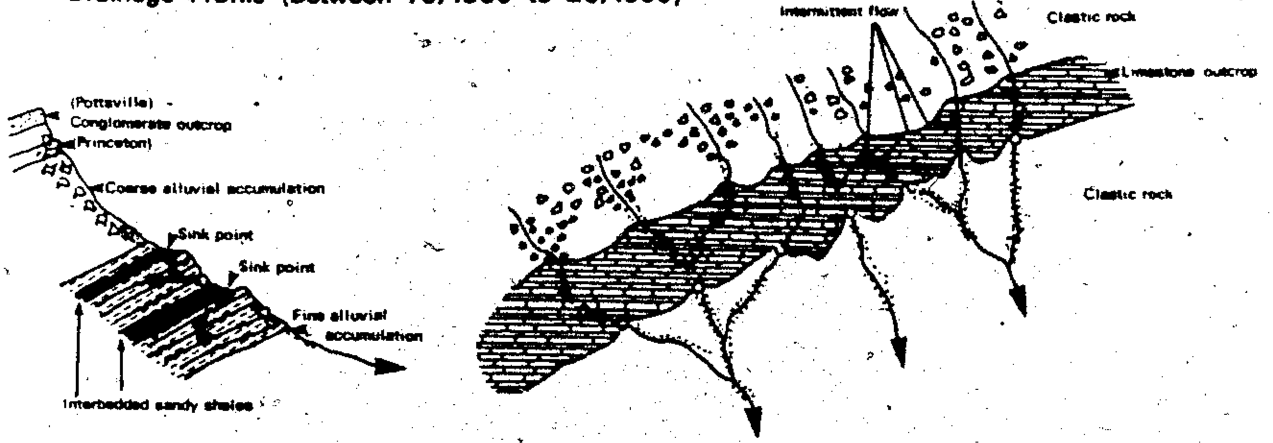
A. Initial Surface Flow



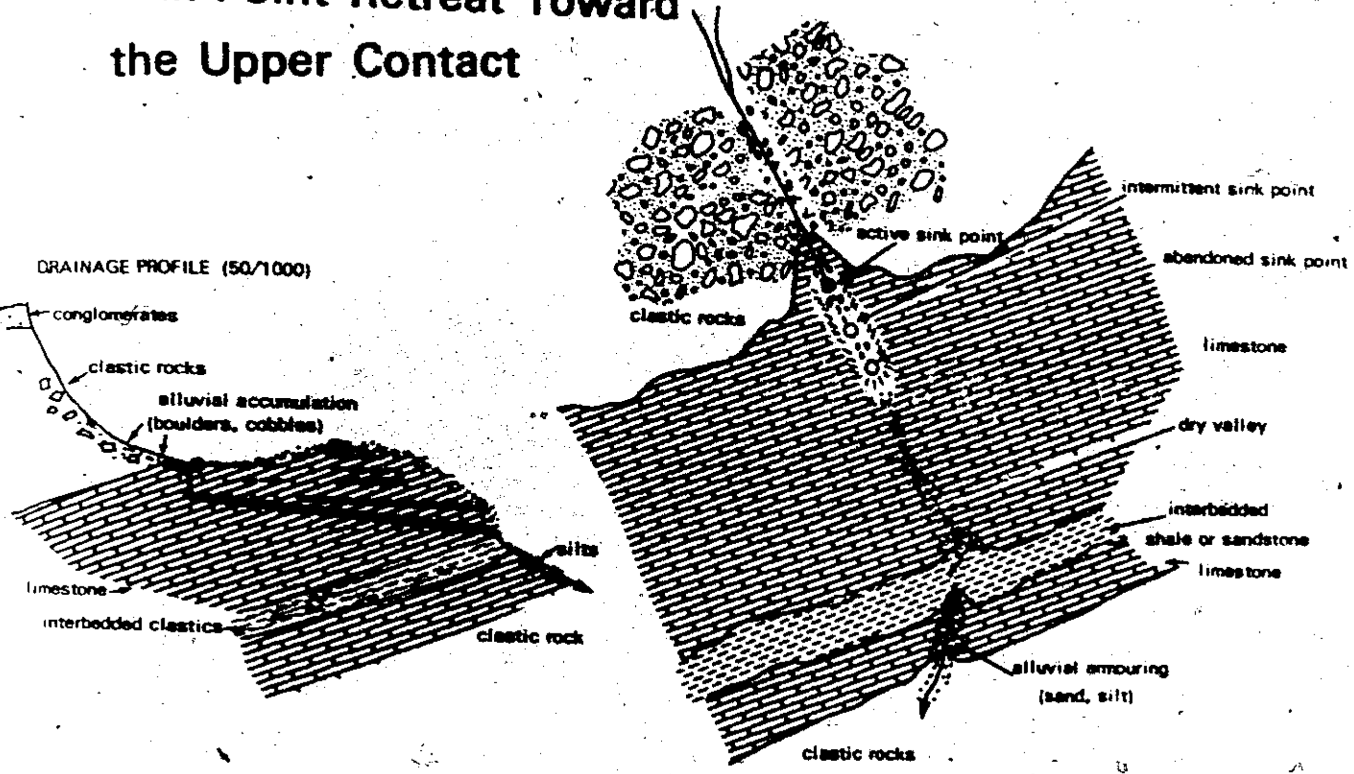
Drainage Profile (> 100/1000)

B. Subterranean Diversion and Intermittent Surface Flow

Drainage Profile (Between 75/1000 to 25/1000)



C. Sink Point Retreat Toward the Upper Contact



D. Lateral Growth by Subterranean Piracy and Diversion Toward the Deepest Conduit

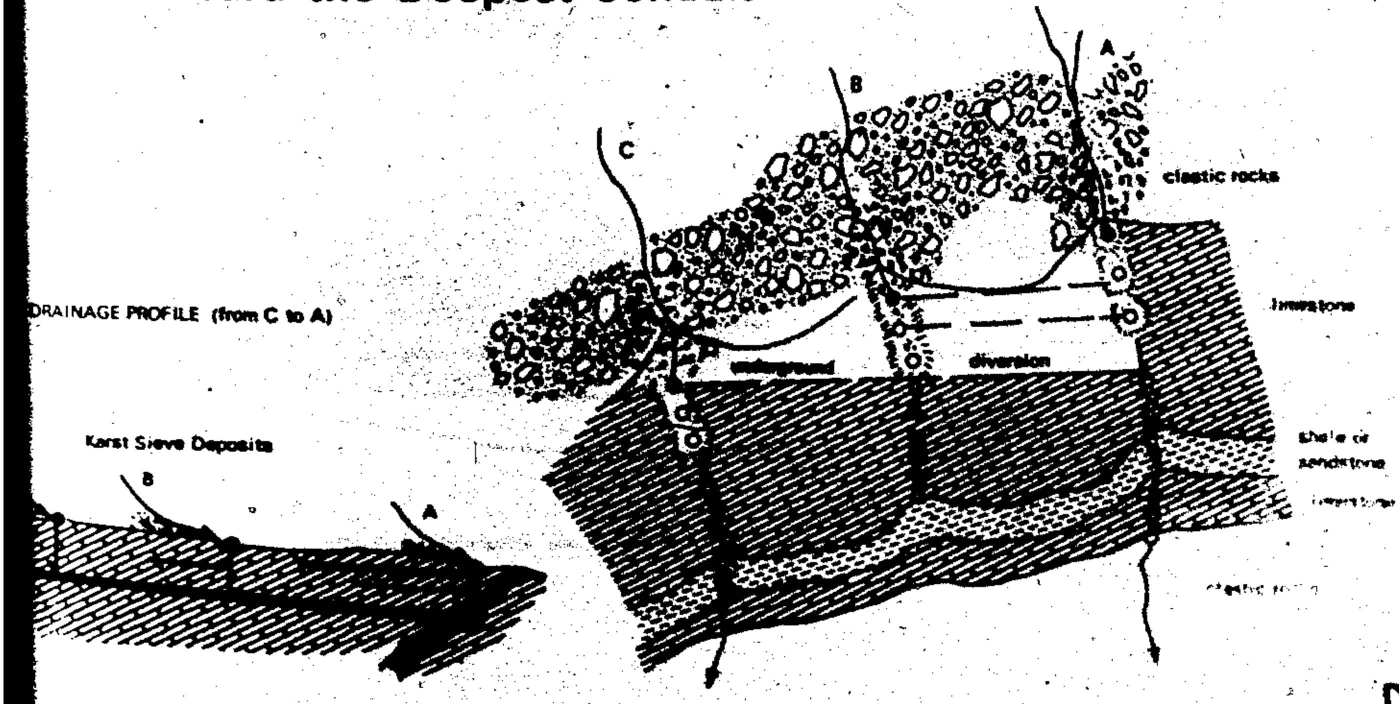
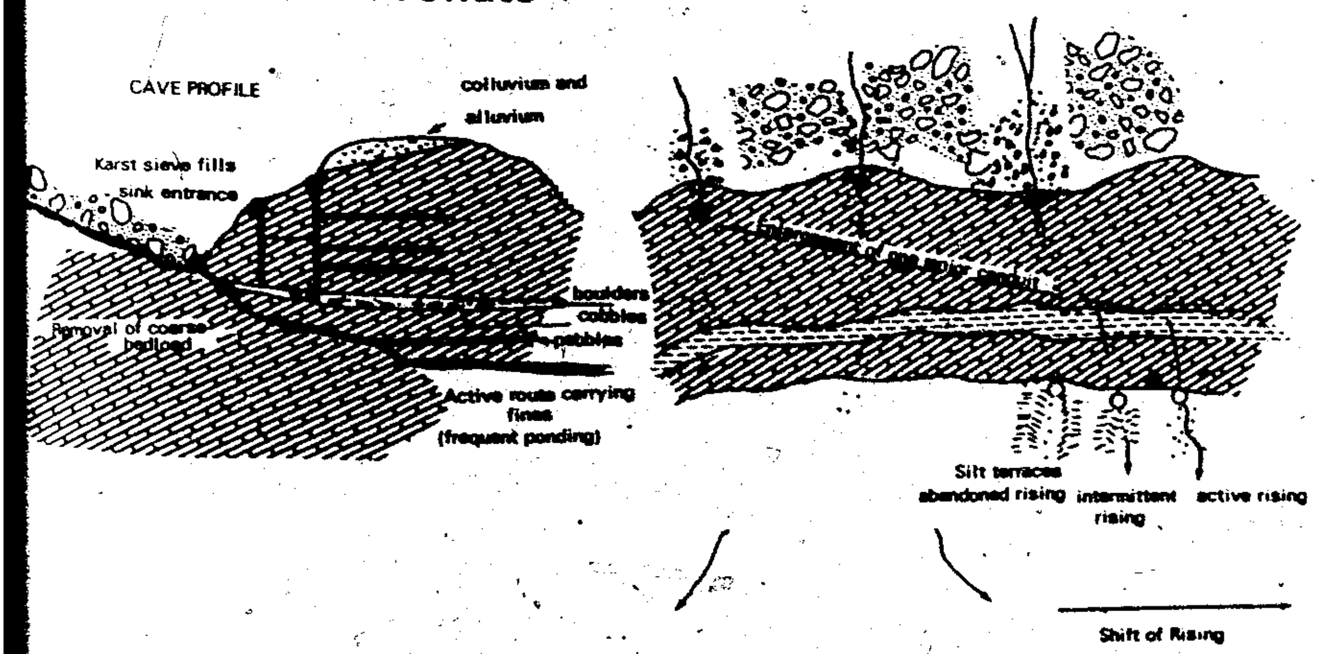
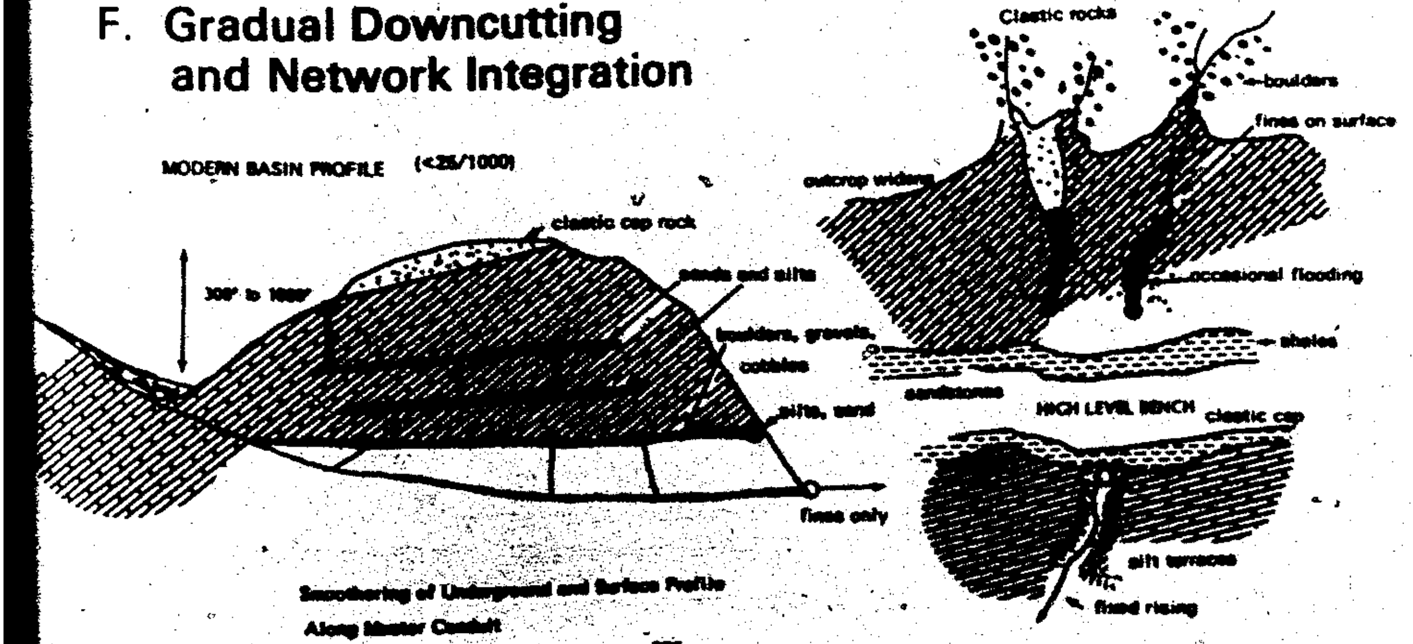


Figure 8.01 (concluded)

E. Shifting of the Rising Along the Lower Clastic/Carbonate Contact



F. Gradual Downcutting and Network Integration



2. Subterranean Diversion and Intermittent Surface Flow

(Figure 8.01B)

An empirical observation on these basins is that a stream gradient range of 75/1000 to 25/1000 across the limestone is necessary for subsurface capture. Steep gradients (over 100/1000) and gentle gradients (under 20/1000) are characteristic of surface flow across the limestone. The steep streams have not yet developed openings in the unexposed limestone or may be considered to be eroding too efficiently for a groundwater circulation to compete. The gentler gradient streams flow on a veneer of fines which shield the limestone beneath from effective penetration.

Ford (1962) has observed that the optimum range of relief for karst basins in the Mendip Hills of England lies between 45/1000 to 4/1000 . This lies partially within the range of the Greenbrier karst gradients; however, in the Greenbrier karst, the gentler gradient streams are supported on alluvium. The variation might be attributable to several factors. The Mendip catchment areas are developed on fine grained clastic rock. The overall basin relief in the Mendips is also much lower. Another possibility is the lithologic variation which causes varying solubility and solution rates.

As surface gradients become gentler, underground piracy occurs along widened joints. These are not usually at the upper limestone contact where surface debris still covers the limestone, but in the central part of the limestone outcrop. A nickpoint in the trunk stream profile develops as a result of this diversion. Occasional surface flow continues beyond the swallow hole during high runoff conditions. This decreases as the opening in the underground network enlarges. Surface fines and small boulders enter the openings and move completely through the cave conduits to the lower basins.

3. Sinkpoint Retreat Toward the Upper Contact (Figure 8.01C)

The initial sink of the surface stream is abandoned gradually as new openings develop upstream. The valley profile becomes "humped" as the limestone surface portion of the basin is no longer subjected to fluvial degradation below the sinkpoint of the active channel. Eventually, this area stands much higher than parts of the upper stream basin. Above and below the limestone fluvial action continues. This produces at least two lithologically induced nickpoints. The lower nickpoint may ultimately recede into the cave. Other nickpoints develop across interbedded shales within the underground portion of the network.

4. Lateral Growth by Subterranean Piracy and Diversion Toward the Deepest Conduit (Figure 8.01D)

Widening of the basin takes place by piracy as the lowering of the main rising continues. This may also result from a breaching of interbedded shales. Surrounding small basins have their headwaters diverted to the basin with the lowest rising. This is usually the one to breach the interbedded shales first. Surrounding risings lose water at the expense of this deeper system.

