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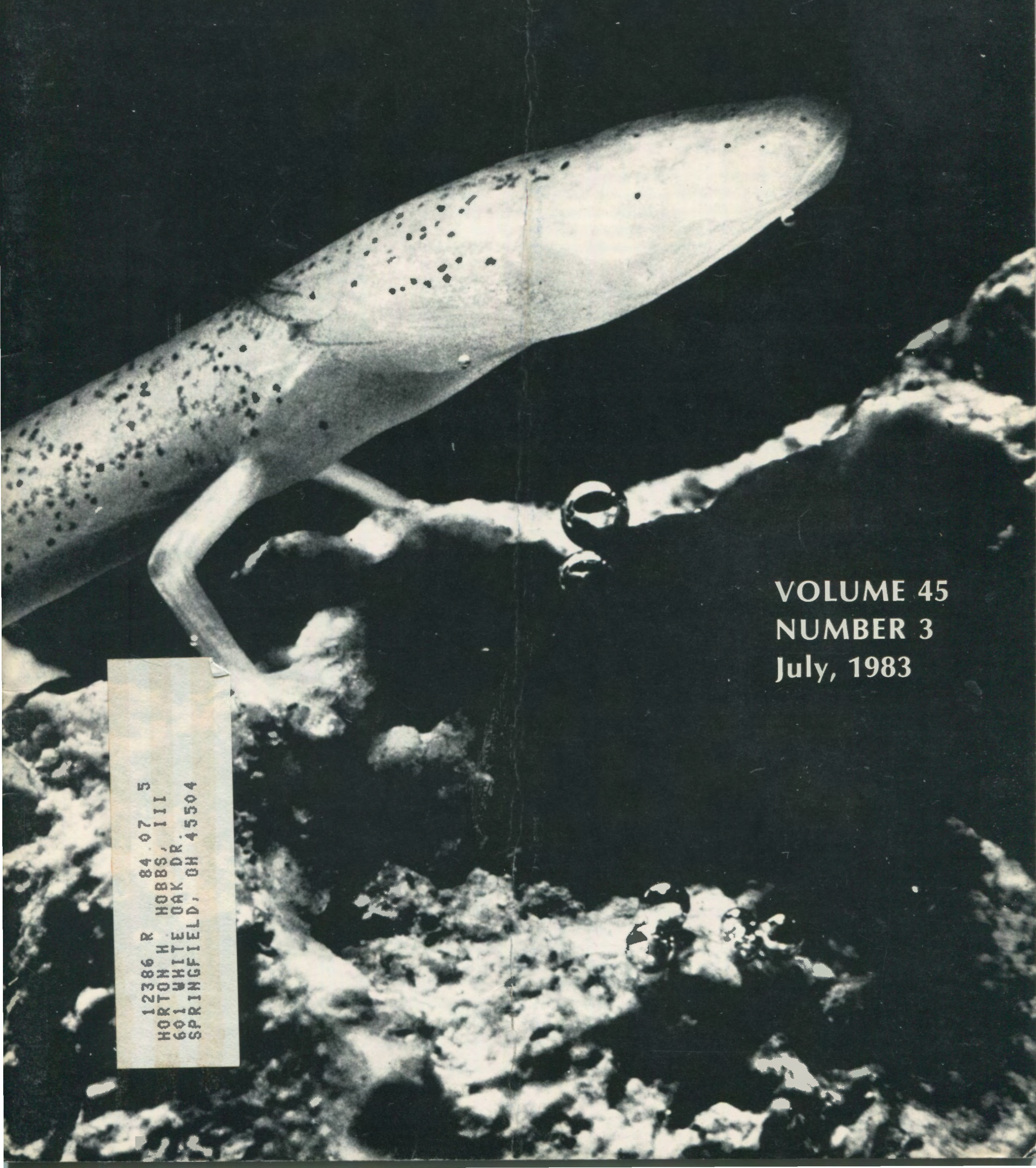

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CONTENTS

CLASTIC SEDIMENTS IN MYSTERY CAVE, SOUTHEASTERN MINNESOTA
Jodi A. Milske, E. Calvin Alexander, Jr., and Richard S. Lively 55

COVER PHOTO—*Hadeotriton wallacei,* Gerards Cave, Florida. Photo by Stewart Peck.

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CLASTIC SEDIMENTS
in
MYSTERY CAVE
Southeastern Minnesota*

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SUMMARY

Mystery Cave is a complex, joint-controlled maze cave developed in the (Ordovician) Dubuque and Galena formations in the fluviokarstic terrain of southeastern Minnesota. The cave system functions as a subterranean meander cut-off for a portion of the entrenched South Branch of the Root River. The cave contains a clastic sedimentary record that can be correlated with radioisotope ages obtained from calcite speleothems. These deposits record the following history: 1) *initial development of the cave system in the shallow phreatic zone proximal to a water table level which pre-dates surface valley entrenchment;* 2) *deposition of a thick bed of finely laminated silt by backflooding of the cave by the South Branch of the Root River;* 3) *lowering of base level and draining of the cave, beginning at about* 160 ka, *resulting in headward erosion of the silt fill by vadose streams captured from the entrenching surface valley; and* 4) *deposition of stream gravels at about* 145 ka *and* 13 ka *at levels 15 to 25 m above the present stream level in the cave. The gravels are derived primarily from surface deposits of pre Late-Wisconsinan 'Old Gray' drift, placing an upper limit of* 145 ka *on the age of this drift in southeastern Minnesota. Episodes of fluvial deposition in the cave correlate approximately with the onset of major cycles of speleothem growth. The stream gravels are interpreted as representing late-stage alluvial terrace deposits corresponding to the retreatal phases of the Wisconsinan and Illinoian Glaciations. This interpretation suggests a potential method for dating surface valley terraces in karst basins by correlation with cave terraces.*

INTRODUCTION

Clastic Sediments

CLASTIC SEDIMENTARY DEPOSITS in caves are a potential tool for the reconstruction of the climatic history and geomorphic evolution of karst terrains. The stable cave environment can preserve a sedimentary record that has since been altered or obliterated from the land surface, and many caves in karst terrains contain a complex suite of both clastic and chemical sediments. In the past decade, the application of $^{234}U/^{230}Th$ disequilibrium dating methods to carbonate speleothems associated with the clastic deposits has begun to provide a chronologic framework beyond the range of ^{14}C within which this stratigraphic record can be interpreted. In order to use clastic cave deposits as an interpretive tool, it is necessary to understand sedimentation processes in caves in relation to the surficial processes that control them.

Previous Studies

Cave Sediment Studies. Cave sediments have been extensively described from an archaeological and paleontological viewpoint, but only in the last several decades have geologists begun to recognize these deposits as a potential tool for interpretation of Pleistocene paleoenvironments and karst processes. Important petrologic studies of cave sediments have been published in Europe by Kukla and Lozek (1958) and Schmid (1958) and in South Africa by Brain (1958). In Great Britain, Bull (1975, 1976, 1977, 1978a, b, 1981) has made an extensive study of clastic cave deposits as indicators of Pleistocene climatic cycles.

In the United States, Davis (1930) discussed the abundance of fine grained clastic deposits in caves as support for his theory that cave systems are formed deep below the water table, concluding that cave fills develop *in situ* from the insoluble residue of the dissolved limestone. Later, Bretz (1942) described "red clay" fills from a large number of North American caves as further support for Davis' hypothesis. The ideas of both authors on the origin of cave deposits were, however, formulated without detailed study of the petrology and grain size characteristics of the sediments. Recent studies have shown that many fine grained cave fills are composed of silt-sized sediment transported into the cave from the surface and are not *in situ* weathering residua.

The work of Davies and Chao (1959) stands as a pioneering study of the petrology of cave deposits and, until very recently, provided the only petrologic data available in the American literature. Their investigation of sediments in Mammoth Cave, Kentucky was the first attempt to describe in detail the stratigraphy of cave fills and to use the mineralogy of the sediments to establish provenance. White and White (1968) used these data to develop a model for the role of sediment transport in the development of integrated karst drainage nets. Collier and Flint (1964) expanded on the earlier work of Davies and Chao in a study of the relationship between recent sedimentation and flood cycles in Mammoth Cave.

Several other important descriptive studies of cave sediments have been produced in the past two decades. Helwig (1964) used the stratigraphy of detrital fills in Carroll Cave, Missouri to interpret the history of that cave. Frank (1965) conducted a petrologic study of sediments in central Texas caves, using his data to infer Holocene paleoclimatological trends. The relationship between cave sedimentation and the geomorphic history of karst basins has been investigated for the Ozark Plateaus Province by Reams (1968) and for the Allegheny Escarpment by Wolfe (1973).

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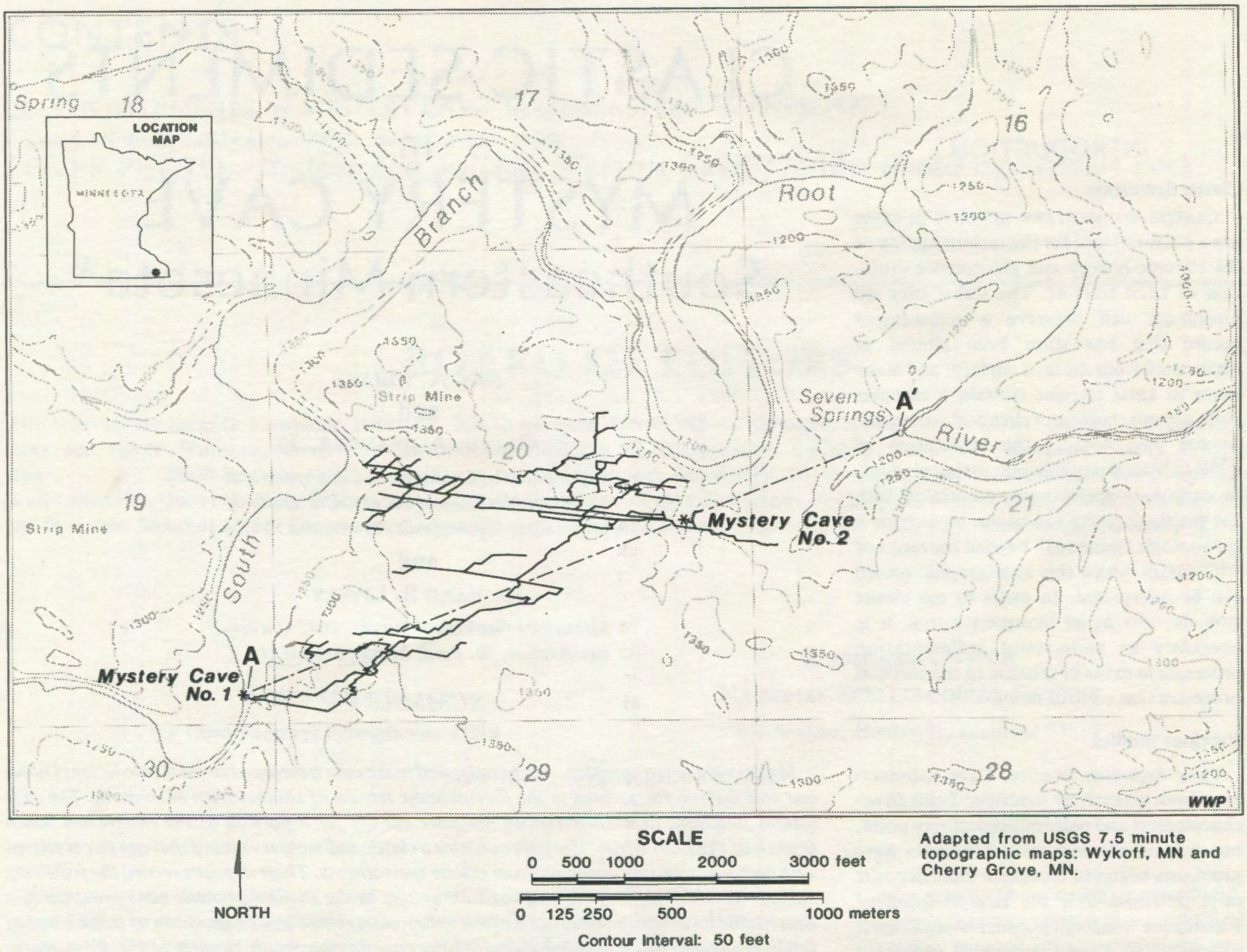


Adapted from USGS 7.5 minute topographic maps: Wykoff, MN and Cherry Grove, MN.

