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Post-depositional weathering of cave sediments in Berry Cave, Pulaski County, Missouri

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**POST-DEPOSITIONAL WEATHERING OF CAVE SEDIMENTS
IN BERRY CAVE, PULASKI COUNTY, MISSOURI**

A Thesis

Presented to the

Department of Geography and Geology

and the

Faculty of the Graduate College

University of Nebraska

In Partial Fulfillment

of the Requirements for the Degree

Master of Arts

University of Nebraska at Omaha

by

Melissa L. Milner

March 1997

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THESIS ACCEPTANCE

Accepted for the faculty of the Graduate College,
University of Nebraska, in partial fulfillment of the
requirements for the degree Master of Arts, University
of Nebraska at Omaha.

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ABSTRACT

Berry Cave is a vadose system, and is classified as a branchwork cave with superposed anastomotic mazes. The cave is situated in the non-glaciated karst region of Roubidoux Creek in Pulaski County, south-central Missouri. Two types of sediment deposits have been identified in the cave: an allogenic fine clay fill preserved in a stream cut canyon and an autogenic/allogenic loam comprising a debris flow. The surface soil above the cave is silt loam, and is the source for the sediments of the debris flow in Berry Cave.

Three episodes of geomorphic development have been determined to be related to sediment deposition within Berry Cave. The first is the deposition of fine clay units in the cave. These units may have been deposited as slackwater deposits. Next is the erosion of the clay fill units resulting in the formation of a stream cut canyon in the cave sediments, which was associated with the cave's transition(s) from vadose flow to phreatic. Finally is the deposition of the debris flow sediments that is related to the present day vadose flow through the cave system. This model of cave sedimentation, though simplified, provides the best understanding of the timing and effects of post-depositional alterations of sediments in Berry Cave.

Although the present literature suggests that the weathering of cave sediments is limited or absent in many cave systems, it is important to recognize that weathering does occur to cave sediments. The sediments in Berry Cave were affected by post-depositional weathering processes throughout the geomorphic evolution of the cave system. These post depositional alterations include: enrichment, melanization, illuviation of clay minerals, iron translocation, and braunification, rubifaction, and ferrugination. The post-depositional processes that affected the clay fill sediments are presently inactive, because

there is not sufficient water available to alter these sediments. Conversely the processes affecting the debris flow are active.

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CHAPTER I

INTRODUCTION

This study investigated post-depositional alterations of sediments within Berry Cave in south-central Missouri (Figures 1 and 2). The primary objective was to determine the magnitude of weathering of those sediments. Surface soils around the cave have been eroded by overland flow and deposited in the cave as soil sediments (Mandel, 1992). These sediments form clay fills and debris flows throughout the cave network. In order to determine physical and chemical alterations of cave deposits, I compared the interior cave sediments with a surface soil contiguous to the sediments at the entrance of the cave.

Significance of the Study

There are two reasons why this research is important. First, little is known about weathering in caves. Several studies suggested that caves are giant sediment traps (e.g., Sweeting, 1973; Warwick, 1976; Ford, T.D., 1976; Colcutt, 1979; Jennings, 1985; Trudgill, 1985). Other studies that examined weathering of cave sediments, focused on the sediments in order to reconstruct paleoenvironments outside the cave at the time of deposition (e.g., Collier and Flint, 1964; Bull, 1976; Quinif, 1981; Schmidt, et al., 1984). These studies generally concentrated on the sediments located at the entrance of the cave (Colcutt, 1979; Farrand, 1985). The remaining studies focused on the age of speleothems (e.g., Gascoyne and Latham, 1981; Goede and Harmon, 1983) or cave biology (e.g., Poulson and White, 1969; Culver, 1970; Des Marais, et al., 1981).

The second reason this research is significant is that it will help determine the depth of weathering in cave sediments and magnitude of post-depositional modifications throughout the cave. Frank (1965: 1) suggested that since cave deposits are protected from subaerial weathering, they are generally unaltered. However, Ford and Williams

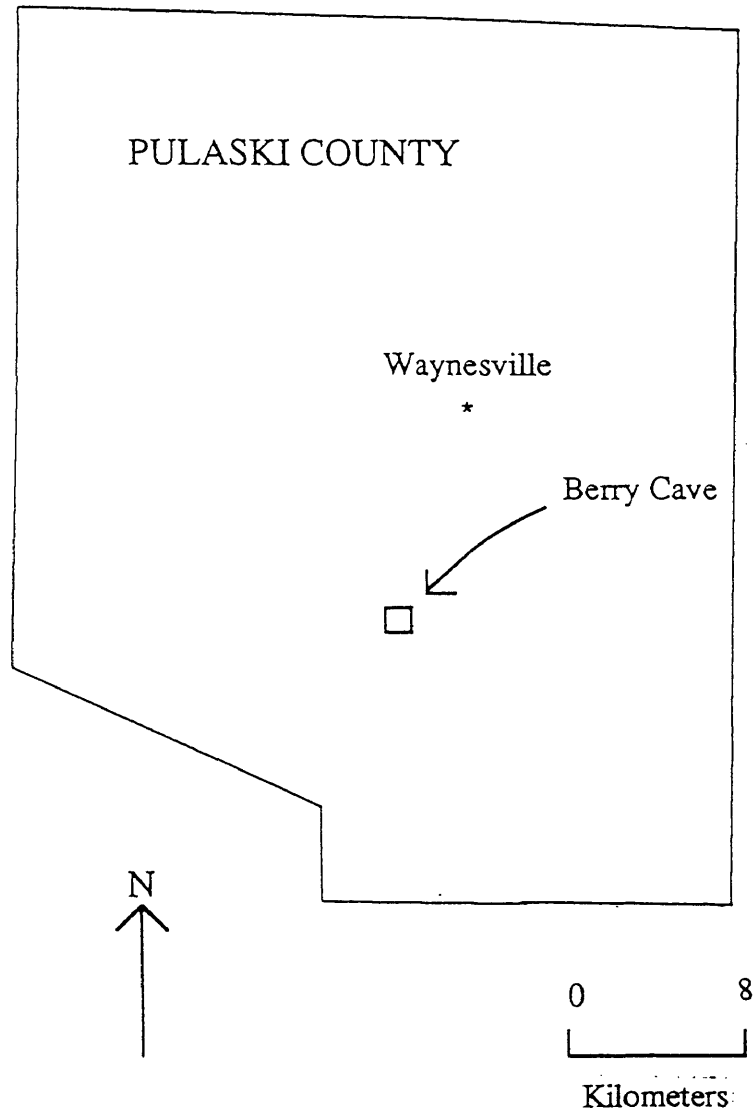
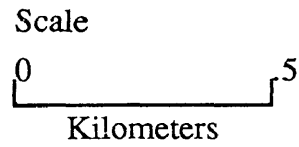
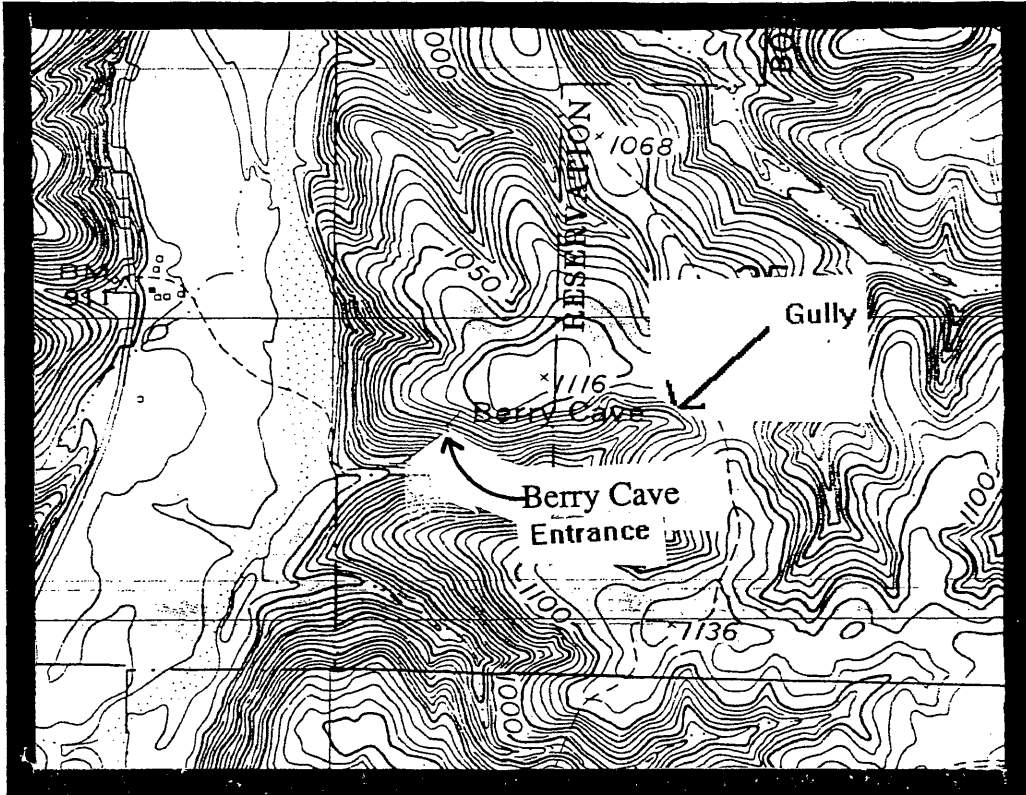


Figure 1. Location of Pulaski County, Missouri and of Berry Cave.



Taken from Bloodland Quadrangle Missouri, 1982

Figure 2. Location of Berry Cave

and Williams (1989: 329-330) list several post-depositional processes affecting cave sediments, such as bioturbation, calcification, and oxidation.

Statement of the Problem

This study stemmed from one of my graduate research papers that dealt with pedogenic processes affecting cave sediments. Previous studies indicated that early diagenic processes can also be viewed as pedogenic processes (Courty, et al. 1989: 138). In addition, several sources listed diagenic processes affecting cave sediments which were similar to pedogenic processes. For example, Ford and Williams (1989: 329-330) described diagenic processes that modify cave sediments, including loading, wetting/drying, bioturbation, oxidation, and calcification. Tinsley et al. (1981) noted that calcification and oxidation occurred in only the oldest unconsolidated sediments in Lilburn Cave, California; however, evidence of these diagenic processes was not present in the youngest sediments. Other researchers indicated that deposits which are isolated from bioclimatic influences, such as those in caves, display weak soil development (Courty et al., 1989: 32). Also, Farrand (1985) stated that determining specific post-depositional modifications can be very complicated because several processes may have modified the sediments.

My first thesis proposal attempt was aimed at trying to classify the post-depositional processes affecting cave sediments as either pedogenic, diagenic, or a combination. However, Goldberg (personal communication, 1992) suggested that the research should focus on the degree of post-depositional modifications. Accordingly, this study will attempt to answer the following research questions regarding Berry Cave and the associated soils and sediments:

- What post depositional processes affect cave sediments, and are these processes still active?
- What is the source of the cave sediments?

- Are the cave sediments autogenic, allogenic, or both?
- How are the cave sediments indicators of landscape evolution?

Previous Research

There have been three main areas of cave research: cave biology, sedimentology, and archaeology. Cave biology is relevant in terms of the affect organisms can have on cave sediments, and archaeology is relevant because of the sediment studies that ensue during cave archaeology projects. The following discussion summarizes each of the three areas of research.

Cave Biology

One area of research in cave biology has been on bat guano. Des Mariais et al. (1981) discussed the age and composition of bat guano from Carlsbad Cave, New Mexico. His research indicated that bat guano can have various compositions based on different bat species and on varying diets within the same bat species. Hill (1981) discovered that the diet of two species of bats in Tamana Cave, West Indies, determines whether cockroaches and other cave animals will be involved in the decomposition of the bat guano or simply burrow into it. Lavoie (1981) and Martin (1981) described the decomposition sequence of cricket, raccoon, and rat dung and bat guano in caves, respectively. Davies and Chao (1959:16) reported bat guano deposits in Mammoth Cave, Kentucky that are more than 38,000 years old. These studies are important because they document the accumulation of organic matter in caves. According to Buol et al. (1989: 122), the accumulation of organic matter, or littering, and subsequent humification are pedogenic processes that affect the mineral component of a deposit.

Another focus of cave biology research has been the distribution and diversity of cave fauna. Culver (1970) listed the predominant species living in cave streams. He noted that caves which flood tend to have less diversity of species than dry caves. Poulson and White (1969) and Ford and Williams (1989) determined that the twilight zone (entrance)

of a cave has the largest and most diverse fauna, while the deep interior of the cave contains the more unique, smaller cave species. Rutherford and Huang, (1994) examined fungi of ancient cave sediments in various West Virginia caves and compared the species found with that in the existing literature. The researchers were interested in using the microfungi as “fingerprints” for local correlation and to establish a stratigraphic sequence. Unfortunately there were reproducibility problems which prevented the use of the microfungi for correlation. Biological studies can also be significant, because larger animals can churn the sediments (bioturbation) or add material to the sediments (littering) located at the entrance of the cave.

Cave Sedimentology

There are four main areas of research in cave sedimentology, which are summarized in Table I. Three related topics are determining the source of the sediments,

Table I. Topics of Research in Cave Sedimentology

| Grain Size & Paleohydrology | Palcomagnetism & Chronostratigraphy | Sediment Source & Paleoenvironment | Post Depositional Alterations (Diagenesis) |
|-----------------------------|-------------------------------------|------------------------------------|--|
| Collier and Flint (1964) | Schmidt, et al. (1984) | Davies and Chao (1959) | Davies and Moore 1957 |
| Warwick (1976) | Springer (1994) | Collier and Flint (1964) | Helwig (1964) |
| Ford (1976) | Lovlie, et al. (1995) | Helwig (1964) | Frank (1965) |
| Bull (1978) | Valen (1995) | Frank (1965) | Reams (1968) |
| Gale (1981) | | Kopper and Creer (1973) | Kopper and Creer (1973) |
| Ek (1981) | | Ford (1975, 1976) | Sweeting (1973) |
| Schroeder (1981) | | Bull (1976) | Ford (1975, 1976) |
| White and White(1981) | | Bull (1981) | Colcutt (1979) |
| | | Quinif (1981) | Schmidt (1984) |
| | | Jennings (1985) | Monroe (1986) |
| | | Trudgill (1985) | Ford and Williams (1989) |
| | | Murray (1993) | |
| | | Springer (1994) | |
| | | Brinkmann and Reeder (1995) | |
| | | Hov, et al. (1995) | |

determining diagenic processes that have modified the sediments, and using the results from the previous two topics to determine the paleoenvironment on the surface at the time

of sediment deposition. The other area of research has focused on the grain size distribution throughout the cave and past hydrological conditions.

Sediment Source and Paleoenvironment

Collier and Flint (1964) examined cave sediments in Mammoth Cave, Kentucky and determined their source was the Green River floodplain sediments located 1/2 mile from the cave. Their study examined physical characteristics and mineralogy of both the cave sediments and Green River sediments to verify the source. They also determined that sedimentation rates of the cave were closely linked to flooding of the Green River.

Quinif (1981) compared the thermoluminescence (TL) curves from cave sediments in Grotte de la Vilaine Source at Arbre in Belgium to the TL curves of the two rock units outside the cave to determine the sediment source. His research also stated that the cave sediment TL curves sometimes do not match any TL curves from sediments outside the cave. It was suggested that those cave sediments could have originated from a paleogeomorphic land surface that had since been eroded away.

Hoy, et al. (1995) compared the fine-grained sediments in The Ohio Caverns, Champaign County, Ohio, to the overlying glacial till. The mineralogy and grain sizes were examined and it was determined that both the cave sediments and glacial till were similar. The cave sediments also exhibited evidence of fluvial transport. Specifically, there was a coarse to fine distribution of grain sizes related to distance into the cave.

Helwig (1964) determined that the sources of various cave fills in Carroll Cave, Camden County, Missouri, are mainly fluvial and partly roof fall. The dominant fill was a red or brown silt with large amounts of gravel. The fill contained chert and its source was residual chert gravels in intermittent stream beds on the land surface. Helwig suggested that the chert gravels and deep red residual surface soils were a result of weathering of the Roubidoux formation. Camden County is the county northwest of Pulaski County (see

Figure 3 in Chapter II). While Berry Cave has red and brown fill, it is dominantly clay with no gravel.

Frank (1965: 55) noted that quartz (chert) and kaolinite along with calcite are the most common minerals in limestone. Therefore, the source of cave sediments can be traced if they contain quartz and kaolinite. It is possible that weathered cave sediments will show large amounts of quartz and kaolinite because they are the most resistant minerals.

Ford (1976: 58;1975: 46) suggested that cave sediments can provide information on the paleoenvironment and possible source areas. He stated that there is much more variability in entrance sediments than interior sediments. Ford also asserted that the color of cave sediments is usually yellow-brown. However, it can be red if terra rossa soils are eroded from the surface and deposited in the cave.

Springer (1994) examined various aspects of sediments in caves along the Cheat River in West Virginia. Types of cave patterns (Palmer, 1991) were designated along with the associated depositional environment with each pattern. Both vadose and phreatic sediments were recognized based on scour surfaces. Scour surfaces are the erosional features in a cave (e.g. ceiling channels, scallops) formed by dissolution of bedrock (White, 1988: 91). These features are used to determine if a cave passage is vadose or phreatic in origin. The sediments in each passage are then classified based on the passage origin. In addition, remnant magnetic polarities of sediments associated with previous base levels of the Cheat River were determined. Springer (1994) also noted that a flood in 1985 eroded the fine-grained overbank sediments from the caves, and deposited tree fragments and overbank, slack water deposits. These slackwater deposits in the caves are excellent indicators of peak stages of the Cheat River, because they are preserved. Similar surface deposits are quickly altered, and are not as reliable.

Davies and Chao (1959: 5) stated that the source of cave sediments and the geological history of a cave can be determined by comparing the sediments to surface soils, sinkhole soils, and sediments on the floodplain of a nearby river. After comparing the cave sediments in Mammoth Cave, Kentucky to these three source areas, it was discovered that the cave sediments and soil/sediments from the source areas had similar physical characteristics. However, there was a difference in color. The older cave sediments were red in color, while the younger cave sediments and surface soils and sediments were brown in color. Possibly, these red colored sediments were eroded from a paleogeomorphic surface that is no longer in existence. Nearly all of the pebbles in the gravel beds in the cave were stained by manganese oxide. In addition to cave sediments, there were extensive deposits of niter earth, which is a dark brown dust derived from bat guano that has been desiccated.

Murray, et al. (1993) determined the source of sediments deposited in the underground river in the Jenolan Cave System in New South Wales, Australia. By using radionuclides (^{226}Ra and ^{232}Th) as tracers to ascertain the sediment source, they found that two drainage catchments provided sediments in equal amounts to the cave system.

Monroe's study (1986) suggested that the source of cave clay fills is a clay that forms *in situ*. Monroe examined an *in situ* clay (autogenic sediment) on surface exposures of limestone. This clay had a gradational contact with the limestone, contained limestone features, fossils, bedding features, and was reddish-brown in color.

Several researchers have examined cave sediments in order to reconstruct the past environmental conditions on the land surface in a given area. Bull (1976) compared quartz sand grains in Agen Allwedd Cave to surface quartz sand grains to determine both the source of the sediments and paleoenvironmental conditions at the time of deposition.

Twenty-two surface features were examined by Scanning Electron Microscope (SEM) and categorized as a result of mechanical or chemical weathering. The surface features of the source were also examined to ensure that the weathering had occurred after the sediments had been eroded from the surface. Chemical and mechanical processes are diagnostic of certain environmental conditions, and previous glacial conditions were determined from the cave sediments (Bull, 1976: 9).

Brinkmann and Reeder (1995) calculated cave sedimentation rates in Peace Sign Cave, Florida in order to demonstrate that local environmental changes caused variations in the rates. Variable sedimentation rates occurred due to the instability of the landscape. Road building, forestry, and extreme precipitation events were identified as the main reasons for the instability. The sedimentation rates had been affected during the last 18 years, and it was suggested that the cave sediments could be compared to “post settlement alluvium”.

Kopper and Creer (1973:14) and Smart (1984) suggested that the cave sediments in the interior of caves can help determine past conditions. They examined interior sediments and determined that they were similar to sediments on the land surface. Sweeting (1973: 173) indicated that since there is no surface weathering in caves, the sediments are preserved and can be used to reconstruct the environmental history in an area.

Ford (1976:49) determined that cave sediments can provide information on their history and that of the cave. He also noted (1976:58;1975:45) that cave sediments cemented with calcium carbonate are indicative of either climatic, hydrologic, or chemical changes in the surface environment. Temperature and surface runoff are two factors which control limestone dissolution (Atkinson and Smith 1976: 155). This dissolution can lead to secondary calcification in the cave. When the environment changes to a more

wet/warm climate, calcification increases. Consequently, if some layers in the cave deposits show secondary calcification and others do not, then the paleoclimate at the time those units were deposited can be reconstructed.

Some researchers have studied cave sediments to determine past climatic conditions. Frank (1965:25, 38) examined sediments in Fyllan Cave, Texas to determine past climates of the area. His research indicated that if cave sediments contain hematite nodules, abundant kaolinite, but small amounts of limestone fragments, then the previous climate was humid. The cave sediments in Fyllan Cave had a decrease of kaolinite from the bottom of the section to the top and the trend towards a drier climate was confirmed by the vertebrate fossil record in the area.

Bull (1981) examined parallel accretion of laminae in Agen Allwedd, South Wales. These laminae are common in all caves with fine-grained sediments. The fine-grained sediments are deposited in pulses which are directly related to surface climatic fluctuations. Bull (1981: 15, 20) asserted that major climatic events are not only recorded in a single cave, but in all the caves of an area.

Trudgill (1985: 77, 79) determined that caves act as repositories for sediments and that these sediments can be used to interpret the environment, mechanism of deposition, and sequence of cave development. Jennings (1985: 159; 1971: 174-177) also noted that caves serve as sediment traps, and exhibit atypical mechanisms of sedimentation. He was making reference to Bull's (1981) research which indicated that pulses of sediments can result in parallel accretion of clay laminae.

Post-Depositional Alterations

Some researchers who have examined post-depositional alterations of cave sediments have concentrated mainly on diagenesis of the sediments. Collcutt (1979) provided an overview of previous studies of cave sediments. He noted that the deposition

of cave sediments is only the beginning of several modifications that will affect the sediments (Colcutt: 294-5). He also concluded that cave sediment studies have not focused on processes occurring inside the cave. Sweeting (1973: 174) indicated that cave sediments tend to become cemented and preserved by calcium carbonate, and Ford (1976:58) noted that the calcification process is an extension of flowstone formation.

Several researchers who have examined the diagenesis of cave sediments have suggested that cave sediments are not modified much after deposition. For example, Frank (1965:1, 12) noted that cave sediments are protected from weathering and there is generally not an effective weathering agent to modify the sediments. He also indicated (1965:19) that calcification in cave sediments increases with depth below the surface of the deposits. Helwig (1964: 13) noted that many sedimentary features in cave sediments remain unchanged because the cave environment protects the sediments from weathering processes at the surface. Reams (1968:63) concluded that cave sediments are mostly unweathered because groundwater flowing through them is saturated and unable to leach them.

Other researchers have suggested that cave sediments can be modified by *in situ* weathering or by animals. Davies and Moore (1957:25) asserted that endellite found in Carlsbad Caverns, New Mexico was a result of diagenesis occurring within the clay fill. Ford (1975: 45) determined that sediments at the cave entrance can be churned by burrowing animals. Ford and Williams (1989:318) suggested that cave sediments are modified by shrinking/swelling, slumping, bioturbation, and calcification. They further asserted that diagenesis in cave sediments has not been studied in sufficient detail.

Finally, Kopper and Creer (1973:19) suggested that the main effect of diagenesis in cave sediments is the magnetic orientation of the particles after deposition.

Paleomagnetism and Chronostratigraphy

Løvlie, et al. (1995) established a chronostratigraphy of cave sediments between three caves in northern Norway by using paleomagnetism. The study found that the cave sediments showed low paleomagnetic inclinations, which were ascribed to DRM (detrital remanent magnetization). The DRM was attributed to post-depositional alteration realigning magnetic grains within the cave sediments (Løvlie, et al., 1995).

Schmidt et al. (1984) used magnetic reversals to date the cave sediments in Wee Jasper, New South Wales. They found no evidence of bioturbation or translocation of iron in the sediments (p. 363).

Valen (1995) examined the lithostratigraphy and paleomagnetism of several caves in Norway. In Sirijordgrotta Cave, only the lithostratigraphy was examined. Valen suggested that three environments of deposition occurred during deglaciation. The sedimentology of two coastal caves was determined to be related to ice dammed lake sediments. Both sediment sequences were litho- and magneto- stratigraphically correlated. The paleomagnetic records from one of the caves indicated that it had previously been covered by ice. Paleomagnetism was utilized to determine the sedimentology and stratigraphy of Hamnsundhelleren Cave and correlate the sediments to glacial advances and retreats.

Grain Size and Paleohydrology

Several researchers have focused on the grain size distribution of cave sediments. Collier and Flint (1964) discovered that fine-grained sediments are deposited at high elevations and coarse-grained sediments at lower elevations in Mammoth Cave, Kentucky. However, they found that the coarse-grain particles tend to migrate to higher elevations with each successive flood. Warwick (1976: 95) suggested that caves act as sediment traps and that there is a coarse to fine grain-size distribution from the entrance to the back

of the cave. Ford (1976:53) noted that when a vadose stream carrying sediments enters the phreatic zone, the velocity of the stream decreases and sediments are deposited in a coarse to fine sequence throughout the cave.