There is evidence for phreatic development of cave conduits along the strike. These were perched upon the interbedded clastics which are thick and sandy in the upper basin. Whether or not underground phreatic development had progressed greatly before the initiation of surface flow is not known. As surface valleys are cut into the limestone, however, movement within the water table occurs toward these youthful channels. As drainage downstream below the risings cuts deeper into the underlying clastic outcrops, vadose flow develops within the underground conduits. These conduits deepen under free surface, high velocity flow. They extend themselves headward along the strike, often perched on an underlying interbedded clastic rock. Progressively they pirate the headwaters of surrounding basins which have not cut down as rapidly.

5. Shifting of the Rising Along the Lower Clastic/Carbonate Contact

(Figure 8.01E)

The locations of risings are not fixed when they reach the lower contact. Initially they migrate along the plunge of the clastic/carbonate contact. This causes variations in the downstream end of the cave conduit. All basins show this initial upstream movement in the location of their risings. When the Greenbrier River cuts well below this lower contact, hydrological control dominates and this trend is reversed (as in Basin II).

Because the Greenbrier River crosses the limestone in the lower part of its basin, Basin III has not shown such reversal. Its point of rising may move somewhat southeastward again, but topographic factors here become significant in fixing its point of rising.

6. Gradual Downcutting and Network Integration (Figure 8.01F)

Above the limestone, fluvial erosion continues the headward growth of the basin. Surface tributaries to the underground, strike-oriented conduit retreat back to the upper contact in a manner similar to the trunk channel.

In the middle basin on the limestone surface, fluvial erosion is minimal and this area may rise to several hundred feet above the upstream areas. Dry valleys are totally abandoned and do not carry surface streams. These former channels are well outlined by the dry valley profiles and their rounded sediments.

In the lower basin, fluvial development is accelerated. Continued subterranean piracy within the limestone increases the discharge at the rising as more of the surrounding drainage is diverted towards this outlet. More of the sediment load is withheld by the surface sieve deposits and siphoning within the cave. These factors, along with the increased lowering of the Greenbrier River, accelerate the rate of downcutting of the risings and the surface channel to the river.

Once the lower basin has been cut well below the limestone, as in the case of Basin II, the rising farthest downstream (with respect to the Greenbrier River) is entrenched and becomes a fixed outlet for the basin. Other outlets are used during high water conditions, but eventually they become abandoned. Shielding of the underground conduit with fines occurs. However, one-in-one-hundred years floods remove much of the accumulated alluvium. This infrequent flushing of the system, along with sieve filtration in the upper basin, maintain the function and enlargement of the underground conduits. Lower level routes are developed below the active shielded conduits and periodic abandonment of the latter occurs. Sediment shielding prevents continuous trenching into the limestone and results in a series of stacked conduits on gentle gradient.

To summarise the foregoing description of drainage development:

i) Initial runoff is in response to the steep slope of the escarpment. This is across colluvial deposits and cuts into the limestone surface.

ii) Strike oriented conduits are generated by phreatic movement toward these surface streams. They may be initially lithologically supported by interbedded clastics within the Greenbrier series.

iii) Surface invasion by way of widened joints occurs after gradients are generally less than 75/1000 across the limestone.

iv) One basin grows laterally at the expense of surrounding higher basins. Sinkpoints retreat headward to the upper clastic/carbonate contact.

v) Gradual integration between surface and subsurface drainage progresses, but is never fully attained.

vi) Hydrologic factors begin to dominate over structural and lithologic ones after the local base level drops well below the lower clastic/carbonate contact.

vii) Lateral and vertical shifts continue to occur within the basin until the rising stream becomes fixed into the lower clastic rock.

viii) Sedimentological alterations continue, but isolated flood events tend to clean out the system which accumulates fines in the lower half of the network. Large boulders and cobbles are sieved out at the upper contact by sieve-type deposits (Section C).

C. Surface Sedimentation

The development of surface sedimentation is tied to the sequence of drainage alteration in clastic/carbonate contact basins (Figure 8.01). Sediments accumulate in response to changes in the basin profile which are due to lithology, base level lowering, and karstification.

1. Alteration and Reworking of Surface Debris (Figure 8.02A)

In the early development of the network, sediments move completely across the steep exposure of limestone. In the upper basin today, between surface streams, large tongues of mass wasted debris are found along the Allegheny escarpment. There is evidence that periglacial activity was the major factor in their accumulation. Today occasional landslides occur, but not of the volume or grain sizes associated with the thick mantle of material located along the steep headwater streams of the karst basins. This material is observed in all basins studied and is found in place beneath the roots of tree stumps cut from the original forest covering during the last century.

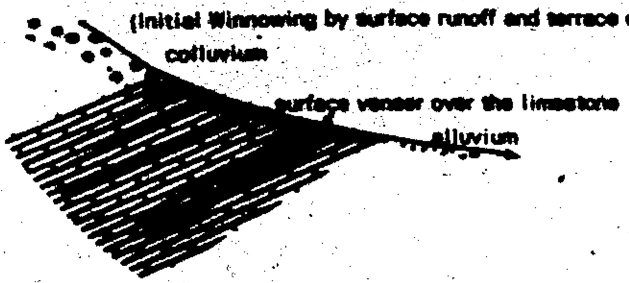
Along the channels of the upper basin tributaries, large angular blocks of conglomerate and sandstone in excess of eight meters remain unmoved. These are now more than two miles from the present outcrops of the same lithology. These same large blocks are found between the basins, in a matrix

SEDIMENTATION ACROSS THE GREENBRIER KARST

Figure 8.02

A Alteration and Reworking of Surface Debris

(Initial Winnowing by surface runoff and terrace development downstream)



B Breaching of Veneer and Dry Valley Development

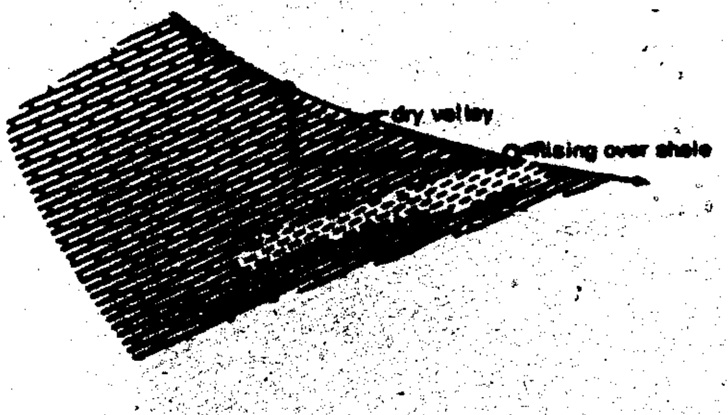
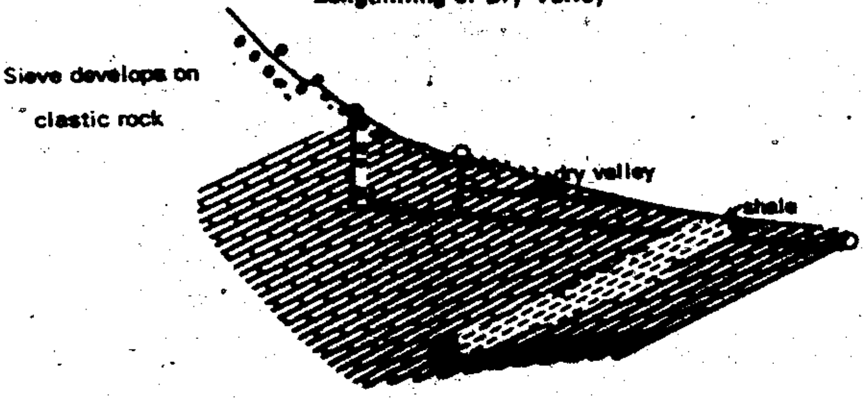


Figure 8.02 (CONTINUED)

C Retreat of the Sink Points to the Upper Clastic/Carbonate Contact and Lengthining of Dry Valley



D Accumulation of Surface Sieve Deposits in Adjoining Basins and Sediment Transport Within the Underground Network

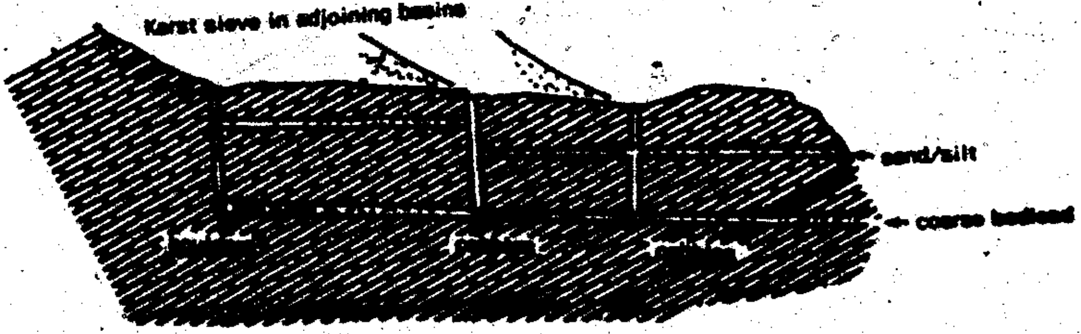
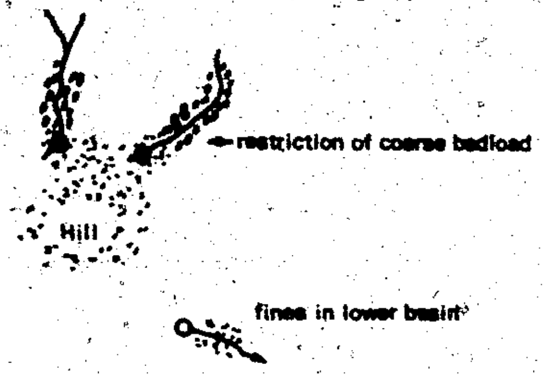
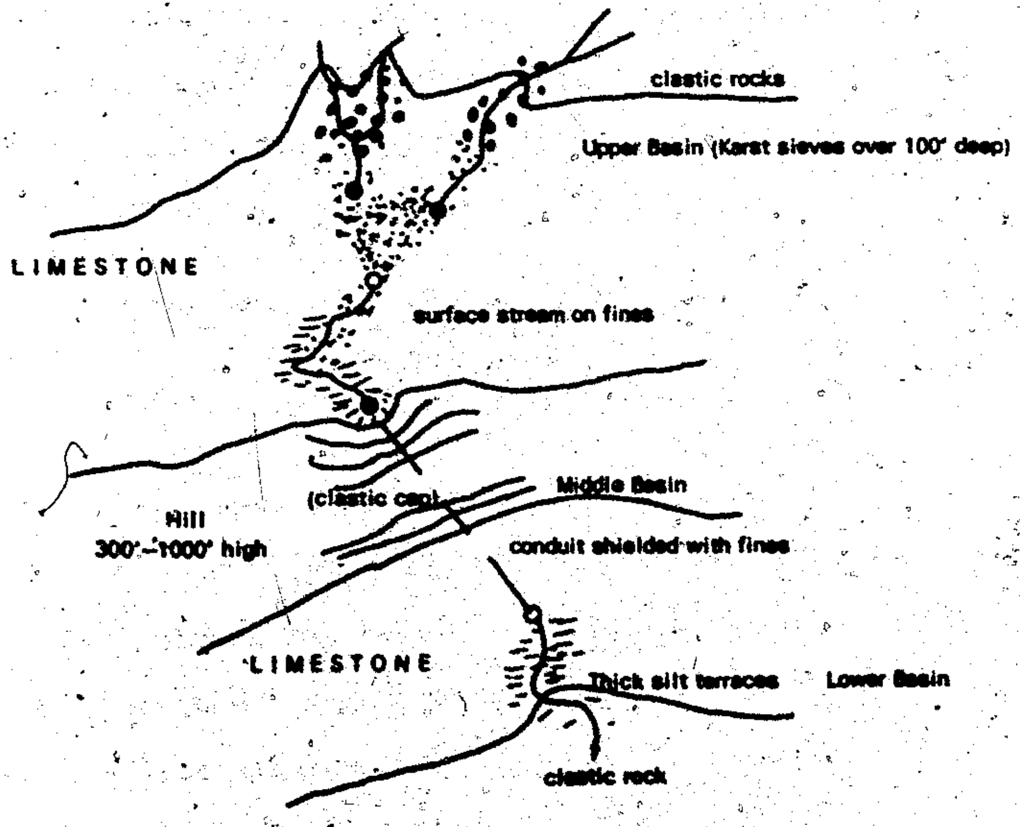


Figure 8.02 (CONTINUED)

E Merging of Surface Alluvium in Adjoining Upper Basin Streams



F Fixing of the Rising and Zoning of Sediments Within Upper, Middle and Lower Basins



of angular boulders and silt. The finer matrix has been removed by surface flow in the channels of the upper basins and in the dry valleys across the limestone. The initial action of surface flow appears to have been to remove the finer material (under one meter) from the colluvium and carry it completely across the limestone to the lower basin. The colluvial veneer is initially very thick and poorly sorted. Fines are winnowed and eventually a channel is cut to the depth of the bedrock, leaving behind only the largest clastic boulders. Silt terraces form rapidly in the lower basin area because of the overloading of the stream due to the abundance of winnowed fines from upstream colluvium.

2. Breaching of the Veneer and Dry Valley Development (Figure 8.02B)

Drainage continues for a short time on the limestone. Under high gradient, intermittent, rapid runoff the surface stream may become entrenched into the first ten feet of limestone. Widening of joints allows for vadose invasion of the stream into existing underground networks. This occurs beyond the upper contact where colluvium is still thickly covering the limestone. Grain sizes up to one meter are carried into the underground network. Larger boulders may fall into the entrance area, but are not transported further (Figure 8.02B).

3. Retreat of the Sinkpoints to the Upper Clastic/Carbonate Contact and Lengthening of Dry Valleys
(Figure 8.02C)

Eventually the upper contact is reached by headward retreat of the underground channel. Downcutting on the upper clastic rock continues and sieve-type accumulation is fixed at the contact. It is here that large material holds back the smaller boulders which eventually may completely cover the swallow. This blockage results in material being held back in the upper basin area which causes a bedload deficit in the cave conduits of "youthful" basins. This increases the rate of solution by invading aggressive surface waters and accelerates vadose trenching in the cave streams. The high gradients certainly aid in this process, but the lack of sediment shielding appears to be important at this time in the basin development. Silt terraces which were formed in the middle basin area below the original sinkpoints are isolated on the limestone surface. Sieve deposits start to extend upstream across the underlying bedrock.

4. Accumulation of Surface Sieve Deposits in Adjoining Basins and Sediment Transport Within the Underground Network
(Figure 8.02D)

As adjoining basin headwaters retreat to the upper contact also, their sinkpoints begin to accumulate sieve-type deposits. Some coarse bedload continues to move through the system. The size of the downstream outlet partially determines the volume of sediment discharge. Occasionally smaller sieve-type accumulations occur along the cave stream and the passage fills with coarse debris. Water and suspended load pass freely through these temporary blockages. Lateral migration of the rising is active along the lower clastic/carbonate contact. Initially this moves upstream along the plunge of the contact. Abandoned outlets are found in several localities in the lower basin. Gravels predominate as the main grain size in the lower basin stream. Small boulders still pass completely through the system, but sizes are smaller than the original bedloads.

5. Merging of Surface Alluvium in Adjoining Upper Basin Streams (Figure 8.02E)

As surface deposits grow in the upper basin due to increased sieve deposition, the lowering of the underlying limestone surface continues. Gradually these surface deposits merge. The dry valleys below the sinkpoints stand much higher than the channel above the sink as downcutting above the sink continues. In the caves, strike oriented passages are joined by vadose channels as integration of the network begins. The risings shift downstream to the southwest as hydrologic effects strengthen. Sediments within the caves show a further decrease in grain size in the lower levels as surface sieving becomes more effective in the upper basin.

6. Fixing of the Rising and Zoning of Sediments Within Upper, Middle and Lower Basin (Figure 8.02F)

After the lower rising is fixed by hydrologic factors, the basin profile smooths. Eventual disappearance of lithologically fixed nickpoints is possible. However, the presence of a high standing ridge in the middle basin prevents utilisation of the surface channel by fluvial overflow. Also the growth of karst sieve-type deposition in the upper basin prevents an even downstream decrease in grain size. Silts predominate as bedload material throughout the middle and lower basin. These are removed by occasional underloaded, high volume discharge, caused by floods in the upper basin.

The role of karst sieves in the accumulation of coarse bedload affects the erosional and sedimentary development of the entire basin throughout its evolution. Filtration in the upper basin prevents further coarse bedload movement downstream. Initially, this accelerates vadose trenching in the underground conduits. This factor also accelerates erosion in the lower basin. In the later history of the basin, the presence of the sieve allows only fine sand and silt to pass completely through the network and allows for sediment shielding of the trunk channel to develop in the middle basin.