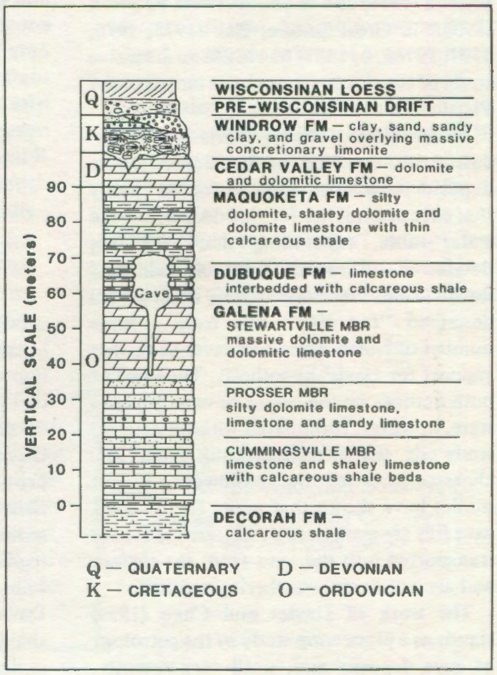
Figure 1. **Mystery Cave in relation to surface topography; mapped extent as of 1981. Cross section A-A' is shown in Figure 3.**

Figure 2. (right) **Generalized stratigraphic column for the Mystery Cave area.**

Minnesota Caves and Karst. Very little has been published about the karst of southeastern Minnesota. Bretz (1938) and Hogberg and Bayer (1967) described several of the hundreds of caves in this region, and Alexander (1980) provided an updated descriptive introduction to caves in Minnesota, Iowa, and Wisconsin. Wopat (1974) gave an overview of karst features in southeastern Minnesota and summarized the available information concerning the geomorphic history of the area.

The glacial deposits and Pleistocene history of southeastern Minnesota have not been studied since the original descriptive work of Leverett (1932). No definite glacial stage has yet been assigned to the drift and outwash deposits that lie east of the late Wisconsinan Des Moines Lobe drift in western Mower County; these deposits are presently mapped only as pre-late Wisconsinan. Recent studies by Lively and Alexander (1980), Lively and others (1981), and Lively (1983) have begun to establish a chronologic record for the Late Pleistocene in this part of the state, based on $^{234}U/^{230}Th$ dating of speleothems.

This paper describes the stratigraphy and petrology of clastic sediments in Mystery Cave, the largest of the more than 300 caves recorded from the karst region of southeastern Minnesota. This research was carried out in conjunction with groundwater dye trace studies and radioisotope dating of speleothems from the cave system. The purpose of this study is to determine the age and provenance of the cave deposits, to reconstruct the depositional history of the cave system in relation to surficial geomorphic processes, and to correlate these events with the chronologic record for southeastern Minnesota based on $^{234}U/^{230}Th$ radioisotope ages.



LOCATION AND GEOLOGIC SETTING

Southeastern Minnesota Karst

Mystery Cave is located in western Fillmore County, southeast of the town of Spring Valley, in sections 19 and 20 of Forestville Township (T. 102 N., R. 12 W.) (Fig. 1). This area of southeastern Minnesota is part of an extensive karstland developed along the northeast edge of an upland plain having an average elevation of about 400 m (1300 to 1350 ft). The plateau is underlain by lower Paleozoic rocks striking northwest-southeast and dipping very gently 2 to 5 m/km to the southwest. Most of the karst lies within the drainage basin of the Root River, in Fillmore County.

The Paleozoic rocks in which the karst is developed are limestones and dolostones of Ordovician and Devonian ages. These include the (Middle Ordovician) Galena Formation, the (Upper Ordovician) Dubuque and Maquoketa formations and the (Middle Devonian) Cedar Valley Limestone (Fig. 2). This sequence of formations forms a single carbonate aquifer underlain by the shale beds of the Decorah Formation (Broussard, *et al.*, 1975). Karst features are also developed in several formations below the Decorah: the (Lower Ordovician) Prairie du Chien Group and the (Middle Ordovician) Platteville Limestone and St. Peter Sandstone. The most extensive karst development occurs in the well-jointed Galena Formation, particularly in the Stewartville and Cummingsville members of this unit.

The Paleozoic bedrock is discontinuously overlain by non-marine deposits of Cretaceous (possibly Tertiary) age. Although Fillmore County is often mapped as part of the driftless area that includes adjacent southwestern Wisconsin and northeastern Iowa, a thin, discontinuous mantle of pre-Late Wisconsinan glacial till covers the county. This drift thickens to the west across adjacent Mower County and then is buried beneath the thick till sheet of the late-Wisconsinan Des Moines Lobe.

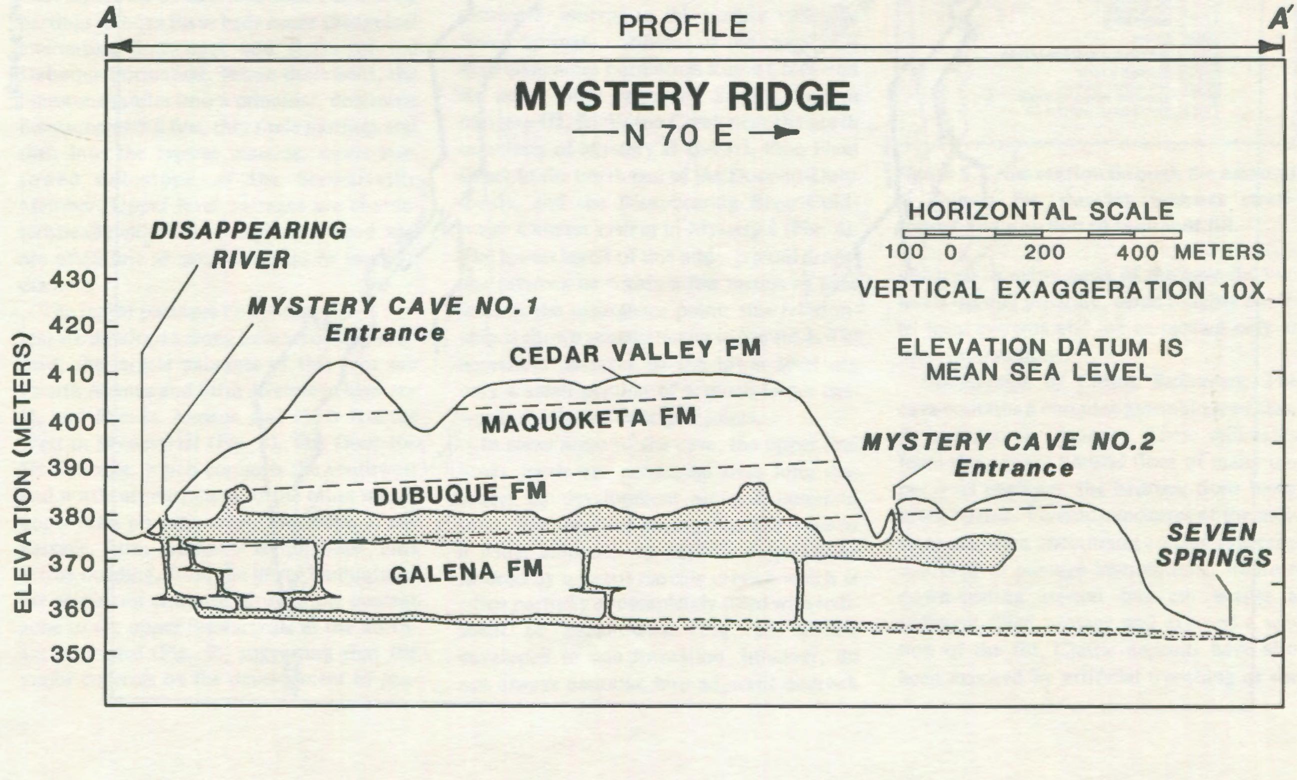
The Root Riveres has its headwaters on this plain of pre-Late Wisconsinan drift in west-central Mower County, approximately 15 km east of the eastern lateral moraine of the Des Moines Lobe. As it flows eastward the channel gradient increases and the river begins to incise bedrock. The valley becomes deeper as the river crosses Fillmore and Houston Counties to its confluence with the Mississippi River: a maximum gradient of about 2.5 m/km occurs where the river crosses the Galena Formation. This process of river incision, resulting in a progressive lowering of base level, is responsible for the present cycle of karst development. Sinkholes and blind valleys are numerous and conspicuous landforms throughout the area, as surface flow intermittently passes underground through solution-enlarged joints in the bedrock and reemerges into the river valley downstream through seeps and springs. By this process, many sediment-filled voids developed along joints and bedding planes in the carbonate bedrock are currently being reexcavated and enlarged by the subterranean stream system. In the classification of Sweeting (1973), the karst terrain of southeastern Minnesota is a "fluviokarst," developed by the combined action of fluvial and karst processes.

The age of the karst is unknown. The present dissection of the upland plain by the Root River is a response to a more regional lowering of base level by incision of the upper Mississippi River. The present course of the Mississippi was established by the early Pleistocene, and the major deepening of the upper Mississippi Valley probably occurred in the early Pleistocene, prior to Kansan time (Frye, 1973; Willman and Frye, 1970). The initial network of solution-enlarged joints, however, appears to pre-date the effects of river incision and may have formed as early as Cretaceous time (Wopat, 1974).

Mystery Cave

General Geology. Mystery Cave is the largest known cave system in Minnesota, with more than 18 km of surveyed passages. The plan of the cave (figs. 1 and 4) is strongly controlled by a system of joints trending east-west and southwest-northeast, with minor development along a third, northwest-southeast direction. As shown in Figure 4, the Mystery system is divided into 3 areas: Mystery I to the southwest, Mystery II to the east, and Mystery III to the north and

***Figure 3.* Cross section through Mystery Ridge, showing position of upper and lower passage levels in Mystery Cave. Location of section A-A' is shown in Figure 1.**



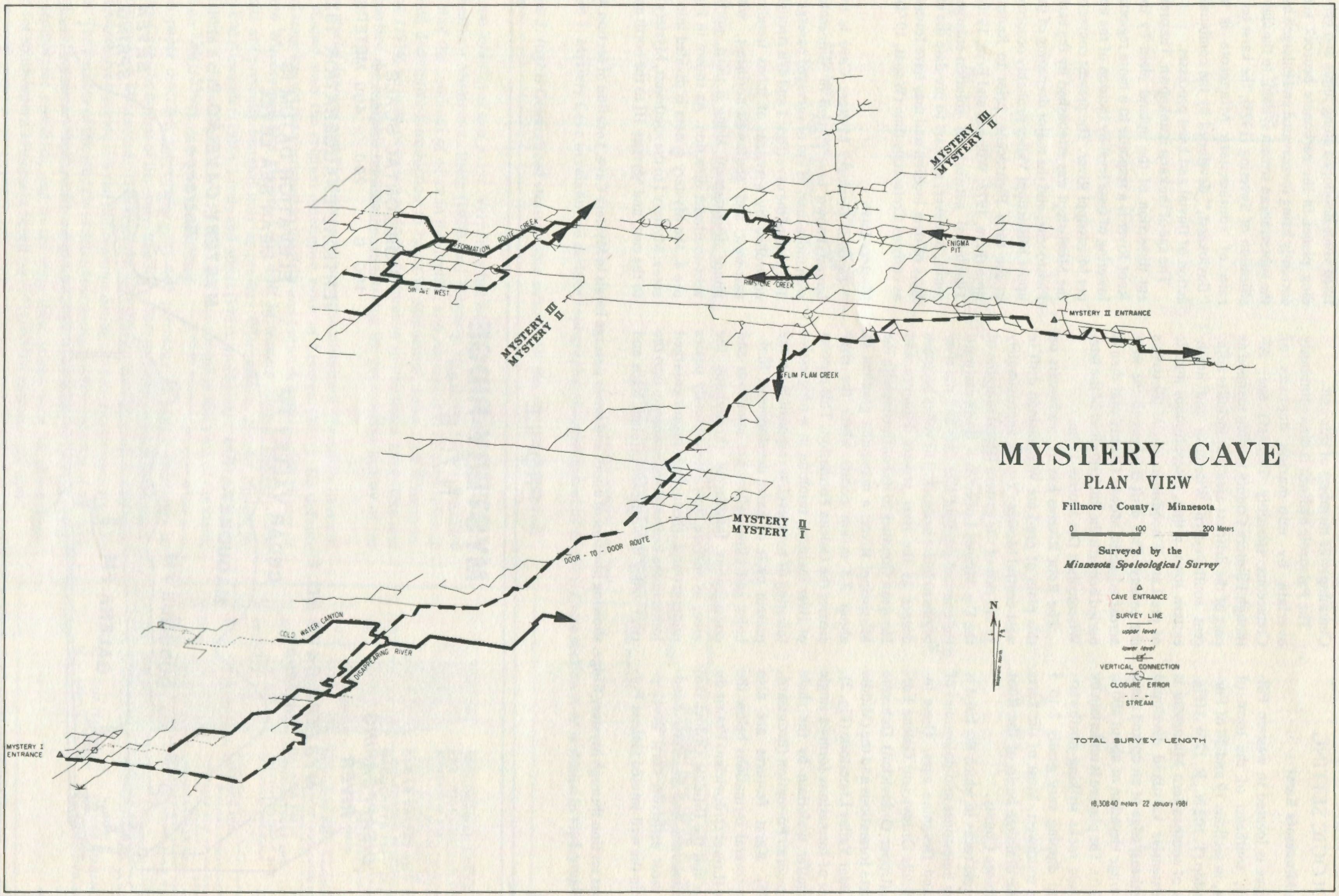


Figure 4. **Sediment sampling locations in Mystery Cave.**

west. The boundaries are arbitrary and relate only to the sequence in which major portions of the system were discovered and explored. Two artificial entrances have been constructed at the southwest and east ends of the cave.