While some researchers focused on the grain-size distribution, others interpreted paleohydrologic conditions from the granulometry of the sediment. Bull (1978: 279) used grain-size analysis to determine that there were various sources for the sediments in Agen Allwedd Cave, South Wales. He analyzed the mineralogy of pebbles within the cave fill to determine the distribution of particular minerals within stratigraphic layers. The distribution of minerals throughout the cave was used to show that the competence of the stream which had deposited each particular layer had decreased. Bull also examined the shape of grains in the sediment to determine roundness values and changes to the grains during transport. He found that grains were more rounded with distance into the cave.

Gale (1981) determined the grain-size distribution of cave fill in Fissure Cave, UK to reconstruct the paleohydraulics of stream flow. Analysis of the grain sizes helped determine which deposits were transported by bedload and suspended load. Using the grain-size analysis, thickness of the cave fills, solution hollows on the cave walls (scallops and flutes), and cave meanders, Gale was able to calculate the former flow competency and depth of flow. In addition, other paleohydrologic variables were inferred, including Reynold's numbers and Darcy-Weisbach friction factors.

Ek (1981) described the source of the sediments in Speos de la Fée, Quebec. She suggested that the sediments were derived from glacial deposits. Her study mainly emphasized the use of sediments to determine the paleoflow in the cave. She demonstrated that there were two directions of flow. One direction of flow was determined by the sediment grain orientations, and an opposite direction of flow was determined from scallop formations on the cave roof.

Currens (1983) described the sedimentology and paleohydrology of a segment of Longs Cave, Kentucky to determine how a cave passage developed. Based on the grain-size analysis, he concluded that the average velocity of the stream depositing the sediments was 28 cm/second. However, scallops (solution hollows) on the walls implied a more moderate flow.

Schroeder (1981: 496) determined the grain-size distribution in Castleguard Cave II, Alberta, Canada, to determine the glacial melting chronology of Castleguard Glacier. Sediments in three levels of the cave were examined: at high elevations where the cave is blocked off by ice, and at the middle and lower elevations. He determined that sediments in the cave passage located under the glacier (blocked by the glacier) contained angular limestone debris and huge roof fall blocks. With increasing distance in the cave, the sediments became less angular and the roof fall blocks were much smaller. Apparently, the glacier affected both the angularity of the sediments and the size of the roof fall blocks, because Schroeder suggested the angular debris and huge roof fall blocks probably are a result of the glacier's movement.

Tinsley et al. (1981) examined the sediment units in Kings Canyon National Park, California to show three episodes of speleogenesis: deposition, erosion, and hydrological passage morphology. The oldest unit contained very fine-grained rhythmites and the middle and youngest units contain coarse grained materials. Some passages had coarse-grained materials (gravel and boulders) intermixed with fine-grained material. The geometry of the passage and stratigraphy of the fill suggests that the intermixed fill is diachronous, because the coarse grained material would not pass through the old passage.

Helwig (1964: 13) concluded that when a cave lies at or near the water table, the best conditions exist for the deposition of sediments. He suggested that gravels and silts

will aggrade when the cave is in the phreatic zone, and that lowering of local base level is recorded by the degradation of cave fills.

Ford (1976: 53, 58; 1975: 45) noted that sediments will be deposited in a cave when the transport agent is interrupted by a climatic change. He further stated that the direction of paleoflow can be determined from the grain-size distribution throughout the cave. Most of the sediment is carried during flood regimes and may be transported completely through the cave system. Ford also noted that clay deposition in a cave does not necessarily mean a cave is in transition from an active cave to one of inactivity. Ford pointed out that the deposition of fine-grained material may be related to climatic fluctuations or sediment source. For example, a glacier near the cave might have a small undermelt flow which allows only fine-grained material to be transported. Alternatively, a fine-grained cave fill may be indicative of a loess cover that was eroded off of the surface.

White and White (1968) determined that suspended load or bedload may be transported out of closed drainage basins by cave streams. They applied standard engineering formulae for sediment transport to show that flows with threshold velocities of tenths of a foot per second are necessary to transport coarse sediments. They implied that the transport of fine sediments only requires flows at least in the turbulent regime. Their study also suggested that there is a coarse to fine grained sequence of deposition throughout the cave system. The velocities of the stream decrease due to a decreased gradient and a transition from channel flow to pipe flow. They maintain that the very fine material can remain in suspension much longer than coarse material because of its lower fall velocity.

Archaeology

Stein (1985: 6) described four stages of sediment development that can provide a foundation in studying archaeological sediments. These stages are: the source of the

sediment, transport history, environment of deposition, and post depositional alteration. Kopper and Creer (1973:14) noted that cave sediments often are the source of invaluable archaeological information. Farrand (1985:21) asserted that caves and rockshelters provide important information to researchers because they have rapid sedimentation rates and roof falls, which make them self sealing. Farrand examined the sediments in rockshelters and cave entrances to determine post-depositional alteration, source, and paleoenvironments at the time of deposition. However, he did not focus on the cave interiors because they are affected by different environmental controls.

Beynon and Donahue (1982: 31) focused on the source of sediments in Meadowcroft Rockshelter, Pennsylvania, to reconstruct the paleotopography, and formation of the rockshelter, and to determine sedimentation rates. Stuckenrath, et al. (1982) also studied strata in Meadowcroft Rockshelter for cultural features. A radiocarbon sequence was determined for periods of human occupation, and the source of the sediments in each strata was determined.

As part of an anthropological investigation, Thackeray, et al. (1993) examined vanadium concentrations in cave sediments from caves in Sterkfontein Valley, South Africa. The vanadium concentrations were studied in order to demonstrate the use of vanadium as a dating method between sites. The cave sediments of this region lack volcanic ash; hence they have been difficult to date. However, cave sediments from sites in this valley contain *Australopithecus robustus* and early *Homo* species. Vanadium concentrations in cave sediments from the hominid sites were compared and it was demonstrated that this method is viable for relative dating of sites.

Moody and Dort (1990: 368) analyzed sediments from Coyote Cave, Idaho. They interpreted the changing environments of the area based on: the cave sediment source, soil development in the sediments, and human occupations.

Wilkinson and Duhon (1990) studied the soils and sediments at Franchthi Paralia in Greece. They focused on various physical and chemical characteristics of the soils and sediments to uncover Aegean Neolithic artifacts and human occupation sites. They noted that the site may have been more extensive in the past. It seemed plausible that a portion of the site may have been eroded and deposited in Kiladha Bay, which is located below the site.

CHAPTER II

STUDY AREA

Regional Physiography and Site Setting

The study area is located in south-central Missouri in Pulaski County (Figure 1). This area is within the Ozark Plateau physiographic province (Fenneman, 1938), which extends from south-eastern Missouri through north-central Arkansas (Figure 3). Throughout geologic history, several geological processes have occurred to form the Ozarks. The basement was formed from a Pre-Cambrian intrusion of magma which cooled to form intrusive igneous and metamorphic rocks. As a result of this intrusive activity, a dome was created in the Ozark region. During the late Cambrian, warping of the Earth's crust caused the Ozark region to be invaded by seas. Advance and retreat of these seas' shorelines caused units of sandstone, limestone, and dolomite to be deposited. From the late Cambrian to approximately 300 Ma there were several uplifts in the area. A final uplift occurred to the Ozark region at approximately 300 Ma. Since that time, erosion of the region has resulted in the development of karst topography in the areas of limestone and dolostone.

Karst is a landscape formed by dissolution of limestone, dolomite, or gypsum. Dissolution is defined as a carbonate rock being dissolved by the solution process (Trudgill, 1985). The dissolution process is affected by several controls. These include: lithology of the rock units, runoff from the drainage basin, temperature, and levels of carbon dioxide (Atkinson and Smith, 1976). Karst topography is usually characterized by caves, sinkholes, fracture/joint patterns, and underground drainage. Typically, karst can also be distinguished by intermittent streamflow and by valleys without streams (Jennings, 1971).

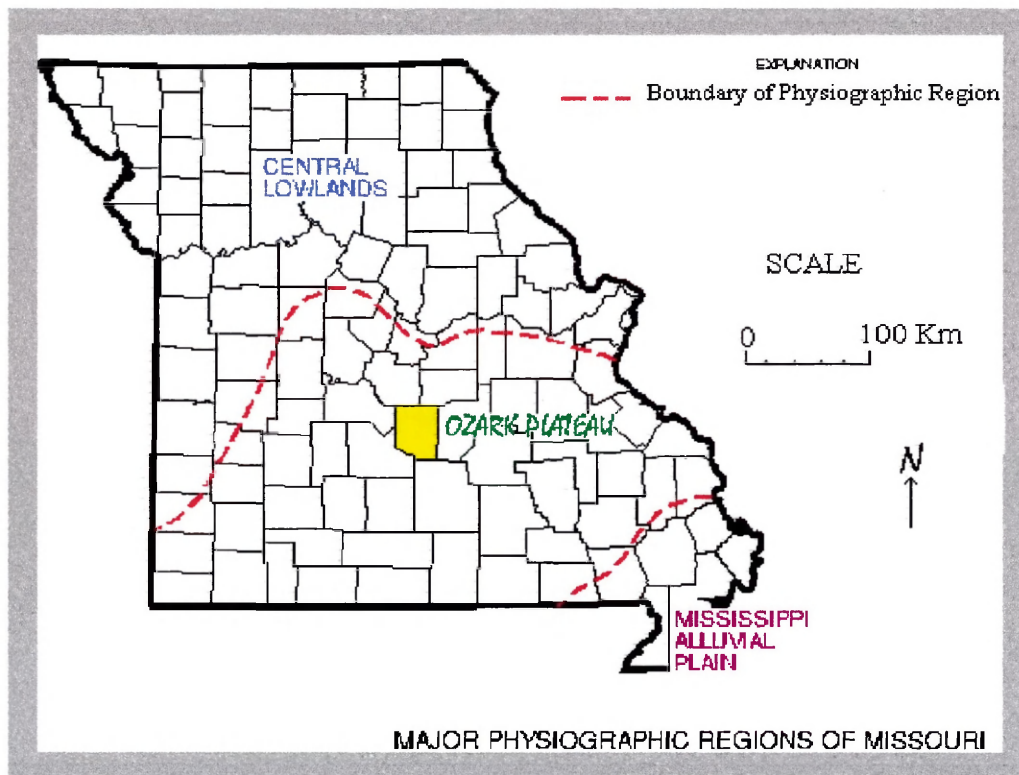


Figure 3. The Location of the Ozark Plateau. The highlighted county is Pulaski County, where the study site is located. (Adapted from USGS, 1996).

Stratigraphy

South-central Missouri is underlain by Pennsylvanian (320 - 286 Ma) and Upper Ordovician (458 - 438 Ma) sedimentary rocks. The bedrock in Pulaski County is composed of sedimentary rocks ranging from Pennsylvanian sandstone and clay to Ordovician cherty limestone (Whitefield, 1989: 71). There is a north-west regional dip of the bedrock of approximately 2 m per 1.6 km (Whitefield, 1989: 71). The exposed bedrock in Pulaski County is cherty dolomite and sandstone. All of these sedimentary rocks rest on Pre-Cambrian igneous bedrock which is approximately 427 m below the surface (Wolf, 1989: 7). Overlying the bedrock is a layer of Pleistocene loess that is typically one foot thick or less (Whitefield, 1989: 71).

Berry Cave has formed between the contact of the Roubidoux and Gasconade formations (Figure 4). Both formations are similar in lithology. The Roubidoux Formation is comprised of sandy dolomite, cherty dolomite, and sandstone (Whitefield, 1989: 71). It is approximately 31 to 46 m thick, and is brown-brownish red. It commonly appears as an outcrop of sandstone and sandy dolomite bluffs on hillsides along small stream valleys and in road cuts (Whitefield, 1989: 71). The Roubidoux Formation has fossil and sedimentary features such as: cryptalgal structures and oolites (Thompson, 1991: 17-20). The sandstone portion of the Formation is brick red, has ripple marks, and some is cross-bedded (Thompson, 1991).

The Gasconade Dolomite is approximately 76 to 91 m thick, and is gray to light brown (Whitefield, 1989: 71). It is mainly dolomite with some chert layers (Thompson, 1991: 17-20). Sedimentary structures of this formation are normally absent, however planispiral gastropod and cryptalgalaminated beds are sometimes found (Thompson, 1991). The high bluffs along the major stream valleys in Pulaski County are outcrops of Gasconade Dolomite (Whitefield, 1989: 71).

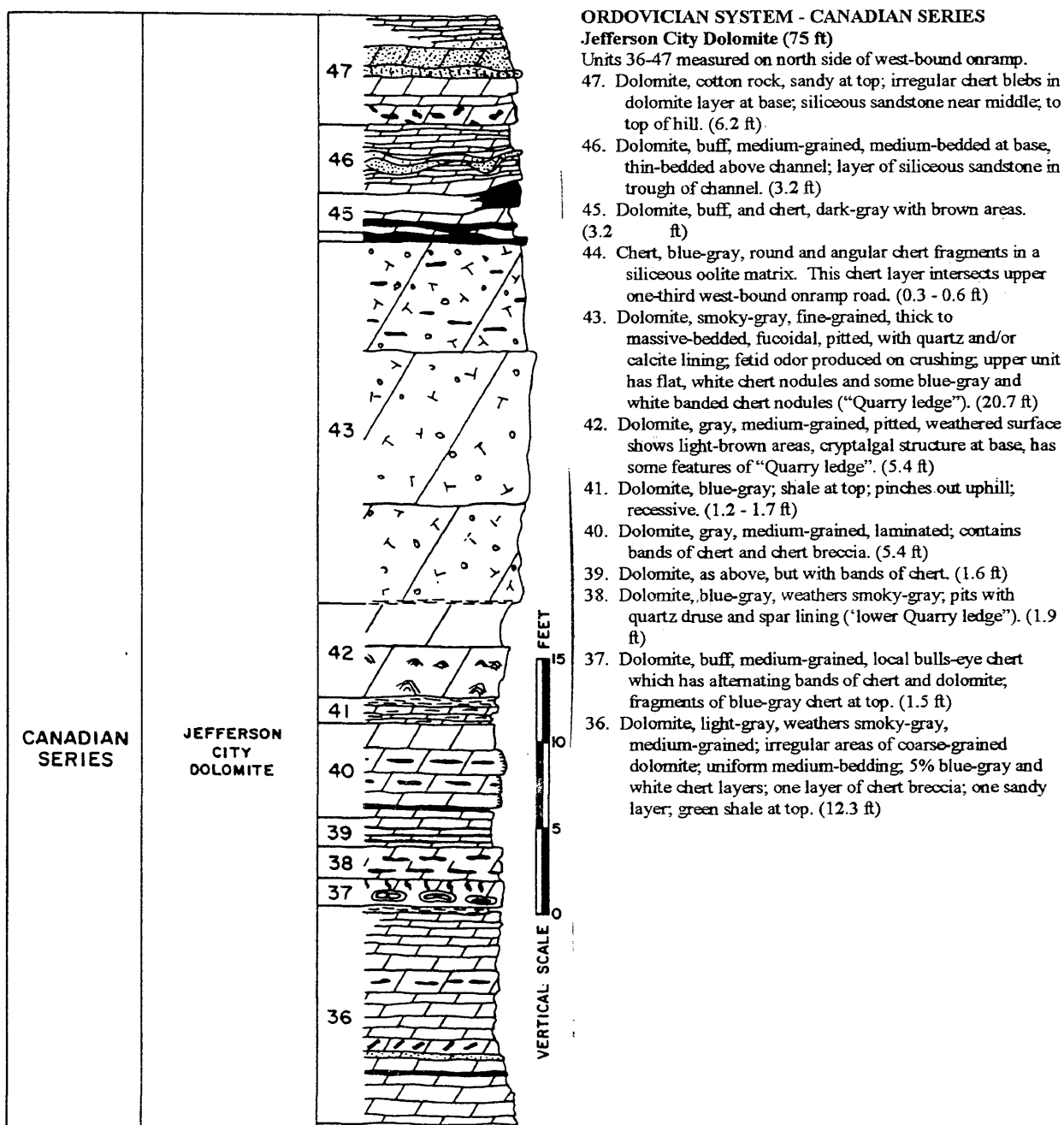


Figure 4. Contact between Roubidoux and Gasconade Formations exposed in a roadcut approximately 7 km Northeast of Berry Cave. (adapted from Thompson, 1991: 17-20).

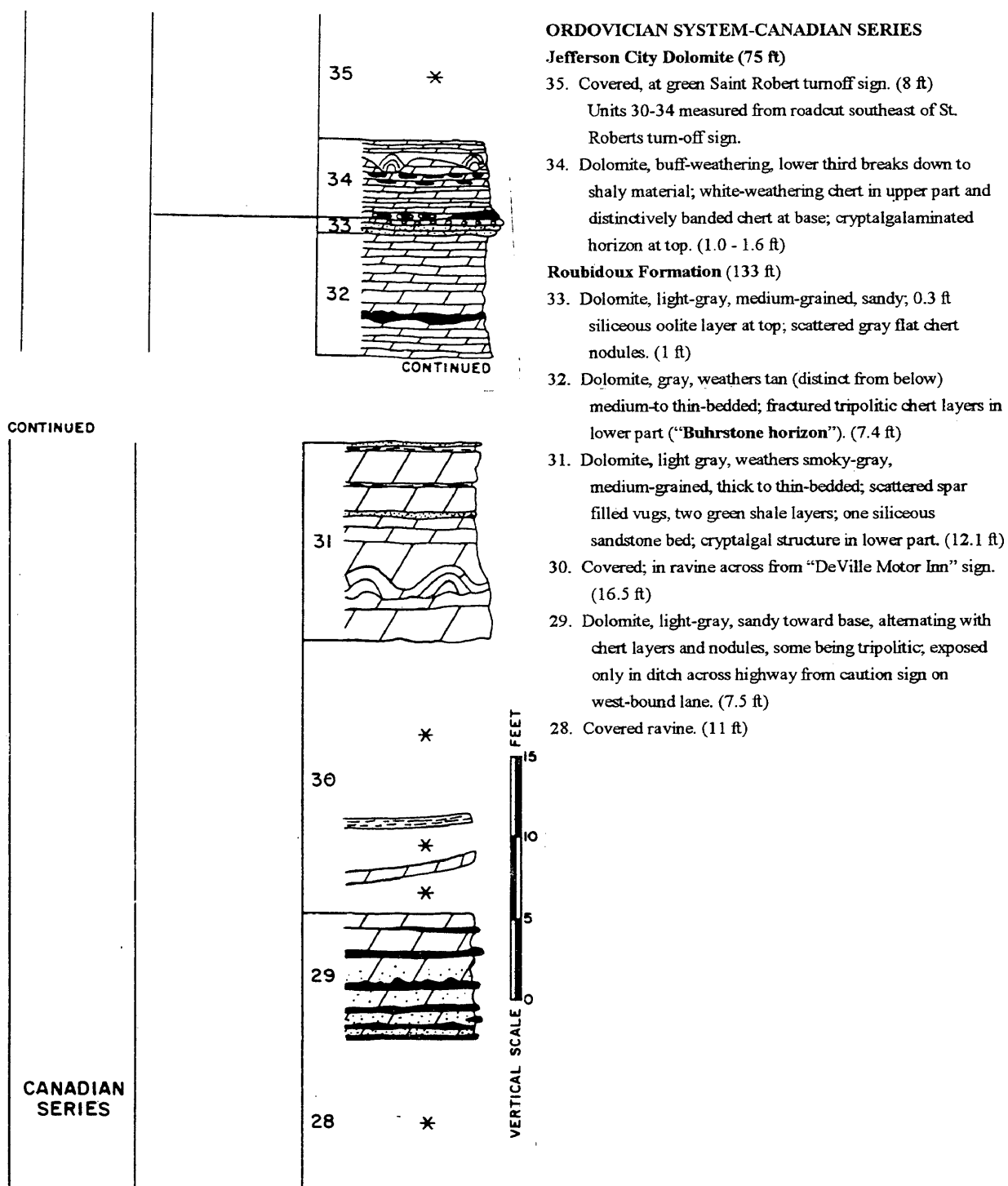


Figure 4. Contact between Roubidoux and Gasconade Formations exposed in a roadcut approximately 7 km Northeast of Berry Cave. (adapted from Thompson, 1991: 17-20).

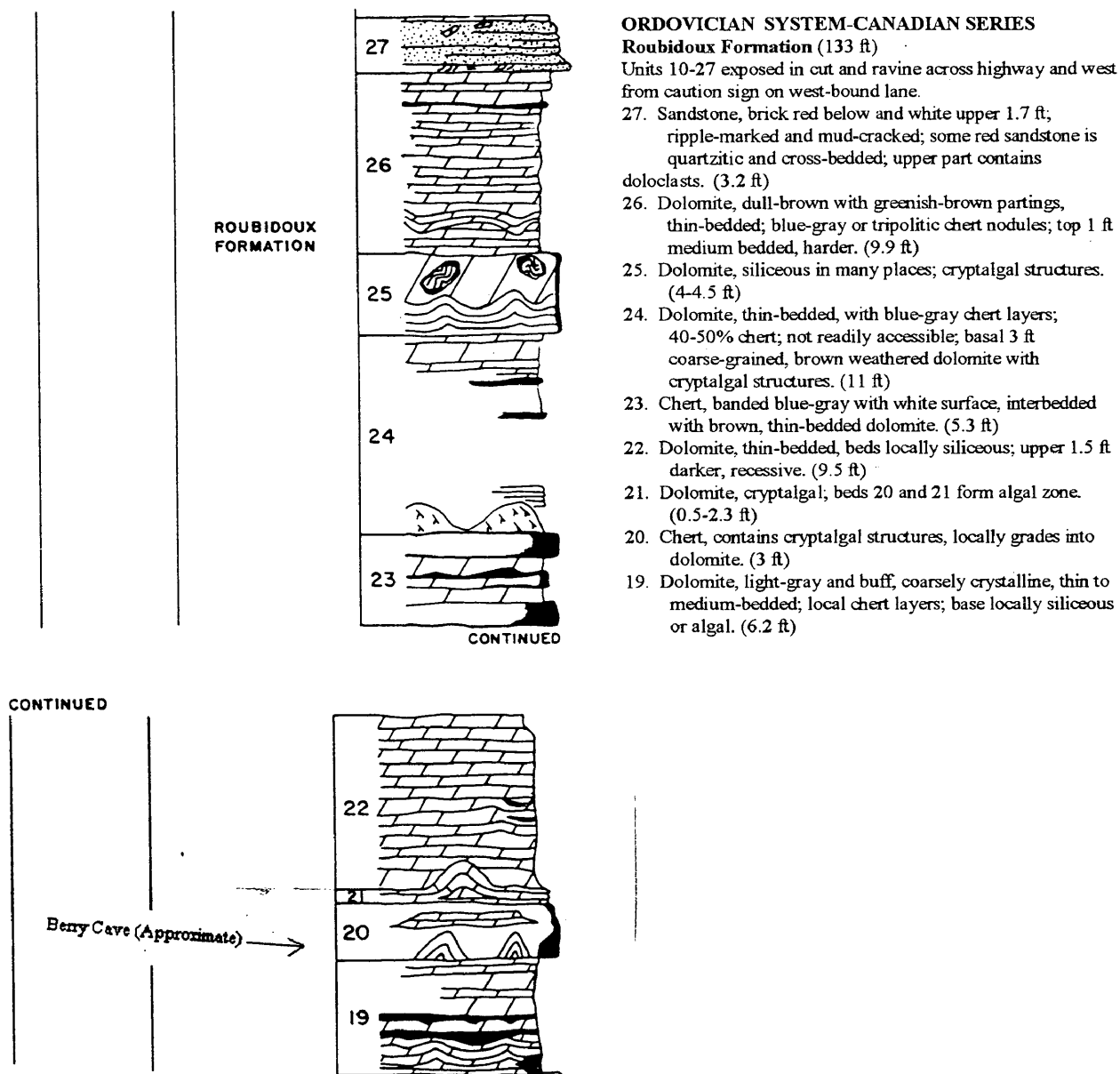


Figure 4. Contact between Roubidoux and Gasconade Formations exposed in a roadcut approximately 7 km Northeast of Berry Cave. (adapted from Thompson, 1991: 17-20).