Erosion occurs within the sieve deposit itself, near the head, when floods cut into the alluvium. The removal of this material and its transportation across the surface of the sieve produces a series of intermittent channels strewn with coarse boulders. Cutting into the sieve may reach the clastic bedrock at the head. This constant reworking across the upper surface may cause complete blockage of the underground openings. Alternate routes and overflow may move coarse material along its surface. The depth of such alluvium is known to reach 165 feet in Basin III. Boulders are not able to cross such a deposit completely because of continued loss of drainage as it flows on the surface of the deposit.

Table 8.07 summarises some of the general characteristics of sieve-type deposits and compares them to the two other common colluvial/alluvial fan-like deposits of the Allegheny Front.

In his observations in the Shenandoah Valley of Virginia, Hack (1957) has pointed out that wherever resistant rock outcrops are drained by large streams, that "fan-like aprons" of alluvium are spread across softer rocks that outcrop downstream. He describes this veneer as a continuous apron spread along the contact zone. This zone of deposition exists along the Allegheny Front; the

Table 8.07

SURFACE COLLUVIAL AND ALLUVIAL DEPOSITS

Characteristics	Landslides	Alluvial Fans	Karst Sieve-Type Deposits
Grain Size and Texture	Large, angular boulders in matrix of fines; no distinct channels	Wide range of grain sizes, boulders to sand, moderately sorted, sub-rounded and layered deposits with many channel deposits	Large range of grain sizes, some sorting, sub-angular, winnowing of fines along semi-permanent channels
Distributary Characteristics	No distributaries	Many distributaries	Few distributaries
Drainage Source	None	Usually fed by one stream	Usually supplied by several streams merging under the deposit
Position in Total Drainage Basin	Generally on steepest slopes in upper part of basin	Near the south of the basin	Usually near the centre of the basin, depends upon limestone position (in clastic/carbonate contact zone
Distance of Sediment Movement	Relatively short distances (generally less than two miles in this area)	As far as the head of the basin (up to 25 miles in this area)	As far as the head of the basin (up to 10 miles in this area)
Overall Size of Feature	Generally less than three sq. miles	Generally less than one square mile	Up to ten square miles
Angle of Slope	Up to 35°	1° - 12°	1° at toe to 8.5° to 12° at head
Process of Deposition	Gravitational transfer	Fluvial action	Fluvial action and loss of stream competence

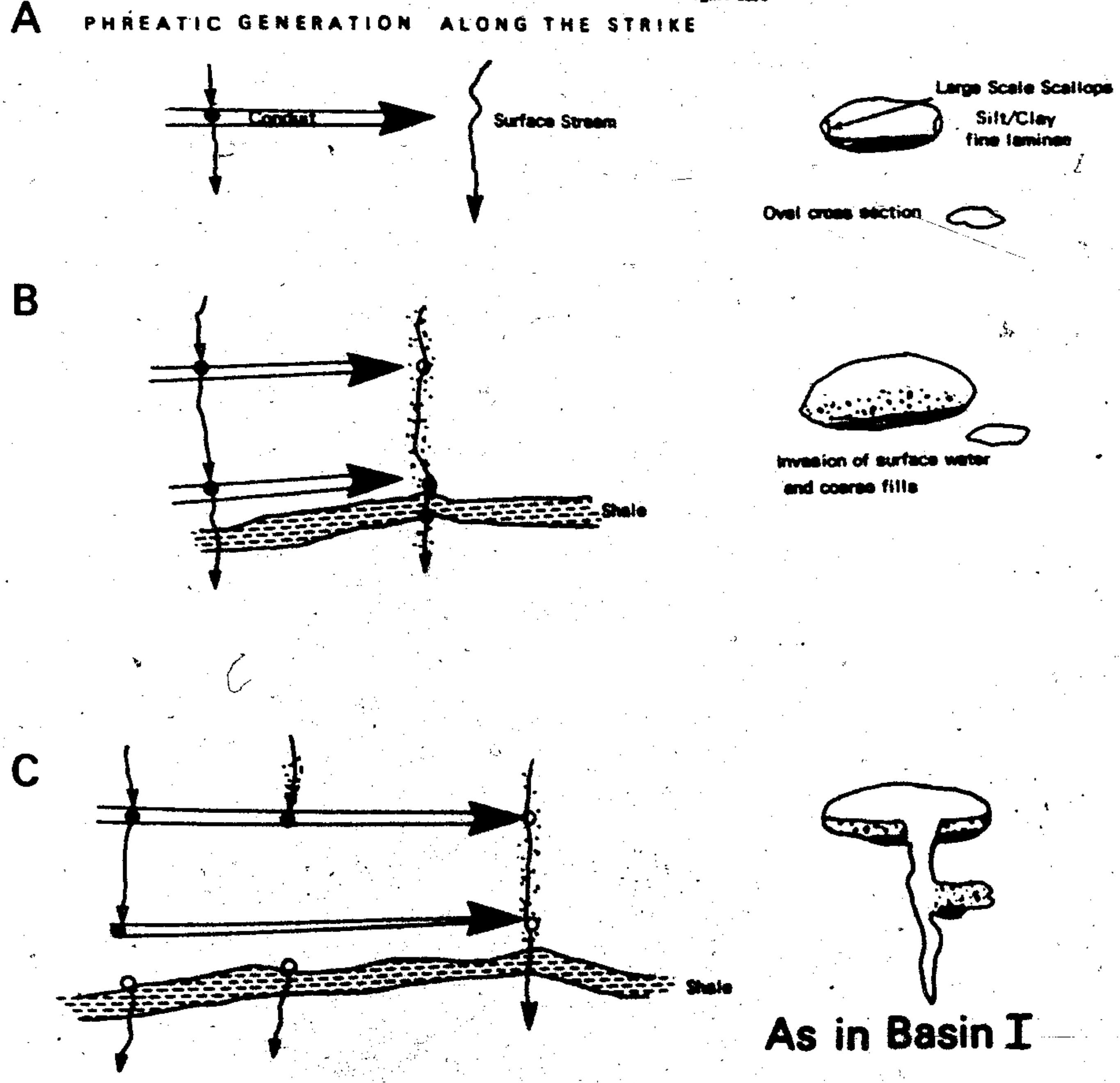
karst sieve deposits are built across this zone and are easily distinguished from it on several accounts. They are of a gentler gradient than the surrounding aprons. They show a greater degree of sorting laterally. They contain many abandoned surface channel deposits. They are always associated with underground drainage into the underlying limestone. Denny (1967) working in arid areas, suggests that processes acting in the Appalachians are the same as those in the Death Valley of California. He applies Hack's principles of "dynamic equilibrium" to the formation of alluvial fans and sediments. The development of karst sieve-type deposits may be related to "dynamic equilibrium" theory. Hack (1972, personal communication) suggests that this is the case. They are, however, distinguishable from the colluvial/alluvial aprons developed across "hard rock"/ "soft rock" contacts elsewhere.

D. Subsurface Drainage and Sedimentation

Figure 8.03 summarises some of the alterations which take place underground as drainage and sedimentation develop and then wither across the limestone surface. The function of an underground conduit depends upon its vertical and lateral location with respect to any active surface channels in the basin. The "basin approach" to this study helps to clarify some of the extremely complex subsurface drainage and sedimentation patterns found in these basins.

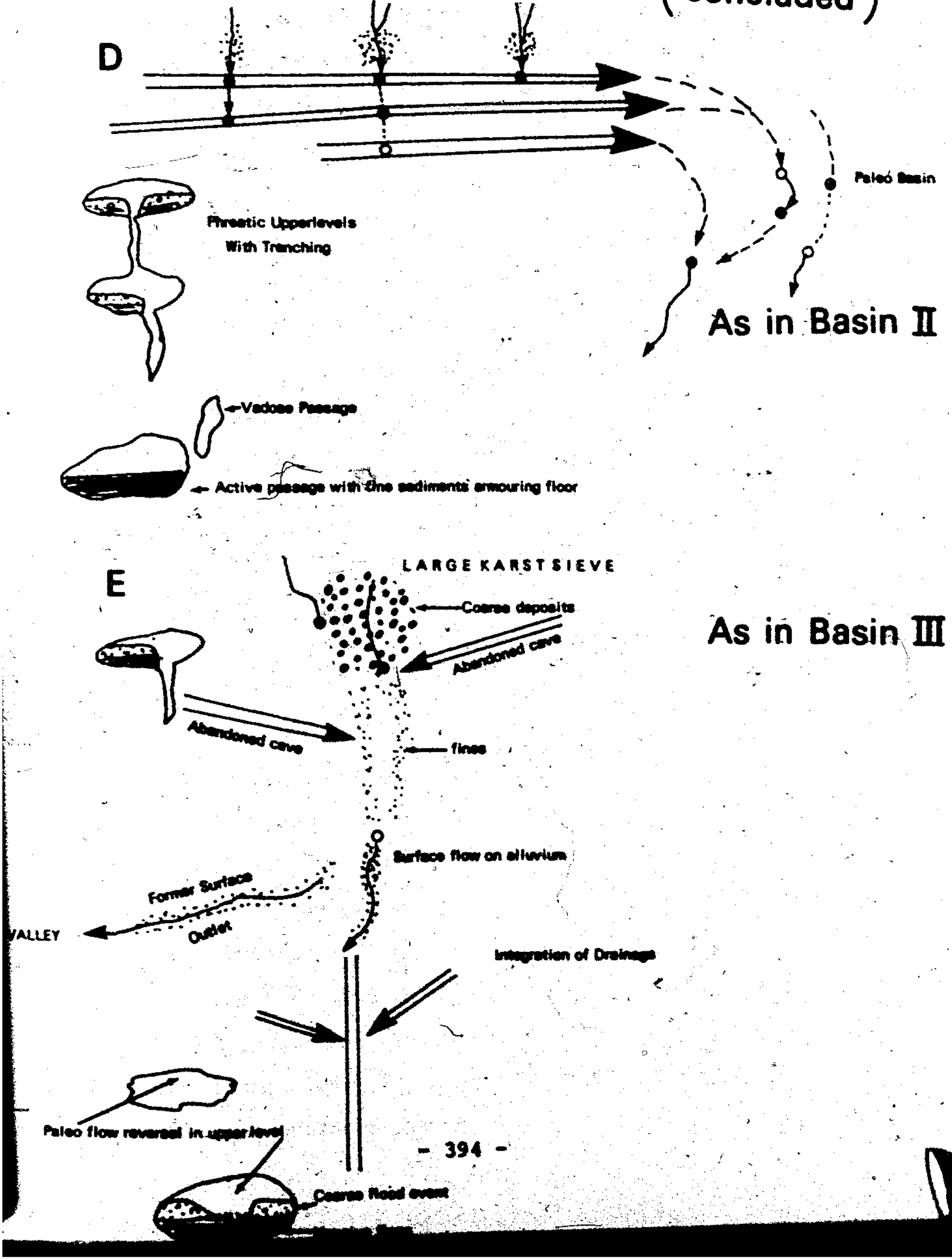
SUBSURFACE DRAINAGE AND SEDIMENTATION THROUGH THE GREENBRIER KARST

Figure 8.83



SUBSURFACE DRAINAGE AND SEDIMENTATION THROUGH THE GREENBRIER KARST

Figure 8.83 (concluded)



However, many local variations in drainage and the sediments cannot be generalised. Passage sinousity, configuration and constriction are important causes of this variability.

Initially, phreatic flow is directed parallel to the strike above the interbedded clastics in the Greenbrier series. Cave sediments are composed of fine clay derived from insoluble residue within the limestone. Flow velocities are low and large scallops are generated (Figure 8.03A).

Invasion by surface stream carries thick, massive deposits of angular boulders and gravels into the cave. Vadose trenching is also common and rapid lowering of regional water tables soon causes abandonment of this uppermost level. The coarsest material in most cave systems throughout the Greenbrier limestone karst generally is found in the highest levels and near the upper part of the outcrop. In later development, sieving and decreased stream gradients do not permit coarse bedload to move completely through the system in the active channels (Figure 8.03B).

Connection between levels is through abandoned pits and active water falls. Occasionally, collapse of the floor will join two passages and add <u>in situ</u> breakdown to fluvial sedimentary material. Vadose trenching is most active where the sediment load is held back by surface sieve deposits. These develop most extensively along the main channel at the upper clastic contact. The cave stream below these deposits often cuts very deeply into the limestone. The deep pit entrances in the system are produced in this manner (Figure 8.03C). Figures 8.02A, B and C are typical of Basin I.

Lateral extension of the vadose network integrates the surrounding surface networks into the system. In the middle basin, several alternative routes are utilised during high discharge. Sediment sizes decrease uniformly downstream below the upper sieve deposits which restrict particle sizes to sand or smaller in the middle and lower basin. Vadose trenching is active in portions of the cave where sediment is unavailable. Lower Hughes Creek Cave in Basin II is such an example. Loss of bedload in this cave is caused by a small sieve deposit between the upper and lower caves. Higher cave levels are also utilised by high discharge. Reworking of fills and deposition of fines over abandoned coarse fills occurs in these passages until total abandonment occurs. Occasionally a passage will be completely isolated as the result of a sudden drop in stream levels. The breaching of one of the interbedded shales, or sudden opening of a new channel or rising is the likely cause of this (Figure 8.03D). Figure 8.03D shows a condition similar to Basin II.

The widening of the limestone outcrop and deroofing of part of the cave conduit extends the trunk channel across much of the limestone surface. The upper level portions of the original network become isolated and more cave passage is destroyed than is generated within the basin.

The main trunk channel becomes well developed across the strike. Higher levels parallel to the strike can be found. Many of these contain coarser fills and provenance not characteristic of the modern channel. Occasional massive discharge will reach the upper levels and deposit fine alluvium. But the uppermost passages are too high for this to occur in them (Figure 8.03E). Figure 8.03E is representative of Basin III.

Figure 8.04 is a generalised sedimentary sequence along an abandoned conduit in the middle basin of a mature aquifer. This is typical of many upper level passages in the Greenbrier karst. By itself, it is difficult to interpret. When viewed as part of the former drainage network as in Figure 8.03E, its function as part of the former drainage and sedimentary development in the basin is clearer.

Figure 8.05 integrates the various parts of the basin and relates the function of the individual components at different stages in the basin history.

E. Properties of Fluvial Cave Sediments

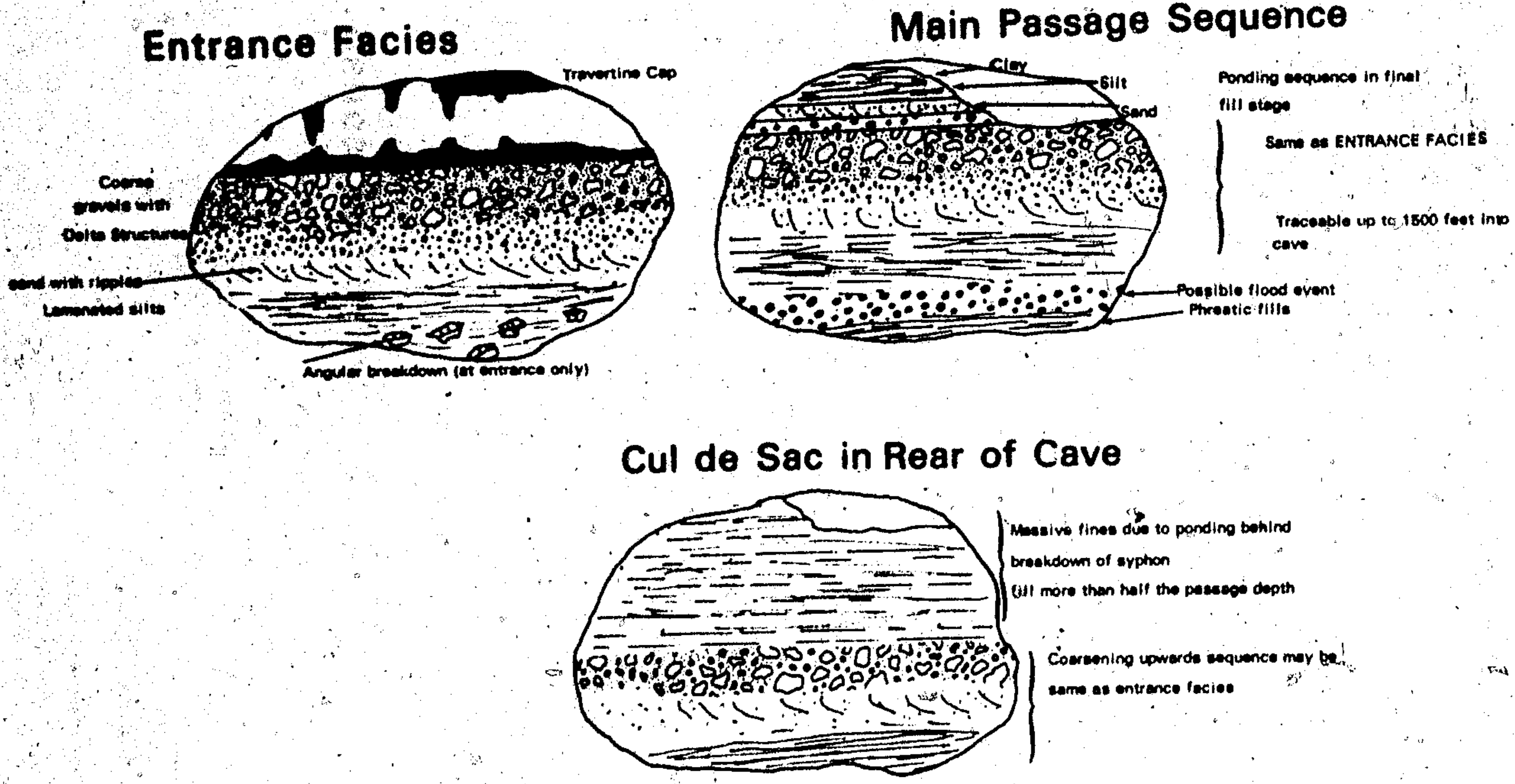
1. Grain Size Distribution

a. Active Conduits

The bedload in most cave streams near the upper basin is poorly sorted and exhibits a wide range of grain sizes in their fixed beds. This includes particle sizes