The cave lies within a ridge flanking a meander loop of the South Branch of the Root River (figs. 1 and 3). The river utilizes the cave as a subterranean meander cutoff, entering the cave through a series of stream sinks within a half km of the southwest entrance (Mystery I). The stream flows north and east through the cave, then resurges in its surface valley at Seven Springs, 2.5 km to the northeast. From sinkpoints to resurgence, the river bypasses 8 km of its surface valley and drops 16 to 19 m in elevation. Under low flow conditions, this bypassed segment of the valley is dry. Dye trace studies have confirmed the stream sink to spring connections and have also identified a complex network of at least 3 integrated stream systems within the cave (Alexander, 1980; Mohring, 1983).

Stratigraphically, the cave system extends from the top of the Dubuque Formation to the lower Stewartville Member of the Galena Formation (figs. 2 and 3), a total vertical distance of 30 to 35 m. In cross section, the cave consists of 2 roughly horizontal passage levels at elevations of 370 to 380 m and ~ 360 m. The upper level (370 to 380 m) is a network of phreatic tubes developed at the contact of the Dubuque Formation and the underlying Stewartville Member. Although the contact is lithologically gradational, it can be recognized throughout the cave by the presence of 5 ripple-bedded limestone beds separated by thin (less than 1 cm) shale partings. Above these beds occur the typical alternating limestones and shales of the Dubuque Formation. Below these beds, the limestone grades into a crinoidal, dolomitic limestone with a few, thin shale partings and then into the typical massive, worm-burrowed dolostone of the Stewartville Member. Upper level passages are characteristically elliptical to keyhole shaped and are often one to several meters or more in diameter.

The major passages of the upper level system are developed along joints trending east-west; the largest passages of this type are Fourth Avenue and Fifth Avenue in Mystery II, and Eureka Avenue and Fifth Avenue West in Mystery III (Fig. 4). The Door-to-Door Route, which connects the southwest and northeast entrances, is the other major upper level phreatic tube. The slope of the passage, from southwest to northeast, cuts across bedding, from the lower Dubuque at the southwest entrance through the contact zone to the upper Stewartville at the northeast entrance (Fig. 3), suggesting that the major controls on the development of passage levels are hydrologic as well as lithologic.

The highest passages in the upper level have developed by upward migration of the original phreatic tubes through progressive collapse of the ceiling rock. The Dubuque Formation with its alternating limestone and poorly cemented shale beds is very susceptible to collapse, especially in passages which contain ceiling joints, and most passages developed in the Dubuque have been altered to some extent by this process. In the Cathedral Room, at the southwest end of the cave system, this upward migration has progressed through the Dubuque to the bottom of the overlying Maquoketa Formation, which forms the ceiling of the passage. Passages formed by ceiling collapse have a characteristic rectangular, flat-roofed cross section floored by breakdown blocks, with walls devoid of scallops or other solution features.

The lower passage level (~ 360 m) occurs entirely within the Stewartville Member, a massive, poorly bedded, relatively pure dolomitic limestone and dolostone. Lower level passages developed in the Stewartville are narrow, vertical, joint-controlled crevices as much as 15 m deep and usually less than 1 m wide. The walls of these crevices have a characteristic rough, pitted texture due to the high dolomite content of the rock and the abundance of fossilized worm burrows, which are slightly more resistant to weathering than the matrix.

The lower level contains a complex network of interconnecting streams which follow sinuous, multidirectional paths through the maze of narrow crevices and ultimately emerge in the surface valley at Seven Springs, northeast of the cave. This system includes Formation Route Creek and its upper level tributary Sand Creek in Mystery III, Rimstone Creek near the north boundary of Mystery II and III, Flim Flam Creek at the north end of the Door-to-Door Route, and the Disappearing River-Coldwater Canyon system in Mystery I (Fig. 4). The lowest levels of this underground drainage network lie within a few meters of base level at the resurgence point; this relationship is shown schematically in Figure 3. The accessible passages of the lower level are only a small portion of a much larger network of solution-enlarged joints.

In some areas of the cave, the upper and lower levels are connected over long distances by development along a common joint. The resulting passage has the form of a wide, elliptical- to keyhole-shaped tube floored by a deep, narrow crevice which is often partially or completely filled with sediment or breakdown (Fig. 5). Joints developed in one formation, however, do not always continue into adjacent bedrock units, so in many parts of the cave the two levels occupy separate, often roughly parallel joint systems and are connected only at joint intersections.

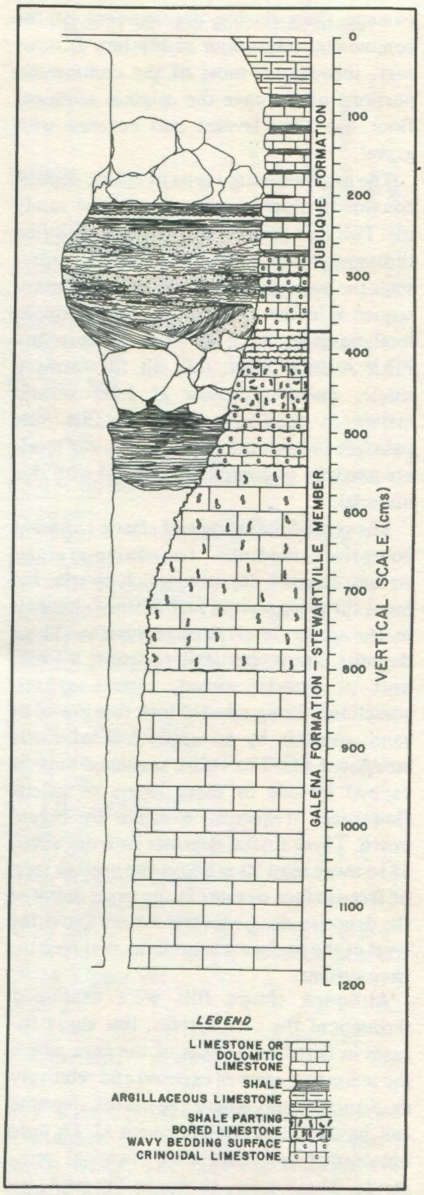


***Figure 5.* Cross section through the east end of Enigma Pit, showing bedrock stratigraphy and position of sediment fill.**

Distribution of Clastic Sediments. The cave contains a complex assemblage of clastic sedimentary deposits. These sediments form the present natural floor of many upper level passages, the bedrock floor being often buried. Vertical exposures of the sediment are often uncommon and are generally confined to passage intersections, where a down-cutting stream has cut across a sediment-filled passage and exposed a section of the fill. Clastic deposits have also been exposed by artificial trenching of the passage floor during development of the commercial tour route in Mystery I; however, throughout most of the commercial portions of the cave the original sediment floor has been leveled and covered with gravel.

The most abundant type of clastic deposit consists of finely laminated silt and sandy silt. This fine-grained fill, widely distributed throughout the entire cave system, represents the basal clastic unit of the sedimentary sequence in the cave. In the largest upper level passages, such as Fifth Avenue and Fifth Avenue West, this silt fill forms a single, massive deposit at least several meters in thickness. Many smaller side passages in both the upper and lower levels are partially or completely choked with this material.

The second major type of clastic sediment comprises medium- to coarse-grained stream channel deposits which overlie the basal silt along several well-defined channels in the upper level passage system. These deposits characteristically contain a lower unit of poorly sorted, coarse gravel, sometimes fining upward into fine gravel or sand, overlain by an upper unit of finely laminated silt. The entire sequence may be capped by one or more layers of calcite flowstone, frequently overlain by breakdown. These fluvial deposits lie from about 15 to more than 20 m above the present level of free-surface streams in the cave; many of the deposits also lie several meters above the level of the surface stream sinks that feed the cave system.

Although clastic fills were examined throughout the cave system, this study focuses in detail on 3 areas of the cave where the sediments are well exposed and relatively undisturbed and where the clastic deposits can be directly correlated with U/Th ages obtained from associated chemical sediments. These areas, shown in Figure 4, include Enigma Pit in Mystery II; the Door-to-Door Route, extending from the southwest end of Mystery I to the northeast end of Mystery II; and the Fifth Avenue West area at the west end of Mystery III. The sediments studied in these areas are representative of the major types of clastic deposits in the cave.

SAMPLING AND LABORATORY PROCEDURES

Sample Collection

Samples were collected from undisturbed deposits exposed by post-depositional stream erosion or by trenching into the passage floor. Locations of 37 sediment samples collected in Mystery Cave are shown in Figure 4.

Analysis of Sediment Samples

Sediment samples were analyzed for grain size, pebble composition, heavy and light mineral composition, and silt and clay mineralogy. Grain size analyses were carried out by dry sieving (coarse fraction) and settling tube analysis (fine fraction). Pebble counts were obtained from the gravel samples using a minimum sample size of 100 grains in the 2 to 64 mm (granule and pebble) fraction. Heavy and light mineral counts were obtained from the 0.25 to 0.64 mm (fine and very fine sand) fraction. A minimum of 300 grains were counted for each heavy mineral sample; light mineral percentages were estimated. Silt and clay mineralogy was determined qualitatively by X-ray diffraction using nickel-filtered copper Kα radiation. A detailed description of laboratory procedures is presented in Milske (1982). Pebble counts, heavy and light mineral counts, and silt and clay composition for samples discussed in this paper are tabulated in Tables 1 to 3.

Speleothem Age Determinations

Sampling of clastic sediments was carried out in conjunction with collection of associated speleothem samples for $^{234}U/^{230}Th$ radioisotope dating. Samples were dated by one of us (R.S.L.) using standard analytical procedures modified from Thompson (1973). Some of these data are presented in Lively and Alexander (1980), Lively, *et al.* (1981), and Lively (1983). Locations and calculated ages for samples discussed in this paper are given in Table 4 and in the Appendix. All of the ages in this paper are reported in units of kiloanno (ka). A kiloannum is one thousand years (10^3 years).

SOURCES OF CLASTIC CAVE SEDIMENTS

A number of classification systems have been proposed for clastic sedimentary deposits in caves, and no single system has received general acceptance. These are summarized by Wolfe (1973). The classification used here is that of Kukla and Lozek (1958). It separates the components of clastic cave deposits into two categories:

1) *autochthonous material*—originating inside the cave system: includes breakdown, and sediments derived from solution and abrasion of the walls, floors and ceilings of cave passages;

2) *allochthonous material*—originating outside the cave system and mechanically transported into the cave.

Autochthonous Sediment Sources

The primary autochthonous sources of detrital sediment in Mystery Cave are the limestone and shale of the Dubuque Formation and the dolomitic limestone of the underlying Stewartville Member of the Galena Formation. The Stewartville Member contains a very small (2 to 3 percent) insoluble residue composed of clay and siliceous silt with very little pyrite, as well as variable amounts of siliceous fossil debris (Weiss, 1957). The limestone beds of the Dubuque Formation contain an average of 10 percent insoluble residue, composed primarily of clay with a small amount of pyrite (Weiss, 1957). Chert is not present in either unit, although nodular chert is abundant in the Prosser Member underlying the Stewartville (Weiss, 1957).

The limestone of the Dubuque Formation is interbedded with friable, gray, calcareous

Table 1. Pebble Composition (in percent by count) of Gravel Samples From Mystery Cave.

Sample	Quartz	Chert	Feldspar	Granitic	Metamorphic	Basaltic*	Quartzite	Sandstone	Limestone	Limonite	Fossils	Other	No. of pebbles counted
ENIGMA PIT													
CS-17F: Upper gravel	9	4	2	12	tr	tr			43	25	4		206
CS-17K: Lower gravel	25	9	1	13		tr	tr		33	15	1	1	279
DOOR-TO-DOOR ROUTE													
CS-21	36	14	2	12	5		3	tr	2	24	tr	1	249
CS-10	45	7	2	15	2	1			2	24	tr	2	185
CS-11	16	8	5	21	2				4	28	8	2	132
CS-12	25	3	7	18	2	2	tr		2	38	1	2	166
CS-7	30	12	2	4	tr	tr			1	49	1		185
CS-26	40	9	4	23	4	1			2	15	tr	2	171
CS-15	37	10	tr	5	1	tr	tr		tr	42		2	249
CS-16	34	4	1	4	2	3			tr	49	tr	1	152
FIFTH AVENUE WEST													
CS-25	30	8	3	13	tr	tr			tr	44			226

tr = less than 1%.
* = includes basalt, greenstone, gabbro, and diabase.

Table 2. Distribution of Heavy and Light Minerals in Study Sediments.