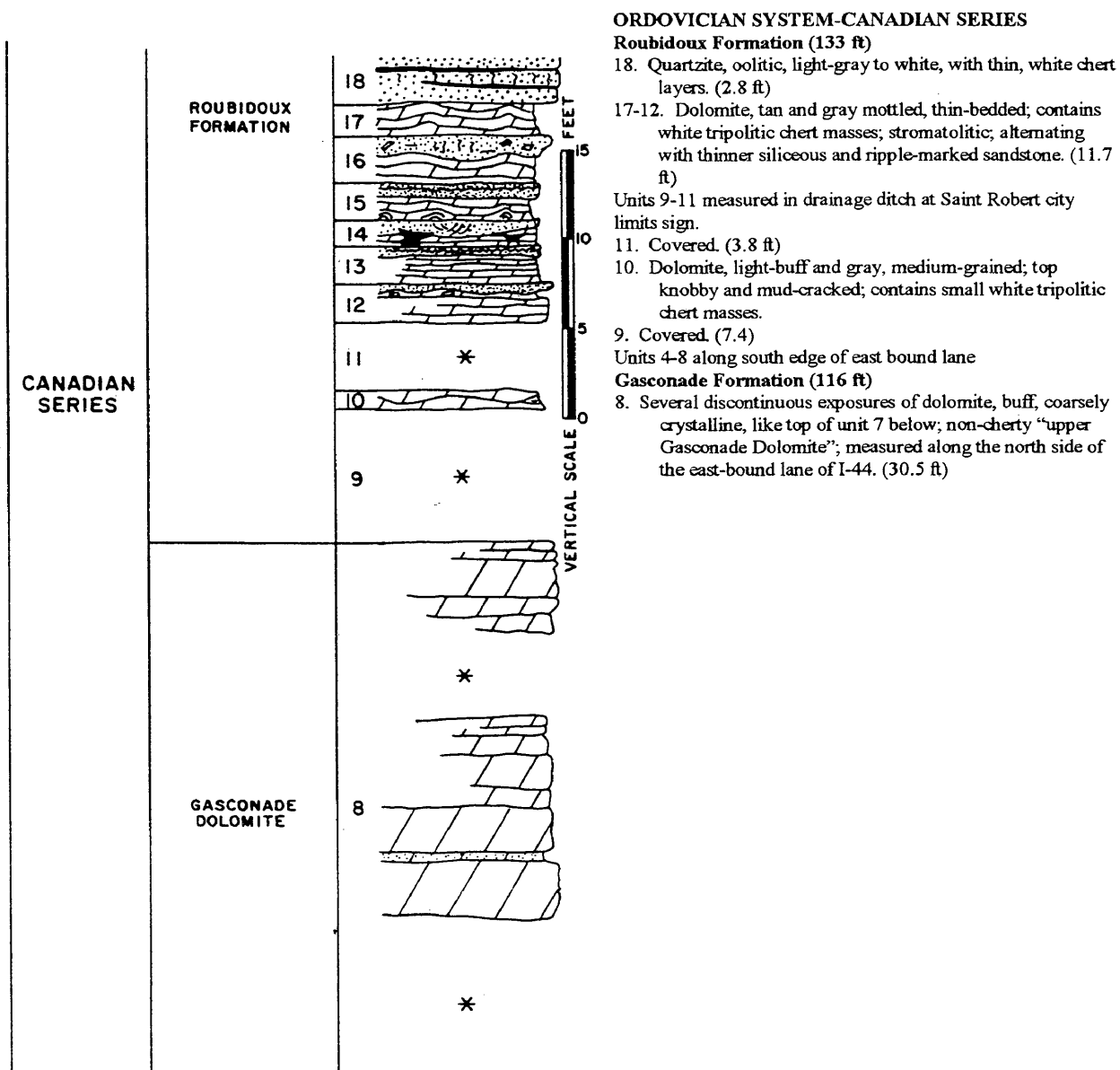


Figure 4. Contact between Roubidoux and Gasconade Formations exposed in a roadcut approximately 7 km Northeast of Berry Cave. (adapted from Thompson, 1991: 17-20).

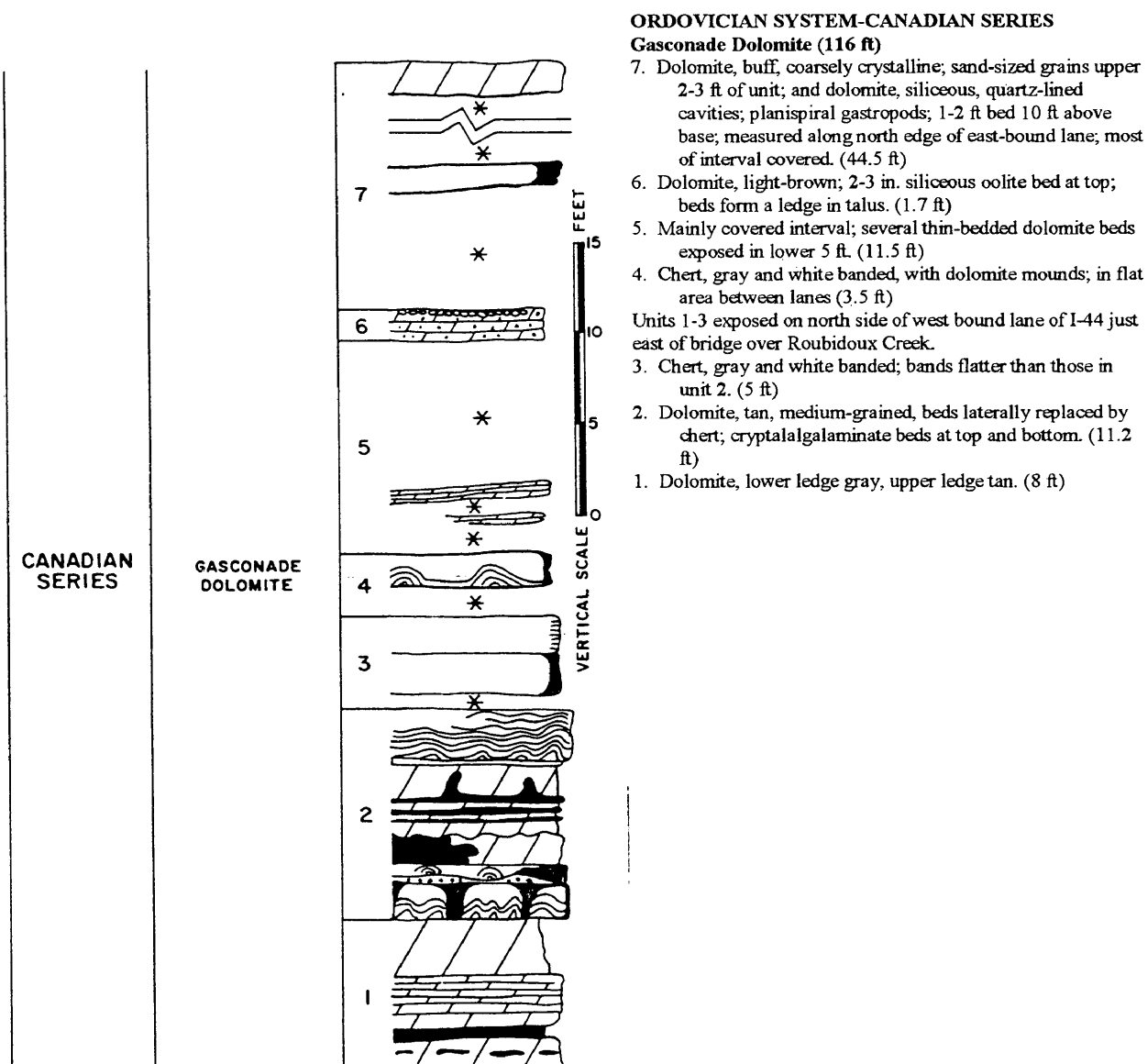


Figure 4. Contact between Roubidoux and Gasconade Formations exposed in a roadcut approximately 7 km Northeast of Berry Cave. (adapted from Thompson, 1991: 17-20).

Berry Cave

The study site is located approximately 7 km southwest of Waynesville, Missouri, and is designated as Berry Cave on the USGS 7.5 Minute Quadrangle (see Figure 2). The cave entrance is at an elevation of approximately 320 m above sea level and is situated on the northeast slope of a small ravine which drains into Roubidoux Creek (Figures 5 and 6). The entrance is about 244 m east of Roubidoux Creek, and local relief between Roubidoux Creek and the study site is approximately 43 m. As can be seen in Figure 5, there are wavy undulations in the bedrock near the cave entrance. These undulations are cryptalgal structures, and are indicative of the Roubidoux Formation. The ceiling of the cave in some locations is a light gray calcareous sandstone, which is typical of the Roubidoux Formation. The floor of the cave in places is formed of both the Roubidoux and Gasconade Formations.

Based on Palmer's (1991: 2) classification system, Berry Cave is a branchwork cave with superposed anastomotic mazes (Figures 7 and 8). Branchwork caves are similar to dendritic river channels on the surface. Closed loops rarely occur, but these caves can have anastomotic tributaries superimposed on them. Anastomotic caves are similar to anastomosing river channels on the surface, with many closed loops or tributaries (Palmer, 1991).

Local Hydrology of Roubidoux Creek

The local hydrology near Berry Cave is important because it provides an example of a karstified region. Roubidoux Creek, immediately west of Berry Cave, has a dendritic drainage pattern. The gradient of the creek in the study area is 3.3m/km. Roubidoux Creek's floodplain is approximately 0.6 km wide, which is surprising, since the majority of the creek has intermittent flow. Although the creek is typically dry or contains water in



Figure 5. Entrance to Berry Cave and outcrop of Roubidoux Formation (view is to the northeast). Notice the cryptalgal structures at the top of the Formation.



Figure 6. Entrance to Berry Cave (view is down into the entrance)

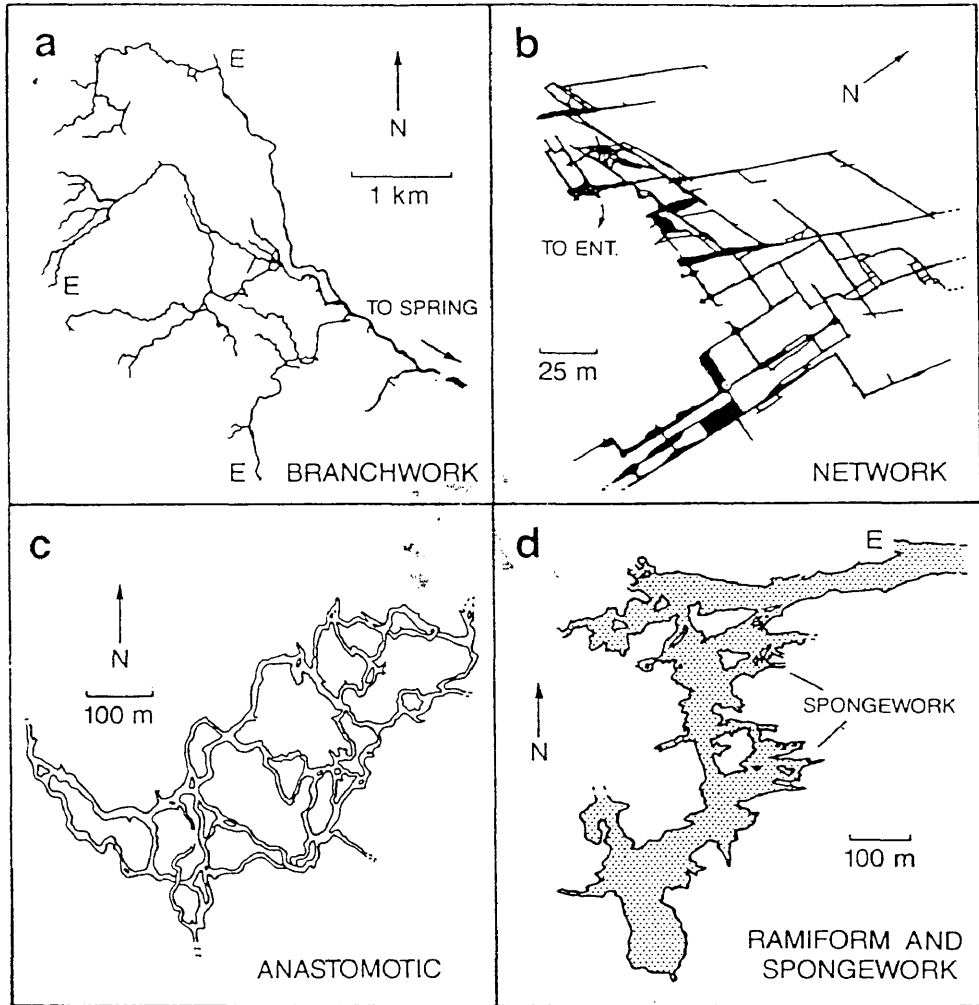


Figure 7. Cave patterns (from Palmer, 1991)

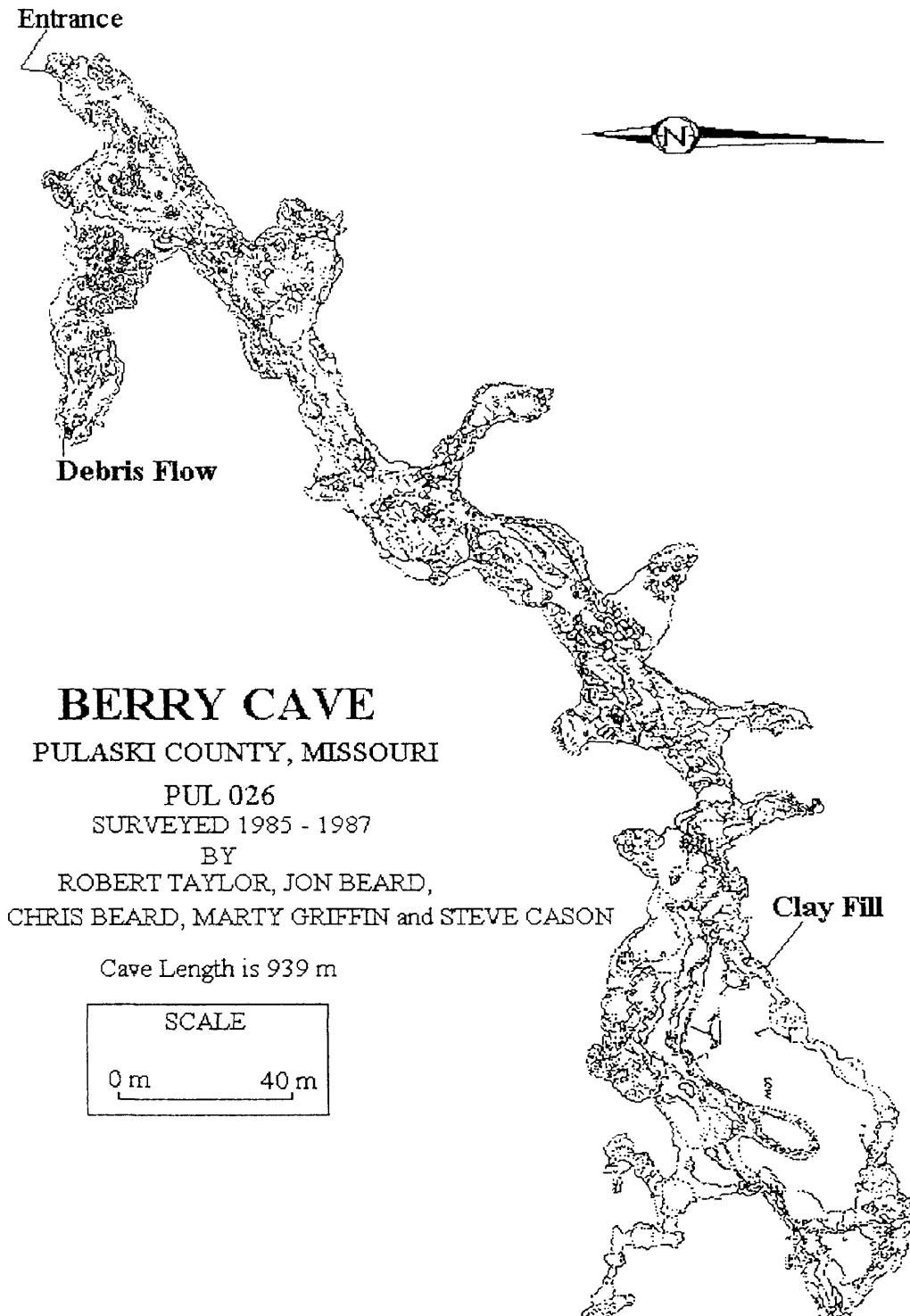


Figure 8. Map of Berry Cave (adapted from Taylor, 1987). The northeastern section of the map was not included, as no samples were taken from that area.

a few shallow pools along its channel, it is subject to rapid fluctuations in stage. Both the landowner and one of my caving colleagues witnessed a rise in water level from 0 to 1 m following a rainstorm. The flow velocity was so high that it was impossible to cross the creek without being swept downstream (Eriksen, 1992: personal communication).

Roubidoux Creek is spring fed at its headwaters, and is a perennial stream. At Flatrock Hollow (1.5 km South of Berry Cave), Roubidoux Creek becomes an intermittent stream, which continues for 23 km. This portion of the drainage basin is characterized as having numerous caves and hollows. These characteristics are typical of the creek at the study site. Then, at Burchard Hollow (21.5 km Northeast of Berry Cave) Roubidoux Creek again becomes a perennial stream. Roubidoux Creek is also fed by a spring located in Waynesville, Missouri, approximately 7 km from the study area. Roubidoux Creek drains into the Gasconade River, a perennial stream with a dendritic drainage pattern and several entrenched meanders.

The upper and lower reaches of Roubidoux Creek are effluent. Effluent streams gain water due to discharge from groundwater. Both reaches also receive an influx of water from springs. The upper reach (headwaters) is obviously being supplied with groundwater, but its source is unknown. The middle reach is intermittent, and is an influent stream; it apparently is losing its water to an aquifer. This can be explained by the geomorphology of the middle reach of Roubidoux Creek. This area appears to be more karstified. When an area has better developed karst than surrounding regions, the subsurface drainage is well developed. Therefore, with any precipitation event, the water immediately infiltrates the surface and recharges the aquifer.

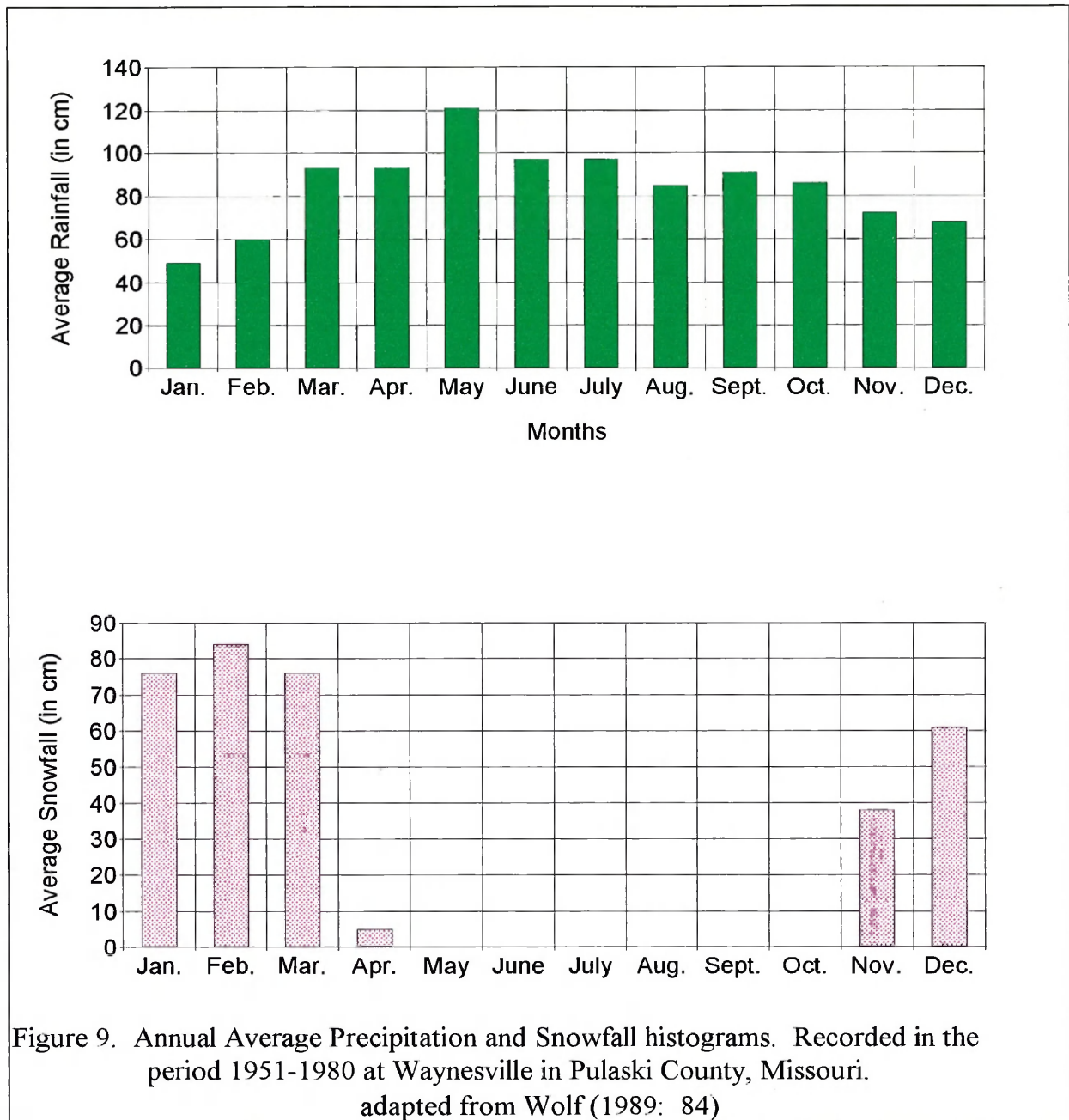
Climate

The study area is located in Thornthwaite's (1948) B₄ Humid climatic region. The average monthly temperatures for January and July at Waynesville, Missouri, during the period 1951-1980 ranged from -0.6^o C to 25.2^o C (Table II).

TABLE II. TEMPERATURE AND PRECIPITATION
(Recorded in the period 1951-1980 at Waynesville, Missouri)
adapted from Wolf (1989: 84)

| Month | Temperature | Precipitation | |
|--------------|----------------------|---------------------------------|---------------------------------|
| | Average degrees C | Average Rainfall millimeters | Average Snowfall millimeters |
| January | 0.2 | 49 | 76 |
| February | -0.6 | 60 | 84 |
| March | 7.4 | 93 | 76 |
| April | 13.9 | 93 | 5 |
| May | 18.2 | 121 | 0 |
| June | 22.4 | 97 | 0 |
| July | 25.2 | 97 | 0 |
| August | 24.3 | 85 | 0 |
| September | 19.2 | 91 | 0 |
| October | 14.4 | 86 | 0 |
| November | 7.6 | 72 | 38 |
| December | 2.7 | 68 | 61 |
| TOTAL | 154.9 | 1012 | 340 |

The mean total annual precipitation during that period was 1,012 millimeters, while the mean annual snowfall was approximately 340 millimeters. More than 75% of the annual precipitation occurs during the months of March through October (Figure 9). This period of high precipitation is largely a result of frontal activity. Maritime polar (mP) and continental polar (cP) air masses that flow into south-central Missouri during late spring and early summer often converge with warm, moist, maritime tropical (mT) air flowing north from the Gulf of Mexico.



The overrunning of mP and cP air by warmer mT air often produces intense rainfalls of short duration along the zone of convergence. Convictional thunderstorms during the late summer months may also produce heavy rainfalls. The winter weather patterns in south-central Missouri generally are not conducive for high precipitation. The region is dominated by dry westerly and northerly air flow from December to the end of

February. Cyclonic frontal cells associated with invading Pacific air masses periodically bring heavy snowfall to the region, but monthly averages rarely exceed 7 cm.

Vegetation

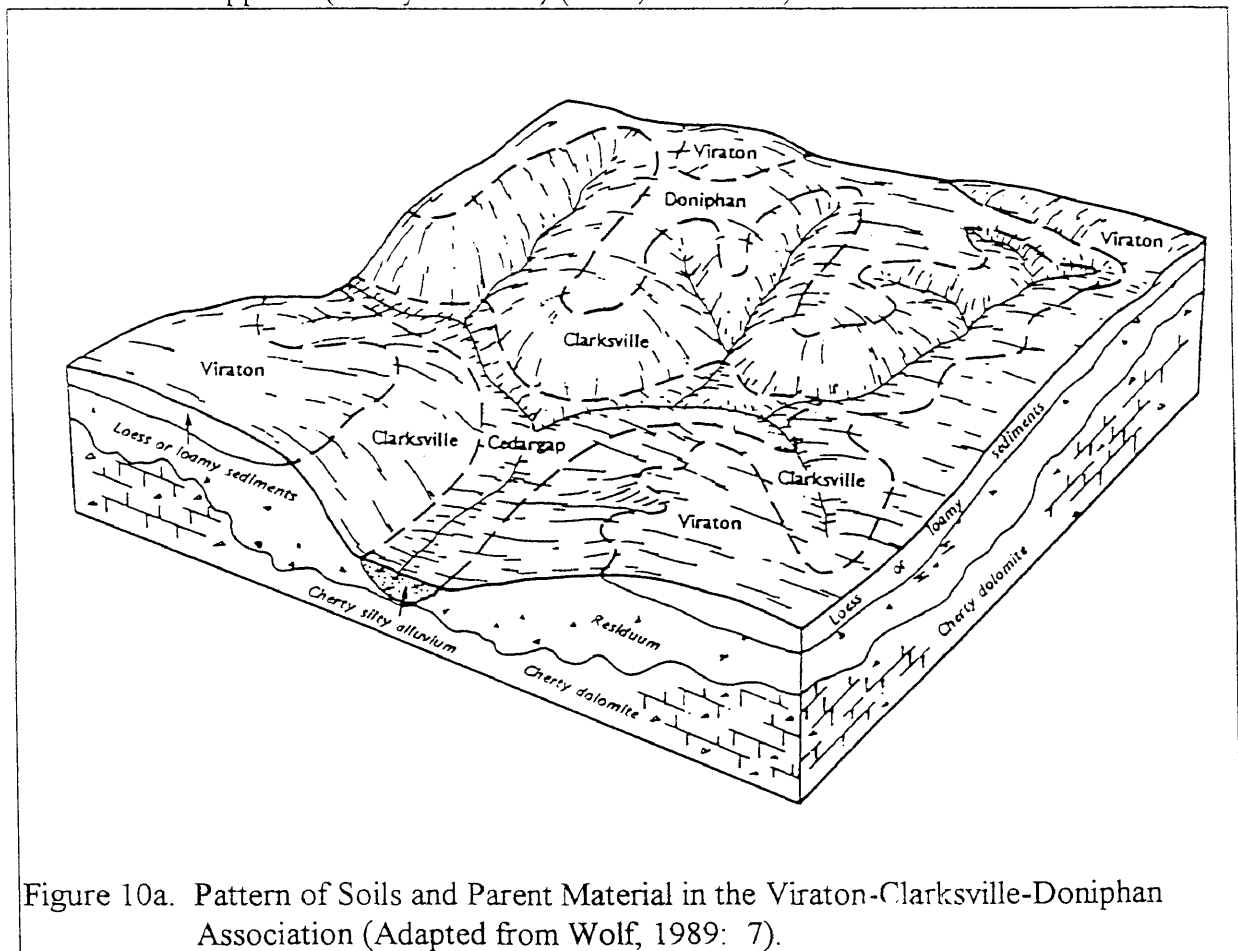
Küchler (1964: 84, 100) described the natural vegetation of south-central Missouri as being in the oak-hickory forest ecotone. Typically the oak-hickory forests occur on steep hillslopes and in ravines. The dominant tree types in this forest are shagbark hickory (*Carya ovata*), bitternut hickory (*Carya Cordiformis*), white oak (*Quercus alba*), red oak (*Quercus rubra*), and black oak (*Quercus velutina*).