GENERALISED SEDIMENTARY SEQUENCE ALONG AN ABANDONED CAVE CONDUIT

Figure 8.04



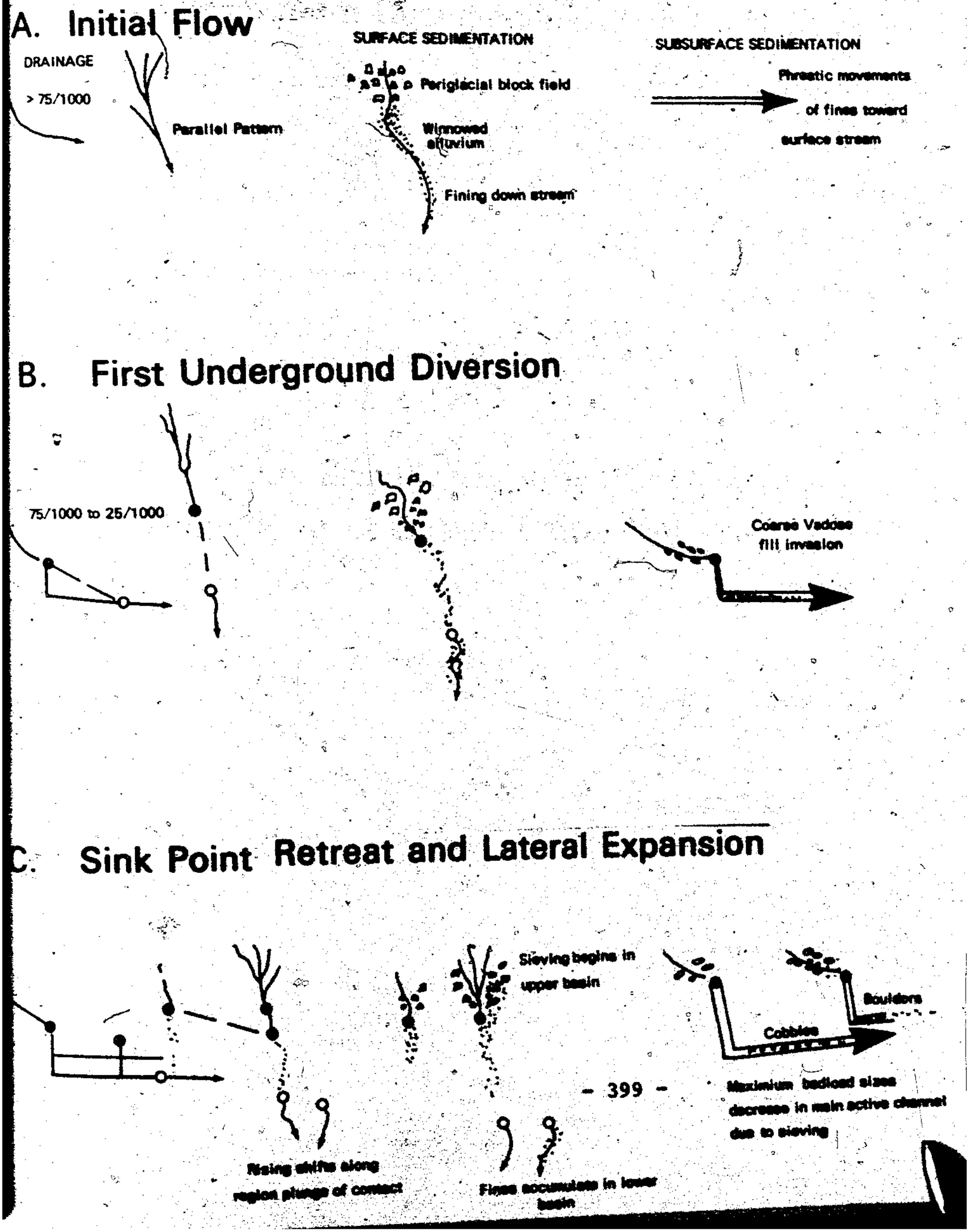
Entrance Facies

Main Passage Sequence

Cul de Sac in Rear of Cave

MODEL FOR DRAINAGE DEVELOPMENT IN GREENBRIER KARST

Figure 8.05



MODEL FOR DRAINAGE IN GREENBRIER KARST

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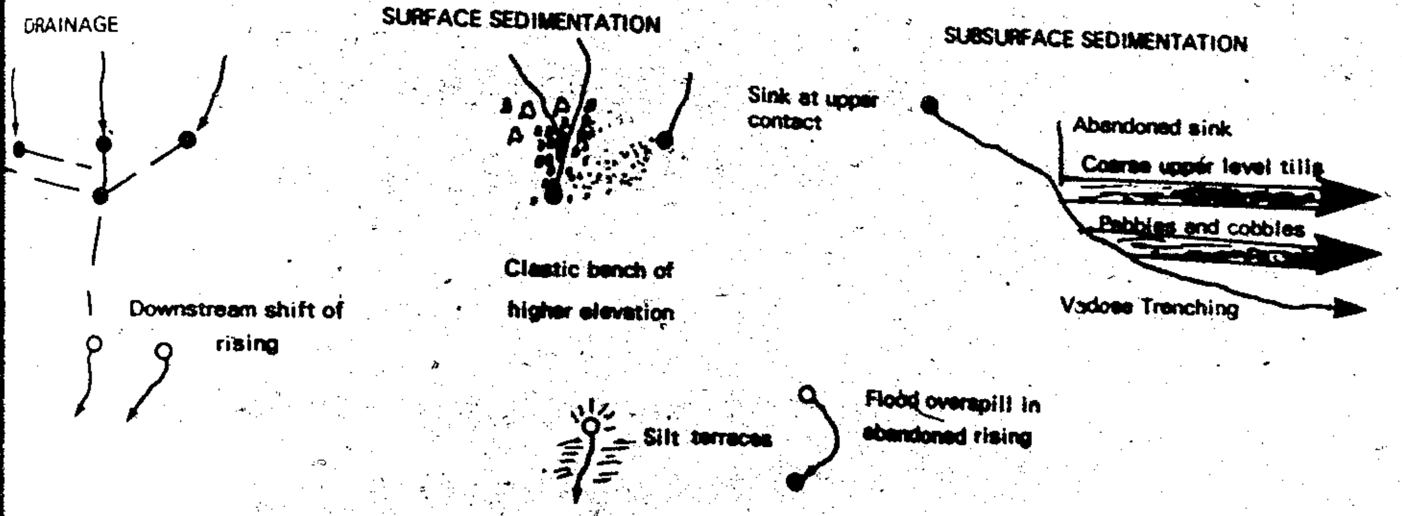
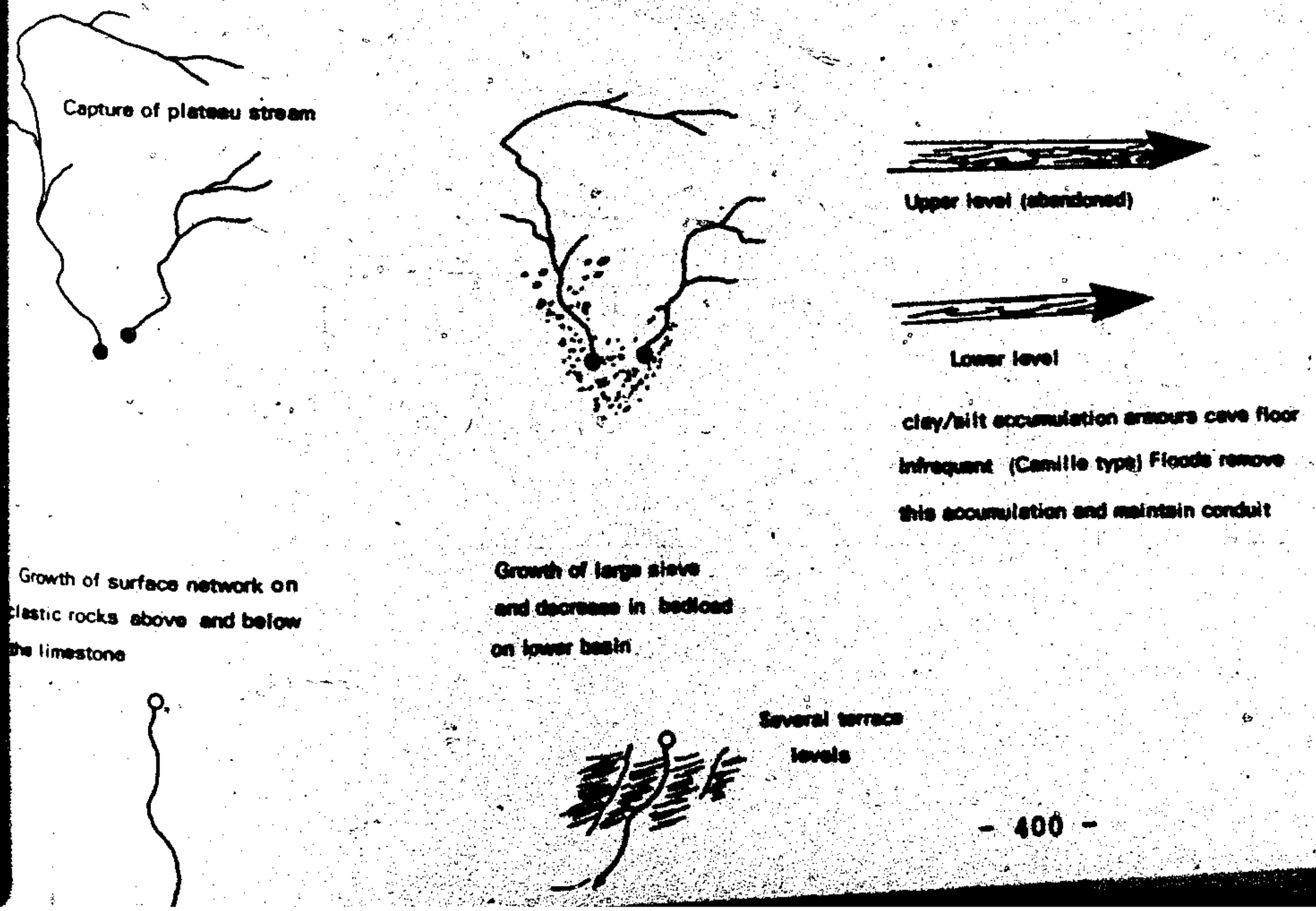
D. Downstream Development of Surface Network



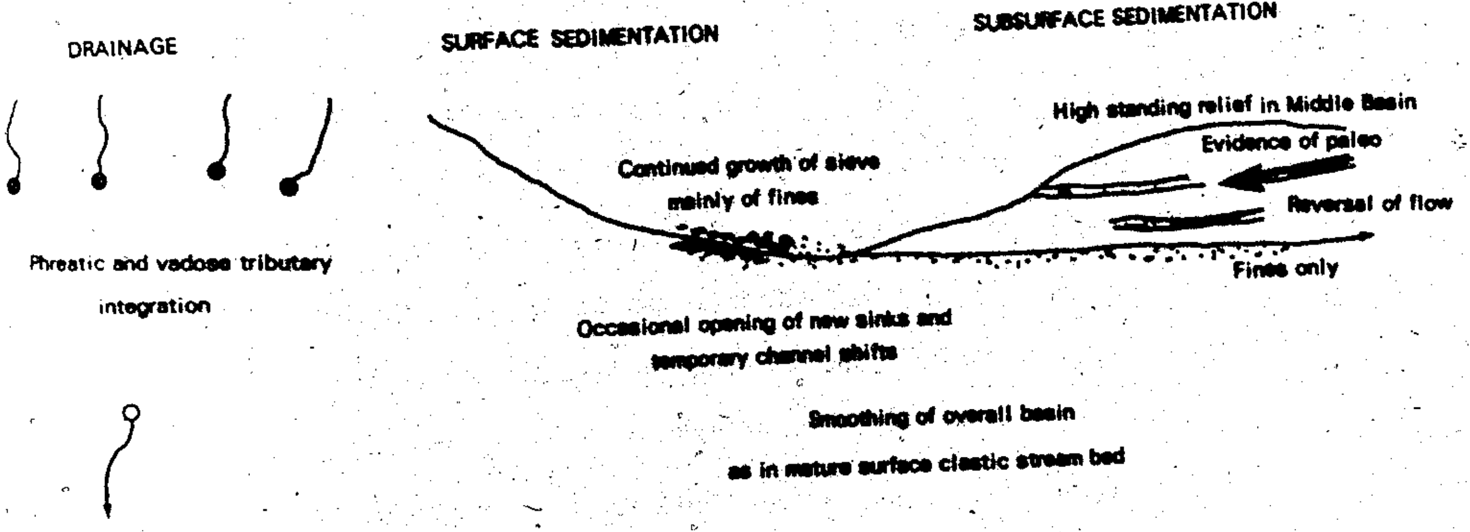
E. Upstream Growth of Surface Drainage and Smoothing of Overall Basin Profile



MODEL FOR DRAINAGE DEVELOPMENT IN GREENBRIER KARST

Figure 2.85 (concluded)

F. Ultimate Integration of Surface and Subsurface Drainage and Sedimentation

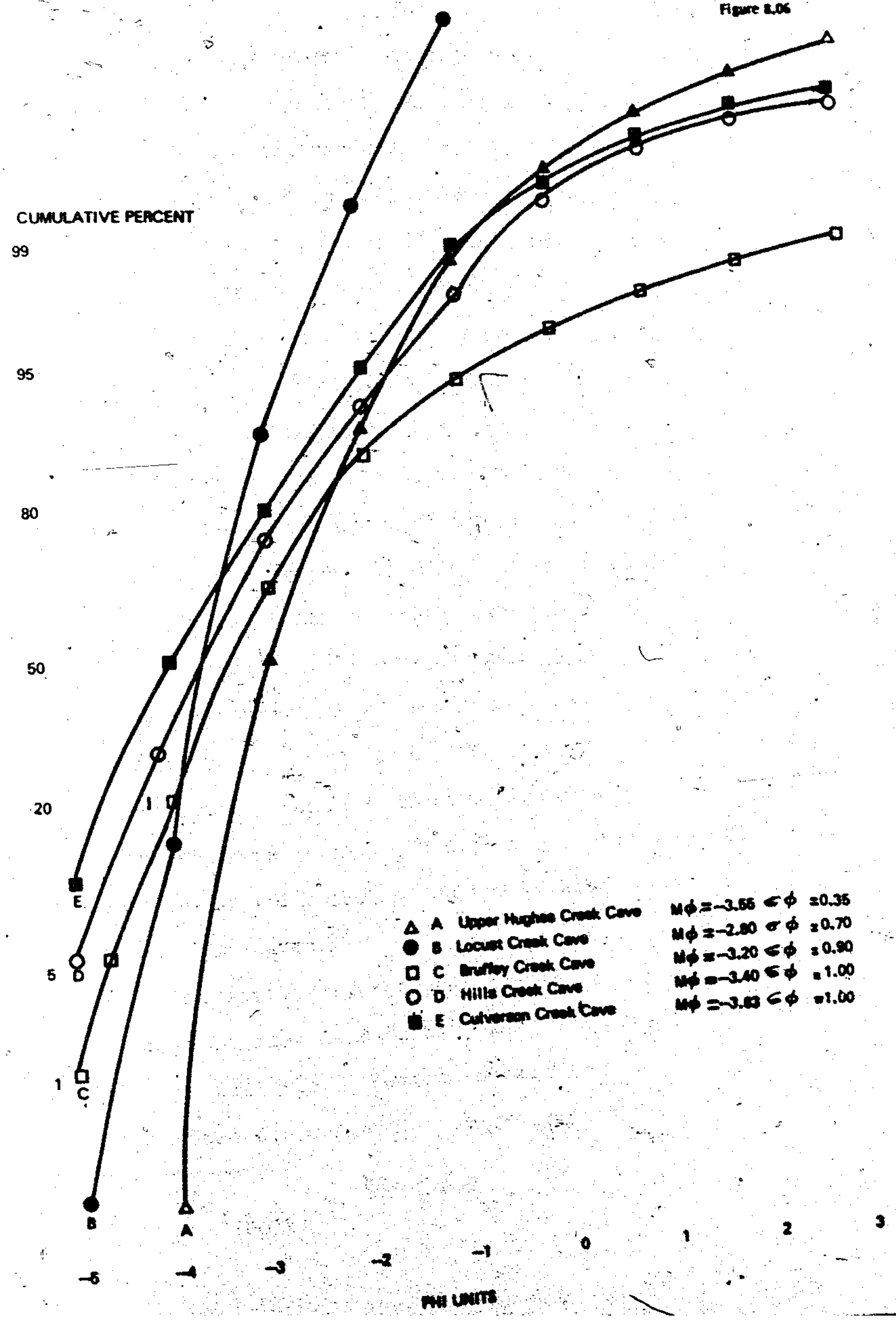


ranging from boulders to silt. Many such streams terminate in karst sieve deposits. The coarser fraction of such material rarely undergoes active transport. In comparison with surface drainage on clastic bedrock, streams flowing onto carbonate rocks show a wider range of runoff variability. Restarović (1969) has observed discharge variations on the Yugoslavian karst with a ratio of Q min: $\bar{Q}$: Q max = 1: 10: 100 . This is moderate when compared with the Greenbrier River at Alderson, where it flows directly on the Greenbrier series. Figures for 1895 to 1910 show a variation of 1: 20: 1,000 (Price and Heck, 1939). Variability for smaller tributaries such as Trout Run can only be estimated. This author would estimate the variation in 1969 during Hurricane Camille to be 1: 100: 10,000 . The large boulders of the fixed load of streams probably undergo active transport once in one hundred years of less frequently. Upon entering the cave systems there is a rapid decrease in grain size distribution and an increase in sorting downstream to the lower basin.