Sample	*heavy*															*light*		
	Opaque	Zircon	Tourmaline	Garnet	Hornblende	Staurolite	Rutile	Sphene	Anatase	Pyroxene	Epidote	Kyanite	Apatite	Other	No. of grains counted	Q'tz + Fels.	Cal. + Dol.	Other
SS-311: Wisconsinan till; Steele Co.	35	tr	1	14	34	1	tr			1	8		2	2	495	95		5
SS-303: Loess, Mystery Ridge	48	tr	2	16	18	6	tr			tr	5		tr	1	446	97		3
SS-309: Channel sand, S. Branch Root River	65	1	tr	13	12	2		tr		tr	3		tr	1	386	93	tr	7
CS-6: Dubuque Shale	90	3		2	2		tr	tr			tr			1	310	1	95	4
ENIGMA PIT																		
CS-17A: Upper silt	96	tr					3				tr			tr	379	1	95	4
CS-17F: Upper gravel	73	4		4	12		tr	2			1	tr		2	344	75	15	10
CS-17K: Lower gravel	69	6	1	3	13	1	tr	tr	tr		2	tr	tr	1	355	80	10	10
CS-17L: Lower silt	84	1	tr	1	7	tr	1	tr		tr	2			2	315	50	20	30
FORMATION ROUTE CREEK:																		
CS-2	69	2	2	2	16			tr			5	1		2	357	94	4	2
DOOR-TO-DOOR ROUTE																		
CS-21: Gravel	74	7	1	5	6	tr		2		tr	2		tr	2	301	93	2	5
CS-10: Gravel	66	4	1	8	7	2	5	4			tr			1	420	84	1	15
CS-11: Sand	54	8	2	7	14		8	3		tr	tr		1	1	339	98	tr	2
CS-12: Gravel	74	4	1	8	7		4	tr	tr		tr	tr		1	334	60	tr	40
CS-13: Silt	60	8	2	2	18		6	2			2	tr		1	342	48	50	2
CS-7: Gravel	73	5		9	6	2	2	3			tr			1	401	97	tr	3
CS-26: Gravel	66	5	tr	7	12	tr	2	3			2	tr		2	332	68	30	2
CS-15: Gravel	70	5	3	1	12	tr	3	3			tr		tr	1	384	96	tr	4
CS-16: Gravel	64	7	1	8	12	tr	1	2	tr	tr	tr		tr	1	383	96	tr	4
CS-3: Gravel	55	6	1	11	18	2	1	1		tr	2	tr	tr	1	349	92	5	3
FIFTH AVENUE WEST:																		
CS-23: Lower silt	67	4	tr	3	18	tr	2	1		tr	1	tr	tr	1	355	52	45	3
CS-24: Upper silt	64	10	tr	3	13	tr	3	tr		1	tr	tr	2	1	555	57	40	3
CS-25: Gravel	54	5	1	8	25	1	2	tr		tr	1		1	1	385	97	1	2

tr = less than 1%.
Heavy minerals in percent by count; light mineral percentages estimated.

Table 3. Silt and Clay Mineralogy of Study Sediments.

Sample	Quartz	Feldspar	Calcite	Dolomite	Illite	Montmorillonite	Kaolinite	Chlorite
CS-6: Dubuque shale								
<20 μm	x	–	x	x	x	–	–	x
< 2 μm	x	–	x	x	x	–	–	x
SS-303: Loess								
<20 μm	x	x	–	x	x	x	x	x
< 2 μm	x	x	–	x	x	x	x	x
SS-310: Soil								
<20 μm	x	x	–	–	x	x	x	x
< 2 μm	x	–	–	–	x	x	x	x
DOOR-TO-DOOR ROUTE:								
CS-13: Bomb Shelter								
<20 μm	x	x	–	x	–	–	–	–
< 2 μm	x	–	–	x	x	x	–	x
ENIGMA PIT								
CS-17A: Upper silt								
<20 μm	x	x	x	x	x	–	–	x
< 2 μm	x	–	–	x	x	–	–	x
CS-17F: Upper gravel								
<20 μm	x	x	–	–	–	–	–	–
< 2 μm	x	–	–	–	x	x	x	x
CS-17J: Middle silt								
<20 μm	x	x	x?	x?	x	–	x	x
< 2 μm	x	–	–	–	x	x	x	x
CS-17L: Lower silt								
<20 μm	x	x	–	x	–	–	–	–
< 2 μm	–	–	–	–	x	x	x	x
FIFTH AVENUE WEST								
CS-23: Lower silt								
<20 μm	x	x	–	x	x	x	x	x
< 2 μm	x	–	–	–	x	x	x	x
CS-24: Upper silt								
<20 μm	x	x?	–	–	x	x	x	x
< 2 μm	x	–	–	–	x	x	x	x

x = present, – = absent

shale beds varying in thickness from less than 1 cm to about 50 cm. The shale is very soft when wet and erodes easily from the walls and ceilings of passages developed in the Dubuque. A sample of this shale collected from the wall of a passage developed in the lower Dubuque is primarily a silty clay with a small amount of fine and very fine sand. The sand fraction consists of 95 percent irregular aggregates of calcite and rhombohedral dolomite, with about 1 percent fine-grained, angular quartz and 4 percent pyrite and other opaque minerals (Table 2). The silt and clay fraction is composed of quartz, dolomite, and the clay minerals illite and chlorite.

The shale contains a very sparse suite of heavy minerals dominated by opaque grains, many of which appear to be aggregates of silt-sized calcite and dolomite. Transparent minerals constitute only 10 percent of the total. Of these, zircon is most abundant, occurring primarily as very small, colorless, well rounded grains. About 10 percent of the zircons are larger and subhedral in shape. Dark green, well rounded hornblende grains and pale pink to deep pink garnets are also present, as are trace amounts of well rounded rutile, sphene, and epidote.

Allochthonous Sediment Sources

Cretaceous deposits. The (Cretaceous) Windrow Formation is exposed in several gravel pits and iron ore strip mines south and east of the town of Spring Valley, on the ridges flanking the Root River west of Mystery Cave. The mineralogy of the Windrow Formation is in most cases distinctive enough to distinguish it from the younger, glacial deposits. The following description is based on a study by Andrews (1958).

In western Fillmore County, the Windrow Formation can be divided into two lithologically distinct members. The upper, East Bluff Member is a sequence of silty clay, sand, and gravel averaging up to 6 m in thickness. The maximum thickness of this unit (exceeding 6.4 m) is observed at Ostrander, Minnesota, approximately 11 km west of Mystery Cave. The diagnostic facies of the member grades from a coarse sand to a peanut gravel composed exclusively of chert and quartz pebbles in an average ratio of approximately 1:1. The pebbles characteristically have moderately to very highly polished surfaces. The term 'Ostrander gravel' refers to this coarse clastic facies. The sand-size fraction contains primarily quartz, with lesser amounts of chert and occasionally white, kaolinized feldspar. The degree of cementation of the sands and gravels is variable, but, where present, the cementing material is always limonite (microcrystalline goethite).

The heavy mineral suite of the East Bluff sediments is dominated by the opaque minerals leucoxene, rutile, and ilmenite. The most abundant translucent minerals are zircon and hyacinth zircon, mostly well rounded but occasionally subhedral, and both green and brown tourmaline. Rutile and staurolite are present in small but persistent amounts, and trace amounts of kyanite and garnet occur in some deposits.

The lower, Iron Hill Member of the Windrow Formation is a concretionary iron oxide deposit consisting of nearly structureless masses of well-indurated to very soft limonite (primarily microcrystalline goethite and

Table 4. Uranium Concentrations, Activity Ratios, and Calculated Ages of Speleothem Samples from Mystery Cave.*

Sample	U ppm	$\frac{^{234}U}{^{238}U}$	$\frac{^{230}Th}{^{234}U}$	$\frac{^{230}Th}{^{232}Th}$	Age (ka)	Sample and location
MC-4a	0.2	1.975 ± .108	0.854 ± .039	53	161 ± 14	W end 5th Ave. stalag. bottom
MC-4hg	0.2	2.151 ± .082	0.743 ± .027	76	124 ± 7	W end 5th Ave. stalag. top
MC-5(avg)	0.2	2.530 ± .271	0.663 ± .031	25	104 ± 8	W end 5th Ave. flowstone
MC-6	0.1	2.101 ± .085	0.845 ± .028	31	158 ± 10	W end 5th Ave. flowstone
MC-11a	0.3	1.309 ± .037	0.761 ± .024	125	142 ± 9	Enigma Pit drapery (inner)
MC-11b	0.3	1.477 ± .022	0.730 ± .018	40	128 ± 6	Enigma Pit drapery (outer)
MC-13	0.3	1.512 ± .027	0.634 ± .015	31	101 ± 4	Enigma Pit upper flowstone
MC-14	0.8	1.337 ± .048	0.701 ± .035	37	122 ± 11	Enigma Pit middle flowstone
MC-16	5.9	1.473 ± .011	0.781 ± .028	224	146 ± 10	Enigma Pit lower flowstone
MC-17	0.7	1.508 ± .045	0.664 ± .021	11	109 ± 6	4th Ave. rimstone
MC-18	0.6	1.285 ± .019	0.696 ± .019	177	121 ± 6	4th Ave. rimstone
MC-20a	0.1	2.625 ± .149	0.805 ± .037	37	141 ± 11	W end 5th Ave. stalag. bottom
MC-20b	0.2	2.411 ± .074	0.674 ± .019	46	106 ± 5	W end 5th Ave. stalag. top
MC-26	1.4	1.330 ± .018	0.691 ± .016	70	119 ± 5	4th Ave. rimstone
MC-19a	0.1	4.094 ± .455	0.456 ± .031	6	61 ± 5	W end 5th Ave. stalag. bottom
MC-19b	0.1	4.404 ± .405	0.434 ± .033	11	57 ± 5	W end 5th Ave. stal. low. mid.
MC-19c	0.1	4.208 ± .267	0.303 ± .014	15	38 ± 2	W end 5th Ave. stalag. middle
MC-19d	0.1	4.760 ± .375	0.291 ± .017	15	36 ± 2	W end 5th Ave. stalag. top
MC-21	2.0	1.929 ± .033	0.324 ± .008	29	41 ± 1	Mud Slide stalactite
MC-1	1.2	1.596 ± .023	0.106 ± .003	1000	12.1 ± 0.3	Angel Loop flowstone
MC-7	1.4	1.380 ± .025	0.106 ± .003	5	12.2 ± 0.4	Bomb Shelter flowstone bottom
MC-8	0.6	1.407 ± .004	0.085 ± .004	12	9.6 ± 0.5	Bomb Shelter flowstone middle
MC-9	0.4	1.495 ± .028	0.069 ± .004	11	7.7 ± 0.4	Bomb Shelter flowstone top
MC-24	1.7	1.674 ± .025	0.076 ± .004	6	8.6 ± 0.5	Wind Tunnel stalagmite
MC-25	1.6	1.766 ± .025	0.105 ± .033	17	12.0 ± 0.4	Wind Tunnel stalag. bottom
MC-25b	1.2	1.611 ± .047	0.111 ± .005	6	12.7 ± 0.6	Wind Tunnel stalagmite top
MC-27	1.6	2.012 ± .039	0.114 ± .005	3	13.0 ± 0.6	Discovery Route flowstone
MC-28a	1.2	1.958 ± .028	0.054 ± .003	37	6.0 ± 0.4	E end Eureka Ave. stalag. bottom
MC-28b	0.9	1.979 ± .037	0.031 ± .001	25	3.4 ± 0.1	E end Eureka Ave. stalag. middle
MC-28c	0.9	2.018 ± .030	0.018 ± .001	14	2.0 ± 0.1	E end Eureka Ave. stalag. top
MC-28d	0.8	2.047 ± .029	0.005 ± .001	2	0.5 ± 0.1	E end Eureka Ave. stalagmite
MC-29	2.2	1.399 ± .015	0.107 ± .003	22	12.2 ± 0.4	Commercial Route 1 flowstone

*Calculated ages based on the following values for λ: ^{234}U, 2.794×10^{-6} yr^{-1}; ^{230}Th, 9.215×10^{-6} yr^{-1}; ^{228}Th, $9.92 \times 10^{-4} d^{-1}$; ^{224}Ra, $1.904 \times 10^{-1} d^{-1}$. All samples have been corrected for detrital ^{230}Th activity using a $^{230}Th/^{232}Th$ detrital ratio of 1.45 at $t = 0$. Data from Lively (1983).

hematite). The ore has a manganese content ranging from 0.5 percent to more than 2.0 percent by weight, reflected in the color of the ore, which varies from bright yellow to very dark brown. The insoluble residue of the ore consists of silt-sized quartz, pyrite, and the clay mineral illite (Bleifuss, 1972).