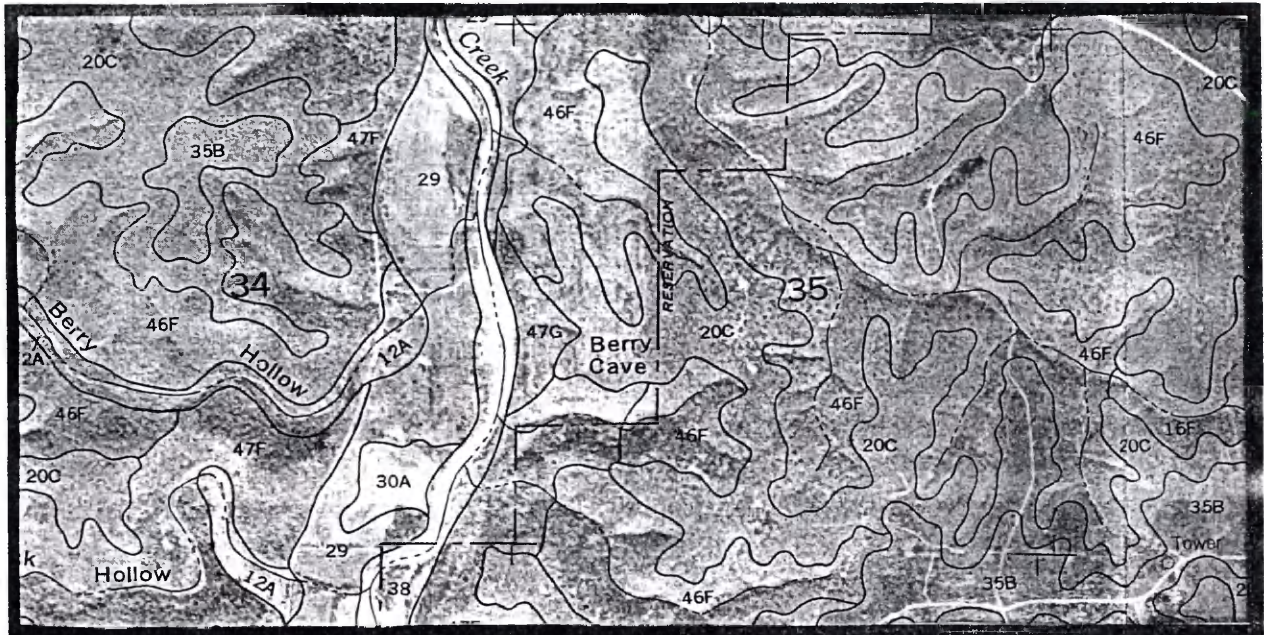
At the study site vegetation varies with landscape position. The Roubidoux floodplain to the west of the cave is typically used for pasture. The vegetation is primarily grasses, including such species as tall fescue (*Festuca arundinacea*), orchard grass (*Dactylis glomerata*), Caucasian bluestem (*Andropogan bladhii*), and indian grass (*Sorghastrum nutans*). Also included are legumes such as alfalfa (*Medicago sativa*), ladino clover (*Trifolium repens*) and red clover (*Trifolium pratense*) (Wolf, 1989: 20). On the hillslopes to the south, east and west of the ravine surrounding the cave entrance tree species include black oak (*Quercus velutina*), shortleaf pine (*Pinus echinata*), white oak (*Quercus alba*), and northern red oak (*Quercus rubra*). Typical grass species include fescue (*Festuca sp.*), Caucasian bluestem (*Andropogan bladhii*), indian grass (*Sorghastrum nutans*), and lespedeza (*Lespedeza sp.*) (Wolf, 1989: 33-35). On the hillslopes directly to the south and west of the cave entrance, post oak (*Quercus stellata*) is also found.

Soils

Soils around the study site include the Clarksville-Gepp association, Doniphan series, Gepp Bardley-Clarksville association and the Gepp Rock Outcrop (Wolf, 1989: Sheet 10). All four of these soils formed on uplands in cherty sediments and dolomite

residuum, are highly acidic, and have thick, clay-rich Bt horizons (Wolf, 1989: 59-60). The Doniphan series, which is a very gravelly silt loam, is located immediately adjacent to the cave (Figures 10a and 10b). This soil forms on ridgetops and backslopes with gentle to moderate slopes. The Gepp-Bardley-Clarksville association, which is a very cherty silt loam, is located south of the cave. This soil forms on side slopes and benches of uplands. The Clarksville-Gepp soil complex is east of Berry Cave. The Clarksville-Gepp complex is a very cherty silt loam on uneven side slopes that are moderately steep to steep (Wolf, 1989: 33). Located west of the cave is the Gepp-Rock outcrop complex. This soil association occurs on ledges and bluffs of side-slopes along rivers and streams. It is developed in colluvium from the uplands which have been intermixed with the well-drained Gepp soil (cherty silt loam) (Wolf, 1989: 35).





Explanation



Scale

1:24,000

20C: Doniphan Series

47G: Gepp-Rock outcrop

46F: Clarksville-Gepp Association

47F: Gepp Bardley-Clarksville Association

Figure 10b. Soils near Berry Cave, Pulaski County, Missouri (taken from Wolf, 1989: Sheet Number 10).

CHAPTER III

METHODS

Map Investigations

The methodology for this study involved several steps. The first step entailed examining topographic, geologic, and soil maps of the study area. Examining topographic maps was important because dolines, which provide drainage into the cave, may be located on these maps. However, the doline at Berry Cave was too small to be depicted at the scale of the topographic map. Geologic maps provided information about the stratigraphic units in which the cave formed (see Figure 4). The Pulaski County Soil Survey (Wolf, 1989) was used to identify the soils near the cave. The soils which are at or near the cave may be the source of sediments in the cave. The USDA. Soil Series Descriptions were also examined to determine the following characteristics of the surface soils near Berry Cave: parent material, slope, pH, and presence of argillic (clay) horizons.

Field Investigations

The second step was a field investigation of the cave. This initially involved a reconnaissance of the cave and establishment of sampling sites. The investigation of the cave and associated deposits was performed to locate clay fills and debris flows for sampling. A clay fill is deposits of clay that have filled an enclosed space such as a cave passage. A debris flow is a mass of rock fragments, soil, and sediments.

Next, the bedrock stratigraphy of the cave was examined. The geologic maps of Pulaski County do not show the rock units in which Berry Cave formed (see Figure 4); however, Whitefield (1989: 71-73) described the physical properties of the bedrock units in Pulaski County, and it was possible to determine the bedrock stratigraphy of the cave from field observations. Understanding the bedrock stratigraphy is important because bedrock influences the chemistry of surface water and groundwater. As these waters

move through cave deposits, minerals precipitate out and thereby enrich the cave sediments.

Sampling methodology and sampling site selection

Prior to selecting sampling sites, a sampling methodology was devised by Mandel (1993, personal communication). The entire horizontal length of each sampling site was examined, and some cave deposits were exposed in test pits to determine if the sediments were stratified or homogeneous. Stratification was used to determine the method of sampling. If the deposits were stratified (heterogeneous), then samples would be taken within each stratum. If the deposits were homogeneous (not stratified), then samples would be taken at 10 cm intervals. The number of samples taken would depend upon the thickness and internal variability of each stratum. Also, any variations in color of the cave sediments was assessed.

The first sampling site was the surface soil nearest to the cave. This soil was examined to determine if it is a possible source of the cave sediments. The soil that was sampled is located in a gully northeast of Berry Cave that trends N55E. The gully was chosen based on the availability of soils for sampling. Simply, there was a paucity of soils to sample on the slopes and ridgetops near and around the cave.

The width of the gully is approximately 3.4 m (Figure 11), and it contains soil/sediment fill that is 15.2 cm thick (Figure 12). A small pit (10 cm long and 16 cm deep) was excavated on the southern wall of the gully. This wall was cleaned and the color, structure, and texture of the soil were described in the field. Only one sample was collected because the soil was relatively homogeneous.

Next, sampling sites in the cave were selected. Since sediments are deposited ubiquitously throughout the cave, representative samples were selected. Cave sediments are not deposited in predictable localities, therefore probability sampling was not

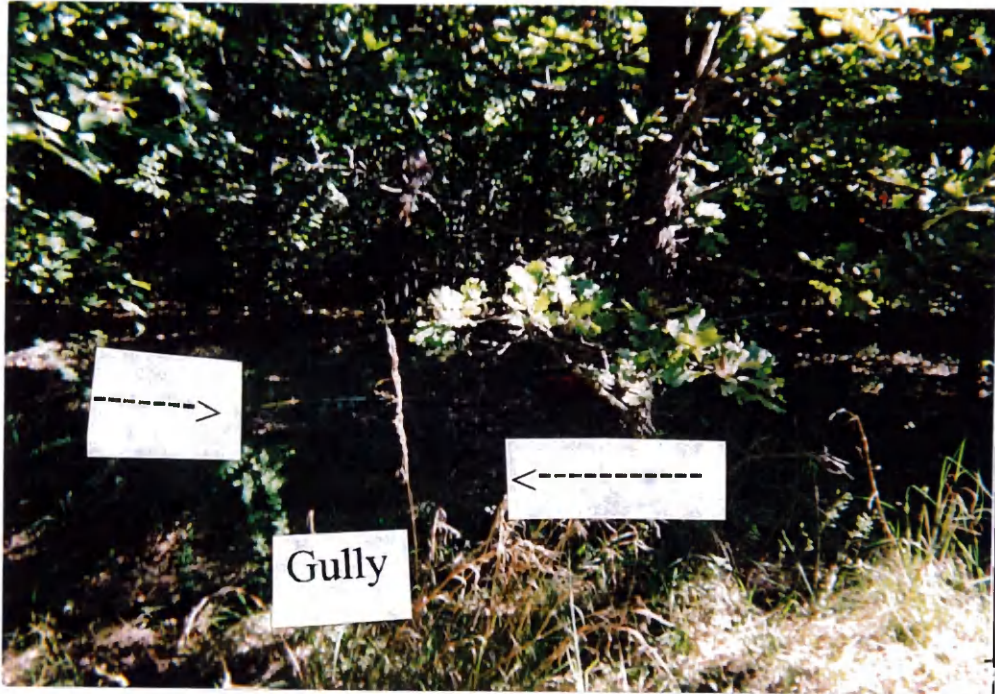


Figure 11. Photos of gully (position of red backpack is the southern wall).



Figure 12. Photos of gully fill (one photo with flash, other without)

applicable in selecting sites. Instead, they were selected using a convenience sampling procedure (Kalton, 1983: 90-94). Each location of obvious sediment deposition became a potential sampling site. One clay fill and one debris flow were selected as sampling sites (their locations are shown on Figure 8).

The debris flow is approximately 85 m from the entrance of the cave in the "Table Room" passage. It was chosen because of its accessibility and surface connection. The debris flow is approximately 3.7 m long, and 3 wide (Figure 13). The debris flow has a strike of S20W, and is dipping 26.5° N. The sediment comprising the flow was essentially a thin veneer (<5 cm thick) covering bedrock. Therefore I was unable to excavate test pits in the debris flow. Instead, three samples were collected and described at the proximal, mid-section, and distal sections of the debris flow (Figure 14).

The clay fill is approximately 583 m from the entrance of the cave, in a passage that has a strike of N340W. The clay fill was chosen because of its accessibility. The clay fill deposit is approximately 1.2 m thick (Figure 15) and is laterally extensive. Stream incision within the cave has produced a low terrace in the clay fill. Cutbanks in the clay fill allowed me to examine the clay fill beneath the terrace. The face of the north cutbank of the clay fill was cleaned and described for its structure, texture, and color, and three individual units were identified based on these characteristics. Samples were taken within each of the three stratigraphic units. A total of eight samples were taken from the clay fill, with two samples from Unit I, three samples from Unit II, and three samples from Unit III. The subunits (e.g. Ia, IIb) represent each sample taken and are **not** indicative of variability within each unit, nor do they represent 8 individual stratigraphic units.

Laboratory Methods

The specific properties that were analyzed in this study are as follows: grain-size distribution, calcium carbonate content, color, organic matter content, free extractable

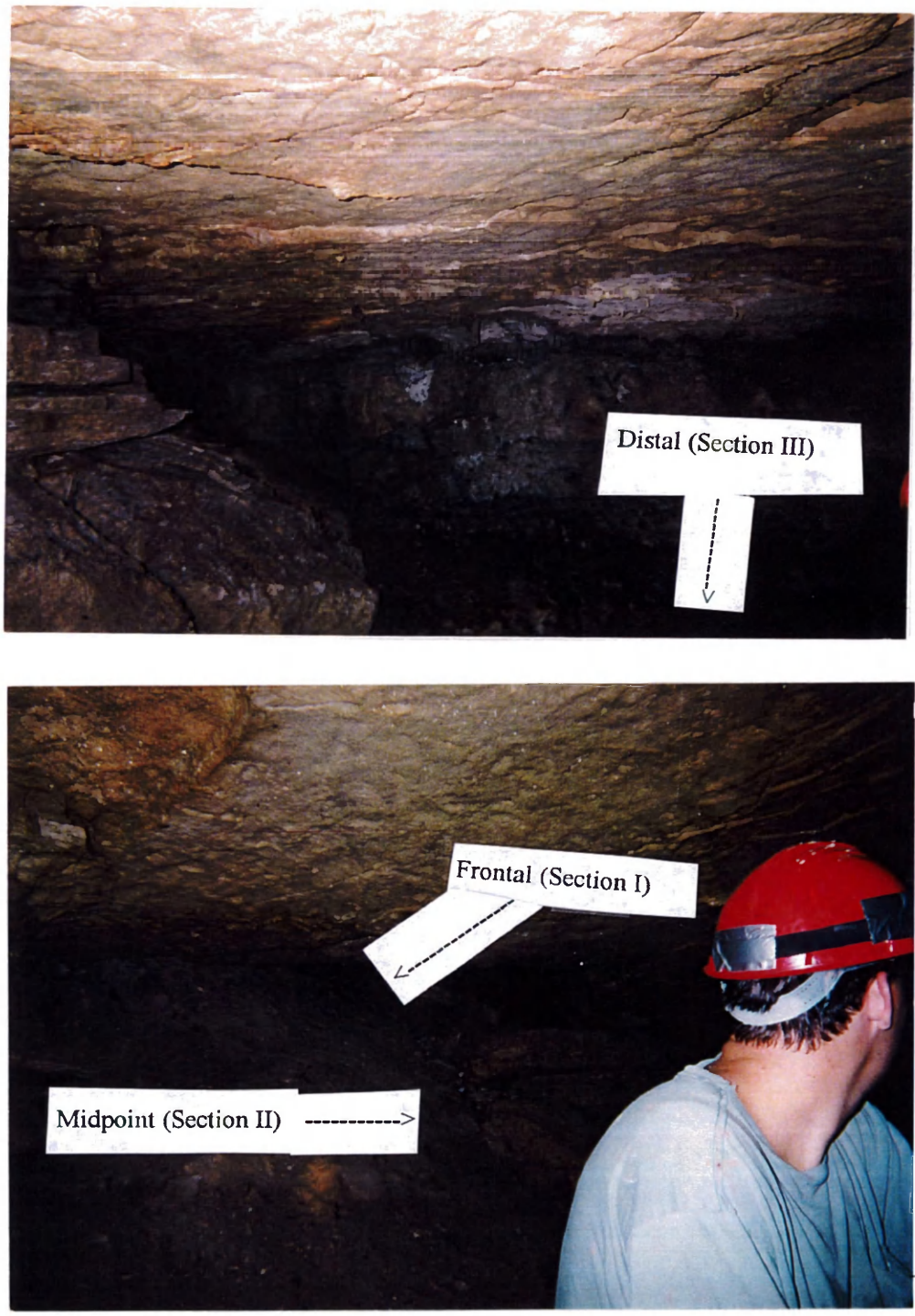


Figure 13. Photos of the debris flow in Berry Cave.



Figure 14. Longitudinal photo of debris flow (view is up dip angle).

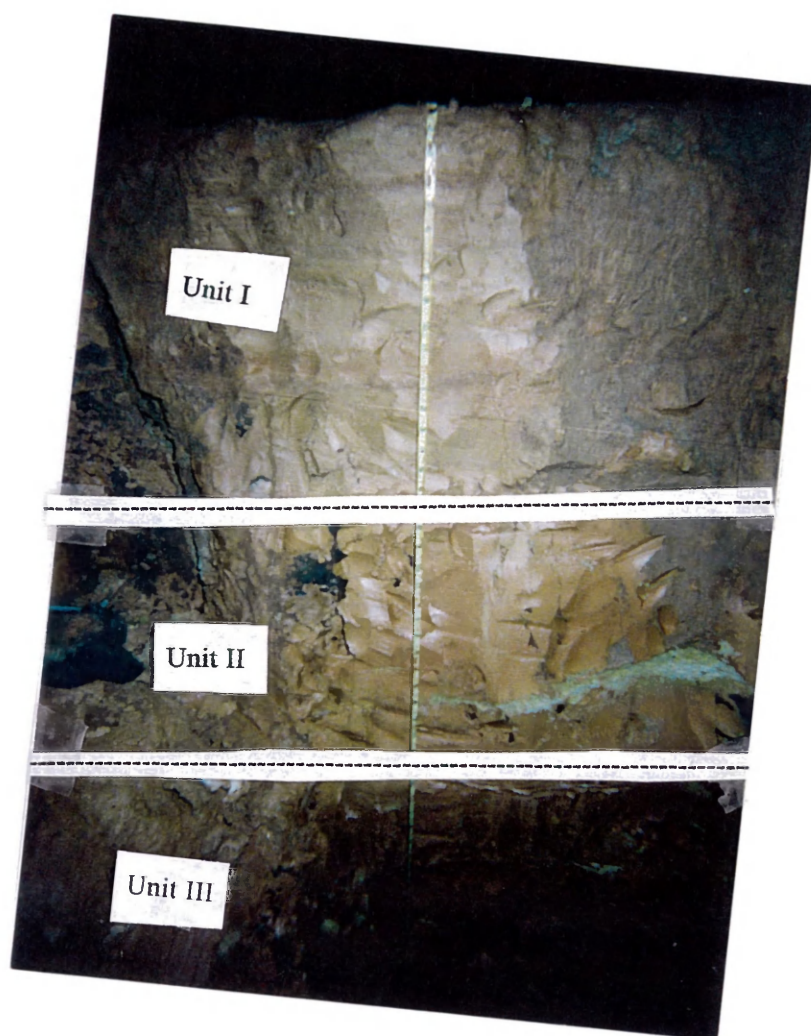


Figure 15. Photo of the clay fill in Berry Cave.

iron and aluminum, and pH. All of the analyses were performed by the USDA. Natural Resources Conservation Service Soil Survey Lab in Lincoln, Nebraska.

Grain Size Analysis

The grain size distribution was calculated for the clay, silt, and sand fractions. The clay and silt fractions were determined by the pipette method, following the Kilmer and Alexander (1949) pipette method (Soil Survey Staff, 1984: 15). The sand fractions were determined by dry sieving (Soil Survey Staff, 1984: 15-17). A 10 g sample of sediment of the <2 mm fraction is pretreated to remove organic matter and soluble salts. Then the sample is oven-dried and dispersed with a sodium hexametaphosphate solution (NaHMP) before being mechanically shaken. The sand fraction is removed by wet sieving and then fractionated by dry sieving (Soil Survey Staff, 1984). The sand fraction is passed through sieves with various size openings. The phi sizes of the sieves are 0.00 (very coarse sand), 1.00 (coarse sand), 2.00 (medium sand), 3.25 (fine sand), and 4.50 (very fine sand). , Histograms (located in Chapter IV. Results) were produced depicting changes in particle size distributions with depth. Also, the ratio of fine clay to coarse clay was calculated to detect clay illuviation.

Buoyocos Texture Analysis

The sand, silt, clay percentages were determined by performing the Bouyoucos texture analysis. This analysis is an extension of the grain size analysis described above. The sand percentage is calculated after dry sieving through a nest of sieves(SCS, 1984: 17). Each separate sand fraction (SW_i) is weighed (SCS, 1984: 17). The SCS (1984: 18) calculates the sand percentage using the following formula:

$$\text{Sand (\%)} = \sum (SW_i / TW) \times 100$$

where: SW_i = Sand Fraction

TW = Total Weight of entire sample.

The silt and clay fractions are determined gravimetrically by removing pipettes of the sample from the suspension (SCS, 1984: 17). The suspension settles according to Stokes' Law, and measurements are taken at predetermined intervals (SCS, 1984: 15).

The clay percentage is calculated by using the following formula (SCS, 1984: 18):

$$\text{Clay (\%)} = 100 \times ((\text{RW}_2 - \text{DW}) \times (\text{CF}/\text{TW}))$$

where:

- RW₂** = residue weight (g) of < 2 μm fraction
- DW** = dispersing agent weight (g) (0.4408/CF)
- CF** = 1000 mL/DV
- DV** = dispensed pipet volume
- TW** = total weight of H₂O₂ treated, oven dry sample

The silt percentage is calculated by using the following formulas (SCS, 1984: 18):

$$\text{Fine Silt (\%)} = 100 \times [(\text{RW}_{20} - \text{DW}) \times (\text{CF}/\text{TW})] - \text{Clay \%}$$

where:

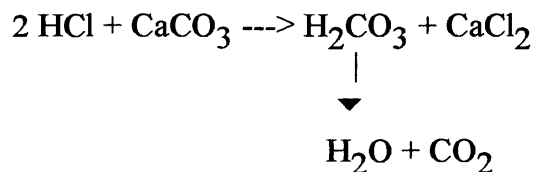
- RW₂₀** = residue weight (g) of <20 μm fraction
- DW** = dispersing agent weight (g) (0.4408/CF)
- CF** = 1000mL/DV
- DV** = dispensed pipet volume
- TW** = total weight of H₂O₂ treated, oven dry sample

$$\text{Coarse Silt (\%)} = 100 - (\text{Clay} + \text{Fine Silt} + \text{Sand \%})$$

Total Silt % = Fine silt % + Coarse silt %. Texture names were given to each sample to be used as a basis for comparison.

Calcium Carbonate Equivalent

Calcium carbonate equivalent was determined using a hydrochloric acid treatment with a modified manometer (Soil Survey Staff, 1984: 187). The sample is placed in a bottle with a gelatin capsule filled with 10 mL of 3 N HCl. The cap of the bottle is quickly replaced, and any pressure in the bottle is released. Once the hydrochloric acid dissolves the capsule it begins reacting with any calcium carbonate (CaCO₃) present and produces carbon dioxide as a side reaction:



After 1 hour, the pressure caused by the buildup of carbon dioxide (CO₂) is measured on a manometer. The calcium carbonate equivalent is calculated as follows (Soil Survey Staff, 1984: 188):

$$\text{CaCO}_3 \text{ equivalent \%} = \frac{(\text{Torrs} - \text{Blank}) \times 0.0916 \times \text{AD/OD} - 0.0364}{\text{Sample}}$$

where:

Torrs = Manometer reading (torrs)

Blank = Reagent blank reading (15.0 torrs)

Sample = Sample weight (g)

AD/OD = Air-dry/oven-dry ratio.

Color

Color of surface soils and cave sediments was determined in the laboratory using a Munsell Color Chart. Only moist colors were determined. The color is comprised of three measurable characteristics: hue, value, and chroma (Buol, 1973: 24). Each page in the Munsell Soil Color book is a specific hue (spectral color). The values are grouped on the vertical axis of the page, while the chromas are on the horizontal axis. The soil sample is compared to color tiles to determine its appropriate hue, value, and chroma. For example, a soil with this Munsell notation 2.5YR 4/3 has a 2.5 yellow-red hue, value of 4, and a chroma of 3.