Figure 8.06 shows the cumulative percent curves for samples taken from the movable beds of the active trunk channels in Basin II and III. A range of 8 ϕ units (from very fine sand to cobbles) is average for the mean discharge conditions for streams entering caves at the upper limestone contact in each basin. This decreases to an average range of 3.5 ϕ at the resurgence at the lower carbonate/clastic

CUMULATIVE PERCENT CURVES OF MOVEABLE BEDS IN ACTIVE CONDUITS IN BASIN II and III

Figure 8.06



contact. Sorting values[24] decrease from 1.0 to .35 downstream. This represents an increase in sorting from "moderate" at the upper contact to "well sorted" in the lower basin according to Folk (1968, p. 46).

In comparison with clastic surface stream channels, karst channels show a great variation in grain size distribution and sorting in the upper basin at the clastic/carbonate contact. Here the wide range of grain size distribution is more like that of ephemeral channels in alluvial fans found in arid climates. The loss of bedload to the karst sieves in the upper basin deprives the caves downstream of the coarser fraction of bedload typical of surface channels in humid areas. Lattman (1960) shows sorting values of 1.67 for a drainage basin in a similar climatic and geomorphic setting in Pennsylvania. Throughout the caves of Basin II and Basin III fluvial sediments average less than 1.00 . Surface drainage in the lower basin has values of less than .40 . This is due to filtration in the upper basin and a lack of supply of surface alluvium from within the caves.

The active underground channel is subjected to a wide range of flow conditions. This may vary from no flow to pipe-full flow. Lateral accretion is not possible as on a surface flood plain. Intermittent channels at

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[24] $\sigma_{I\,(\mathrm{Folk})} = \frac{\phi 84 - \phi 16}{2}$.

higher levels must therefore receive overflow drainage. Sediment deposition results under these conditions in higher level passages. Collier and Flint (1964) have observed the deposition of fines in intermediate levels simultaneously with coarser bedload in the lower active channels.

Surface observations on the frequency of floods show a lower rate of flooding on carbonate rocks (White and Reich, 1970). This is a reflection of the diversion underground of runoff during flood. At these times intermittent channels are utilised. This lessens the surface runoff in comparison with clastic basins. These factors contribute to the narrower range of grain sizes found in active and intermittent channels in the middle and lower basin than in surface clastic stream beds. Ultimately the size of the opening and availability of grain sizes entering the system are more important than the transporting power of the stream in determining the sedimentary properties of fluvial cave deposits.

b. Intermittent Conduits

Due to a lack of a flood plain underground, excessive discharge must seek an overland flow route or a higher level cave passage. The latter is often the only alternative route in surface streams which terminate in deeply incised blind valleys. This is the case in Basin I and Basin II. There is a wide range of grain sizes as in the surficial deposits along these channels. Particles are generally finer than in the active streams immediately below them within the cave system. Like the active conduits these intermittent channels show an increase in sorting and decrease in grain size variation in a downstream direction. One interesting difference, however, is a bimodal distribution of particles which appears in Basin II. Figure 8.07 shows the cumulative percent curves for the intermittent conduits in Basin II.

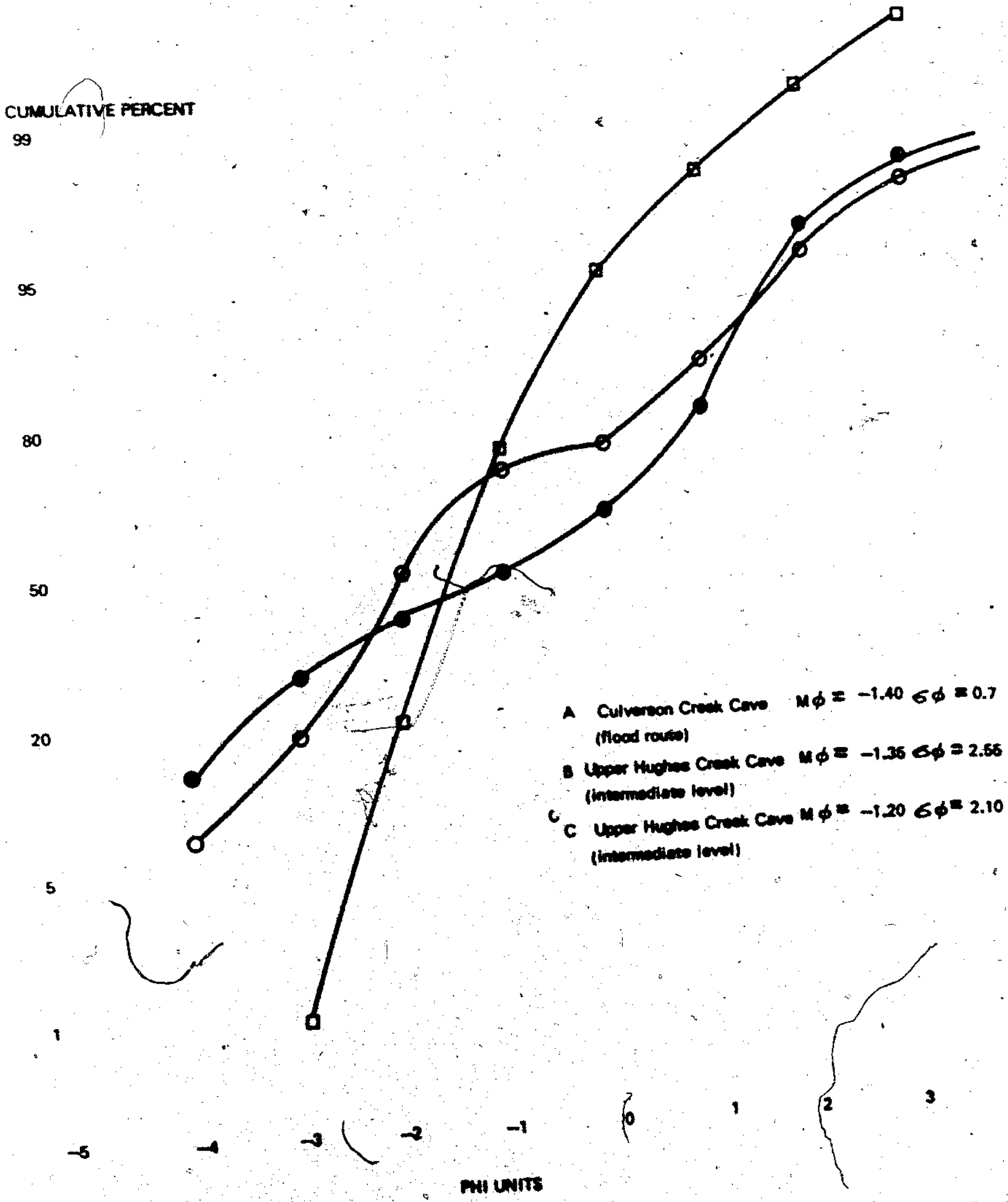
c. Abandoned Conduits

The inactive conduits of Poor Farm Cave and Upper Hughes Creek Cave in Basin II and Bob Gee Cave in Basin III show similar grain size distributions and sorting factors. These compare favorably with samples from the intermittent conduits. An average range of 8 ø units from fine sand to cobbles and a sorting factor of 1.07 (poorly sorted) is typical for many abandoned passage fills. Figure 8.08 illustrates the range of grain sizes found in most abandoned fluvial cave conduits.

In general, all transported cave sediments analysed in the three basins can be fitted into the scheme of active intermittent, and abandoned. Figure 8.09 shows a comparison between these types. Active sediments are better sorted. They do display a wide range of grain size near the upper contact which decreases rapidly downstream. Intermittent conduits display a bimodal distribu-

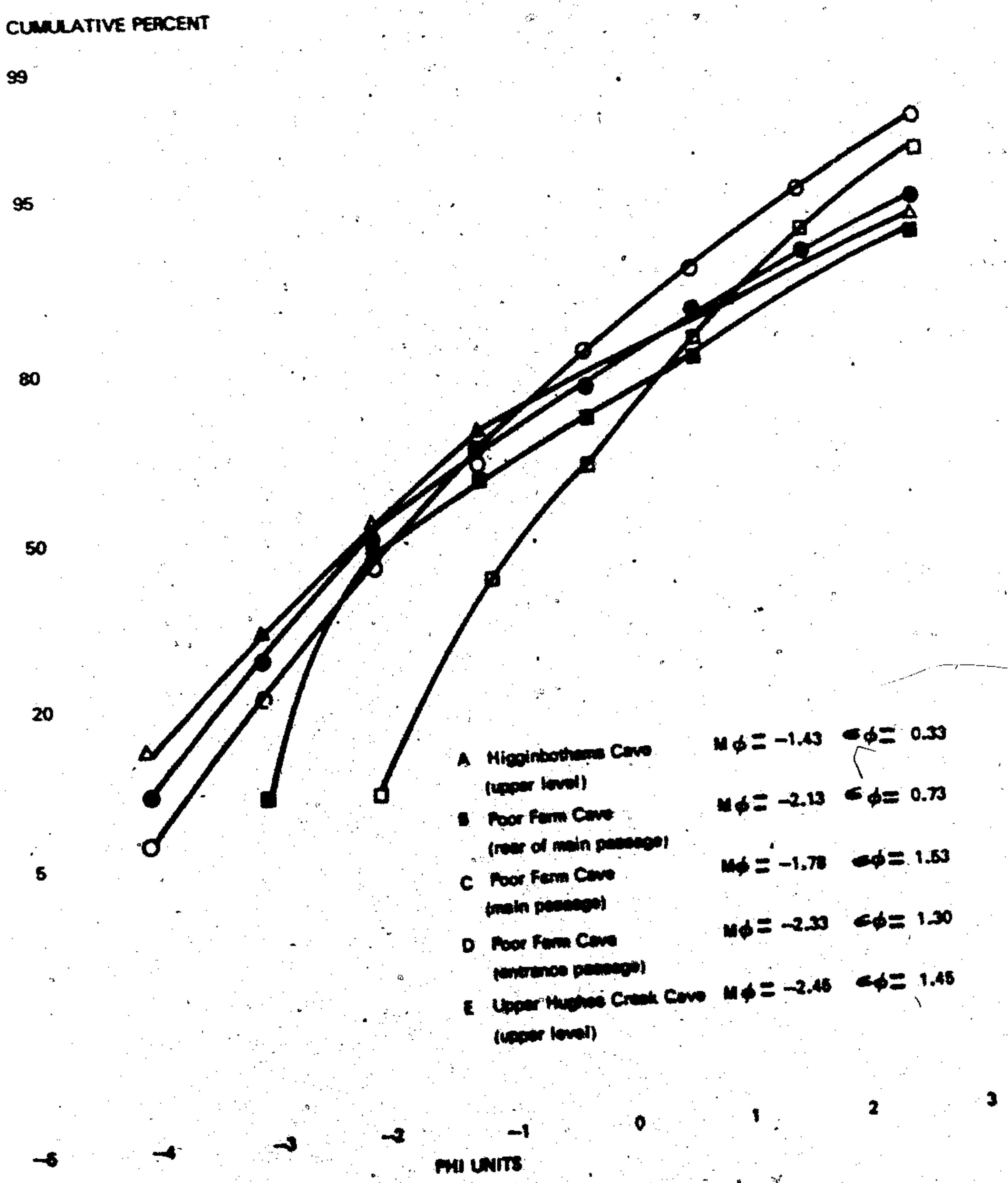
CUMULATIVE PERCENT CURVES FOR INTERMITTENT CONDUITS IN BASINS II and III

Figure 8.07



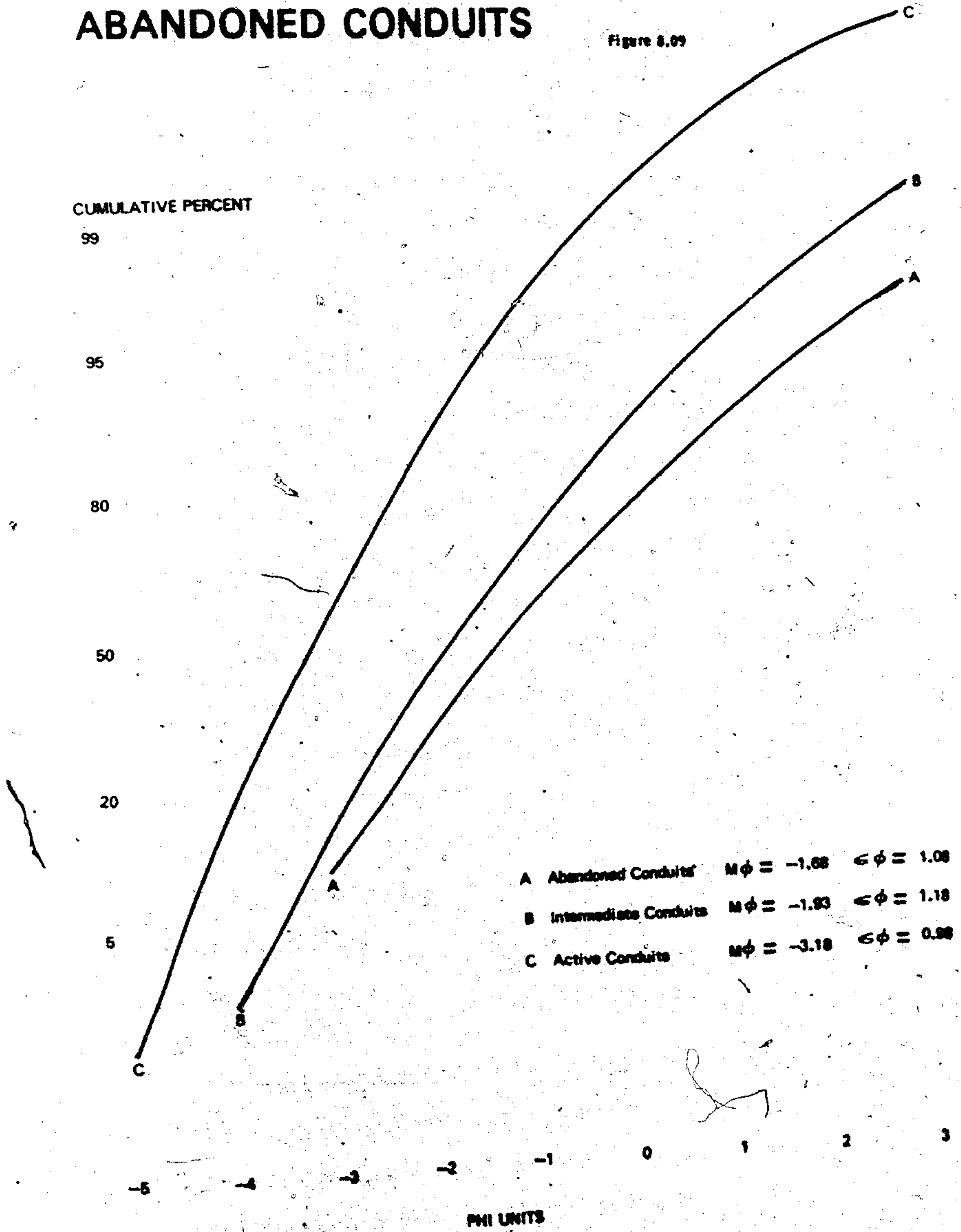
CUMULATIVE PERCENT CURVES FOR ABANDONDED CONDUITS IN BASINS II and III

Figure 8.08



REPRESENTATIVE CUMULATIVE PERCENT CURVES FROM ACTIVE, INTERMITTENT and ABANDONED CONDUITS

Figure 8.09



tion and do not increase in sorting as rapidly downstream as active bedloads. Abandoned conduits display a wide range of particle size and are not well sorted in any part of the basin. Special mention should be made of the abandoned sediments in the side passages of McClungs Cave in Basin III. Sorting factors here are greater than 4.0 (extremely poorly sorted). Sediments range from boulders to silt. The larger particles are angular and generally of low sphericity. It is questionable whether this massive deposit can be termed "fluvial". It appears that mass movement of the entire deposit with some stream flow in isolated pockets occurred at the time of deposition. This deposit stands out because of its unusual properties and location on the karst plain. Evidence for periglacial activity has been cited by Clark (1968) and others along the Allegheny escarpment. The deposits in McClungs Cave would indicate that such activity also occurred at elevations below 2,500 feet in the West Virginia karst. This is nearly 2,000 feet lower than previously described localities in the area.