The Iron Hill Member is exposed in an abandoned strip mine in the NW ¼ of sec. 20 (Fig. 1). Here, all but the lower 1 to 2 m of the deposit has been eroded or mined away, and the underlying Cedar Valley Limestone is exposed in several places at the bottom of the easternmost of a series of shallow pits. The deposit is overlain by about 1 m of loess capped by a thin mantle of soil. A sample of ore collected from the bottom 1 m of the deposit consists of concretionary reddish brown to dark brown limonite with a residue of fine quartz sand and silt. The heavy minerals recovered from the sample consist exclusively of angular, dark opaque fragments which break down readily to a fine, reddish-brown powder. The light mineral fraction contains only quartz. Attempts to determine the mineralogy of the clay fraction by X-ray diffraction methods proved inconclusive, due to the difficulty of separating the clay minerals from the iron oxides in the sample.

Glacial deposits (Pre-Late Wisconsinan deposits). The pre-Late Wisconsinan Old Gray glacial drift, which occurs as patchy remnant deposits across western Fillmore County, has received little attention since the early work of Leverett (1932). The drift has been tentatively correlated with similar deposits in northeastern Iowa identified as Kansan in age by Ruhe (1969). The age of the drift in southeastern Minnesota is uncertain because stratigraphic control is lacking, and Kansan sediments cannot be distinguished from those of Nebraskan age on the basis of lithology alone (Wright and Ruhe, 1965). Post-Kansan drift has not been reported from Fillmore County, which was apparently unglaciated during the Illinoian and Wisconsinan stages.

The older drifts can, however, be distinguished from the underlying Cretaceous deposits on the basis of pebble lithology, clay mineralogy, and heavy mineral content. In the glacial sediments, a wide variety of pebble lithologies are represented, dominated by granitic, basaltic, and metamorphic rock fragments. Limestone and dolomite pebbles are abundant in unweathered deposits, although in southeastern Minnesota the till has been extensively leached of carbonates. Where present, the limestone pebbles tend to be very soft and are easily crushed to a fine powder. Blue-gray Cretaceous shale pebbles, which are characteristic of Wisconsinan (Des Moines Lobe) till in southern Minnesota, are not present in the older drifts.

The heavy mineral suite of the Kansan till is dominated by the translucent minerals hornblende, garnet, pyroxene, epidote, and zircon, and the opaque minerals pyrite, magnetite, and ilmenite (Kay and Apfel, 1929). This wide variety of mineral species, characteristic of glacial deposits in general, serves to distinguish these sediments from primary Cretaceous sand deposits, which can otherwise be very similar in appearance.

Glacial deposits (Loess and Alluvium). The drift is overlain by a blanket of loess that thickens eastward toward the Mississippi River. In adjacent northeastern Iowa, this loess yields ^{14}C dates of 29 000 to 16 500 YBP (Wright, 1972). In the area of Mystery Cave, the loess is a sandy silt composed of well rounded to angular quartz and feldspar. Dolomite is absent from the sand fraction, but is present in the silt and clay fraction along with quartz, feldspar, and the clay minerals illite, montmorillonite, kaolinite, and chlorite. The soil developed on the loess is a silt loam composed of quartz, feldspar, trace amounts of calcite and dolomite, illite, montmorillonite, kaolinite, and chlorite.

In the heavy mineral fraction of the loess, opaque grains make up nearly half the total count. The opaques are very clean and generally well rounded, without the irregular, powdery appearance characteristic of the opaques in the limonite-cemented Cretaceous sands. Well rounded hornblende is abundant and both green and brown, well rounded tourmalines are present. The deficiency of zircons, the great abundance and variety of garnets (colors ranging from colorless through pale pink to deep salmon pink), and the relative abundance of staurolite are most notable. Hornblende and garnet are both common detrital minerals in the glacial deposits of southern Minnesota and Iowa, but in these deposits the ultrastable mineral zircon is also persistently present and staurolite is generally uncommon.

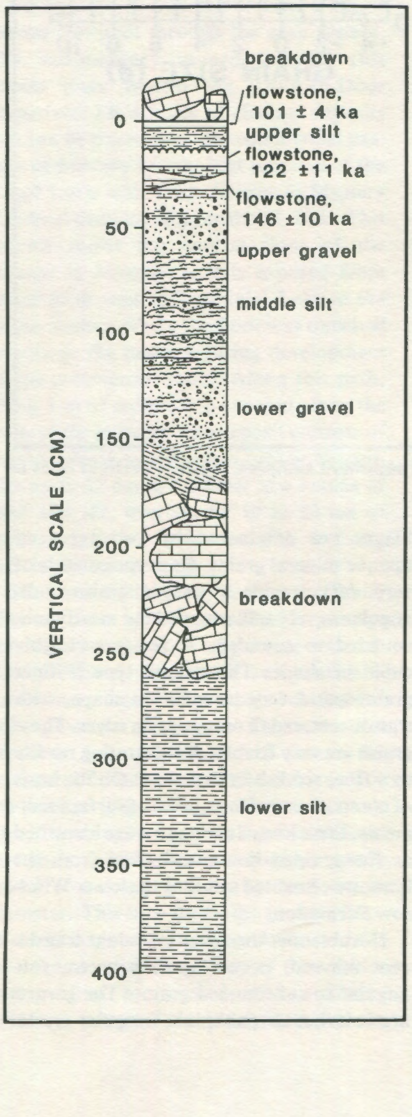
An assemblage of both heavy and light minerals very similar to that of the loess occurs in the fine and very fine sand fraction in the present bedload of the Root River where it sinks underground at the entrance to Mystery I. The only apparent difference between these samples is a slightly higher percentage of opaques in the river sand, with a corresponding decrease in the proportions of translucent minerals. A similar heavy mineral suite is also seen in a sample of glacial sand from the eastern edge of the (Wisconsinan) Des Moines Lobe in southeastern Steele County. The amounts of zircon and garnet are approximately the same, and the opaques are similar in shape and appearance. The sample contains a smaller percentage of opaques, however, and a higher percentage of epidote, apatite, and, especially, hornblende, which has a very fresh, unweathered appearance. With the exception of the zircons, which are very small and well rounded, all the mineral grains in the glacial sand are more angular and appear to have undergone less abrasion than the grains in the loess and loess-derived alluvium.

ENIGMA PIT SEDIMENTS

Enigma Pit is located in the northeast portion of the cave system, near the northern boundary of Mystery II and III (Fig. 4). The pit is developed in an east-west trending passage at the contact of the Dubuque and Galena formations. The passage was at one time filled with sediment and breakdown to within about a meter of the ceiling, but a small waterfall entering the passage along a Dubuque shale parting in the north wall has locally excavated the fill and eroded the wall rock to form the pit. A measured cross section through the east end of the pit (Fig. 5) illustrates the characteristic shape of upper level Dubuque passages and of lower level Stewartville passages. Erosion of the fill by the waterfall has exposed a section of unconsolidated sediment 3 m thick at the east end of the pit (figs. 5 and 6).

The lowest unit in the section is a dark brown, very thinly plane-laminated mud consisting of alternating layers of coarse to medium silt and fine silt to clay. The individual laminae are 1 mm or less in thickness. This unit, the lower silt of Figure 6, is overlain by a 1 m thick pile of breakdown consisting of angular blocks of Dubuque limestone which have collapsed from the upper walls and ceiling of the passage. The breakdown is overlain by a 1.7 m thick sequence of interbedded sand, silt and gravel fining upward into finely laminated silt capped by flowstone. This sequence is roughly divided into 4 clastic units having gradational contacts: the lower gravel, middle silt, upper gravel, and upper silt beds of Figure 6. Both gravel units are very silty, and the intervening silt bed contains numerous thin lenses of sand and fine gravel. The clastic sequence as a whole appears to have been deposited by a rapidly aggrading, meandering stream.

***Figure* 6. Stratigraphic section of the Enigma Pit sediments.**



Like the lower silt unit, the middle and upper silts are very finely laminated, although individual laminae are somewhat thicker (0.5 to 2 mm). The laminae consist of alternating layers of light brown fine sand to coarse silt, and dark brown medium silt to fine clay. The middle silt contains ripple marks and very small scale cross-bedding; the lower and upper silts are plane-laminated. The gravel units have no well developed bedding structure.

Grain Size and Composition of the Enigma Pit Sediments

Grain size histograms for Enigma Pit sediment samples are shown in Figure 7. Both the middle and upper silts show a unimodal size distribution. The middle silt has both a mean and a modal diameter in the medium silt range; the upper silt has a strongly fine-skewed distribution, with a mean diameter of medium silt but a modal diameter in the coarse silt range. The lower silt shows a bimodal size distribution, with a principal mode in the medium silt range and small secondary mode in the medium clay size interval. Both the upper and lower gravel units are extremely poorly sorted, with modal diameters in the medium sand and medium silt size intervals and a possible third mode in the coarse to medium clay fraction. The upper gravel has an additional mode in the medium pebble range and a corresponding deficiency in granules and very coarse sand, a distribution pattern characteristic of fluvial deposits (Pettijohn, 1975).

The pebble and granule fraction of both the upper and the lower gravel is dominated by subrounded to well rounded fragments of limestone and dolostone that have been partially or entirely leached of carbonate. These pebbles have a white, bleached appearance and the texture of a soft, friable shale. These leached grains constitute more than a third of the gravel fraction. A few of the carbon-

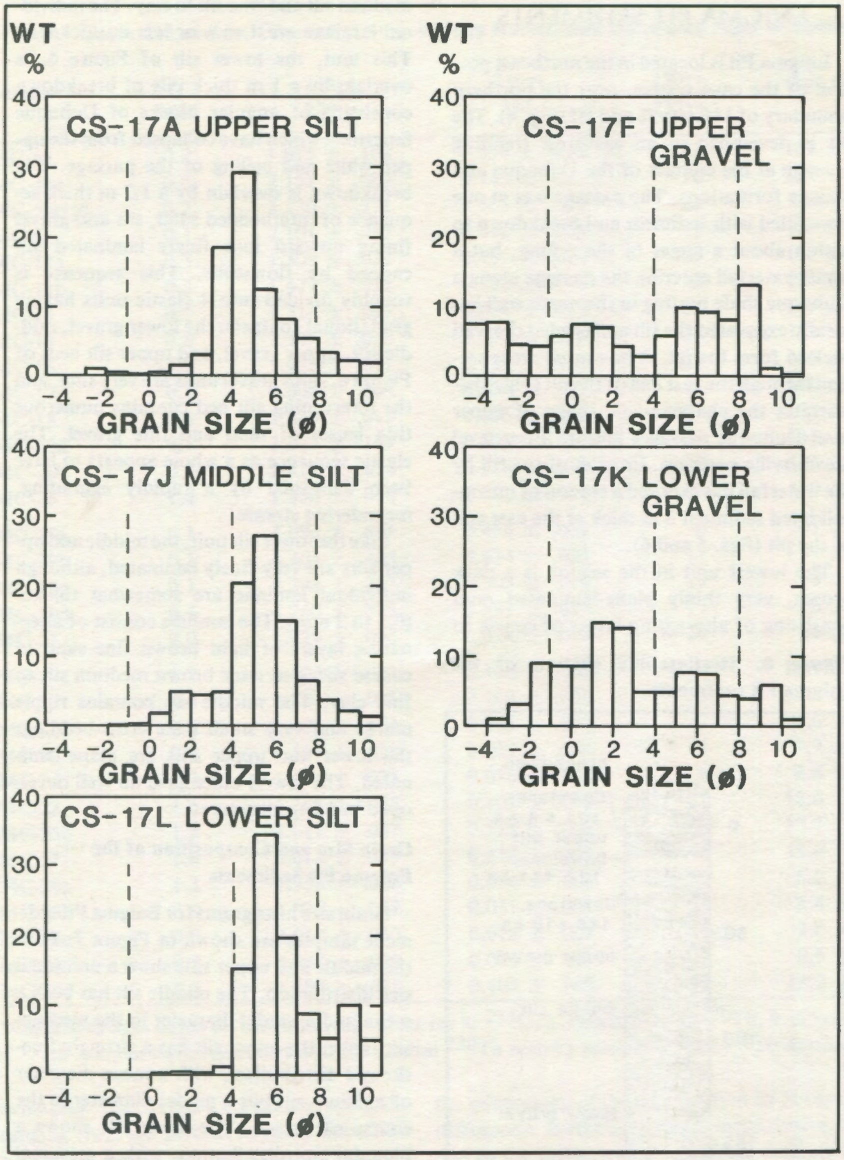


Figure 7. **Grain size distributions of Enigma Pit sediment samples. Dashed vertical lines indicate gravel, sand, silt, and clay size intervals.**

ate fragments contain siliceous fossils of crinoids and brachiopods. Brachiopod specimens in the gravel fraction include the species *Paucicrura corpulenta* (Sardeson) and *Sowerbyella recedens* (Sardeson), both found in the Maquoketa and uppermost Dubuque Formations (Weiss, 1953). The remainder of the gravel fraction consists primarily of angular to subrounded limonite, subangular granitic rock fragments, and subrounded to very well rounded quartz and chert pebbles. The chert grains are mostly dark green to brown, occasionally white or pink. The surface texture of both the quartz and chert pebbles varies from frosted and pitted to very smooth and highly polished.