Organic Carbon

Organic carbon analysis was performed using a FeSO₄ Titration, Automatic Titration method (Soil Survey Staff, 1984: 157). A sample is titrated with a 1:2 volume of 1 N potassium dichromate (K₂Cr₂O₇) and sulfuric acid (H₂SO₄). The titration beaker is placed on a reciprocating shaker for 1 minute. Distilled water is then added to stop the reaction. Titrations are run through an automatic titrator, and results are printed. The organic carbon (OC) percentage is calculated (Soil Survey Staff, 1992: 157-159):

$$\text{OC(\%)} = \frac{(\text{Blank} \times \text{Volume}) - (10 \times \text{Titer}) \times 3 \times 100 \times \text{AD/OD}}{\text{Blank} \times \text{Sample} \times 0.77 \times 1000}$$

where

OC(%) = Organic C (%)

Blank = Average titer of reagent blanks (mL)

Volume = Volume of 1N $K_2Cr_2O_4$ (mL)

Titer = Titer of $FeSO_4$ (mL)

Sample = Weight of sample (g)

AD/OD = Air-dry/oven-dry ratio

3 = Equivalents per C (assumed)

1000 = Meq eq⁻¹

100 = Convert to 100-g basis

0.77 = Assumed C oxidation factor.

Free extractable iron and aluminum

Free (extractable) iron and aluminum were determined using the DTPA method (Soil Survey Staff, 1984: 171). A sample is mixed with sodium dithionite ($Na_2S_2O_4$), sodium citrate ($Na_3C_6H_5O_7 \cdot 2H_2O$), and distilled deionized (DDI) water and shaken overnight. A reagent is added, and the solution settles to allow for a clear extract to be taken from the sample. The extract is diluted with DDI water and aspirated into an atomic absorption spectrophotometer. The wavelengths of iron and aluminum are detected from this instrument are recorded on a microcomputer. A line graph and bar graphs were produced showing both aluminum and iron percentages with depth for each sample.

pH

The pH of each sample was determined using two soil pH measurements. The pH is measured in sample-water (1:1) and sample-salt (1:2 $CaCl_2$) solutions. A 20 g sample is mixed with 20 mL of distilled water with stirring. The sample stands 1 hour with occasional stirring, then is stirred for 30 seconds and the pH is measured. Then 20 mL $CaCl_2$ is stirred into the sample suspension, and the salt pH is measured.

CHAPTER IV

RESULTS AND DISCUSSION

Introduction

This chapter is divided into several sections. The data which are the basis for the discussion in this chapter are summarized in Table III. First, relationships between the physical and chemical characteristics of the clay fill sediments and post depositional processes are considered. These post depositional processes are evaluated to establish if they are currently active. Then, the parent material of the surface soil is identified since the soil may be the source of the cave sediments. Next, the source of the debris flow is determined and post depositional processes are ascertained. Then, the source of the clay fill is determined, so that it can be classified as either allogenic or autogenic. Finally, a hypothetical model of landscape evolution is proposed to explain the sequence of soil development, erosion, and transportation of those soils and their subsequent deposition and alteration(s) within Berry Cave.

Clay Fill Unit Stratigraphy

The 1.23 m (approximately 4 feet) thick clay fill is comprised of three stratigraphic units, which are described in Table IV. It is important to note that these units are vastly different than both a surface soil sample collected in the study area and debris flow sediments found in the cave. Also of interest is the microstratigraphy within each unit (specifically Unit I - see Figure 15). As indicated in the discussion of the surface soil sample, there was no argillic horizon. However, the soils designated in the study site by the Soil Conservation Survey have extensive argillic (clay-rich) horizons (see Appendix A). The contact between Unit III and the cave floor is sharp and horizontally extensive. Each unit, which was differentiated based upon color, has a blocky structure, slickensides, and variable amounts of roof fall fragments.

Table III. Selected physical and chemical properties of soil, debris flow, and clay fill samples from above and within Berry Cave.

| Depth (m) | Horizon, Section, Sample | Sand wt. % | Silt wt. % | Fine Clay | | Coarse Clay wt. % | Texture Name | CaCO ₃ % | Organic Carbon | | | pH |
|--------------------------|--------------------------|------------|------------|-----------|-------|-------------------|--------------|---------------------|----------------|------|------|-----|
| | | | | wt. % | wt. % | | | | % | Fe % | Al % | |
| Surface Soil 0 - 0.15 | A | 26.2 | 65.2 | 8 | | | Silt Loam | 0 | 1.53 | 0.6 | 0.1 | 5.9 |
| Debris Flow | | | | | | | | | | | | |
| 0 - 1.20 | I | 49.1 | 37.7 | 13.2 | | | Loam | 0 | 1.17 | 0.5 | 0.1 | 7.4 |
| 1.2-2.4 | II | 49.6 | 33.8 | 16.6 | | | Loam | 1 | 1.18 | 0.7 | 0.1 | 8 |
| 2.4-3.7 | III | 46.8 | 29.9 | 23.3 | | | Loam | 4 | 1.15 | 0.8 | 0.1 | 8.1 |
| Clay Fill | | | | | | | | | | | | |
| 0 - 0.30 | Ia | 1.2 | 47 | 17 | 34.8 | | Clay | trace | trace | 2 | 0.1 | 8.1 |
| 0.30-0.46 | Ib | 0.9 | 50 | 16.1 | 33 | | Clay | 1 | 0.01 | 1.9 | 0.1 | 8.1 |
| 0.46-0.58 | IIa | 0.3 | 25.2 | 31.5 | 43 | | Clay | trace | trace | 2.7 | 0.2 | 8 |
| 0.58-0.71 | IIb | 0.2 | 20.5 | 38.2 | 41.1 | | Clay | 0 | trace | 3 | 0.2 | 8.1 |
| 0.71-0.84 | IIc | 0.4 | 14.5 | 43.5 | 41.6 | | Clay | 0 | 0.05 | 3 | 0.2 | 8.2 |
| 0.84-1.02 | IIIa | 1.7 | 6.2 | 74.2 | 17.9 | | Clay | trace | 0.09 | 3.1 | 0.2 | 7.7 |
| 1.02-1.12 | IIIb | 2 | 10.5 | 55.7 | 32.2 | | Clay | 0 | 0.04 | 3.4 | 0.4 | 7.8 |
| 1.12-1.23 | IIIc | 4.4 | 9.4 | 51.2 | 35.3 | | Clay | 0 | 0.05 | 2.8 | 0.2 | 7.8 |

Table IV. Description of clay fill stratigraphic units

| Unit | Sample | Depth (m) | Description |
|------|--------|-------------|--|
| I | Ia | 0.00 - 0.30 | dense light brown clay (5 YR5/8), stratified with coarse beds that are ~1-2 cm thick, medium angular blocky structure, common nearly continuous ferromanganese coats on faces of structural units, common slickensides |
| | Ib | 0.30 - 0.46 | |
| II | IIa | 0.46 - 0.58 | massive orange clay (5 YR6/9), no evidence of bedding, few roof fall fragments, coarse angular blocky structure, common nearly continuous ferromanganese coats, many distinct slickensides |
| | IIb | 0.58 - 0.71 | |
| | IIc | 0.71 - 0.84 | |
| III | IIIa | 0.84 - 1.02 | massive dark red clay (2.5 YR5/8), common roof fall fragments, coarse angular blocky structure, common nearly continuous ferromanganese coats on faces of structural units, common slickensides |
| | IIIb | 1.02 - 1.12 | |
| | IIIc | 1.12 - 1.23 | |

Post Depositional Alterations of the Clay Fill

The ubiquitous blocky structure, associated slickensides, and ferromanganese coats throughout each stratigraphic unit of the clay fill may be a result of post-depositional processes. Blocky structure forms as a result of two processes: (1) swelling and shrinking during wetting/drying events, and (2) cementation (Donahue *et al.* 1977: 58). As a soil swells during wetting events, it increases its surface area. With subsequent drying, the soil shrinks. Vertical and horizontal lines of weakness develop in soils and sediments as they are affected by shrinking stress (Donahue *et al.* 1977: 58). Iron oxides, clays, and organic materials can act as cementing agents along the lines of weakness (Donahue *et al.* 1977: 58). This is possible evidence for illuviation of clays and iron translocation, both of which are post-depositional processes. Clay and iron illuviation involve the accumulation in a lower unit of soils or sediments of iron and clay that has been transported downward from an upper unit (Buol, 1973: 89-90).

Additionally, the formation of the blocky structure and formation of the slickensides in the clay fill may be an explanation for the downward translocation of clays and iron (illuviation). Slickensides are classified as being a secondary structure related to the development of blocky structure (Terzaghi, *et al.* 1996: 32). The Soil Survey of Pulaski County Missouri (1989: 80) defines a slickenside as a polished, grooved surface created when one mass moves past another. They may result from volume changes generated by chemical processes or from deformations produced by the force of gravity, which includes slippage along the walls of existing or newly formed lines of weakness (Terzaghi, *et al.* 1996: 32). Lines of weakness in the clay fill formed as a result of stress and unloading following wetting/drying events. The swelling and subsequent stress from shrinking of the mineral structure can cause masses to move past each other, thereby forming slickensides.

The units in the clay fill are distinctly red in color. Within each unit there is internal variability in the red color (see Figure 15). The color is important, as it can be influenced by parent materials and/or post-depositional processes. According to Buol (1980: 71, 90), the percentage of free iron increases as weathering and soil age increases, and it is either in the form of clay particle coatings or as discrete particles. Also, free iron decreases as drainage decreases (Buol, 1980: 90). As free iron increases or decreases, it can affect soil colors. The color of the clay fill sediments appears to be altered by braunification, rubifaction, and ferrugination. These terms describe the gradual reddening of soil or sediment color from brown to reddish brown to red. The processes occur in response to the progressive oxidation of iron (Buol, 1973: 96; Buol, 1980: 93; Birkeland, 1985: 296).

In Figure 16 and Table III, there is a significant increase in extractable iron with depth, which suggests that iron oxide has been illuviated through the clay fill. The iron “hitches” a ride with clay particles and, if mobile, is translocated downward in the soil profile. Thus, if there is an increase in iron with depth, that is often indicative of illuviation or translocation of iron and clay particles (Buol, 1973: 69). Also, it appears likely that manganese and free iron is translocated downward through cracks in the clay to form the ferromanganese coatings (see Figure 15, Units I and II on the left side).

Grain size distributions (at whole phi intervals) for samples collected from the clay fill units are presented in Tables Va and Vb. The histograms of grain size sieve analysis for the clay fill are shown in Figure 17. Table VI displays the conversion from screen size composed of particle sizes > 5.0 Phi (see Tables Va and b), the histograms were produced to phi number and size class names. Since the units in the clay fill are almost entirely

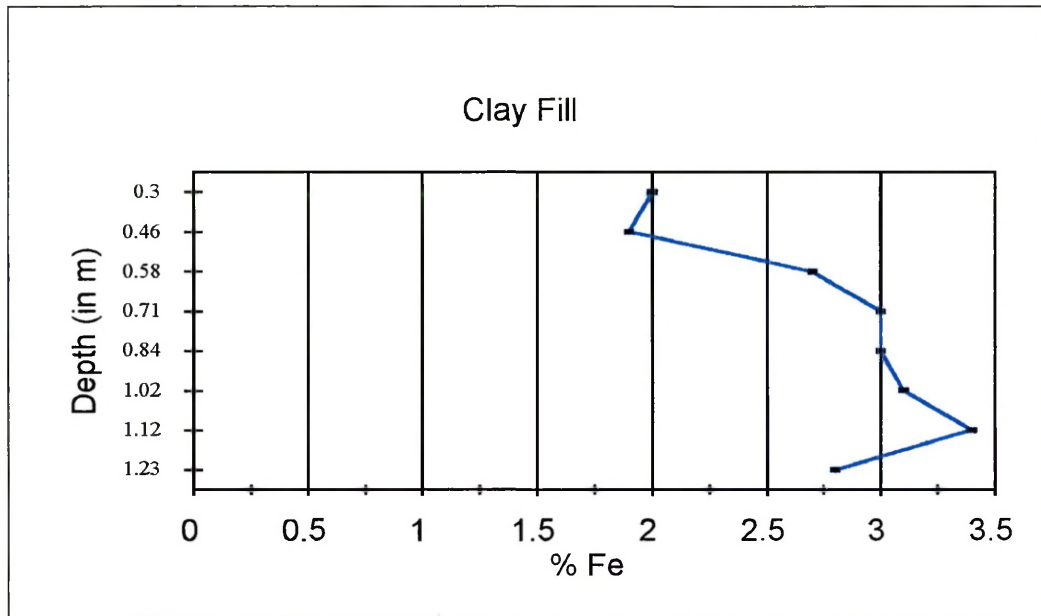


Figure 16. Results from Extractable Iron Analysis of clay fill samples taken from within Berry Cave. Presented as a line graph to facilitate discussion of variation with depth.

Table Va. Results from sieve analysis completed on clay fill units from within Berry Cave, Pulaski County, Missouri. Note: phi sizes only pertain to sand sized particles. For the clay and silt fractions ($< 20 \mu\text{m}$), the particle size was used.

Abundance by phi size

| Clay Fill | | | | | | | | | |
|------------------|-----------|--------------|-----------|----------|----------|----------|-------------|------------|--------------|
| Unit | -4 | -2.25 | -1 | 0 | 1 | 2 | 3.25 | 4.5 | >5 |
| Unit Ia | 0 | 0 | 0 | 0 | 0.1 | 0.4 | 0.4 | 0.3 | 98.8 |
| Unit Ib | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.4 | 0.3 | 99.1 |
| Unit IIa | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.1 | 0.1 | 99.7 |
| Unit IIb | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.1 | 99.8 |
| Unit IIc | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.1 | 0.2 | 99.6 |
| Unit IIIa | 0 | 0 | 0 | 0 | 0.2 | 0.7 | 0.6 | 0.2 | 98.3 |
| Unit IIIb | 0 | 0 | 0 | 0.2 | 0.2 | 1 | 0 | 0.4 | 98.4 |
| Unit IIIc | 0 | 0 | 0 | 0 | 0.3 | 2 | 1.3 | 0.8 | 95.9 |

Table Vb. Results of silt and clay size particle analysis for clay fill samples collected from within Berry Cave, Pulaski County, Missouri.

Distribution of > 5.0 Phi size by particle size

| Clay Fill Unit | Coarse Silt | Fine Silt | Coarse Clay | Fine Clay |
|----------------|-------------|------------|-------------|-----------|
| | .02 - .05 | .002 - .02 | < .002 | < .0002 |
| Unit Ia | 4.5 | 42.5 | 34.8 | 17 |
| Unit Ib | 5 | 45 | 33 | 16.1 |
| Unit IIa | 1.1 | 24.1 | 43 | 31.5 |
| Unit IIb | 1 | 19.5 | 41.1 | 38.2 |
| Unit IIc | 1.3 | 13.2 | 41.6 | 43.5 |
| Unit IIIa | 0.6 | 5.6 | 17.9 | 74.2 |
| Unit IIIb | 0 | 10.5 | 32.2 | 55.7 |
| Unit IIIc | 0 | 9.4 | 35.3 | 51.2 |

Table VI. Conversion of Phi sizes to Sieve Mesh Opening and Particle Size Classification

| Phi Size | Sieve Mesh Opening (mm) | Range of particle size (mm) | Particle Size Classification |
|----------|-------------------------|-----------------------------|------------------------------|
| -4 | > 20 | 20 - 75 | |
| -2.25 | 5 | 5 - 20 | |
| -1 | 2 | 2 - 5 | gravel and larger |
| 0 | 1 | 1 - 2 | very coarse sand |
| 1 | 0.5 | 0.5 - 1 | coarse sand |
| 2 | 0.25 | 0.25 - 0.50 | medium sand |
| 3.25 | 0.1 | 0.10 - 0.25 | fine sand |
| 4.5 | 0.05 | 0.05 - 0.10 | very fine sand |
| > 5 | 0.02 | 0.02 - 0.05 | coarse silt |
| > 5 | 0.002 | 0.002 - 0.05 | fine silt |
| > 5 | | < 0.002 | coarse clay |
| > 5 | | <0.0002 | fine clay |

composed of particle sizes > 5.0 Phi (see Tables Va and b), the histograms were produced using particle sizes rather than phi sizes. The grain size analysis is important as several persistent grain sizes can provide information about post-depositional alterations of the sediments (Farrand, 1985: 33). For example, if the proportion of clay increases with depth, this may indicate clay illuviation. Buol (1973) suggests that clay illuviation may occur if the fine clay ratio is greater than the coarse clay ratio in the original sediment deposit. Table Vb and Figure 17 indicate that the percentage of fine clay generally increases with depth, with Unit III of the clay fill containing the highest percentage of fine

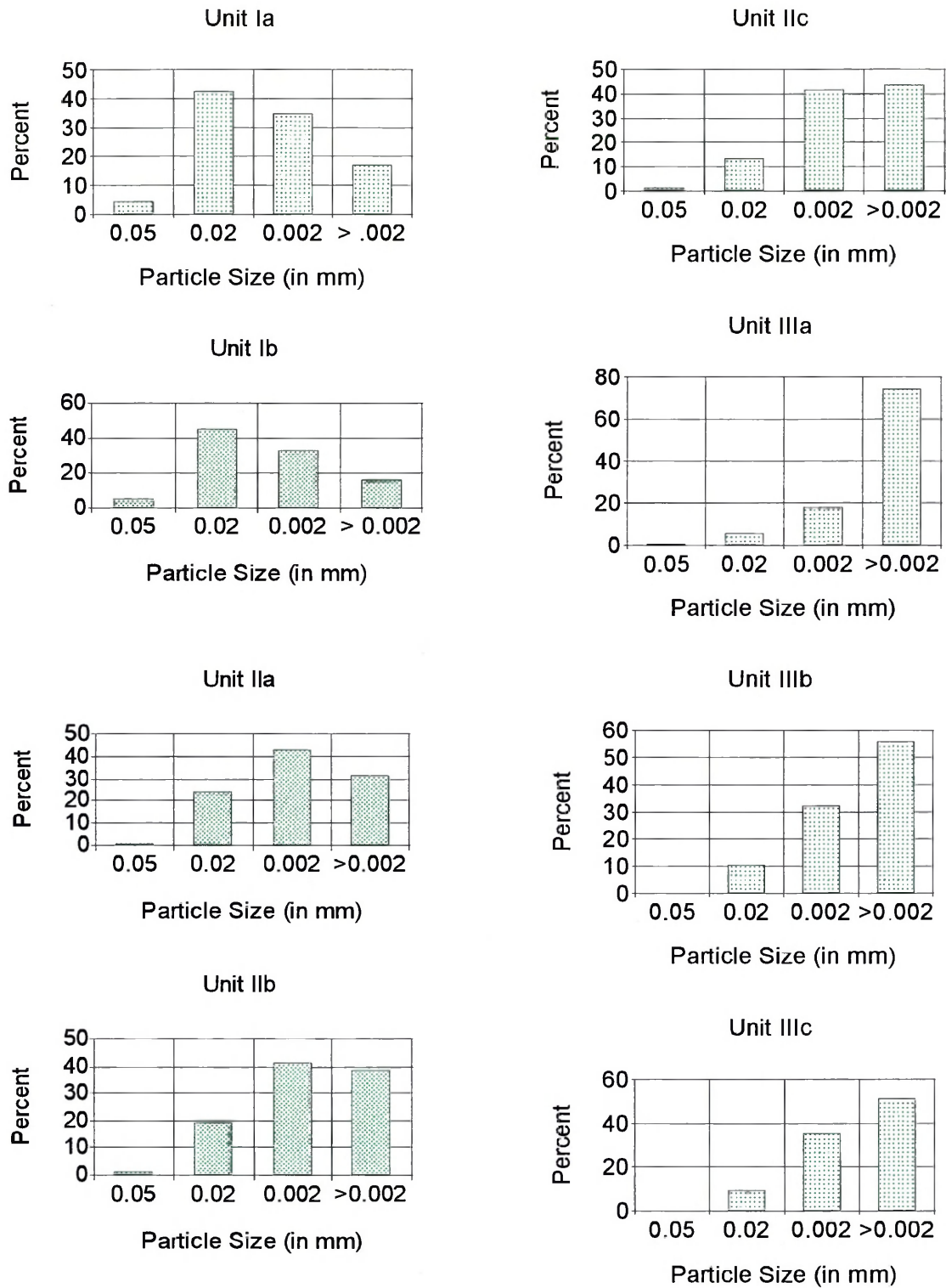


Figure 17. Histograms showing the weight percent of silt and clay particle size classes for samples collected from the clay fill (ϕ size in mm).

clay. Based upon the distribution of particle sizes in the clay fill, it appears that the sediments have probably been affected by clay illuviation.

The evidence for illuviation can be further explained. The distribution of grain sizes in Units Ia through IIIc is dissimilar, with Unit I dominated by fine silt followed by coarse clay. Unit IIa and b are predominantly coarse clay followed by fine clay, and Unit IIc is dominated by fine clay followed by coarse clay. Unit III is predominantly fine clay followed by coarse clay. It is possible that Unit I is dominated by silt and coarse clay because the fine clay has been removed by illuviation. The predominant grain sizes in Units IIa and IIb also is indicative that fine clay may have illuviated downward. The lower units of the clay fill (Units IIc and IIIa,b,c) are dominated by fine clay. This fine clay probably originated from the upper units (Units I, IIa and IIb) and was translocated into the lower units.

Perhaps even more compelling evidence for illuviation of iron and clay is the geochemistry of the clay fill sediments. Figure 15 illustrates the ubiquitous distribution of ferromanganese coats throughout all three units of the clay fill. In Unit II, there also exists a layer of reduced iron or manganese precipitate. Faure (1991: 326) points out that acidic conditions must exist for iron oxides to be soluble, and as pH values increase (become more basic) and materials are aerated, then iron oxides will precipitate. Thus, in the clay fill sediments, ferromanganese was in solution under acidic conditions, then precipitated as ferromanganese coats under basic pH conditions.

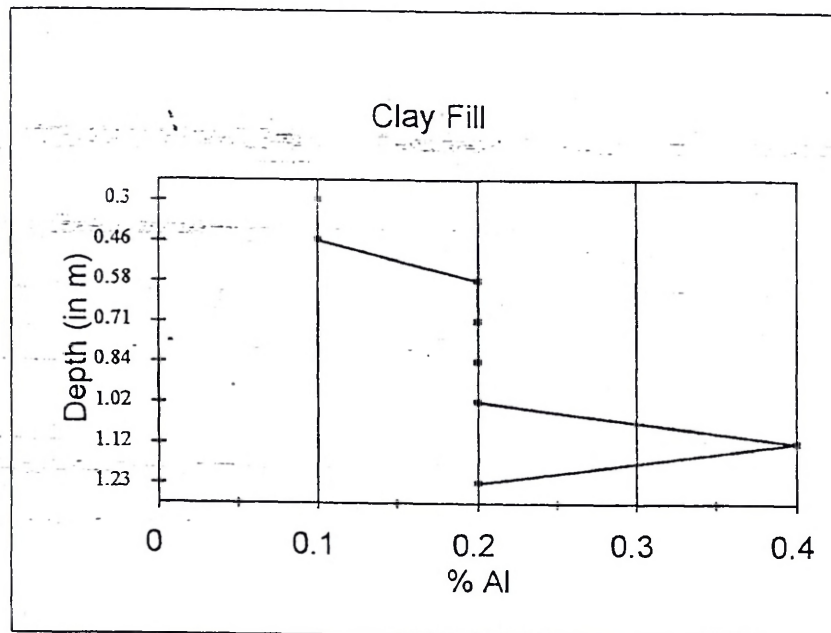
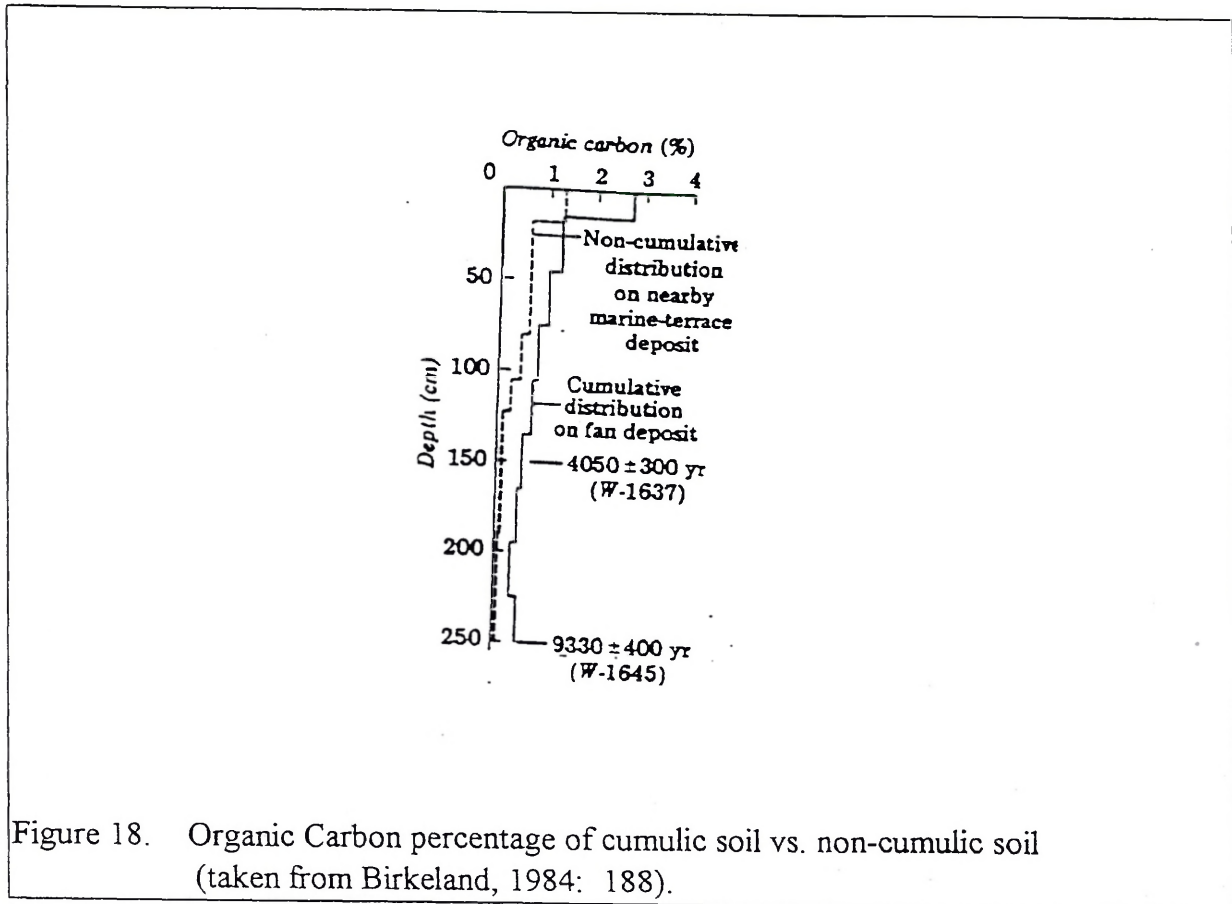
Although the process of illuviation typically involves the obliteration of all primary sedimentary features (Mandel, 1997), the clay fill still exhibits sharp boundaries between each unit. An important observation of numerous researchers studying weathering processes in caves is that the magnitude of these processes is diminished in cave environments. Thus, post-depositional processes, such as illuviation, may not necessarily

completely obliterate primary sedimentary features. As is seen in Unit I of the clay fill (see Figure 15), there are several micro-units. Since they are not as distinct as the three main depositional units, perhaps they have only been slightly affected by weathering processes.