2. Distribution of Milky Quartz Pebbles

Within the basins the distribution of milky quartz pebbles is closely related to the distance from the Pottsville and Princeton outcrops at the basin head. Although the percentage of quartz pebbles in selected size fractions is greater near the basin head, distribution

C

is ubiquitous in all cave passages and surface channels of Basin I. Massive conglomerate boulders have moved completely across the surface and continue to supply more milky quartz pebbles randomly throughout colluvial and alluvial deposits. The highest percentages in the optimum sizes are concentrated along active streams immediately downstream from surface block fields.

The distribution of milky quartz in Basin II is not ubiquitous. Streams flowing westward on the karst plain along the regional dip do not contain milky quartz pebbles. In these streams, material which normally comprise the size ranges of the quartz pebbles is made up of chert and shale fragments derived from within the limestone and MacCrady Formation. Provenance distinction of paleodrainage from the east and west can be made on this basis.

All high level abandoned passages of Upper Hughes Creek Cave and Poor Farm Cave contain milky quartz. This associates them with a western provenance. The abandoned passage of Upper Martha's Cave and other caves of the karst plain do not contain milky quartz. All modern active channels of Hills Creek, Bruffey Creek to Locust Creek network contain quartz, as do their surface overflow channels. Colluvium comprised of milky quartz fragments is not found on the karst plain of Basin II. This material is confined to the upper basin and can only be supplied to the middle and lower basin via the underground conduits of the Locust

Creek network. This factor makes the use of this material a reliable tracer in provenance of ancient and modern drainage networks in the karst of Basin II.

In Basin III the distribution of quartz pebbles is limited. They are found in karst sieves and colluvial aprons immediately along the escarpment and in the major trunk channels which head on the conglomerates. Milky quartz is not found in any of the caves of the karst plain. Provenance for these caves was from derivation within the limestone or from the east away from the modern Greenbrier River. Quartz is also found along paleochannels across the karst plain, as along the "Great Banana River". It appears that the oldest caves derived their fills from within the limestone. Provenance from the west has only recently entered the karst plain caves since capture of the Culverson Creek network by Spring Creek. This is only in their lowest active and intermittent levels. In general the abandoned passage of caves in the upper basin areas contain quartz, while those in the lower basin do not. This may be due in part to the initial structural control of drainage when the karst plain caves were acquiring their fills. Since that time hydrologic factors in response to regional slope have become dominant and provenance is from the west.

In a comparison of the three basins, it appears that quartz distribution is ubiquitous in the early stages of basin development at the base of the escarpment. As the basin lengthens, headward portions of the basin retain western provenance while the lower basin derives new material from the east. This is due to a widening of the karst plain and a drop in base level. As the basin grows the distribution of quartz is restricted to cave conduits and surface channels which continue to flow completely across the limestone.

3. Sedimentary Structures as Indicators of Paleocurrent Direction and Conditions

Briggs and Middleton (1965, p. 5) cite several reasons for investigating sedimentary structures. Their use as indicators of conditions of sedimentation and of paleocurrent direction is applicable to this study. Imbrication of large elongate cobbles andpebbles is also useful as an indication of flow direction. This also provides a check on structural evidence. Delta structures similar to those produced by Jopling (1965) in flume studies are commonly found in gravels of the karst plain caves in Basin II. The orientation of paleocurrent is in agreement with provenance as indicated by the presence or absence of milky quartz.

The absence of antidunes suggests that many conduits have undergone pipe-full flow. This factor has been observed in laboratory studies which have shown that antidunes will not form under pipe-full flow conditions (Acaroglu and Graf, 1968). In another pipe flow study dune heights have been observed to be 1/3 to 1 times the hydraulic mean depth with actual water depth two to ten times dune height (McDonald and Vincent, 1972). In these respects sedimentary structures have been shown to have a direct relationship to pipe-full flow conditions. Dune heights in karst plain caves fall within these parameters. Upwards solution of the passage may alter the ceiling height, but incoming sediments appear to keep pace with solution of the passage as pipe-full conditions are maintained.

The upwards retreat of the ceiling in ice caves has been postulated as the reason for dune heights of greater than expected values in esker deposits (McDonald and Vincent, 1972, p. 27). The solution of the overlying limestone in cave passages appears to produce elongate horizontal oval passage cross-sections as those described for glacier tunnels (Stokes, 1958). However, it does not appear that the rate of solution in caves is great enough to produce the disproportionately large dune amplitudes which have been noted in esker deposits.

The absence of sedimentary structures in fluvial cave deposits is considered by this observer to be rare. In Basin III, in the side passage of McClungs Cave the absence of graded bedding or sedimentary structures suggests a quasi-fluvial origin for the deposit. Mass movement due to mud flow and solifluction into the passage from surface sinks during periglacial conditions seems to be a valid explanation. Poor sorting and high angularity of the large fragments of local provenance has also been cited as evidence for this type of deposition. In addition to the general lack of structures, these deposits possess an overall homogeneity of composition from floor to ceiling. This would suggest a single depositional event.

4. Scallops as Indicators of Speleogenesis

In the light of the literature on speleogenesis, the observations made in the Greenbrier limestone karst reflect aspects of both vadose and shallow phreatic theories. There is abundant evidence in most cave systems, from scallop size and location, to indicate slow uniform flow in contact with all parts of the passage, moving under hydrostatic pressure. In the case of karst plain caves, scallops indicate flow in opposition to the slope of the passage. Such flow could not have been a free-surface, down gradient stream as indicated in the empirical model for drainage development in this chapter. This model does not consider in detail the complex sub-water table development within the basins. It is, however, based upon field and laboratory observations of the enterable passages in the now sub-aerial networks. Postulation of the phreatic development of the networks can be made on the basis of evidence in the form of uniform large scallops, finely laminated sediments of clay size particles, and general cross-sections and profile characteristics of the passage. Vadose flow is evident from present conditions as indicated by small scallops and the trenching of passages.

It is not clear whether a certain sediment grain size limit can be placed on phreatic versus vadose transport. The limits of grain size appear to depend upon passage constrictions and availability of grain sizes within the network.

It would appear that most cave systems experience initial slow phreatic flow along strike-oriented passages. This is followed by vadose and para-phreatic invasion of surface water and coarse bedloads. Later, when gradients are under 20/1000 the passage may again undergo pipe-full flow on top of sediment accumulation. This concentrates solutional processes on the upper walls and ceiling of the passage. Coarse bedload is not associated with the initial or later stages of cave development. There is reason, however, to suppose that the middle basin conduits are completely pipe-full and transporting coarse material from upper basin areas until sieving restricts the intake of coarse sediment.

5. Clay Mineral Distribution Within the Greenbrier Basin

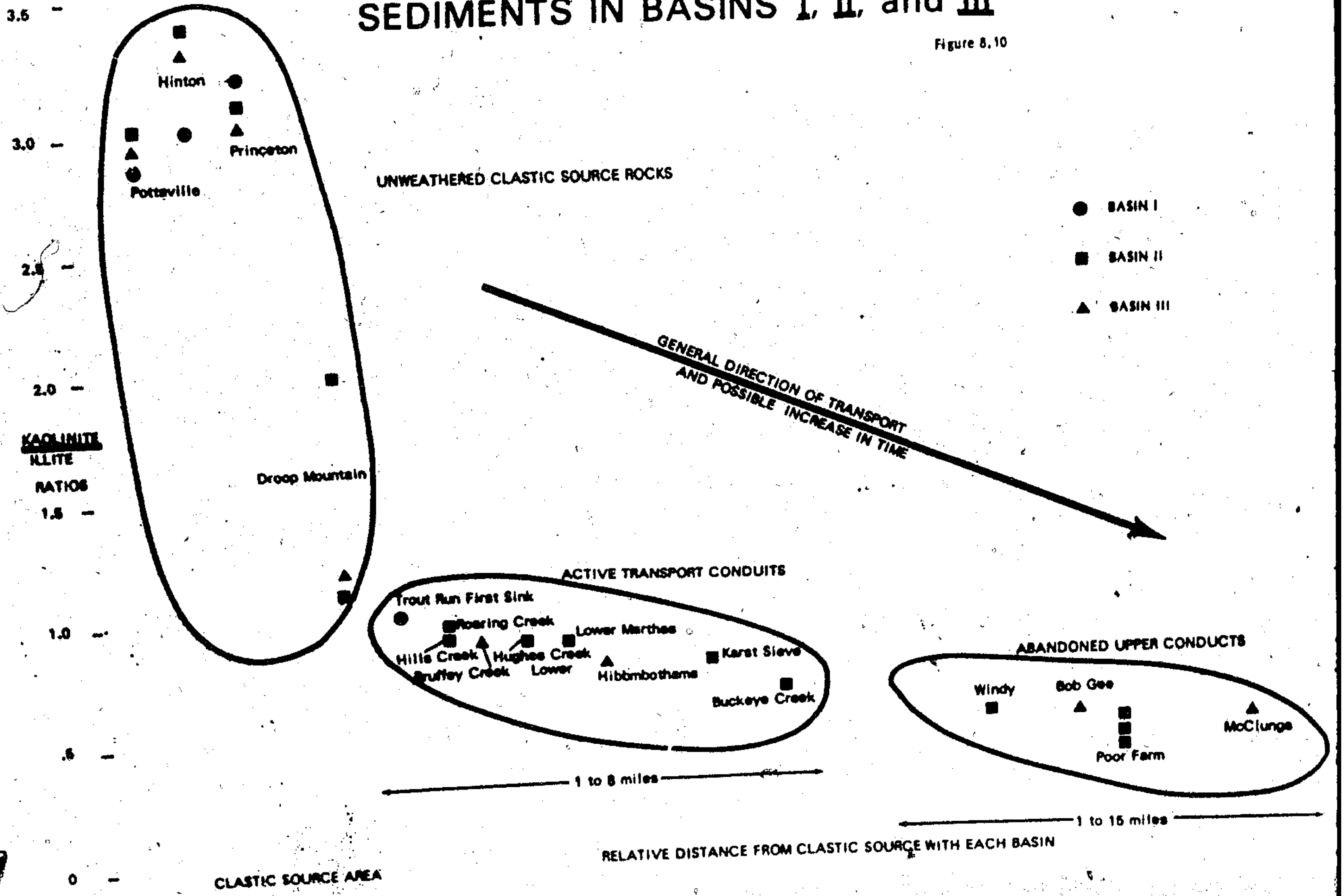
The overall distribution of clay minerals is dependent upon parent material, transporting agents and time.

Kaolinite/illite ratios are highest on unweathered clastic rocks in all basins. These average around 2.500 . Weathering of this material tends to lower ratios close to 1.000 . Unweathered carbonate bedrock samples are generally less than 0.675 , while weathered samples approach 1.000 . Most weathered surface samples from all lithologies from the regolith fall within 0.750 to 1.100 . Samples from active cave routes reflect modern surface regolith ratios. These are very close to 1.000 . Samples from intermittent cave levels are also within this range. Abandoned cave passage samples are not. These range from 0.435 to 0.673 . This may be a reflection of the cave environment, a lack of mixing with surficial material, or of climatic factors.

Figure 8.10 shows some representative ratios for the three basins. There is an apparent decrease in ratios with general increase in distance from the transported clastic source material. This is especially true if the deposit is no longer undergoing active transport. Unweathered clastic rocks show high ratios. Active transport conduits show ratios close to 1.000 . The abandoned upper levels of caves show the lowest ratios throughout the Greenbrier karst. Bob Gee Cave is shown in this group. Although it lies relatively near the clastic source, its deposits are completely abandoned. With the exception of this cave, all points on this graph are in their correct relative positions. It is impossible to date all of these deposits accurately; however, there is little

REPRESENTATIVE $\frac{\text{KAOLINITE}}{\text{ILLITE}}$ $\frac{(3.58\text{Å})}{(10.0\text{Å})}$ RATIOS OF TRANSPORTED SEDIMENTS IN BASINS I, II, and III

Figure 8.10



doubt that the oldest deposits have the lower ratios.

Clay mineral studies are not extremely accurate in any situation. The value of clay minerals in this study has been to clearly distinguish between the ancient and modern weathering zones. The climatic applications are unclear. Frank (1968, p. 8) has observed a decrease in kaolinite with depth, while illite remained constant; this would yield lower ratios in deeper weathered surfaces. Frank has used this information to interpret climatic records from caves in Texas and Australia (1965, 1969). Illite is usually associated with an arid environment while kaolinite is associated with humid conditions of low pH (Keller, 1964). Low kaolinite/illite ratios in the abandoned levels might be interpreted as evidence for a dryer climate or simply a dryer environment in the upper levels of the cave as opposed to the humid environment in the lower active levels and on the modern surface regolith. Climatic interpretation cannot be based solely on clay mineral data. McClungs Cave deposition which, on the basis of provenance, structure and particle properties, is considered to be of periglacial origin, has a low ratio of kaolinite to illite (0.505). This would be interpreted as a dry environment using Frank's criteria. It is true that the passage is completely abandoned and free of any surface water. Locally this is a dry cave environment today and has probably remained so since the time of deposition. Clay mineral studies are considered to be useful when a wide source of clay mineral data is used along with other data on sedimentary structures.

F. Discussion

Of the previous investigations into the properties of cave sediments, the study by Reams (1968) is nearest to the work of this investigation. In a comparison with Reams, this author would emphasise the importance of a "basin approach" in the analysis of sedimentary material Reams' failure to find any relationship between the deposits of several caves or to trace a given zone of deposition throughout one cave may also be in part due to a lack of adequate provenance zonation on the surface. The variety of clastic outcrops along the Allegheny escarpment in fixed localities across each of the three basins provides accurate provenance location for most cave deposits. The steeper gradients encountered in the headwaters of West Virginia basins may also provide better lateral and horizontal sorting between coarse and fine material.

Correlation of cave levels and their associated sedimentary material on the basis of elevation has been suggested by Sweeting (1950). This has been shown to be inaccurate (Sweeting, 1964, personal communication). Great caution must be used in any attempt to join the depositional sequences of one cave to another. Modern basins show that a wide range of sedimentary conditions exist along the same active channel. Karst sieves at the upper contact result in the absence of coarse bedload in the lower basin, fines are deposited there while boulders accumulate in the upper basin. Within a cave passage, distinct provenance zones can be identified. Different flow regimes, direction of flow and provenance can be shown to exist between different levels in the same cave. The coarse/fine contact in Poor Farm Cave is traceable for more than 1500 feet along the same passage. This contact also appears to exist in another nearby cave which lies in the same position in the lower paleodrainage network of the same or similar system. An attempt to extend this contact zone throughout the cave or through the paleobasin would be an inaccurate assumption.

On the question of the role of sediments in speleogenesis, Renault (1967) and others have described the upwards solution of limestone cave ceilings and walls. This is to take place while the floor is shielded by sediments. This has also been suggested as a mechanism for the upwards growth of esker deposition in glacial ice caves (McDonald and Vincent, 1972). Evidence for such solutional processes appears to exist in some of the caves in the Greenbrier River basin. Passage profiles in the entrance passage of Poor Farm Cave, Upper Martha's Cave, Upper Hughes Creek Cave and Culverson Creek Cave indicate an enlargement of the passage upwards and sideways. This results in an oval-shaped cross-section with an elongated horizontal axis.