The heavy mineral suites of the upper and lower gravels are very similar. Both assemblages are dominated by two types of opaque mineral grains. One type consists of very dark, regularly shaped grains, subangular to very well rounded but mostly subrounded to rounded. A few are roughly cubic in shape. The second type is finer grained and very irregular in shape, with translucent, red to orange grain edges. These grains are very friable, disintegrating readily to a fine, reddish orange dust. On the basis of comparisons with samples of surface sediments, these irregular opaques are identified as fine-grained limonite derived from the limonite-cemented sands of the lower Windrow Formation.

Hornblende, the most abundant translucent mineral, occurs as dark green, subangular to subrounded grains. The garnets are colorless or pale pink, irregular crystal fragments with conchoidally fractured edges. The zircons occur in two distinct populations. One type consists of very well rounded, subspherical, clear grains and the second of slightly worn, euhedral, inclusion-filled, prismatic crystals varying in color from colorless to violet pink. Several other minerals each constitute 2 percent or less of the sample.

The lower silt contains a similarly diverse suite of heavy minerals, including limonite and other opaques, well rounded, dark-green hornblende, pale-pink garnet, and large, very well rounded zircons. Euhedral zircon is not present in this unit. In contrast to the gravels and lower silt, the upper silt unit has a very sparse heavy-mineral assemblage, containing only opaques (primarily limonite), red, well rounded rutile, and trace amounts of zircon and epidote.

The light mineral fractions of the upper and lower gravel units are dominated by subangular to rounded quartz and feldspar, with a small amount (10 to 15 percent) of rhombohedral dolomite. Approximately 10 percent of these samples consists of fine-grained limonite, probably as a result of contamination by the heavy fraction during separation. The lower silt shows a similar composition, with slightly higher percentages of dolomite and fine opaques. In contrast, the sand fraction of the upper silt consists almost entirely of dolomite rhombs and irregular aggregates of calcite, with only a few percent of subangular, very fine-grained quartz.

The silt and clay fraction of the middle and lower silt beds contains quartz, feldspar, a small amount of silt-sized dolomite, and a diverse suite of clay minerals including illite, montmorillonite, kaolinite, and chlorite. The gravel sample shows the same mineral assemblage, except that dolomite is absent. The mineralogy of the upper silt bed is different from that of the underlying units, in that large amounts of calcite and dolomite are present, and the clay mineral suite includes only illite and chlorite. This mineral assemblage is very similar to that of the Dubuque shale.

Age of the Enigma Pit Deposits

The Enigma Pit sediments can be directly correlated with $^{234}U/^{230}Th$ ages obtained from flowstone units that overlie the clastic deposits in the upper 35 cm of the section. The lowest flowstone, which caps the upper gravel beds, yields an age of 146 ± 10 ka (Fig. 6). A thin layer of calcite-cemented silt caps this unit and is overlain by a second flowstone yielding an age of 122 ± 11 ka. The upper surface of this middle unit exhibits a botryoidal texture, indicating precipitation beneath a standing pool of water. This flowstone is overlain by the upper silt, and the entire section is capped by a third flowstone dated at 101 ± 4 ka. A flowstone drapery that hangs from the north wall of the passage directly above the section dates from 142 ± 9 ka to 128 ± 6 ka.

These dates place only a younger age limit on the clastic deposit, and it is possible that the sediments are much older than the overlying flowstone. However, the upper 1.7 m of the deposit appears to have been deposited rapidly and continuously. It contains no evidence of a depositional hiatus; neither is there physical evidence of a hiatus between clastic deposition and onset of speleothem growth. It is therefore assumed that the channel deposit is not significantly older than the oldest flowstone age of about 145 ka. In the lower portion of the section, the transition from finely plane-laminated silt (the lower silt unit) to coarse fluvial sediments with an intervening episode of ceiling collapse might represent a significant depositional hiatus, but as yet no datable speleothems have been found within this lower clastic unit to provide a more precise minimum age for the lower silt or a maximum age for the overlying fluvial deposit.

Within the limits of analytical error, the period of speleothem growth from about 150 ka to 100 ka, correlates well with speleothem dates obtained from Fourth Avenue and Fifth Avenue. These passages are large, east-west trending, upper level conduits floored by laminated silt and breakdown. Two stalagmites collected from the west end of Fifth Avenue date from 161 ± 14 ka (bottom) to 124 ± 7 ka (top) and from 141 ± 11 ka (bottom) to 106 ± 5 ka (top). Two flowstone samples from the same area yield dates of 158 ± 10 ka and 104 ± 8 ka. Samples of rimstone from Fourth Avenue give dates ranging from 121 ± 6 ka to 109 ± 6 ka.

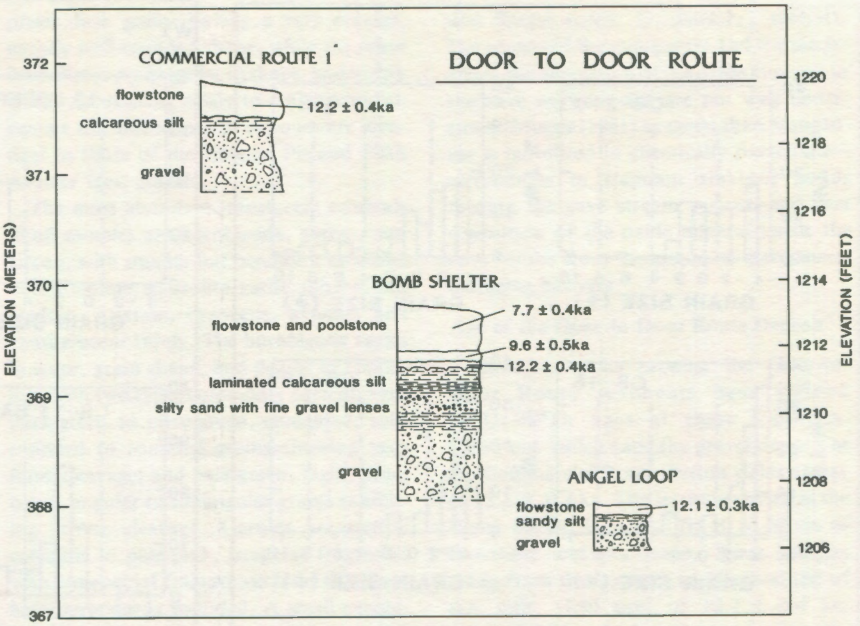


Figure 8. **Stratigraphic sections of the Door-to-Door Route sediments at the Commercial Route, Bomb Shelter, and Angel Loop localities.**

DOOR-TO-DOOR ROUTE SEDIMENTS

The Door-to-Door Route is the major southwest-northeast trending passage connecting the two cave entrances (Fig. 4). The trend of the passage is approximately perpendicular to the strike of the surrounding limestone beds, but the passage floor slopes gently downward, southwest to northeast, at about 3 m/km. The slope is opposite the northeast to southwest dip direction. The passage, therefore, extends stratigraphically from the lower Dubuque Formation at the southwest entrance to the upper Stewartville at the northeast entrance (Fig. 3). The elevation of the passage averages 12 m above the level of the Disappearing River, which follows a roughly parallel course in the lower level of the cave.

Although the Door-to-Door Route is now a dry passage, it was at one time a major vadose flowpath through the cave system. The sedimentary record left by this stream (here termed the 'Door-to-Door Paleoriver') is a series of channel deposits that can be traced from the commercial passage of Mystery I to the east junction of the Angel Loop with Fifth Avenue in Mystery II, a total distance of more than 1.2 km. This deposit forms the natural floor of the passage in Mystery I. It is exposed from about 50 m west of Turquoise Lake to the Bomb Shelter, where the floor was trenched to enlarge the passage during development of the commercial route. Along this path, about 1 m of sediment is exposed along the walls of the passage. The deposit consists of coarse, poorly sorted gravel containing cobbles up to 12 cm in diameter in a matrix of sand and silt, overlain by 10 to 25 cm of laminated, yellow flowstone (Fig. 8; Commercial Route section).

The commercial route ends at the Bomb Shelter, from which a small side passage continues northeast. The passage was originally choked with clastic sediments and flowstone, which were excavated during initial exploration of the cave. The excavation exposed a 1.5 m high section of channel deposits and flowstone along the north wall of the passage (Fig. 8; Bomb Shelter section). The lowest exposed unit in the section is an extremely poorly sorted, muddy, sandy gravel containing cobbles up to 8 cm in diameter. This unit forms the present floor of the passage and continues downward for an unknown distance. Many of the cobbles and pebbles are coated with a black, powdery, manganese oxide deposit, and the sand fraction is heavily stained with dark orange iron oxides. The unit is very poorly bedded and lacks evidence of imbrication.

The gravel fines upward into a slightly gravelly, muddy sand with lenses of sandy, fine gravel. The top of this unit is marked by a sharp contact with the overlying bed, a finely laminated silt capped by 50 to 60 cm of porous, yellow poolstone and laminated flowstone. The upper surface of the silt bed contains polygonal dessication cracks preserved as casts on the lower surface of the overlying flowstone. Both the silt bed and the poolstone are found only in the small section of passage immediately northeast of the Bomb Shelter.

The lower gravel bed continues northeast from the Bomb Shelter to the junction with Big Fork. For most of this distance, the gravel is covered by breakdown, but, immediately southwest of the junction, it is well exposed along the walls of the passage as a series of gravel bars 20 to 30 cm high. At the junction with Big Fork, the gravel disappears beneath several meters of breakdown debris, but is again sporadically exposed southwest of the junction with Little Fork in the passage that continues northeast toward Mystery II. At the boundary of Mystery I and II the Door-to-Door Route descends from the upper cave level into the underlying system of Stewartville crevices. Gravel deposits marking the original path of the Door-to-Door Paleoriver through the upper level can be seen in the Lost Hill Passage, which is reached from an underlying crevice in the Stewartville. The Lost Hill Passage continues northeast to Sand Camp, although the connection is presently blocked

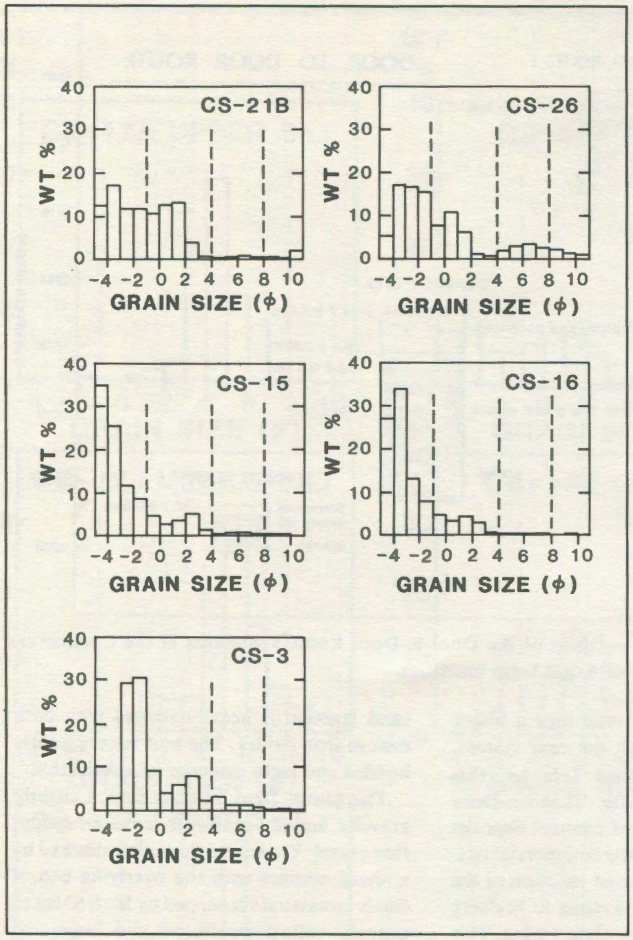


Figure 9. (left) **Grain size distributions of Door-to-Door Route sediment samples. Dashed vertical lines indicate gravel, sand, silt, and clay size intervals.**

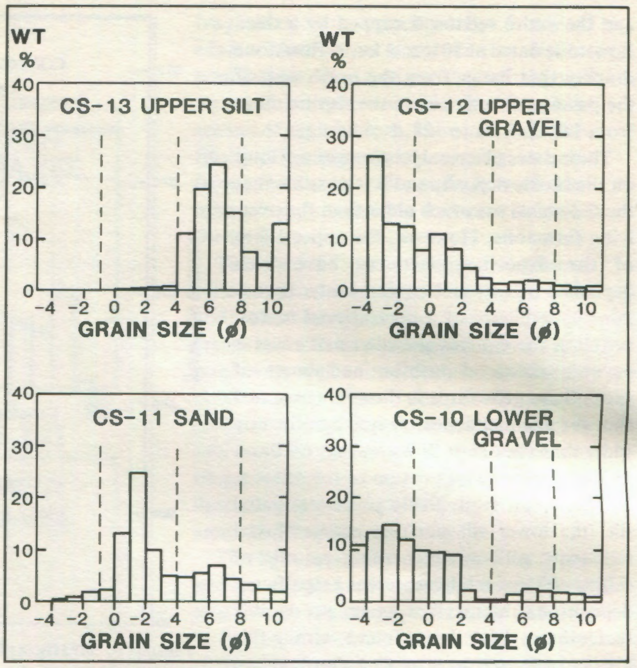


Figure 10. (above) **Grain size distributions of Door-to-Door Route sediment samples from the Bomb Shelter section. Dashed vertical lines indicate gravel, sand, silt, and clay size intervals.**

by breakdown.