According to Stoke's Law, coarse particles in a slackwater deposit settle first, followed by fine particles (i.e., a fining upward sequence). Yet, the clay fill has a general fining downward sequence. This is evidence of possible illuviation. The greater proportion of fine silt in Unit I is also a reflection of this, in that as fine clay is removed, the percentages of fine silt, as well as coarse clay, will increase. Hence, fine silt decreases with depth because fine clay percentages increase.

There are several pieces of evidence that demonstrate that clay illuviation and iron translocation occurred after the clay was deposited in the cave. If a comparison is made between the clay fill and a cumulative soil profile, an interesting piece of evidence is found. A cumulative soil profile is one that receives pulses of sediments (i.e., they accumulate) (Birkeland, 1984: 184). This results in chemical characteristics showing up on a graph in an irregular distribution (Figure 18), which is distinctive of cumulative soil profiles. If we consider that the clay fill sediments were deposited in pulses (as indicated by the three variations in color within the clay fill), then there should be the same irregular distribution of its chemical characteristics if no changes had occurred after deposition.

This is not the case as evinced by the extractable iron data (see Table III and Figure 16), and extractable aluminum data (Figure 19). Both of these chemical properties of the clay fill generally increase with depth, with the exception of the lowermost sample. It appears that iron and aluminum must have been altered after deposition within Berry Cave. Based upon the increase in the percentage of fine clay with depth, increases in iron, aluminum, and red color with depth, the presence of slickensides, and the presence of



blocky structure, it is suggested that the clay fill sediments were deposited and subsequently altered *in situ*.

There is a need to provide further explanation of the red color and the clay found in the clay fill units. Birkeland (1985: 305) suggests that some soil (sediment) properties are more persistent than others when affected by a change in environmental conditions. If these properties are resistant to subsequent pedogenesis and/or diagenesis, then they can be useful for paleoclimatic reconstruction. Table VII shows soil horizons or features ranked as persistent, which can endure environmental change. The argillic horizon (another name for a clay-rich horizon) can endure environmental change and maintain

Table VII. Relative Persistence of Soil Horizons and Features as Possible Indicators of Former Conditions (modified from Birkeland, 1984: 305).

| Easily Altered | Relatively Persistent | Persistent |
|-----------------------|------------------------------|-------------------|
| Mollic epipedon | Umbric epipedon | Oxic horizon |
| Salic horizon | Argillic horizon | Argillic horizon |
| Gypsic horizon | Spodic horizon | K horizon |
| Mottles | Calcic horizon | Duripan |

many of its original features (e.g. red color from iron oxide, and angular blocky structure).

Iron trends in buried soils and sediments can persist for long periods and endure environmental change, but the pH is soon altered by enrichment or leaching after burial (Birkeland, 1985: 33). Enrichment is a post-depositional process defined as the addition of material to a soil (sediment) body (Buol, 1973: 89-90). Leaching is also a post-depositional process which involves removal of material from a soil or sediment. The pH will increase if CaCO₃-rich water is enriching the clay fill with calcite, and it will decrease if calcium carbonate is being leached from the clay fill unit. Also, the pH will determine if iron oxides are soluble (Faure, 1991). Acidic pH conditions allows iron oxides to become more soluble, and possibly removed by acidic solutions (Faure, 1991: 326).

Presently the clay fill sediments' pH values (see Table III and Figure 20) are basic. However, at the time of deposition, it is likely that the clay fill sediments were acidic,

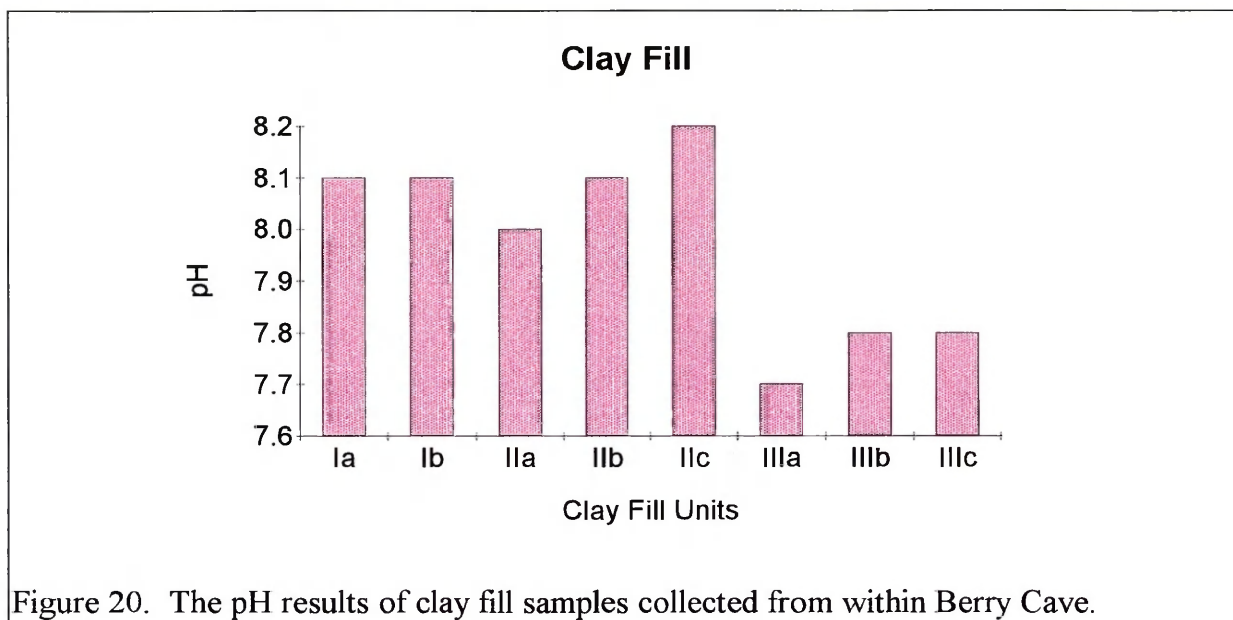
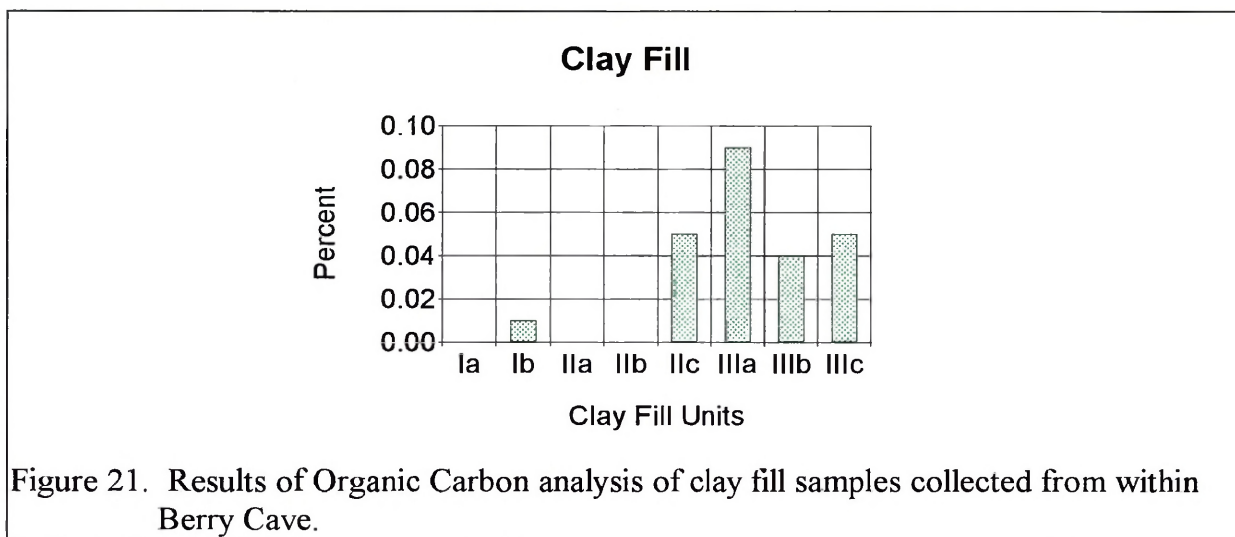


Figure 20. The pH results of clay fill samples collected from within Berry Cave.

because the present day surface soils in the study area (see discussion later in this chapter) are comprised of thick, clay-rich horizons with very acidic pH values. It is possible that acidic, clay rich paleosols were eroded off of the land surface and deposited in the cave. Once in the cave, the clay fill sediments may have been enriched by calcium from supersaturated waters, that moved through the sediments depositing Ca^{++} ions at available cation exchange sites on the clay particle surface (Donahue 1977: 113-4). This enrichment by calcium-rich water caused the acidic pH values of the clay fill sediments to become more basic. However, there are no carbonate threads or films present in the clay fill sediments.

Perhaps undersaturated water low in calcium carbonate, most likely derived from direct runoff from the land surface, leached all of the available carbonate from the clay fill sediments. However, if enrichment of the clay surface exceeds the leaching of calcium cations, the clay fill unit will remain basic. Once isolated in a dry portion of the cave, the enrichment and leaching processes cease and the clay fill unit will remain basic. Hence, the present day pH values of the clay fill are basic because the clay fill is currently in a normally dry portion of the cave.

Since there is a paucity of flowing water throughout the cave, it is difficult to transport organic materials throughout the entire cave network. This could explain why the clay fill units, which are located in the back portion of the cave, have very little organic carbon (Table III and Figure 21), and do not appear to be altered by melanization.



Melanization is a post depositional process which involves the darkening of soils or sediments by the presence of organic matter (Buol, 1980: 93). In the geologic past, it is likely that the cave had a greater amount of water flowing through it, thus more organic materials could have been transported a greater distance into the cave. An explanation for the negligible amounts of organic matter currently in the clay fill is that the oxidizing nature of the clay fill enhanced the decay of any organic material.

It was determined that the clay fill sediments sampled in Berry Cave were affected by (1) shrinking and swelling, (2) illuviation of clay and iron, (3) enrichment by calcium carbonate, (4) braunification, (5) rubifaction, and (6) ferrugination. These processes are not presently active, because there is a paucity of water currently available in this section of the cave. A possible explanation for the post depositional alterations is that the clay fill is affected by water associated with flood events. Since soil, sediment, and their

post-depositional alteration take considerable time to develop (Birkeland, 1984: 165), the flood events have probably affected the sediments over a considerable period of time. Additionally, if the flow velocity during these flood events were high enough, then scouring and erosion of a portion of the clay fill may be expected. Within the passage that contains the clay fill units, a stream cut canyon formed within the clay fill unit provides evidence that these sediments have been eroded, most likely by intermittent streams that form in Berry Cave during flood events.

Characteristics of a Surface Soil Sample

Because very little soil is present in the study area, only one soil sample was collected. Detailed comparison between the surface soil sample and cave sediments was not possible because the one soil sample may not be representative of the entire area above the cave. Although little information regarding the relationship between surface soils and cave sediments can be drawn from the collected soil sample, the physical and chemical characteristics of the soil will be discussed in order to provide as many details as possible about the physical landscape in the study area. The soil profile contains one horizon, which is described in Table VIII. Since the surface soil has a weakly developed A horizon with bedrock directly beneath it, the surface soil was interpreted to be an Entisol (Birkeland, 1984: 47). This soil is formed within a small gully on the shoulder of a side slope. The soil probably originally formed as a result of *in situ* weathering of the dolomite

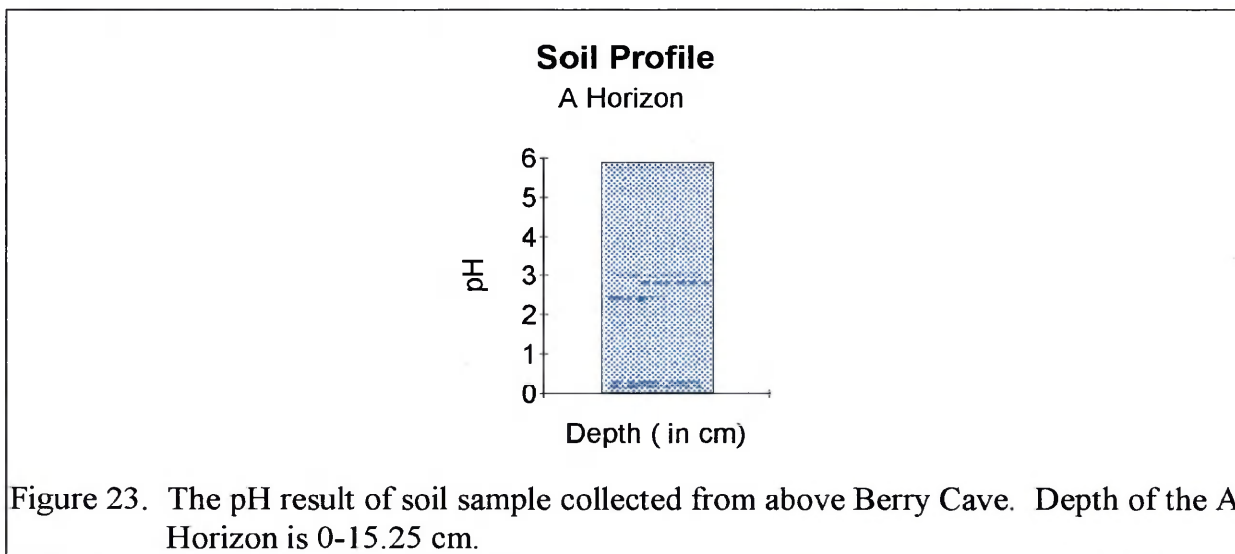
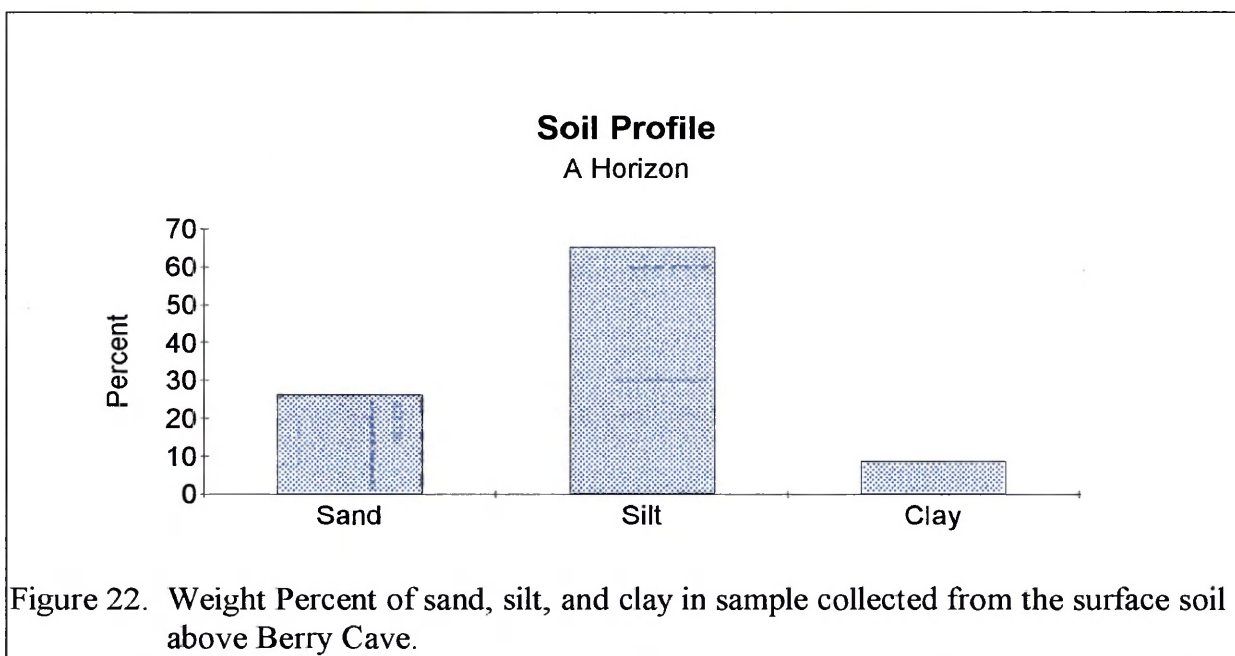
| Table VIII. Description of surface soil comprising gully fill | | |
|---|------------|--|
| Horizon | Depth (cm) | Description |
| A | 0 - 15.24 | uniform light gray (2.5 Y6/2) silt, common roots, friable, common angular shards of bedrock, contact with dolomite bedrock (Roubidoux Fm.) at base of gully fill |

bedrock. Then it was eroded and deposited along the gully system, which exists within the study area's contemporary landscape. The gully system may be formed above a joint developed in the Roubidoux Formation.

It is important to note that the surface soil is not typical of the soils mapped by the SCS in this area (see Figure 10a). They designate the surface soil near Berry Cave as the Doniphan Soil Series (20C on Figure 10a), however the surface soil is more like the Clarksville Series. The Clarksville Soil has only one B_t horizon. That horizon is subdivided on the basis of color, texture, and structure. The same is true for the Doniphan Series. The Doniphan Series, (Appendix A), is formed in residuum from the Jefferson City Formation. The A horizon is a dark yellowish brown gravelly silt loam with a neutral pH (6.6) (see Appendix A). This soil has a clay-rich argillic (B_t) horizon that is reddish brown to dark red (Missouri Soil Characterization Laboratory, 1990). The pH range of the B_t horizon is 4.2 - 4.8, which is extremely acidic to strongly acidic. The thickness of the B_t horizon is 1.4 m (Missouri Soil Characterization Laboratory, 1990). Also of interest are the clay films on the faces of the peds throughout this argillic horizon (see Appendix A), which are indicative of illuviation.

On the other hand, the Clarksville Series (46F on Figure 10a) is formed in residuum from the Roubidoux Formation and is classified as a very gravelly silt loam. It forms on the shoulder of side slopes. There is an A horizon and an argillic (B_t) horizon. The A horizon is a very dark grayish brown and has a pH of 6.3 (see Appendix A). The thickness of the B_t horizon is 1.1 m (Missouri Soil Characterization Laboratory, 1992). The pH range of the B_t horizon is 4.8 - 5.7, which is very strongly acidic to acidic (see Appendix A). Also of interest is the ubiquitous distribution of clay films throughout the argillic horizon, which is indicative of illuviation.

The Buoyoucos texture analysis indicates that the surface soil above Berry Cave is silt loam (Table III and Figure 22). This soil has only an A-R soil profile, and the A horizon is light gray and has an acidic pH of 5.9 (Figure 23). Based on this evidence, I am speculating that the surface soil is actually the Clarksville Series rather than the Doniphan Series (see Figures 10a and 10b).



The percentage of silt present in the surface soil can be directly related to the soil forming factor parent material. Buol, et al. (1973: 110) suggests that if the parent material of a soil is limestone or dolomite that is rich in sand and chert, then the soil that forms may be coarse loamy and/or gravelly. Also, the type of soil formed (e.g. clayey) is connected to the impurities that dominate the dolomite (Buol, et al. 1973:110; Birkeland, 1984: 181). The histogram of grain size sieve analysis for the surface soil is presented in Figure 24 and Table IXa and b. Nearly 50% of the surface soil is comprised of silt, and nearly 20% is sand. The Roubidoux Formation is a sandy-cherty dolomite, and sandstone (SCS, 1989: 71). The lithology of the Roubidoux Formation accounts for the sand fraction, but not the silt fraction in the surface soil. The silt fraction is either an impurity in the Roubidoux Formation, or possibly of aeolian origin. It is likely that the silt is redeposited from loess deposits in the local area near Berry Cave.

The following chemical characteristics of the surface soil will be discussed: (1) organic carbon and (2) extractable iron. The extractable aluminum and calcium carbonate contents are either negligible or absent in the surface soil; hence, a discussion of these characteristics will not be included. The high organic carbon content of the surface

Table IXa. Results from sieve analysis completed on a soil sample collected from above Berry Cave, Pulaski County, Missouri. Note: phi sizes only pertain to sand sized particles. For the clay and silt fractions (< 20 μm), the particle size was used.