Bob Gee Cave, on the other hand, may have undergone a short period of upwards solution on sediments but the rapid drop in regional base level caused vadose entrenchment through the fills and downward into the underlying limestone. There does not appear to be a single solutional process applicable to all caves in this respect. Ceiling scallops are rarely in accord with the flow velocities indicated by the sediments of the floor deposits.

Climatic inferences on the basis of sedimentary material have been made by many authors. Climatic conditions do not appear to have altered the fluvial aspects of cave sediments in the Greenbrier basin. Fluvial sediments are by far the most common of all cave fills. The exception is the poorly sorted, angular, and relatively structureless deposits of McClungs Cave.

Ford (1962) working in steeply dipping bedrock in the Mendips of England has attributed periglacial climatic conditions for the lack of sorting, graded bedding and sedimentary structures in the cave fills there. Similar observations were made by Ford on the Nakimu Caves of British Columbia (1973, personal communication). More than 400 feet of poorly sorted material found in the lower levels of Nakimu Cave are capped with graded gravels and carved silts. He attributes ice blockage at the lower entrance facing a glacial trough as partially responsible for the accumulation of these massive fills. Modern drainage through the cave is in the process of reworking some of these poorly sorted deposits.

G. Conclusions

1. Surface Drainage

a. Greatest drainage development today is in the upper basin areas. Piracy of plateau streams and steep upper basin gradients are responsible for this.

b. Risings at the lower contact are constantly shifting laterally until the local base level drops well below the limestone. After this, entrenchment into the lower clastics fixes the risings.

c. Lower basin drainage on clastic bedrock cuts rapidly to local base level and adjustments to grade are made within the limestone conduits. This is caused by a general lack of sediment in the lower basin area.

2. Surface Sediments

a. The main activity of most streams is to remove the massive periglacial colluvial aprons along the Allegheny Front. Much of this material still remains between the channels. The largest blocks are too big to be carried by fluvial action.

b. Karst sieves develop at the upper contact these are a major feature of clastic/carbonate contact basins and affect the sedimentation are hydrology of the entire basin.

c. Silt terraces are common in two areas of the karst basins: in the upper basin below the karst sieve, the terraces are due to the initial winnowing of fines from the colluvial deposits in the upper basin; in the lower basin, the terraces are found on clastic bedrock. This is due to the lowering of the base level stream and to the gentle gradients in the lower basin. This deposition of fine material apparently occurs simultaneously with the deposition of coarse bedload in the upper basin.

d. Basin evolution is strongly related to sediment accumulation, transport and removal. To attempt an explanation of carbonate aquifers without examining their transported fills is to ignore a major aspect of the model!

e. It appears now that what the author originally thought of as ubiquitous "karst sieves" in all basins are not. In the upper third of the Greenbrier basin, as in Basin I, the thick veneer of material found completely covering the limestone is colluvium of periglacial origins. The "karst sieve" is characteristic of maturely developed headwaters drainage, as in Basins II and III, at the upper clastic/carbonate contact and is a fluvial alteration of the original colluvial material. This entails addition of new sediment at its head from erosion in the upper basin and removal of fines at the toe of the deposit by underloaded high discharge.

3. Subsurface Drainage

a. A single heavy flood can completely remove fines that have accumulated over many years. These floods can also completely fill other downstream areas of a cave with sediment. In the process, all evidence of former deposition is removed except in high level abandoned routes.

b. The present rate of drainage discharge from these basins is not significantly different from that of the past. It is true that available sedimentary material has decreased with increased vegetation covering and possible climatic changes, however.

c. The lack of sediment passing through an underground conduit greatly increases its ability to trench into the limestone. Where sedimentation is high, continuous passage trenching does not occur. The result is a series of stacked passages joined by occasional pits.

d. The overall function of the basin trunk channel is to integrate the surface and subsurface networks by overcoming lithologic and sedimentary barriers. This is never fully accomplished in any observed basin.

e. The lack of general "concave upward" profile of the cave stream is a strong arguement against a purely vadose development of most cave passages. Integration of the network tends towards such a profile in the later stages of development.

f. Steep gradients show transport of bedload through caves up to one meter in size.

g. Caves play an important function in the removal, transport, and accumulation of surface sediments in karst basins.

4. Subsurface Sediments

a. As they are found today, most cave deposits show evidence of only a few depositional events.

b. The overall sedimentary budget of most basins shows a greater loss of sediment than input. There is extreme variation across the basin, however. The upper basin is accumulating sediment. The middle basin has a deficit. In the longer range of infrequent flood events, the lower basin also experiences a greater loss than gain in sediment.

c. It appears that cave fills were deposited at a greater rate initially, when surface colluvium was abundant. This was in association with colder climates. Warm climates, such as that which prevail in the area today, are more conducive to the removal of fills and to the deposition of travertine. This latter fact is confirmed by Thompson (1973).

d. One does not necessarily have to postulate climatic change to explain changes in provenance and sedimentary sequences. These changes can evolve as a result of piracy and diversions. This alters the position and function of the cave conduit laterally and vertically within the basin.

e. The distribution of identifiable lithologic material is a valuable mappable indicator of former drainage movement within the basins.

f. The present rate of deposition in caves is less, by a factor of ten, than during earlier periglacial climatic and depositional environments. The massive, poorly sorted fills of McClungs cave and some high level upper basin caves could not have occurred only under the present fluvial conditions.

g. X-ray diffraction is of use in distinguishing the environment, origin and antiquity of finer deposits. It is not meaningful by itself, however.

h. Sedimentary structures are useful indicators of flow directions. They are not necessarily useful in determining former discharge or velocities. Individual grain size and imbrication is a helpful tool when used along with these measurements.

i. The "basin approach" to the analysis of deposits in caves is essential to the understanding and interpretation of their origin and development. The provenance distribution of ancient and modern fills is closely ties to the "basin approach".

j. This study alone is not sufficient to establish whether or not a cycle of deposition in caves of the Greenbrier karst exists.

k. The lack of a floodplain, the construction of cave entrances, passages and exits, the location of sediment and debris fills, the presence of karst sieves or their absence are some factors affecting the differences between surface and subsurface fluvial deposits.

l. There is little evidence for early phreatic deposition in caves. Vadose deposits dominate most cases, there is widespread evidence for para-phreatic deposition during flood as in the case of Hurricane Camille.

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BASIN I

CASSELLS CAVE (Misery Alley) (Intermittent) (15 Sites)

Phi Size	Cumulative Percent	Percent Milky Quartz
-5.0 ø	5.1	47
-4.5 ø	51.74	55
-4.0 ø	67.11	32
-3.5 ø	79.91	21
-3.0 ø	84.12	10
-2.5 ø	90.44	none
-2.0 ø	95.71	none
-1.5 ø	97.72	none
-1.0 ø	99.10	none
-0.5 ø	99.31	none
0.0 ø	99.53	none
0.5 ø	99.78	none
1.0 ø	99.86	none
1.5 ø	99.91	none
2.0 ø	99.95	none
2.5 ø	99.99	none

BASIN I

GRIMES CAVE (6 Sites) (Active)

Phi Size	Cumulative Percent	Percent Milky Quartz
-5.0 ø	31.70	90
-4.5 ø	51.77	65
-4.0 ø	74.50	50
-3.5 ø	81.50	41
-3.0 ø	93.46	33
-2.5 ø	95.77	20
-2.0 ø	98.11	none
-1.5 ø	99.05	10
-1.0 ø	99.27	none
-0.5 ø	99.41	none
0.0 ø	99.50	none
0.5 ø	99.74	none
1.0 ø	99.85	none
1.5 ø	99.87	none
2.0 ø	99.90	none
2.5 ø	99.96	none
3.0 ø	99.98	none

BASIN II

HILLS CREEK CAVE (6 Sites) (Active)

Phi Size	Cumulative Percent	Percent Milky Quartz
-4.0 ø	26.86	30
-3.5 ø	40.79	15
-3.0 ø	73.44	75
-2.5 ø	80.32	none
-2.0 ø	91.82	40
-1.5 ø	95.72	none
-1.0 ø	97.87	none
-0.5 ø	99.04	none
0.0 ø	99.47	none
0.5 ø	99.74	none
1.0 ø	99.78	none
1.5 ø	99.81	none
2.0 ø	99.84	none
2.5 ø	99.86	none
3.0 ø	99.99	none

BASIN II

BRUFFEY CREEK CAVE (4 Sites) (Active)

Phi Size	Cumulative Percent	Percent Milky Quartz
-4.5 ø	3.90	20
-4.0 ø	25.43	20
-3.5 ø	41.07	10
-3.0 ø	68.53	5
-2.5 ø	76.83	1
-2.0 ø	87.46	1
-1.5 ø	90.87	1
-1.0 ø	92.52	none
-0.5 ø	94.13	none
0.0 ø	95.75	none
0.5 ø	96.11	none
1.0 ø	97.86	none
1.5 ø	98.50	none
2.0 ø	98.96	none
2.5 ø	99.01	none
3.0 ø	99.10	none
3.5 ø	99.97	none

BASIN II

UPPER HUGHES CREEK CAVE (Upper Passage)[1] (10 Sites) (Inactive)

Phi Size	Cumulative Percent	Percent Milky Quartz
-2.0 Ø	40.53	16
-1.5 Ø	55.24	8
-1.0 Ø	62.52	none
-0.5 Ø	69.22	none
0.0 Ø	70.28	none
0.5 Ø	73.23	none
1.0 Ø	77.69	none
1.5 Ø	83.36	none
2.0 Ø	90.54	none
2.5 Ø	95.57	none
3.0 Ø	97.56	none
3.5 Ø	98.52	none
4.0 Ø	99.94	none

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[1] Milky quartz pebbles are found in the Upper Hughes Creek Cave at -4.5 Ø , -4.0 Ø , -3.5 Ø , -3.0 Ø and -2.5 Ø elsewhere along the stream passage in the lower level.

BASIN II

POOR FARM CAVE (Main Passage) (37 Sites) (Inactive)

Phi Size	Cumulative Percent	Percent Milky Quartz
-4.0 Ø	6.42	7
-3.5 Ø	12.15	12
-3.0 Ø	26.78	5
-2.5 Ø	33.06	5
-2.0 Ø	46.10	1
-1.5 Ø	53.84	2
-1.0 Ø	60.71	none
-0.5 Ø	66.84	none
0.0 Ø	71.06	none
0.5 Ø	74.33	none
1.0 Ø	82.29	none
1.5 Ø	88.38	none
2.0 Ø	92.54	none
2.5 Ø	94.99	none
3.0 Ø	99.98	none
3.5 Ø		

BASIN III

BOB GEE CAVE (12 Sites) (Inactive)

Phi Size	Cumulative Percent	Percent Milky Quartz
-5.5 ø	20.44	25
-5.0 ø	37.92	22
-4.5 ø	49.42	12
-4.0 ø	70.93	11
-3.5 ø	73.89	5
-3.0 ø	82.62	5
-2.5 ø	85.64	5
-2.0 ø	89.53	5
-1.5 ø	91.79	4
-1.0 ø	93.16	trace
-0.5 ø	93.70	none
0.0 ø	94.24	none
0.5 ø	94.55	none
1.0 ø	94.87	none
1.5 ø	95.66	none
2.0 ø	96.76	none
2.5 ø	98.57	none
3.0 ø	101.01	none

BASIN III

McCLUNGS CAVE (6 Sites) (Inactive)

Phi Size	Cumulative Percent	Percent Milky Quartz
-6.0 ø	34.21	none
-5.5 ø	74.32	none
-5.0 ø	97.84	none
-4.5 ø	98.75	none
-3.5 ø	99.97	none

BASIN III

BUCKEYE CREEK CAVE (2 Sites) (Active)

Phi Size	Cumulative Percent	Percent Milky Quartz
-4.5 Ø	24.72	none
-4.0 Ø	37.42	none
-3.5 Ø	39.92	none
-3.0 Ø	65.42	none
-2.5 Ø	77.32	none
-2.0 Ø	78.21	none
-1.5 Ø	87.33	none
-1.0 Ø	94.47	none
-0.5 Ø	96.77	none
0.0 Ø	99.05	none
0.5 Ø	99.74	none
1.0 Ø	99.81	none
1.5 Ø	99.84	none
2.0 Ø	99.91	none
2.5 Ø	99.99	none

BASIN III

CULVERSON CREEK (8 Sites) (Active)

Phi Size	Cumulative Percent	Percent Milky Quartz
-5.0 Ø	18.71	31
-4.5 Ø	37.60	47
-4.0 Ø	51.21	10
-3.5 Ø	76.51	33
-3.0 Ø	80.10	50
-2.5 Ø	90.33	21
-2.0 Ø	95.37	trace
-1.5 Ø	96.58	none
-1.0 Ø	99.10	none
-0.5 Ø	99.24	none
0.0 Ø	99.36	none
0.5 Ø	99.48	none
1.0 Ø	99.52	none
1.5 Ø	99.73	none
2.0 Ø	99.88	none
2.5 Ø	99.91	none
3.0 Ø	99.99	none

Appendix B

X-RAY DIFFRACTION DATA FROM BASINS I, II AND III

BASIN I

Sample	3.58Å	4.74Å	10.0Å	$\frac{3.58\text{Å}}{10.0\text{Å}}$	$\frac{4.74\text{Å}}{10.0\text{Å}} \times \frac{100}{80}$	14.0Å	Comments
C-1 Cassells	3.80	2.75	4.25	0.894	0.905	3.45	Active
G-1 Grimes	3.55	2.85	4.25	0.798	1.004	4.10	Active
CG Gunsite	3.30	2.75	4.60	0.777	1.041	3.50	Active
CP Pit	3.50	2.50	3.80	0.921	0.893	3.10	Active
W Windy	3.05	2.70	5.65	0.540	1.107	4.50	Fossil
CGE Gunsite	2.75	1.85	4.10	0.671	0.841	2.35	Fossil
TR_1 Trout Run Rising	2.90	2.00	3.35	0.866	0.862	2.30	Active
TR_2 Trout Run U. Sink	2.90	2.00	2.85	1.017	0.862	2.30	Active

BETWEEN BASIN I AND BASIN II

(Supplement) Overholts Cave (Swago Area)

Main Stream 0-1	2.30	2.00	2.40	0.958	1.087	2.10	Active
Anns Ave. 0-2	3.40	2.80	5.05	0.673	1.029	5.75	Fossil

BASIN II

SUBSURFACE SAMPLES

PEAK HEIGHTS (1/10")

Sample	3.58Å	4.74Å	10.0Å	$\frac{3.58\text{Å}}{10.0\text{Å}}$	$\frac{4.74\text{Å}}{10.0\text{Å}} \times \frac{100}{80}$	14.0Å	Comments
Poor Farm Cave							
(Site #3)							
Sample 1	4.80	3.40	8.40	0.571	0.885	3.10	Inactive samples along entrance and margin passages of Poor Farm Cave.
Sample 2	3.70	2.90	4.40	0.841	0.979	3.30	
Sample 3	3.30	2.70	5.70	0.579	1.023	3.10	
Sample 4	4.70	2.90	7.70	0.610	0.077	4.60	
Sample 5				0.517			
(Site #8)							
PF6 "Glei"	4.25	3.50	7.10	0.599	1.029	9.20	
PF8 + 50'	5.20	3.70	6.85	0.759	0.889	6.50	
(Site #1)							
Dark PF(D)	4.50	3.70	7.70	0.584	1.028	5.00	
Light PF(L)	3.50	2.90	5.20	0.673	1.038	3.90	
#8 Left	2.20	1.58	4.50	0.488	0.898	2.75	
#8 Right	2.42	1.80	5.56	0.435	0.929	3.20	
Upper Hughes Cr. Cave							
UH-1	3.80	2.80	4.50	0.844	0.9210	3.35	Active samples.
UH-2	2.50	2.80	3.80	0.921	1.000	3.50	
UH-6	3.25	2.50	3.60	0.903	0.962	3.40	
Lower Martha's Cave	3.25	2.80	3.82	0.851	1.077	3.50	Active.
Martens Cave							
MT-1	4.40	4.00	4.20	1.047	1.136	3.20	Active.
MT-2	3.50	3.20	4.25	0.823	1.143	3.50	

BASIN II

SURFACE SAMPLES

PEAK HEIGHTS (1/10") DIRECTLY ONLS.