From Sand Camp to the northeast end of Straddle Gallery, the gravel is exposed in a nearly continuous deposit. Along this route, the passage is developed along a major northeast-southwest trending joint extending from the lower Dubuque downward into the Stewartville. The maximum passage width is developed in the transitional zone at the gradational contact between the two formations. At the bottom of this zone the passage abruptly narrows to become a floor crevice 0.5 to 2 m wide flanked by horizontal to slightly sloping ledges. The gravel is exposed along the ledges as unconsolidated deposits 5 to 25 cm thick. The crevice is filled with a deposit of fine silt that slopes downward toward the Jump Off. At the Jump Off, Flim Flam Creek intersects the Straddle Gallery passage in the lower cave level. The stream has eroded the mud fill, excavating the crevice at the intersection to a depth of 14 m.

Northeast of the Jump Off, the Straddle Gallery passage ends at its intersection with the Angel Loop. The gravel can be traced east of this intersection to the Carrot Sticks area, where it occurs as a channel bar 25 to 30 cm thick, capped by 3 to 8 cm of laminated flowstone (Fig. 8; Angel Loop section). The passage then turns north and intersects Fifth Avenue. Although the natural floor of Fifth Avenue east of the Angel Loop was leveled and covered with gravel during development of the commercial route in Mystery II, it is apparent that the Door-to-Door Paleoriver turned east down Fifth Avenue from the junction with Angel Loop, because a 4 m thick section of silt fill has been eroded from the floor of Fifth Avenue extending from the junction with Angel Loop east to Garden of the Gods.[1] Garden of the Gods marks the east end of the cave system, which underlies the western flank of a northeast trending surface tributary valley that joins the main valley of the South Branch at Seven Springs, the resurgence point for the present Disappearing River.

The sediments along the Door-to-Door Route give evidence of a southwest to northeast paleoflow direction for the Door-to-Door Paleoriver. From southwest to northeast, the gravel bed decreases in thickness from more than 70 cm to less than 30 cm. The maximum clast diameter also decreases, from about 12 cm to less than 2 cm. This flow direction is consistent with both the gradient of the passage floor and the prevailing flow path of the present stream system in the cave.

Grain Size and Composition of Door-to-Door Sediments

Grain size histograms of Door-to-Door sediment samples are shown in figures 9 and 10. In the terminology of Folk (1974), the gravel deposit is characterized as a very poorly sorted to extremely poorly sorted, muddy, sandy gravel. Most samples analyzed have a bimodal grain size distribution, with the slight deficiency of grains in the 1 to 4 mm size fraction (very coarse sand to granule) typical of fluvial deposits (Pettijohn, 1975). Two samples (CS-10 and CS-26) have a third mode in the fine- to medium-silt fraction, with a corresponding deficiency in the coarse-silt to fine-sand fraction. The cap mud which overlies the gravel deposit at the Bomb Shelter section (Fig. 9; CS-13) is the only fine-grained sediment exposed along the Door-to-Door Route. This deposit has a size distribution that characterizes it as a poorly sorted

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[1] Thin exposures of gravel similar in appearance to the Door-to-Door gravels have recently been found along the Commercial Route 50 m east of Garden of the Gods. These deposits do not contain datable flowstones; their relationship to the Door-to-Door gravels is uncertain.

medium silt. The poor sorting of the deposit as a whole results from the bimodal nature of the size distribution. Unlike the lower gravels, this silt unit shows well defined bedding structure, consisting of thin (< 2 mm) alternating layers of silt and silty clay. The laminated silt is a very localized deposit found only at the Bomb Shelter section.

The pebble and granule fraction of the Door-to-Door Route gravel is dominated by angular to subangular fragments of limonite, often containing grains of very clear, highly polished, well rounded quartz. The limonite pebbles vary in color and texture, grading from rust orange and very friable to black and well indurated. Quartz pebbles are subrounded to well rounded and clear to milky white in color, with rose quartz occurring less commonly. The chert pebbles are dark green or dark brown, rarely black or white, with pitted to highly polished surfaces. Much of the chert consists of well rounded grains that have been broken and secondarily rounded slightly along the fractured edges. As a whole, the chert is characterized as subangular to subrounded. Granitic rock fragments and feldspar grains are subangular to rounded, with little or no evidence of chemical alteration. Most of the granitic pebbles are aggregates of clear quartz, white to pale-pink feldspar, and mica. Metamorphic rock fragments, present in small but persistent amounts (1 to 5 percent), consist primarily of very friable, green to black, mica schist. Fragments of limestone and siliceous fossils (primarily crinoids and brachiopods) are a very minor component of most samples. Pink quartzite and fine-grained basaltic rock fragments are occasionally present.

The light mineral fraction of the gravel samples consists almost exclusively of quartz and feldspar, with very little carbonate.[2] In contrast, the laminated silt bed that caps the gravel at the Bomb Shelter (CS-13) contains as much as 50 percent dolomite. Two distinct populations of noncarbonate mineral grains are present in all samples, one consisting of well rounded to very well rounded quartz and the other of subrounded to angular quartz and feldspar. Where present, the dolomite grains are angular rhombohedrons exhibiting little or no rounding.

The heavy mineral fraction of all samples is dominated by opaque mineral grains of two distinct textural types. One type comprises dark grains having a very regular, usually well rounded shape, while the other is smaller, very irregular in shape, and highly friable, crumbling easily to a fine, reddish orange silt. Both types of opaques are identical to those of the Enigma Pit and Fifth Avenue West gravels.

The most abundant translucent minerals in all samples are hornblende, garnet, and zircon, with smaller but persistent amounts of tourmaline, staurolite, rutile, sphene, and epidote. Anatase, pyroxene, kyanite, and apatite occur rarely. The hornblende varies in color, grain shape, and degree of rounding, with two types commonly present: very dark-green to olive-green, elongated, subrounded to rounded grains showing very faint cleavage; and pale-green, highly fractured, angular to subangular grains exhibiting strong cleavage. Garnets are mostly colorless to pale-pink, irregular fragments with conchoidal fracture surfaces that have been secondarily rounded. A small percentage of the garnets are deep-pink dodecahedrons showing only slight rounding. The zircons are mostly colorless and very well rounded; hyacinth zircon occurs less commonly, as very small, slightly rounded euhedra. Tourmaline also occurs in two varieties, one brown in color and very well rounded, the other green, elongated, and only slightly rounded.

Dolomite is present in both the $< 20\ \mu m$ and $< 2\ \mu m$ fractions of the cap mud at the Bomb Shelter section, consistent with the high dolomite content in the coarse fraction of this deposit. In this respect, the Bomb Shelter cap mud is similar to the upper silt unit which caps the channel deposits at Enigma Pit.

Occurrence of Manganese Oxide Deposits

A characteristic feature of the Door-to-Door Route gravels is the presence of a very fine-grained, black material that coats many of the pebble and granule-sized clasts. The coating varies in appearance from hard and lustrous to very soft, dull, and powdery, and is usually less than 1 mm in thickness. This type of deposit, usually referred to as 'manganese oxide,' is common in many caves (White, 1962). In Mammoth Cave, Kentucky, it commonly occurs as a pebble cement in gravel deposits (Davies and Chao, 1959).

Moore (1981) studied manganese oxide deposits in Matts Black Cave, West Virginia and identified the material as the mineral birnessite ($CaMn_60_{13} \bullet 3H_20$). A chemical analysis of this material, taken from the surface of a pebble in sample CS-16 (Door-to-Door Route at the south end of Straddle Gallery), yielded the following composition by weight percent: Mn, 25.9; Fe, 7.97; Ca, 7.91; Mg, 2.51; K, 2.30; Si, 4.19 (DCP Emission Spectroscopy; D. Janecky, analyst). The source of the manganese and the mechanism for deposition of the oxide minerals in the cave environment are not well understood. Moore (1981) suggests than manganese is mobilized in chemically reducing environments in stagnant sinkhole ponds feeding the cave stream system, and that deposition of the oxide mineral inside the cave results from the action of manganese-oxidizing bacteria.

Age of the Door-to-Door Route Deposit

Flowstone units capping the Door-to-Door Route sediments have yielded $^{234}U/^{230}Th$ ages at three localities. Flowstone which caps the gravel deposit at the Commercial Route section yields an age of 12.2 ± 0.4 ka. The section exposed at the Bomb Shelter is capped by 50 to 60 cm of flowstone and poolstone. Three samples taken from the bottom, middle, and top of this unit, yield ages of 12.2 ± 0.4 ka, 9.6 ± 0.5 ka and 7.7 ± 0.4 ka respectively. At the Angel Loop section, a thin flowstone unit capping the channel deposit yields an age of 12.1 ± 0.3 ka. The ages of the three samples of flowstone which directly cap the Door-to-Door Route sediments are in good agreement. An isochron analysis of these three samples (see Fig. 16 in the Appendix) yields a combined age of 12.14 ± 0.24 ka. That value is our best estimate for the cessation of stream deposition and the onset of speleothem growth along the Door-to-Door Route. Two stalagmite samples from the Wind Tunnel (west of the junction of the Door-to-Door Route with Big Fork) yield the same range of ages. One sample yields ages of 12.0 ± 0.4 ka (bottom) and 12.7 ± 0.6 ka (top). The other sample yields an age of 8.6 ± 0.5 ka.

FIFTH AVENUE WEST SEDIMENTS

The northwest portion of the cave system, referred to as Mystery III, consists of an upper level network of wide Dubuque passages underlain by a system of narrow Stewartville crevices. An active stream system, Formation Route Creek, enters the cave through one or more stream sinks in the channel of the south branch of the Root River at the west end of Mystery III (Fig. 1). The stream flows east and north through the lower cave, and, although it appears to exit the cave flowing north in the lower level passage beneath the west end of Lily Pad Lake, dye tracer studies show that it resurges at Seven Springs via Flim Flam Creek in Mystery II (Alexander, 1980). The connection between the surface valley and the west end of the cave system is apparently short and direct.

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[2] An exception is sample CS-26, from the Door-to-Door Route near the junction with Little Fork, which contains about 30 percent rhombohedral dolomite in the light fraction. This sample was collected from a very thin exposure of gravel underlying the breakdown that floors the passage, and the dolomite content is probably the result of contamination by locally derived autochthonous sediment.

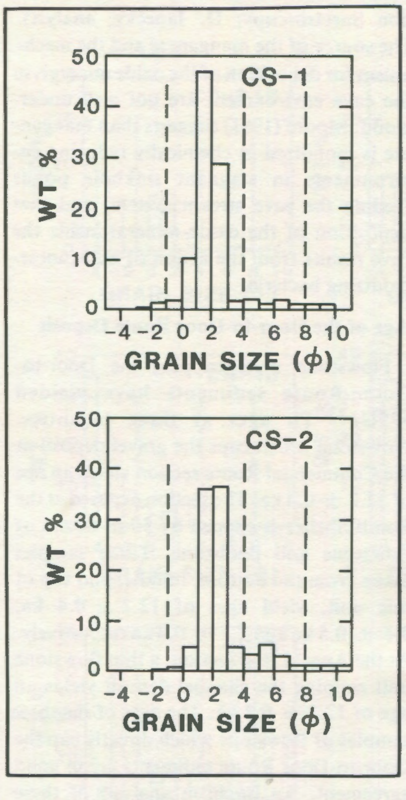


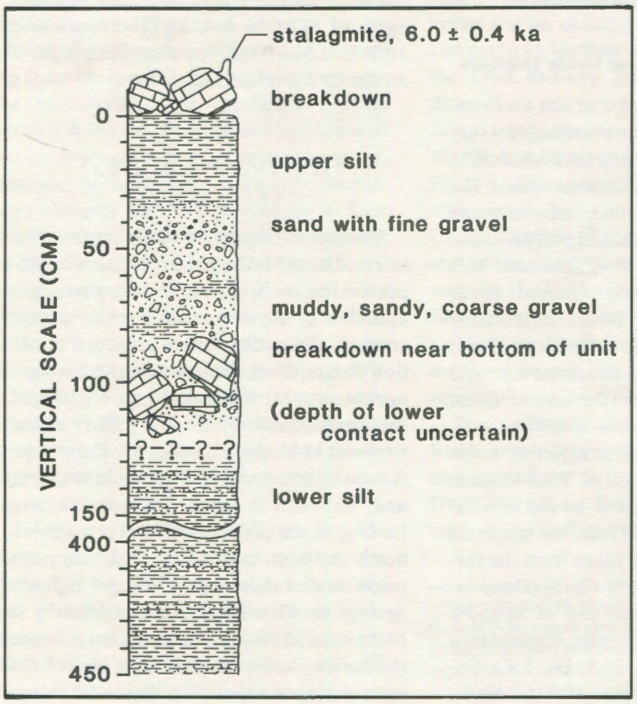
Figure 11. **Grain size distributions of Sand Creek sediment samples. Dashed vertical lines indicate gravel, sand, silt, and clay size intervals.**

The water in Formation Route Creek during the summer months is considerably warmer than the surrounding cave air, and air currents are frequently detectable in the passages leading east and north from Sand Source.