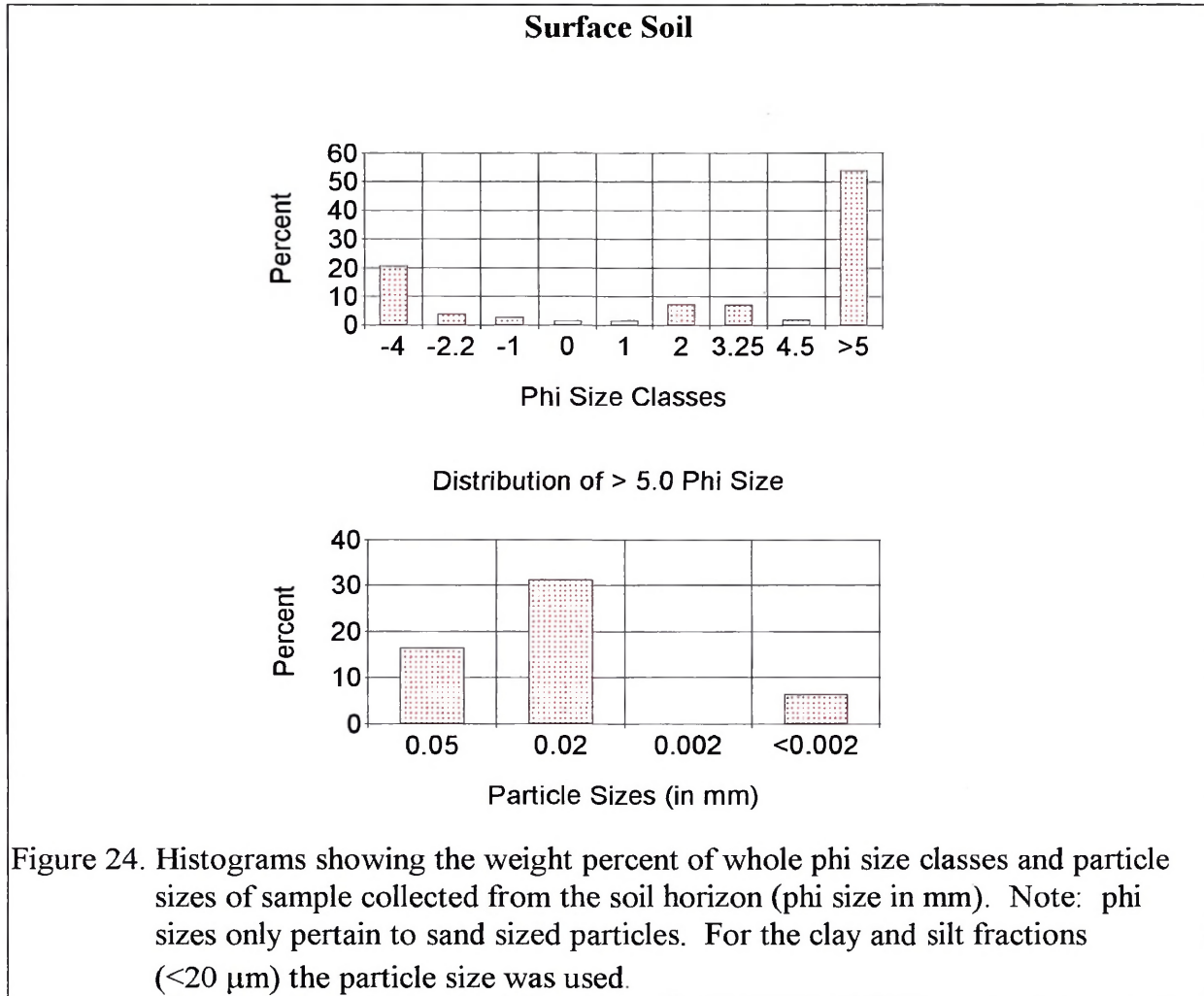
Abundance by phi size

| Horizon | -4 | -2.25 | -1 | 0 | 1 | 2 | 3.25 | 4.5 | >5 |
|----------------|-----------|--------------|-----------|----------|----------|----------|-------------|------------|--------------|
| A horizon | 20.5 | 3.8 | 2.7 | 1.5 | 1.5 | 7.4 | 7 | 1.7 | 53.9 |

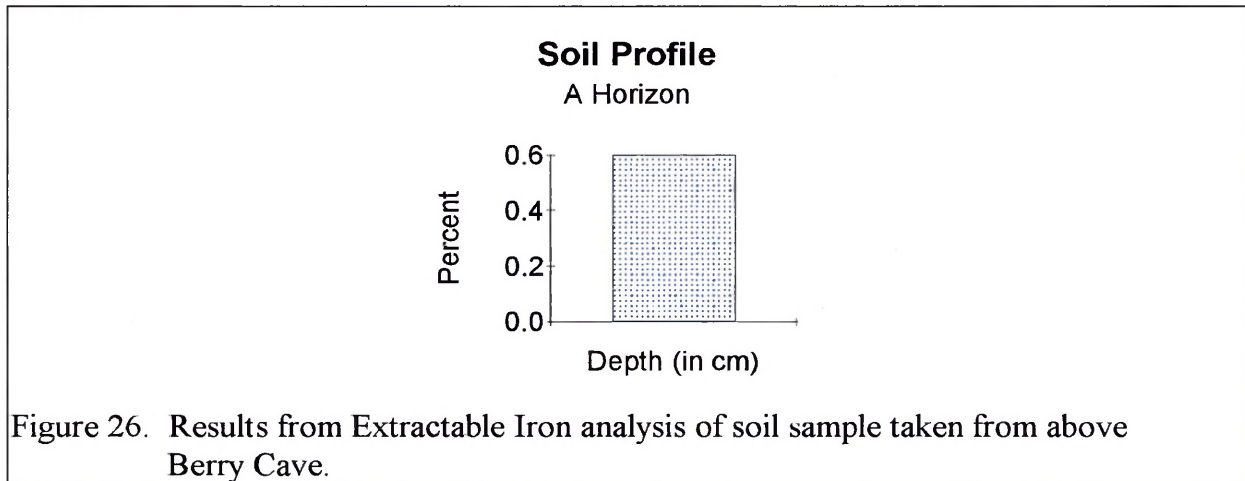
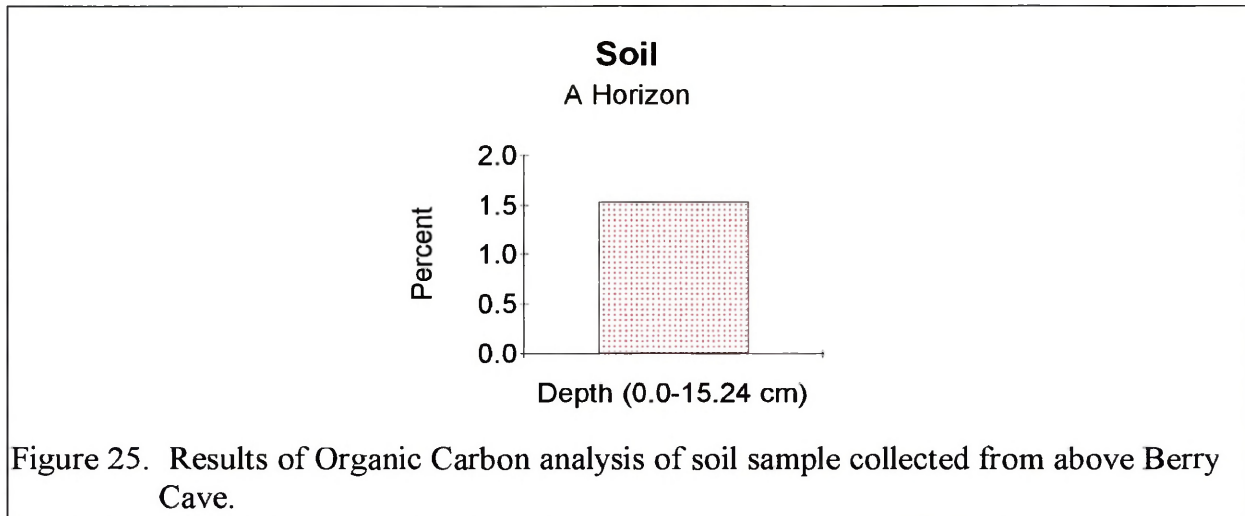
Table IXb. Results of silt and clay size particle analysis for soil sample collected from above Berry Cave, Pulaski County, Missouri.

Distribution of > 5.0 Phi size by particle size

| Horizon, or Section | Coarse Silt .02 - .05 | Fine Silt .002 - .02 | Coarse Clay < .002 | Fine Clay < .0002 |
|---------------------|--------------------------|-------------------------|-----------------------|----------------------|
| A horizon | 16.4 | 31.2 | | 6.3 |



soil is to be expected because the A horizon is subject to accumulation of decaying vegetative matter (see Table III and Figure 25). In Figure 26, extractable iron is graphed.



Because the soil is light gray in color, it appears that braunification, rubifaction, and ferrugination have not occurred.

Debris Flow Stratigraphy

The debris flow is comprised of three sections, which are described in Table X. These sections were identified based upon their position along the length of the debris flow. Section I is the proximal portion of the debris flow, Section II is the midpoint, and

Section III is the distal portion of the debris flow. All of the sediment samples taken from the debris flow were light grayish brown in color. The color is important, as it can be influenced by parent materials and/or post-depositional processes.

The debris flow sediments were classified as having a loam texture (see Table III). The sieve analysis for the debris flow (see Table XIa and b, and Figure 27a, b) shows that

| Section | Position | Length (in m) | Description |
|---------|-------------|---------------|---|
| I | Proximal | 0.0 - 1.2 | light grayish brown (5 Y6/2) sandy silt with roof fall fragments, 50% of sample is coarse bedrock fragments |
| II | Mid-section | 1.2 - 2.4 | light grayish brown (2.5 Y5/2) silty sand with roof fall fragments, 65% of sample is coarse bedrock fragments |
| III | Distal | 2.4 - 3.7 | light grayish brown (2/5 Y5/4) sand with roof fall fragments, 90% of sample is coarse bedrock fragments |

Table XIa. Results from sieve analysis completed on a debris flow samples collected from within Berry Cave, Pulaski County, Missouri. Note: phi sizes only pertain to sand sized particles. For the clay and silt fractions (< 20 μm), the particle size was used.

Abundance by phi size

| Section | -4 | -2.25 | -1 | 0 | 1 | 2 | 3.25 | 4.5 | >5 |
|-------------|------|-------|-----|-----|-----|------|------|-----|------|
| Section I | 23.2 | 4.2 | 2.6 | 3.2 | 5.4 | 14.8 | 9.2 | 1.8 | 35.7 |
| Section II | 30.2 | 15.9 | 4.9 | 2.5 | 4.1 | 10.7 | 5.9 | 1.1 | 24.7 |
| Section III | 40.6 | 30.8 | 4.7 | 1.7 | 1.9 | 4.2 | 2.8 | 0.6 | 12.8 |

Table XIb. Results of silt and clay size particle analysis for debris flow samples collected from within Berry Cave, Pulaski County, Missouri.

| Distribution of > 5.0 Phi size by particle size | | | | |
|---|--------------------|-------------------|--------------------|-------------------|
| | Coarse Silt | Fine Silt | Coarse Clay | Fine Clay |
| Section | .02 - .05 | .002 - .02 | < .002 | < .0002 |
| Section I | 5.7 | 20.8 | | 9.2 |
| Section II | 4.9 | 11.7 | | 8.1 |
| Section III | 2 | 5.2 | | 5.6 |

the coarse fraction (-4, -2.25, and -1 phi sizes) increases from 30% to 76.1% as sediments are transported along the length of the debris flow. The texture analysis of the debris flow sediments (Figure 28) shows that the coarse fraction is dominant along the length of the flow. The expected grain size distribution for a debris flow due to sorting and transport is a coarse to fine distribution from the proximal to distal portions of the flow.

Why doesn't the coarse fraction decrease with distance along the debris flow? It is possible that roof fall fragments are incorporated into the flow, creating an autogenic/allogenic sediment mix. As the bedrock fragments fall from the roof onto the debris flow, they are transported downslope. It appears that the angle of the debris flow causes them to roll downslope due to the influence of gravity. Thus, the coarse fraction at the bottom of the slope skews the expected grain size distribution.

The proportion of organic matter and the color of the debris flow sediments were used as indicators of melanization in the debris flow sediments (see Table III and Figure 29). The organic carbon content of the debris flow sediments is very similar to a surface soil. Because of a lack of sunlight in the cave environment, photosynthesis cannot occur, and green plants will not grow even if sufficient organic carbon is present. The stem portion of a green plant was found (see Figure 14) at the proximal end of the debris flow, which indicates that it was probably transported from the surface through a fissure and into the cave from a recent sediment flow event. The presence of organic matter in the

Debris Flow

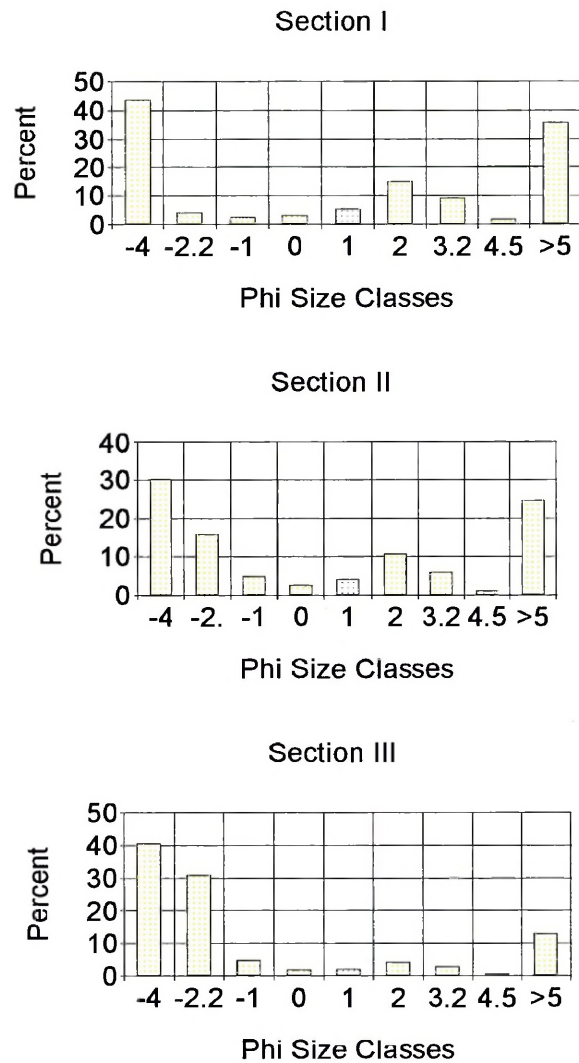


Figure 27a. Histograms showing the weight percent of particle size classes (in phi sizes) of samples collected from the sections of the debris flow. Note: phi sizes only pertain to sand sized particles. For the clay and silt fractions ($< 20 \mu\text{m}$) the particle size was used.

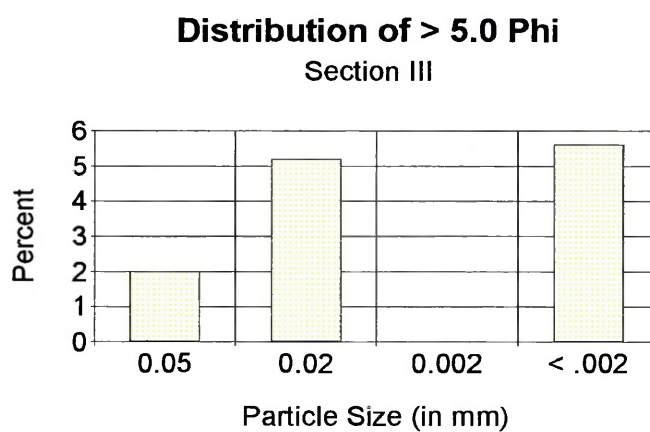
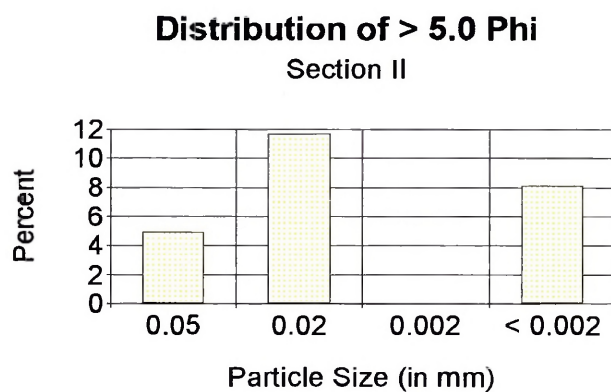
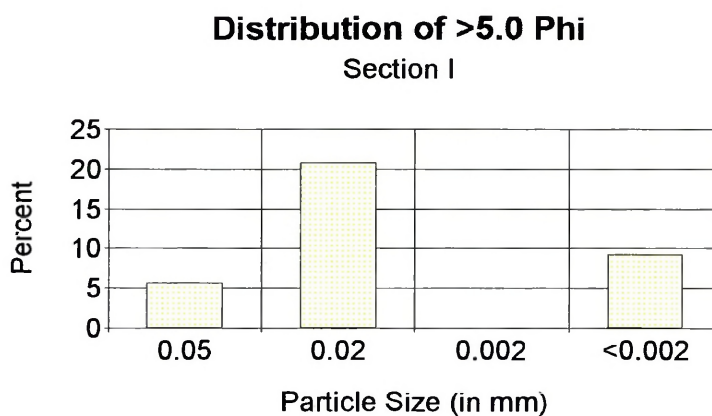


Figure 27b. Histograms showing the weight percent of silt and clay size particles (in mm) for samples collected from the debris flow sections within Berry Cave.

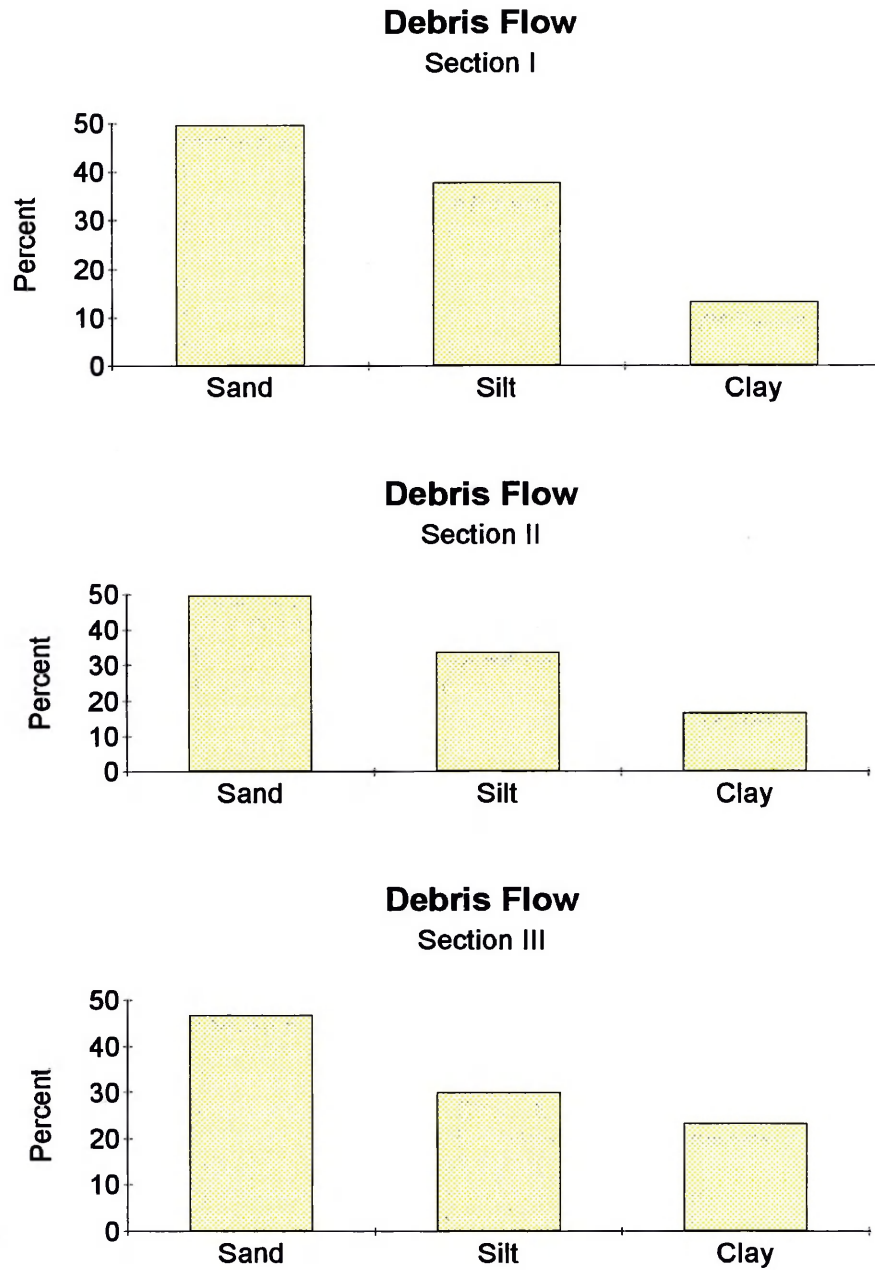
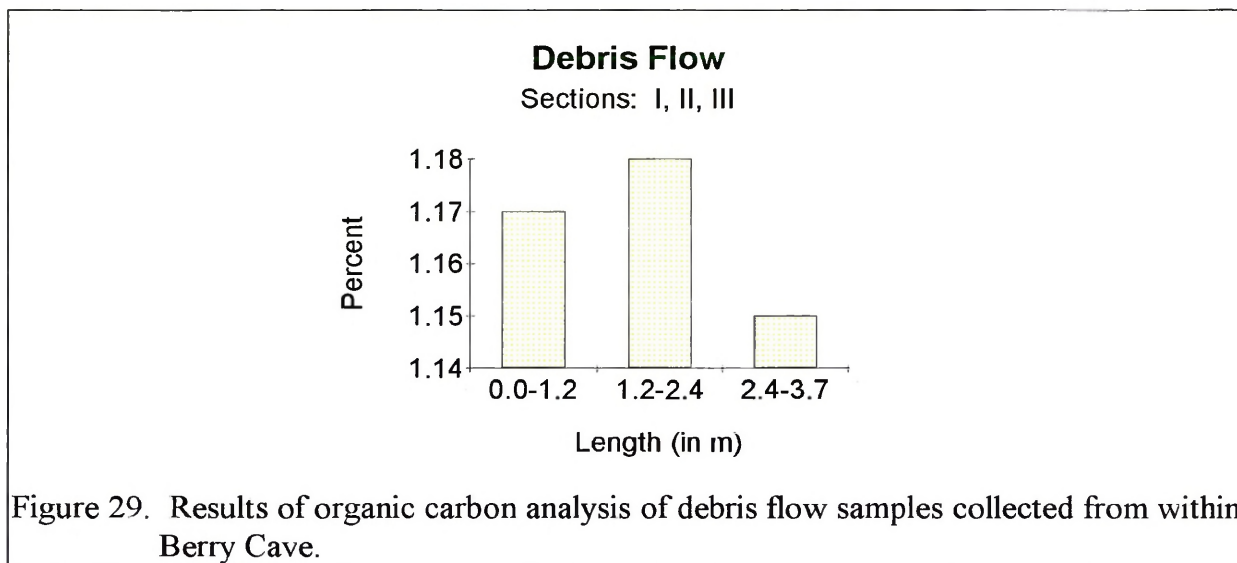


Figure 28. Weight percent of sand, silt, and clay in samples collected from the debris flow within Berry Cave.

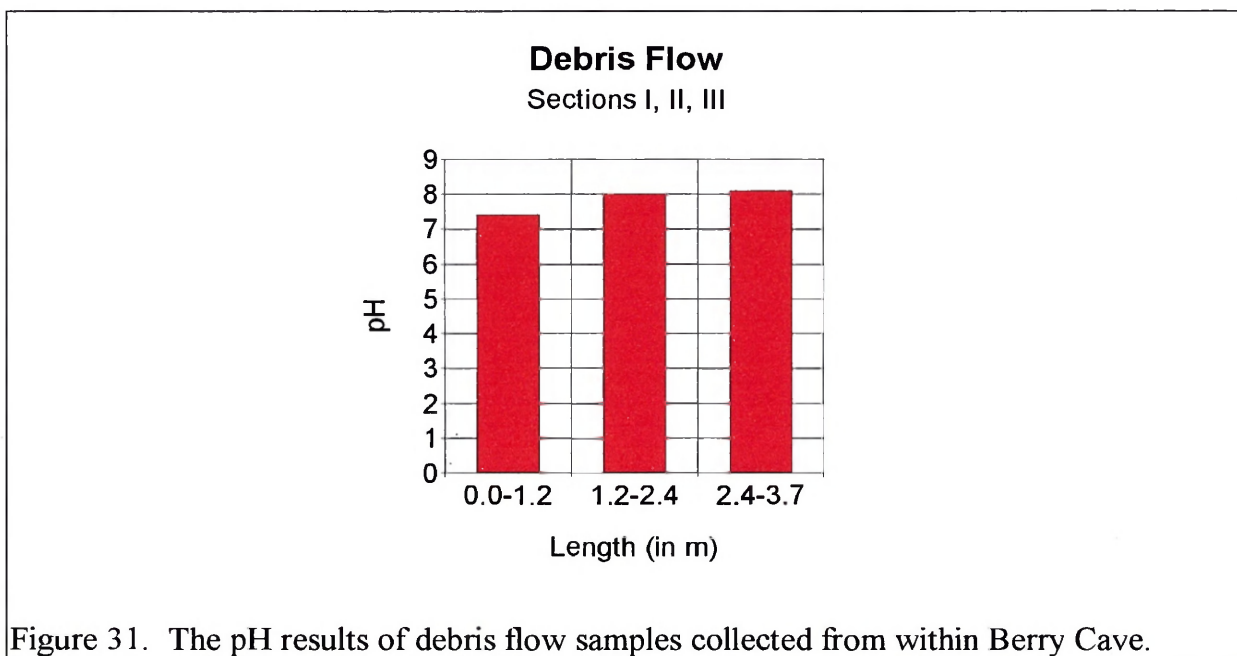
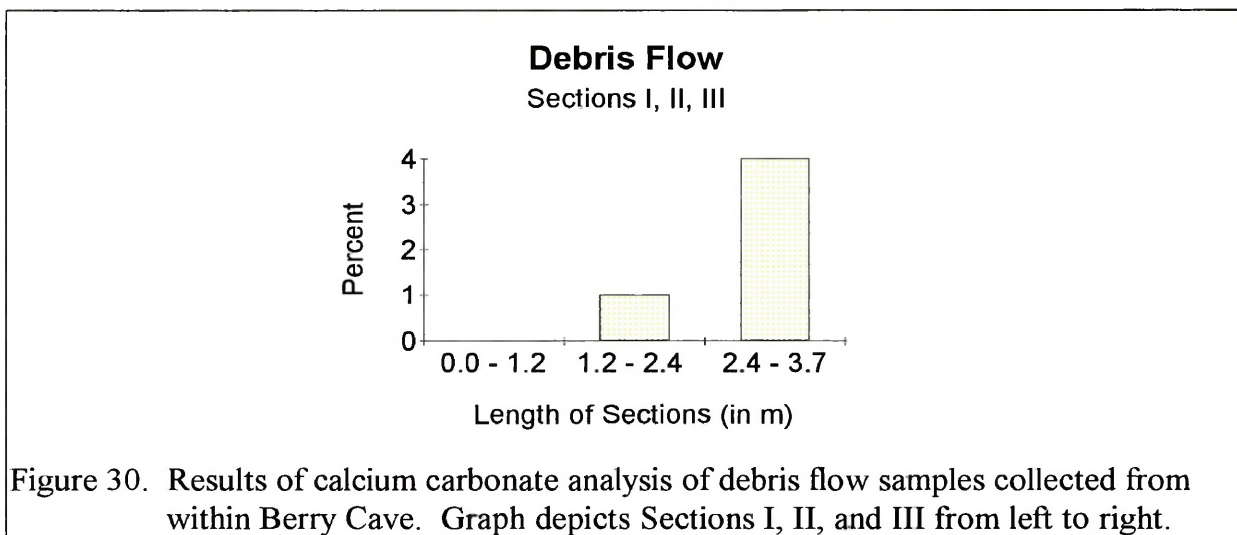


debris flow indicates that some mechanism must be at work supplying the cave sediments with organic materials.

Runoff containing organic materials and surface soil probably wash into the cave via the same openings through which the green plant entered the cave. The same precipitation that transported the surface materials into the cave also distribute them along the debris flow. With the addition of organic materials to the debris flow sediments it would be expected that the color of these sediments would become darker. This melanization (darkening) of sediments by the addition of organic material could conceivably change a light gray sediment to a light grayish brown.