Karst Plain

Sample	3.58Å	4.74Å	10.0A	$\frac{3.58\text{Å}}{10.0\text{Å}}$	$\frac{4.74\text{Å}}{10.0\text{Å}} \times \frac{100}{80}$	14.0Å	Comments
U-3 Sinks Grove Ls.	2.50	2.20	2.35	1.106	1.057	2.60	Bedrock
U-4 Hillsdale Ls.	2.30	2.05	2.15	1.070	1.114	2.00	samples.
U-7 McCrady Terrace	2.35	2.00	2.10	1.119	1.064	2.00	
				Upper Clastics			
U-1 Head	5.40	3.82	7.01	0.770	0.884	8.30	Along
U-2 Fan	3.25	2.65	4.01	0.810	1.019	2.92	active
U-8 Hills Cr.	3.60	2.75	3.70	0.973	0.954	4.50	stream
U-9 Bruf. Cr.	3.75	2.90	3.80	0.987	0.966	4.00	channels.
				Lower Clastics			
U-5 McCrady Fossils Shale Terrace	2.50	2.25	4.60	0.543	1.125	3.00	
U-6 McNeals Sed. Trap.	2.50	2.40	3.10	0.806	1.200	2.45	
U-10 Locust	4.10	3.50	5.30	0.774	1.067	5.10	Terrace
Beards B.H.	N.A.	N.A.	N.A.	0.875	N.A.	N.A.	Terrace
U-11 Locust Fossil Terrace	3.85	3.50	4.40	0.875	1.136	6.20	Terrace

BASIN III

Sample	3.58Å	4.74Å	10.0Å	$\frac{3.58\text{Å}}{10.0\text{Å}}$	$\frac{4.74\text{Å}}{10.0\text{Å}} \times \frac{100}{80}$	14.0Å	Comments :
Bone	2.70	2.30	2.90	0.931	1.065	2.80	Active
McFerrin^2 (stream)	2.70	2.15	3.30	0.818	0.995	2.30	Active
McFerrin^1 (cave earth)	2.30	2.00	3.60	0.639	1.087	2.20	Fossil
Higginbothams II	3.20	2.80	3.85	0.831	1.094	2.80	Active
219 Over Cul. Cr.	2.80	2.40	3.00	0.933	1.071	2.50	Surface
219 Maxwelton Sink	3.30	2.90	5.10	0.647	1.098	5.20	Fossil
McClungs	2.70	2.50	5.35	0.505	1.157	3.00	
Buckeye Creek Cave	2.50	2.00	2.60	0.962	1.000	2.00	Surface
Above Buck. Cr. Cave	2.61	2.30	3.52	0.741	1.102	2.25	Active
Culverson Creek	2.80	2.40	3.00	0.933	1.071	2.50	Active
Bob Gee	N.A.	N.A.	N.A.	0.540	N.A.	N.A.	Fossil
Gr. Banana	1.23	0.95	2.90	0.424	0.965	2.45	Fossil (Terrace)
Gr. Banana	2.22	1.85	5.52	0.402	1.042	1.95	Fossil (Terrace)
Spring Creek	3.20	2.50	4.10	0.780	0.977	4.00	Active Rising
Fort Spring	3.75	3.45	3.90	0.962	1.150	3.30	Active Rising

BASINS I, II AND III

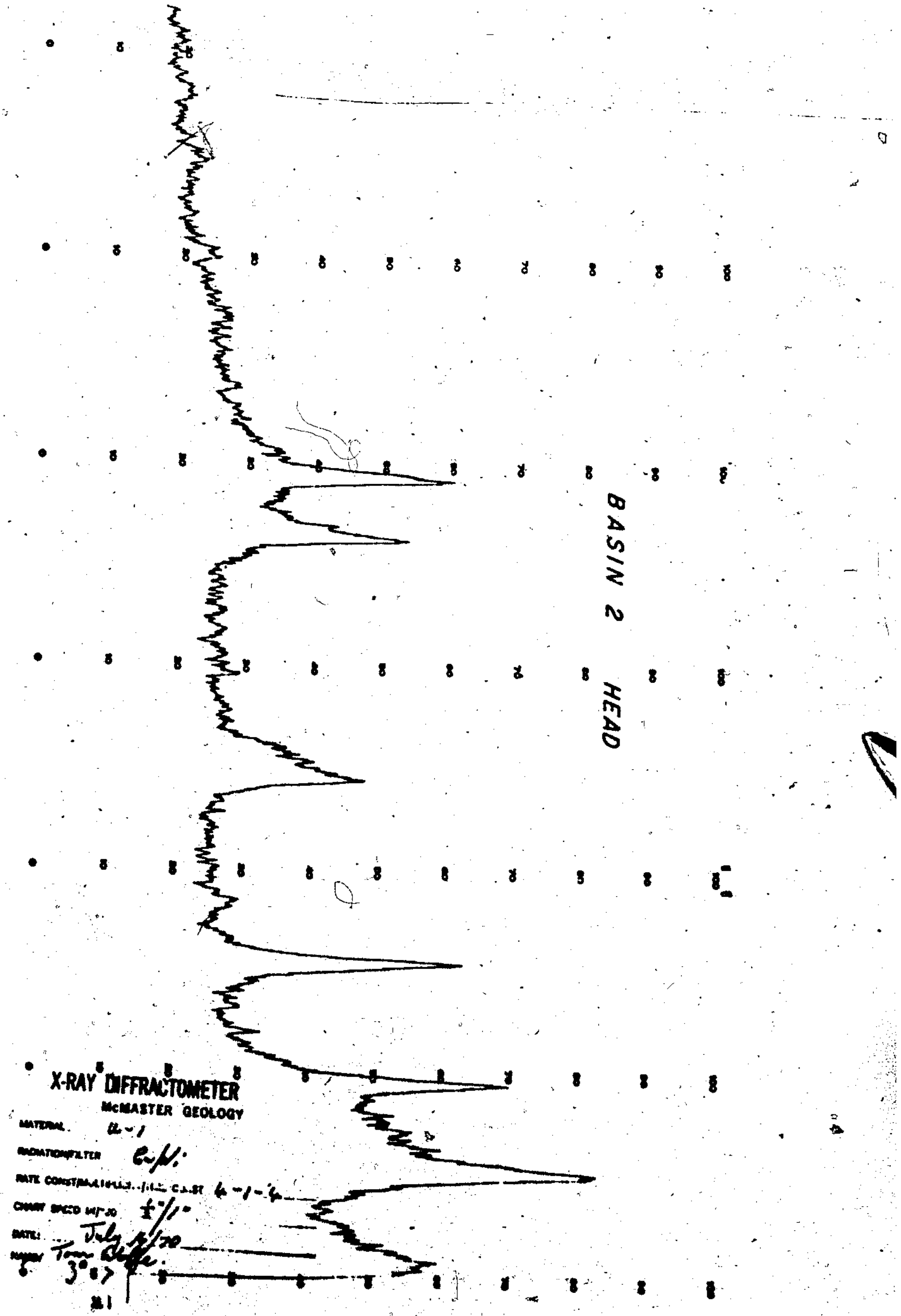
BEDROCK SAMPLES

Clastics

Unweathered Samples	3.58Å	4.74Å	10.0Å	$\frac{3.58Å}{10.0Å}$	$\frac{4.74Å}{10.0Å} \times \frac{100}{80}$	14.0Å	Comments
Mauch Chunk Ss.	4.10	2.23	4.90	0.837	0.680	2.40	Unweathered
Droop Ss.	2.31	1.93	1.92	1.203	1.044	1.76	Unweathered
Droop Ss.	2.77	2.22	2.70	1.026	1.002	2.10	Unweathered
Hinton Ss.	5.80	1.22	1.70	3.412	0.263	1.20	Unweathered
Pottsville Ss.	7.80	0.70	2.72	2.868	0.112	0.60	Unweathered
Princeton Ss.	5.30	0.90	1.62	3.272	0.212	0.75	Unweathered

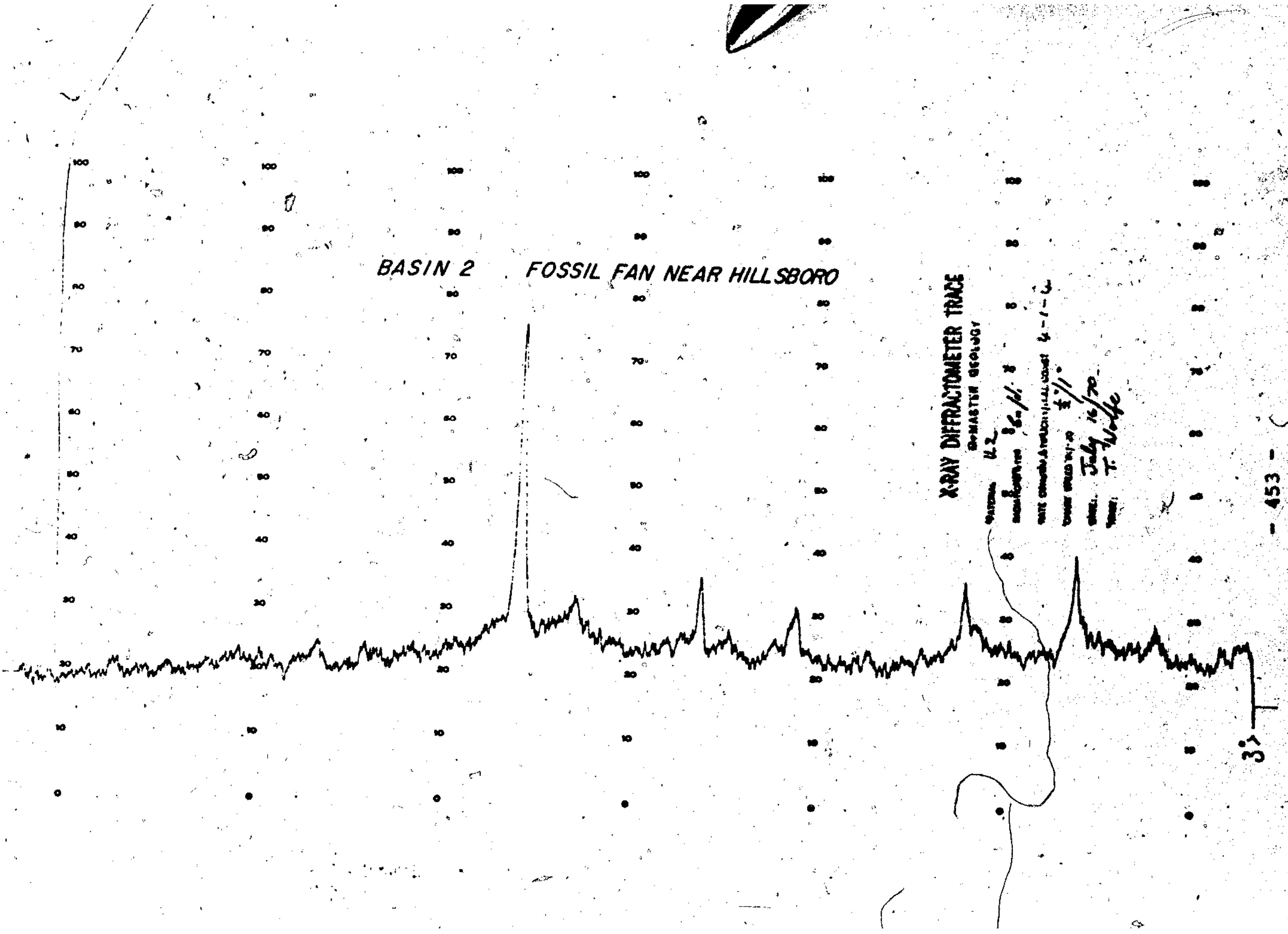
Carbonates

Unweathered Samples	3.58Å	4.74Å	10.0Å	$\frac{3.58Å}{10.0Å}$	$\frac{4.74Å}{10.0Å} \times \frac{100}{80}$	14.0Å	Comments
Sinks Grove	1.21	1.00	1.78	0.679	1.033	0.70	Unweathered
Taggard	2.05	1.50	3.61	0.568	0.915	1.54	Unweathered
Alderson Ls.	1.70	1.22	3.40	0.500	0.897	1.42	Unweathered
Taggard	2.22	1.85	5.52	0.402	1.041	1.95	Unweathered
Union Ls.	1.35	1.05	2.00	0.680	0.970	1.00	Unweathered
Pickaway Ls.	N.A.	N.A.	N.A.	0.993	N.A.	N.A.	Weathered



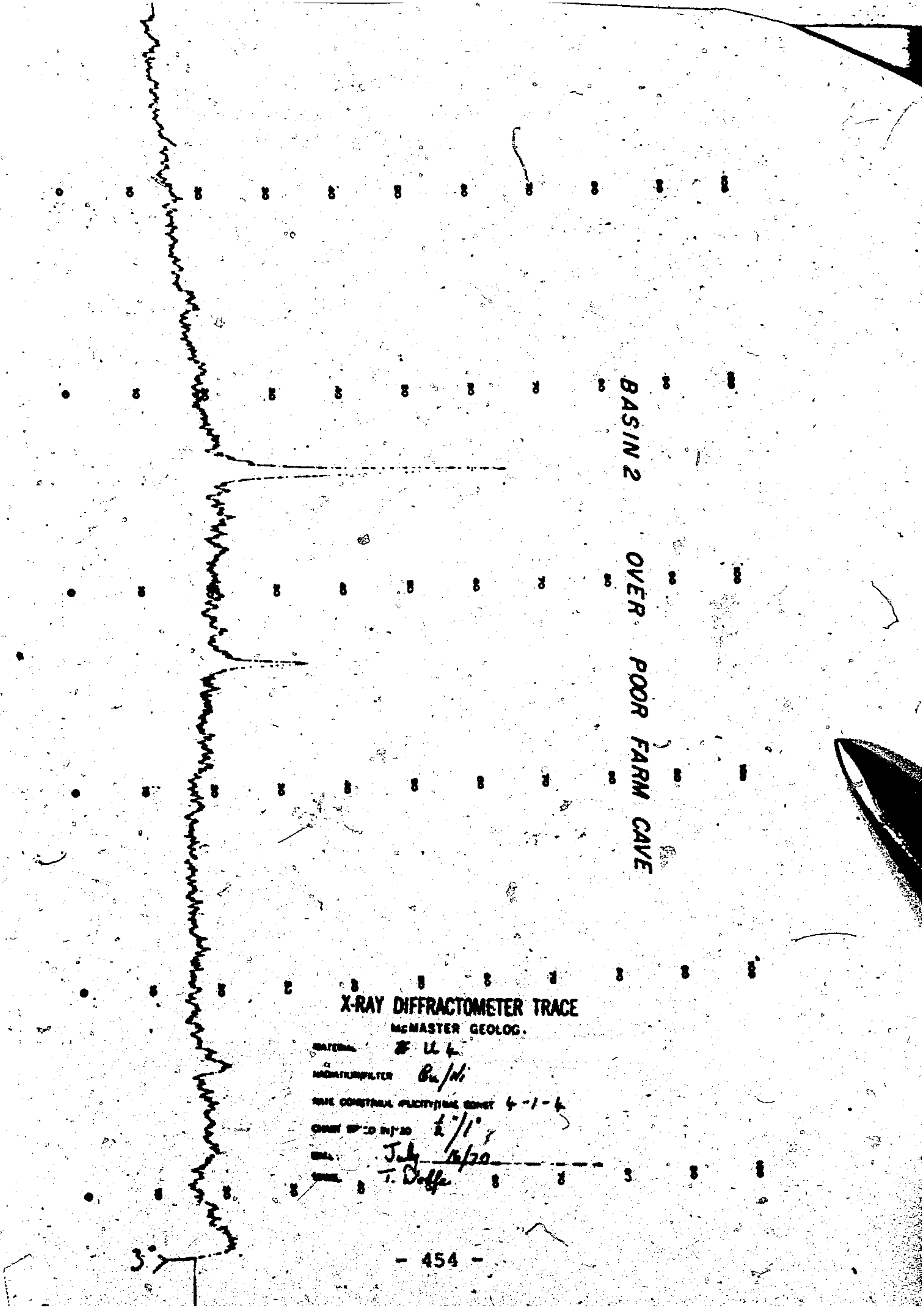
X-RAY DIFFRACTOMETER
McMASTER GEOLOGY

MATERIAL. a-1
RADIATION/FILTER Cu/Ni.
RATE CONST/[illegible] C.J.ST 4-1-4
CHART SPEED IN/°2θ 1°/1"
DATE: July ?/70
NAME Tom Duffe
3°-67
21



X-RAY DIFFRACTOMETER TRACE
McMASTER GEOLOGY

MATERIAL: U2
RADIATION/FILTER: Cu/Ni
RATE COUNTS/ATTENUATION/TIME CONST: 4-1-4
CHART SPEED IN/-2θ: ½°/1'
DATE: July 16/70
[illegible]: T. Wolfe



X-RAY DIFFRACTOMETER TRACE
McMASTER GEOLOG.

MATERIAL # U 4
RADIATION/FILTER Cu/Ni
RATE CONST/MULTIPLICITY/TIME CONST 4-1-4
CHART SPEED IN/°2θ ½"/1°
DATE July 16/70
NAME T. Dolfe

POOR FARM CAVE

(Site #3)

Four X-Ray Diffractogram Traces

(Untreated)