There is not enough calcium carbonate in the debris flow sediments to cause calcification, so is it possible that the debris flow sediments were initially calcareous? Their link to the surface soil has been established via the evidence of the green plant fragment (see also the debris flow source discussion). The surface soil has a pH value of 5.9, while the debris flow shows an increase of pH values from 7.4 to 8.1. It is likely that

the pH values become more basic due to enrichment by a basic water solution. The increase in calcium carbonate along the debris flow may be evidence that enrichment of the sediments is affecting the pH of the sediments (see Table III, Figures 30 and 31). Buol et



al. (1973: 68) suggests that pH values from 6.5 - 8 are fully base saturated, and may have free calcium carbonate available only if well protected inside soil aggregates.

The basic pH values of the debris flow sediments may be caused by the addition of basic ions from the waters which are transporting the sediment and organic matter into the cave (see Brinkmann and Reeder, 1995: 102). Vadose water infiltrates through the soil, where CO₂ is plentiful. Dissolution occurs to the dolomite bedrock along lines of weakness, and this increases the pH of the water solution. Then, upon entering the cave and depositing the sediments, the water solution increases the pH of the sediments already in place (White, 1988).

Additionally, the basic pH values could also be affected by roof fall clasts which are incorporated into the debris flow sediments. These clasts of dolomitic bedrock are possibly weathering in place and causing these sediments to have a basic pH. Hence, the pH values for the debris flow sediments are affected by both basic water solution and roof fall fragments.

Sediment Source: Allogenic or Autogenic?

Determining the sediment source helps determine if a sediment is allogenic or autogenic. An allogenic sediment occurs when surface sediments are deposited in a cave, and an autogenic sediment is one which forms as a result of weathering the cave's bedrock (Brinkmann and Reeder, 1995: 95). Some examples of autogenic sediments in caves are breakdown (roof fall) from physical weathering, and/or clays from the weathering of the bedrock (Brinkmann and Reeder, 1995: 95). Hoy (1995: 83) suggests that allogenic sediments maintain physical characteristics from their source material.

Source of Debris Flow Sediments

Both the surface gully system and the cave system have northeast trends. Soil sediments and organic materials from the surface can be deposited into fissures in the dolomite bedrock. This is what appears to be occurring at the debris flow during episodic rainfall events. In Figure 14 a green plant is protruding from the top of the debris flow.

The depositional event associated with the plant being transported into the cave was recent, as evinced by the fact that the plant has maintained its color in the dark cave environment. Therefore, this is direct evidence that the debris flow sediments are being “fed” by soil sediments, and organic material along a fissure. The source of these materials is probably surface soils which mantle the land surface above the cave.

The debris flow seems to be comprised of a mix of both allogenic and autogenic materials. The coarse fraction is mainly roof fall/wall fragments which comprise the autogenic portion of the debris flow. The finer fractions are the silt and sand from the surface soil, and these make up the allogenic portion of the debris flow. In addition, the debris flow sediments and surface soil sample collected in the study area have similar physical and chemical characteristics such as grain size, texture, color, organic carbon, extractable iron, and extractable aluminum. Thus, it appears that the sources of the debris flow sediments may be the surface soil, and breakdown material inside the cave. Because only one soil sample was collected from above the cave, it is unknown if this sample is representative of all the soils above the cave, and hence the sources for the allogenic portion of the debris flow.

Source of Clay Fill Sediments

As discussed previously, the clay fill sediments are dissimilar to the debris flow sediments. Is it possible that the clay fill is autogenic and its source is the residuum from the weathering of the bedrock within Berry Cave? Autogenic sediments can contain physical weathering products from roof or wall collapse. These sediments should also contain fossils, bedding features associated with the bedrock, and display a gradational contact with the bedrock (Hoy, 1995: 83). In Monroe’s (1986) study, *in situ* clays displayed this gradational contact with the bedrock. Features such as these are preserved because cave environments and temperatures are relatively constant, thereby minimizing

the effects of weathering (Hoy, 1995: 95). In addition, autogenic sediments would not be able to develop a unit of great thickness within the cave environment since weathering processes are limited.

The clay fill sediments in Berry Cave are similar to autogenic sediments in two respects: they are clay and do contain roof fall fragments. But that is where the similarity ends. The clay fill contains no fossils, has no bedding features associated with the bedrock, and has a sharp contact with the bedrock floor. In addition, the clay fill is laterally extensive, vertically thick, and displays features such as a blocky structure and slickensides that are often characteristic of soils. The sharp contact with the bedrock floor, lack of fossils, lack of bedding features associated with bedrock, and vertical thickness are all indicative of an allogenic sediment (Hoy, 1995: 83).

Geomorphic Evolution

The clay fill sediments are allogenic, but what is their source? Reconstruction of the geomorphic evolution of the local area may provide an answer. A scenario for this evolution is as follows. The cave begins developing along the contact between the Roubidoux and Gasconade Formations. In the past 10,000 years climate fluctuations may have resulted in wetter conditions than at present. Relict paleosols, perhaps forerunners of the Doniphan and Clarksville Soil Series, begin to form in parent material derived from the Jefferson City Formation and the Roubidoux Formation. Both soils have clay horizons and acidic pH values, similar to the present day soils (see Appendix A). Since there exist acidic pH values, iron and clay are illuviated throughout the clay horizon.

Subsequent soil erosion occurs, and various portions of the clay soil horizons are deposited throughout Berry Cave under low energy conditions (Figure 32). The pH of the clay fills maintain their acidic values, which allows for iron and clay illuviation within the clay fill. Berry Cave acts as a sediment trap for the clay fill sediments, and they are

enriched by calcium carbonate rich waters. The transport and deposition of the clay fill sediments probably occurred as the cave was in transition from phreatic to vadose flow conditions, probably in response to fluctuating climatic conditions.

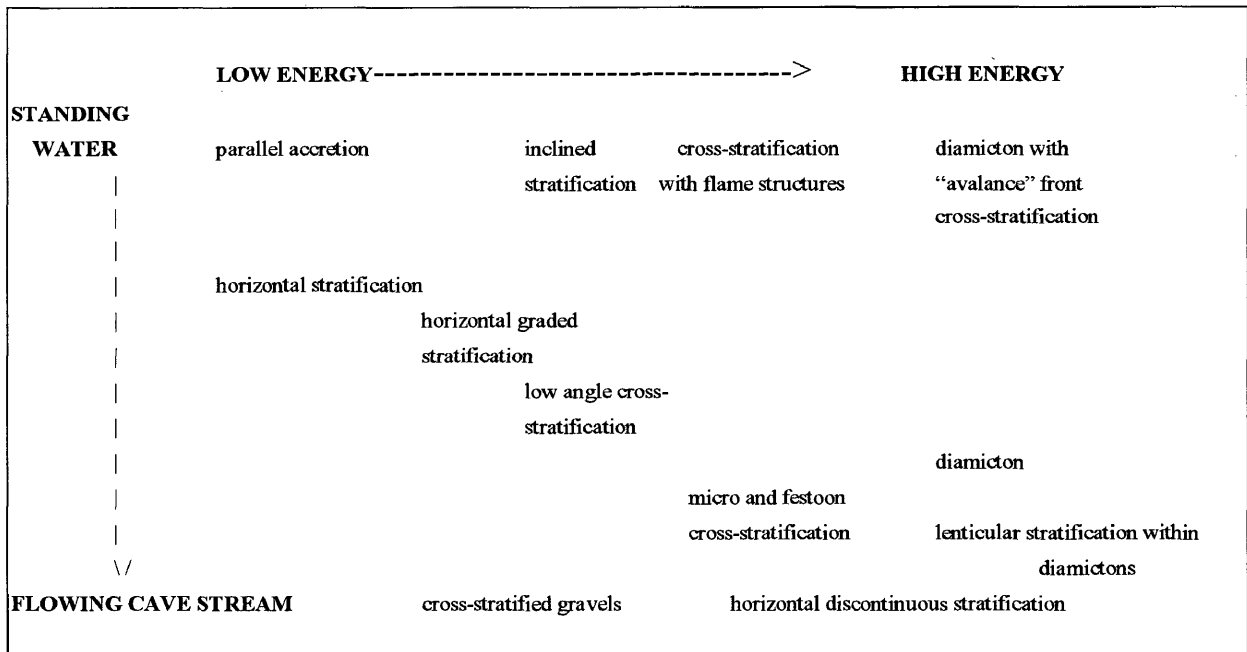


Figure 32. Depositional environments within caves associated with transport conditions. Adapted from Springer, 1994: 17.

The location of the clay fill is in a portion of Berry Cave that is at a lower elevation than the entrance. Beyond this low area, the cave passage then grades upward toward the surface, thus the low area acts as a sediment trap. A pool or perhaps even a sump formed in the vicinity of this low area and clay particles were deposited in this slackwater environment. As is depicted in Figure 32, parallel accretion and horizontal stratification of sediments are depositional environments associated with low energy transport conditions and standing water. As the water table lowered, the pool drained leaving behind the clay fill deposits. Since the low area in Berry Cave was trapping portions of former surface soils, the clay fill deposits represent relict surface paleosols of the geologic past.

This scenario outlined above occurred three or more times, as evidenced by the three distinct units of clay. These units possibly represent three separate depositional events. There were possibly more clay units at one time, however they have since been eroded away. The clay units currently present in Berry Cave are persistent, and maintain their structure and color. As the clay undergoes wetting and drying sequences, the clay units shrink and swell resulting in the formation of angular blocky structure and slickensides. Vadose and phreatic waters enriched these sediments with calcium carbonate and changed the pH values of the sediments from acidic to basic.

Next, the local water table rises, and the cave changes from vadose flow to phreatic flow. This results in erosion of the clay fills and formation of the present stream cut canyon. As the water table subsequently drops and reaches its present level, Berry Cave becomes a dry cave. Vadose water is now the only form of water available to erode or transport materials, and the clay fill is now isolated from large influxes of water. During this time the surface gully system forms along the same trend as the cave. The soils in the gully are transported into the cave via fissures and deposited in the debris flows. The debris flow sediments are comprised of sediments similar to the modern soil, while the clay fill sediments are paleo-analogues to soils that are no longer in existence at the study site.

CHAPTER V

SUMMARY AND CONCLUSIONS

This research attempted to answer the following four research questions:

- (1) What post-depositional processes affect the cave sediments, and are these processes still active?
- (2) What is the source of the cave sediments?
- (3) Are the cave sediments autogenic, allogenic, or both? and
- (4) How are the cave sediments indicators of landscape evolution?

It was determined that both the debris flow sediments and clay fill sediments were altered after deposition. The debris flow sediments were affected by both melanization and enrichment. Melanization was indicated by organic carbon content and sediment color. The debris flow sediments contained varying amounts of organic carbon, which indicates a connection with a surface source of organic material. The brown color in the debris flow sediments indicates that sediments in the cave are mixing with soils and organic material, which is being contributed from a surface source. Further evidence of this, and that these processes are still occurring, is the presence of a green plant fragment at the proximal end of the debris flow. The debris flow sediments are also similar to the surface soil sample in terms of texture, but it is not known if the surface soil sample is truly representative of all area soils.

Enrichment of the debris flow sediments with calcium carbonate has affected the sediment's pH values. Area soil survey data and the soil sample collected above Berry Cave indicate that those soils are acidic. Because the surface soils appear to be the source of the debris flow sediments, if unaltered in the cave environment, these sediments should also be acidic. However, the debris flow sediments are very basic. These sediments have been enriched by either calcium carbonate-rich vadose seepage and/or by *in situ* weathering of limestone breakdown mixed with the debris flow sediments. It appears that this enrichment is still occurring.

The clay fill sediments were also affected by enrichment from calcium carbonate, as well as other post-depositional processes. Similar to the debris flow sediments, the clay fill was enriched, thereby changing the original acidic pH to basic. It is possible that the clay fill is a redeposited relict paleosol, which formerly mantled the study area. If the soils in the past develop in parent material similar to the present day soils, and there existed similar climatic conditions (uniformitarianism), then soils in the past would have similar characteristics (e.g. acidic pH values) to present day soils.

Another post-depositional process that affected the clay fill was clay and iron illuviation. It was determined that both clay and extractable iron content increased with depth within the clay fill, which is indicative of a sediment that has undergone illuviation. The presence of slickensides and blocky structure within the clay fill may also be related to the illuviation process. Also, the color of the clay fill appears to have been altered after deposition by way of the processes of braunification, rubifaction, and ferrugination, all of which occur within the cave after deposition. It appears that the post-depositional processes that have affected the clay fill sediments are inactive. This is due to the fact that Berry Cave is generally a dry cave and the clay fill is located in a dry portion of the cave where there is a paucity of water currently available.

Regarding whether the cave sediments are autogenic, allogenic, or both as previously indicated, surface soil appears to be the source of the debris flow. The debris flow also contains roof fall fragments, which contribute the coarse fraction. Since the debris flow sediments are derived from outside the cave and the coarse fragments are the result of breakdown within the cave, this deposit is an allogenic/autogenic sediment mix. The clay fill contains sediments unlike any on the modern day surface, but it is postulated that these sediments are derived from now eroded soils that were present in a past environment. Hence, the clay fill sediments appear to be allogenic.

Finally, cave sediments can be indicators of landscape evolution because caves can trap surface soils and sediments as the landscape is modified by weathering, erosion and deposition. It was determined that surface soils were the possible source of the debris flow sediments deposited in the cave, and that relict paleosols were the source of the clay fill. However, the contemporary processes at work in the study area are not sufficient to explain the copious amounts of sediment deposited throughout the cave network. The clay fill sediments do not correspond with the present day surface soils and also, the clay fill is too thick to have formed in place. Geomorphic evidence derived from field and laboratory analysis indicates that the clay fill was probably deposited in a slackwater environment when Berry Cave was at or near the water table. As the hydrologic system within the cave was in transition from phreatic to vadose flow, the clay fill was incised by a free flowing stream under vadose conditions, resulting in the present canyon that exists in Berry Cave. As the water table elevations continue to decrease, the cave was entirely in the vadose zone, and conditions were created in which the debris flow developed.

While this research unveiled new evidence regarding alteration of cave sediments, much work still remains. I think it would be prudent to duplicate the results in this study by representative sampling along the entire length of the clay fill and other clay fills in Berry Cave. Also of interest would be a correlation of the results from Berry Cave with other caves in the local and regional area. Additional soil samples from the Clarksville and Doniphan soil associations should be collected and compared to the sediments in Berry Cave to determine if these soils are actually the sources of these materials. Additional soils samples should also be collected from above Berry Cave to better establish the relationship between the contemporary soils, the debris flow and clay fill units. Finally micromorphological analyses should be performed on the clay fill sediments. This analyses will confirm the presence of clay and iron illuviation and enrichment of calcium carbonate.

The fabric of a sediment is examined under a microscope, and the presence of clay, organic, iron, and calcium films can then be determined. Also, this analysis can be used to ascertain if the material has been transported and then altered after deposition, because clay, iron, organic, and calcium films have a particular orientation once formed *in situ*. If sediments with these films are subsequently transported, the films will not maintain that orientation.

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APPENDIX A

This appendix contains soil descriptions from the Doniphan and Clarksville Soil Series located at the study site. The Doniphan Series and Clarksville Series are referenced in the text in Chapter IV.

CLARKSVILLE SOIL SERIES

NSSL ID#: 9210571

Soil Survey # S92-MO-105-338

Map Unit Symbol 17D

Transect ID: 133

Photo Number: 301-117

Description Type: full pedon description

Location: 600' East & 150' South NW corner, Sec. 32, T35N R16W on John Varble Farm

Latitude: 37° 43' 58" N Longitude: 92° 43' 41" W

Classification: loamy-skeletal, siliceous, mesic Typic Paleudult**Physiography:** Hillside in Level or Undulating Upland**Geomorphic Position:** on upper third, shoulder of a side slope

Slope Characteristics: 11% convex

Elevation: 1210' MSL

Precipitation: udic moisture regime

MLRA: 116B

Hydraulic Conductivity: high

Drainage Class: Somewhat excessively

Land Use: pasture land and native pasture

Particle Size Control Section: 17 to 37 inches

Parent Material: residuum from interbedded sedimentary material

Vegetation Code: Fescue

Described by: GWS, MJM

Date: 04/92

Notes: Last stop on Transect 133, Roubidoux Formation

A: 00 - 05"; very dark grayish brown (10YR 3/2) very gravelly silt loam; weak fine granular structure; friable; common fine roots, and few medium roots; 45% gravel; clear smooth boundary.

E: 05 - 17"; brown (10YR 5/3) extremely gravelly silt loam; weak fine granular structure; friable; many fine roots, and few medium roots; 70% gravel; gradual smooth boundary.

Bt1: 17 - 28"; strong brown (7.5YR 4/6) very gravelly silt loam; weak medium subangular blocky structure; firm; common fine roots; few discontinuous faint clay films; common distinct brown (10YR 5/3) continuous skeletal (sand or silt); 45% gravel; clear smooth boundary.

Bt2: 28 - 39"; dark red (2.5YR 3/6) very gravelly silty clay loam; weak fine subangular blocky structure; firm; common fine roots; common distinct discontinuous clay films (cutans); 40% gravel; 15% gravel; clear smooth boundary.

Bt3: 39 - 60"; dark red (2.5YR 3/6) very gravelly silty clay; weak fine subangular blocky structure; firm; few fine roots; many distinct continuous clay films (cutans); 30% gravel; 10% gravel.

Selected physical and chemical properties of Clarksville Series

Clarksville Map Unit 17D

Loamy-skeletal, siliceous, mesic Typic Paleudult

11/06/92

Samples M921057101 - M921057106

Missouri Soil Characterization Laboratory

Laclede County

| Sample# | Depth cm | Horizon | Clay | Silt | Sand | Fine Silt | Coarse Silt | VF Sand | Fine Sand | Med Sand | Coarse Sand | VC Sand | >VF Sand | Text. Class |
|---------|-------------|---------|------|------|------|--------------|----------------|------------|--------------|-------------|----------------|------------|-------------|----------------|
| 1 | 0 - 13 | A | 8.6 | 69.7 | 21.7 | 45 | 24.8 | 1.4 | 3.4 | 3 | 4.5 | 9.4 | 20.3 | Silt |
| 2 | 13- 43 | E | 9 | 70.8 | 20.3 | 49 | 21.8 | 1.2 | 2.5 | 2.1 | 3.4 | 11.1 | 19.1 | Silt |
| 3 | 43-71 | Bt1 | 14.9 | 73.3 | 11.8 | 44.4 | 28.9 | 2.2 | 3.4 | 1.9 | 2 | 2.2 | 9.6 | Silt |
| 4 | 71-99 | Bt2 | 31.1 | 56.7 | 12.2 | 36.1 | 20.6 | 1.5 | 2.5 | 1.7 | 2.8 | 3.7 | 10.7 | Silty clay |
| 5 | 99-152 | Bt3 | 48.4 | 39.4 | 12.2 | 25.6 | 13.8 | 1.4 | 2.7 | 1.3 | 2.4 | 4.3 | 10.8 | Clay |
| 6 | | B.S. | | | | | | | | | | | | |

| Sample # | Ca | Mg | Extractable Al | Organic Carbon | pH |
|------------|-----|-----|-------------------|-------------------|-----|
| M921057101 | 7.9 | 0.8 | 0 | 2.6 | 6.3 |
| M921057102 | 3 | 0 | 0 | 0.4 | 6.2 |
| M921057103 | 3.6 | 0.8 | 0.4 | 0.2 | 5.7 |
| M921057104 | 1 | 1.2 | 5.8 | trace | 5 |
| M921057105 | 1.4 | 2 | 7.1 | 0.1 | 4.9 |
| M921057106 | 1.4 | 2.4 | 6.7 | 0.1 | 4.8 |

DONIPHAN SOIL SERIES

NSSL ID#: 9210571

Soil Survey # S90-MO-215-1(1-7)

Map Unit Symbol 46D

Transect ID: 133

Photo Number: 301-117

Pedon Description: Doniphan very gravelly silt loam

Location: 2100' West and 1800' South of the Northeast corner of Section 28, Township 30 North, Range 8 West in Texas County, Missouri

Classification: clayey, mixed, mesic Typic Paleudults**Physiography:** Backslope**Geomorphic Position:** on upper third, shoulder of a side slope

Slope Characteristics: 12% convex

Elevation: 1280'

Permeability: moderate

Drainage Class: Well

Erosion: Slight

Moisture: 50% capacity

Groundwater: > 60"

Parent Material: residuum from Jefferson City Formation

Vegetation Code: Fescue pasture

Described by: Sid Vander Veen & John Preston

Date: 08/89

Ap: 0 - 3"; dark yellowish brown (10YR 4/4) very gravelly silt loam, light yellowish brown (10YR 6/4) dry; weak fine granular structure; very friable; many very fine roots; many very fine irregular pores; 50 % chert pebbles; neutral (pH 6.6); abrupt smooth boundary.

E: 3 - 6"; dark yellowish brown (10YR 4/4) very gravelly silt loam; weak fine subangular blocky structure; very friable; common very fine roots; common very fine tubular and irregular pores; many prominent silt coats on faces of peds; 50% chert pebbles; neutral (pH 6.6); abrupt smooth boundary.

2Bt1: 6 - 11"; reddish brown (5YR 4/4) clay; strong very fine angular blocky structure; very firm; common distinct clay films on faces of peds; common prominent silt coats on faces of peds; 10% chert pebbles; very strongly acid (pH 4.8); clear smooth boundary.

2Bt2: 11 - 18"; yellowish red (5YR 4/6) clay; strong fine angular blocky structure; very firm; common very fine roots; common very fine tubular pores; many fine distinct clay films on faces of peds; 10% chert fragments; very strongly acid (pH 4.6); clear wavy boundary.

2Bt3: 18 - 27"; yellowish red (5YR 5/6) gravelly clay; strong medium angular blocky structure; very firm; common very fine roots; common very fine tubular pores; many medium prominent clay films on faces of peds; 20% chert pebbles and 5% chert cobbles; extremely acid (pH 4.2).

2Bt4: 27 - 44"; red (2.5YR 4/6), yellowish red (5YR 5/8) and white (5YR 8/1) clay; strong medium subangular blocky structure; firm; few very fine roots; common very fine tubular and irregular pores; many medium prominent clay films on faces of peds; 5% chert pebbles and 5% chert cobbles; extremely acid (pH 4.2).

2Bt5: 44 - 60"; gray (5YR 6/1), light gray (5YR 7/1) and dark red (2.5YR 3/6) very cobbly clay; strong coarse subangular blocky structure; firm; common very fine irregular pores; many medium prominent clay films on faces of peds; 35% chert cobbles and 5% chert pebbles; extremely acid (pH 4.2).

Selected physical and chemical properties of Doniphan Series

Doniphan Map Unit 46D

Clayey, mixed, mesic Typic Paleudult

7/03/90

Samples M902150101 - M902150107

Missouri Soil Characterization Laboratory

Texas County

| Sample# | Depth cm | Horizon | Clay | Silt | Sand | Fine Silt | Coarse Silt | VF Sand | Fine Sand | Med Sand | Coarse Sand | VC Sand | >VF Sand | Text. Class |
|---------|-------------|---------|------|------|------|--------------|----------------|------------|--------------|-------------|----------------|------------|-------------|----------------|
| 1 | 0 - 8 | A | 16.5 | 52 | 31.6 | 33.4 | 18.6 | 2.2 | 16.2 | 6.5 | | 3 | 3.6 | Silt |
| 2 | 8-15 | E | 16.7 | 54.9 | 28.4 | 35.8 | 19.2 | 2.1 | 15.6 | 5.7 | | 2.6 | 2.3 | Silt |
| 3 | 15-28 | 2Bt1 | 55.9 | 32.7 | 11.4 | 20.5 | 12.2 | 1.4 | 5.8 | 2.5 | | 1 | 0.8 | Clay |
| 4 | 28-46 | 2Bt2 | 68.5 | 24.3 | 7.1 | 15.7 | 8.6 | 1.3 | 3.1 | 1.1 | | 1 | 0.7 | Clay |
| 5 | 46-69 | 2Bt3 | 70.4 | 22.7 | 6.9 | 14.6 | 8 | 1.4 | 2.3 | 1.1 | | 1.2 | 0.9 | Clay |
| 6 | 69-112 | 2Bt4 | 76.2 | 20.2 | 3.7 | 15.2 | 5 | 0.8 | 1.4 | 0.5 | | 0.6 | 0.4 | Clay |
| 7 | 112-152 | 2Bt5 | 72.7 | 23.6 | 3.7 | 16.4 | 7.2 | 1.2 | 1.4 | 0.5 | | 0.4 | 0.2 | Clay |

| Sample # | Ca | Mg | Extractable Al | Organic Carbon | pH |
|------------|-----|-----|-------------------|-------------------|-----|
| M902150101 | 6.6 | 3.5 | 0 | 2.6 | 6.6 |
| M902150102 | 4.8 | 2.8 | 0 | 1.3 | 7.1 |
| M902150103 | 3.6 | 5.1 | 3.2 | 0.9 | 5.3 |
| M902150104 | 1.3 | 3.3 | 10.4 | 1 | 4.9 |
| M902150105 | 0.7 | 3.1 | 10.6 | 0.5 | 4.9 |
| M902150106 | 0.9 | 2.2 | 10.5 | 0.3 | 4.8 |
| M902150107 | 0.2 | 1.9 | 14.1 | 0.2 | 4.8 |