An intermittent tributary of the Formation Route Creek system, here referred to as Sand Creek, enters the cave from a surface stream sink west of Sand Source. It flows in the upper passage level east and north through the Fingers Area, crosses Fifth Avenue West, and continues north to the First Triangle Room, where it drops down to join the main channel of Formation Route Creek in the lower level. Sand Creek functions as an overflow channel for surface drainage during periods of high flow, so the stream bed is dry for most of the year. When surface discharge is large, as during spring flooding, the stream carries in and transports through the cave a large volume of sand-sized sediment. The sediment is deposited along the path of the stream as a continuous bed of sand 2 to 20 cm thick, fining in a downstream direction from a slightly gravelly medium sand at Sand Source to a fine sand at the First Triangle Room (Fig. 11). With respect to mineralogy, grain size, and grain morphology, the Sand Creek sediment is very similar to that forming the alluvial bed of the surface valley. The surface connection is at least 10 cm wide, because the right astragalus bone of a horse was found in the channel of Sand Creek near the west end of Sand Source.

The upper level passage system, which lies 10 to 14 m above the Formation Route stream passage, is floored by a thick sequence of clastic sediments (Fig. 12). The lowest unit in this sequence is a thick deposit of finely laminated silt (the lower silt of Fig. 12). It is overlain by breakdown blocks of Dubuque limestone. This deposit is partially exposed at the Mud Slide, where it fills the 6 m high passage to within 1 m of the ceiling. A second exposure, approximately 4 m thick, occurs at the intersection of Sand Creek with Fifth Avenue West. The deposit is extremely uniform in appearance, both vertically and laterally. It is finely plane-laminated to slightly ripple-laminated throughout, the individual laminae ranging in thickness from about 0.5 to 2 mm. The laminae consist of pale-tan to buff layers of coarse silt to fine sand alternating with brown to reddish-brown layers of clayey, fine to medium silt.

The silt fill is locally overlain by a bed of gravel, approximately 0.5 to 1 m thick, deposited on top of and around the breakdown which caps the underlying silt. The gravel can be traced along Fifth Avenue West to the east end of this passage, then north across the intersection with Eureka Avenue and along the Discovery Route to the west end of Lily Pad Lake. The unit consists of pebbles and cobbles 0.5 to 8 cm in diameter in a sandy matrix, with scattered lenses of fine, clayey silt. There is no evidence of imbrication and very little bedding structure, although on a gross scale the bedding is slightly graded, fining upward to a silty sand with fine pebble lenses in the upper 10 cm of the unit.



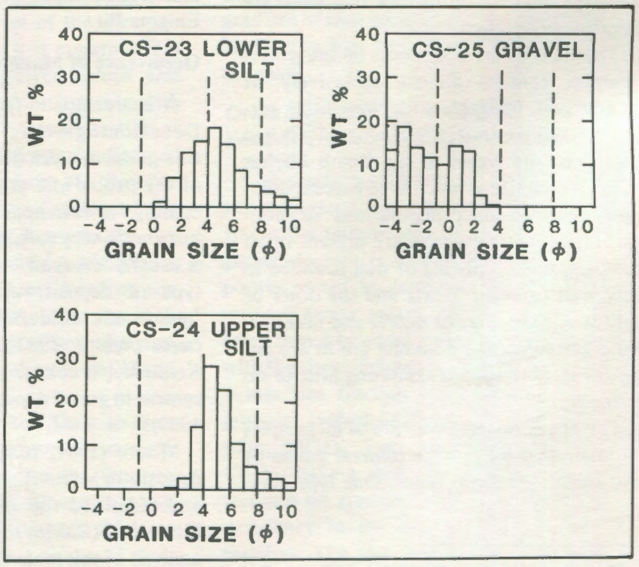


Figure 12. (left) **Stratigraphic section of the Fifth Avenue West sediments.**

Figure 13. (above) **Grain size distributions of Fifth Avenue West sediment samples. Dashed vertical lines indicate gravel, sand, silt, and clay size intervals.**

Along Fifth Avenue West, the gravel is capped by a second silt bed, 30 to 40 cm thick (the upper silt of Fig. 12), and the entire sequence is overlain by scattered breakdown. Like the lower silt, the upper unit is finely plane-laminated to slightly ripple-laminated, with alternating layers of tan, sandy, coarse to medium silt and brown, clayey, fine silt.

Grain Size and Composition of Fifth Avenue West Sediments

Grain size histograms for Fifth Avenue West sediment samples are shown in Figure 13. Both the lower and upper silt beds show a unimodal size distribution, with a modal diameter in the coarse silt range. The upper silt is more strongly fine skewed, however, and slightly better sorted than the lower unit. The intervening gravel unit is characterized as a very poorly to extremely poorly sorted sandy gravel. The size distribution of this unit is roughly bimodal, with modal diameters in the medium pebble and the coarse sand size ranges, and the deficiency of granules and very coarse sand characteristics of fluvial gravels (Pettijohn, 1975).

The light mineral fractions of the lower and upper silt beds are very similar. Both assemblages consist of 50 to 60 percent quartz and feldspar, very well rounded to angular but mostly subrounded to subangular, and 40 to 50 percent carbonate minerals, primarily rhombohedral dolomite grains. In contrast, the light mineral fraction of the intervening gravel contains only about 1 percent carbonate. The remainder consists of quartz and feldspar, very well rounded to angular but mostly rounded to subrounded. There is a minor amount of opaque material.

The distribution of heavy mineral species shows little difference between the upper and lower silt beds. The greater abundance of zircon in the upper silt, with a corresponding deficiency in hornblende, probably results from the greater amount of very fine sand relative to fine sand in this unit. Two varieties of hornblende occur: a dark green variety forming well rounded grains lacking cleavage fractures, and a very pale green variety forming elongated, highly fractured, subangular to subrounded grains. The zircons are very small, colorless, very well rounded grains, and the garnets are colorless to pale pink, conchoidally fractured fragments of larger crystals. Both assemblages are dominated by opaque grains of various shapes and surface textures, but mostly regular in shape and moderately to well rounded. Notably absent in the opaque fraction of the Fifth Avenue West sediments are the abundant powdery iron oxide grains found in both the Enigma Pit and Door-to-Door deposits.

The gravel unit contains a simlar suite of heavy mineral species in comparable abundances. Here, also, the greater abundance of hornblende relative to zircon may be largely due to a deficiency of grains in the finest sand grade. The gravel, however, contains two distinct varieties of the minerals zircon and garnet. Zircon occurs both as very well rounded, subspherical, colorless grains, and as pink-to-violet, euhedral, slightly rounded crystals containing numerous minute inclusions. Garnet occurs as both colorless to pink, fractured crystal fragments and as deep pink to brown, slightly rounded dodecahedra.

The composition of the pebble fraction of the Fifth Avenue West gravel is very similar to that of the Door-to-Door gravel. Subangular to subrounded limonite fragments and well rounded quartz pebbles together constitute 75 percent of the pebble fraction. Chert pebbles are subangular to well rounded, mostly dark brown or dark green, and frequently have moderately to highly polished surfaces. Granitic pebbles are subrounded to well rounded, fine- to medium-grained aggregates of pink to white feldspar and clear to white quartz. Trace amounts of limestone and basaltic and metamorphic rock fragments are present as very worn, friable pebbles showing moderate to extreme chemical alteration. Some grains in the pebble and granule fraction are coated with a black manganese oxide deposit similar to that which characterizes the Door-to-Door gravels, although here the coating is thinner and tends to be hard and lustrous rather than soft and powdery.

The silt- and clay-size fractions of the upper and lower silts consist primarily of quartz plus the clay minerals illite, montmorillonite, chlorite, and kaolinite. The clay mineral content of the two units is further evidence of the strong similarity in mineralogy seen in the sand size fractions. Dolomite is identified only in the $< 20\,\mu m$ fraction of the lower silt, so apparently most of the carbonate in the bulk samples occurs as fine sand rather than as silt and clay-sized grains.

Age of the Fifth Avenue West Deposits

Most exposures of the Fifth Avenue West sediments are not directly capped by datable flowstone deposits. At one locality near the north end of the Discovery Route, however, a thin flowstone overlying the gravel unit yields an age of 13.0 ± 0.6 ka. Several other ages have been obtained from stalagmites deposited on breakdown blocks overlying the clastic sediments. A stalagmite collected at the east end of Eureka Avenue dates from 6.0 ± 0.4 ka (bottom) to 2.0 ± 0.1 ka (top). A second, smaller, stalagmite, found growing on the first, yields an age of 0.5 ± 0.1 ka. This range of ages, which places an upper limit of about 13 000 years for time of deposition of the clastic units, correlates within error bars with ages obtained from the Door-to-Door Route.

DEPOSITIONAL HISTORY OF MYSTERY CAVE

Source of Clastic Fills

Laminated silt deposits. Laminated silt is the predominant clastic sediment in Mystery Cave. Throughout the cave, these silt deposits are remarkably uniform in both grain-size distribution and mineralogy and, with one exception (discussed below), represent a mixture of both allochthonous and autochthonous sediment sources. The autochthonous component consists of fine-grained carbonate, which makes up as much as 50 percent of the sand fraction in the form of angular, rhombohedral dolomite and irregular aggregates of silt-sized calcite. The absence of carbonate minerals from the fine fractions of surface deposits near the cave, and the extreme angularity of the grains, indicate that this calcareous component was derived directly from carbonate bedrock within the cave and probably underwent little transport prior to deposition.

At least 50 percent of the silt, however, is derived from sources outside the cave. This allochthonous component consists of fine-grained quartz and feldspar exhibiting a variety of grain-surface textures and variable degrees of rounding. The diverse suite of heavy minerals and clay minerals present in the insoluble fractions of the silt deposits also indicate an allochthonous, primarily glacial, source.

An exception to this mixed-sediment source is the upper silt bed capping the clastic section at Enigma Pit. This unit is essentially a pure carbonate silt, containing only trace amounts of quartz, heavy minerals, illite, and chlorite. This deposit appears to be of completely autochthonous origin, formed by accumulation of fine-grained carbonate and insoluble residue derived from the shale beds of the Dubuque Formation.

Gravel Deposits. The Enigma Pit, Door-to-Door, and Fifth Avenue West gravel deposits are clearly of allochthonous origin, containing little or no autochthonous carbonate. The abundance of hornblende and garnet and the diversity of clay mineral species in these sediments are indicative of a glacial source, as is the abundance and variety of lithic fragments in the pebble fraction. All deposits also contain a large number of iron ore fragments and highly polished quartz and chert pebbles derived from the pre-glacial Windrow Formation. Despite their relative softness, the limonite pebbles are in general less rounded than the rest of the gravel fraction, indicating that they are probably derived from ore deposits very near the cave.

The major differences in composition among the 3 channel deposits occur in the gravel fraction. Quartz and limonite predominate in the Door-to-Door and Fifth Avenue West gravels, and black manganese oxide coatings are common in clasts of granule to cobble size. In contrast, the gravel fraction of Enigma Pit samples consists primarily of limestone fragments, with lesser amounts of quartz and limonite, and manganese oxide deposits are not present. The limestone pebbles are, in general, only moderately rounded, but exhibit moderate to extreme chemical weathering. Many have been almost completely leached of carbonate and can be easily crushed to a fine, white powder. These leached pebbles are present, but uncommon, in the gravel fractions of the Door-to-Door and Fifth Avenue West channel deposits. Siliceous fossils associated with the pebbles are characteristic of the Maquoketa and uppermost Dubuque formations, indicating that at least part of the limestone is derived from local sources.

Leaching of the carbonate pebbles clearly occurred prior to transport and deposition of the gravel in the cave, because the degree of chemical alteration is constant with depth, and pebbles sampled from any single stratigraphic level exhibit considerable variation in extent of decomposition. The matrix of the gravel contains as much as 15 percent angular carbonate sand showing no evidence of chemical alteration. The leached pebbles are apparently an original component of the glacial deposit from which the cave gravels are derived. Although limestone is the most abundant lithic fragment in the pre-Late Wisconsinan drift east of the Des Moines Lobe (hence, the descriptive name Old Gray Drift applied to these deposits), in western Fillmore County this thin drift sheet has undergone such extensive chemical weathering that most deposits are entirely leached of carbonate rock. Mystery Cave lies at the eastern edge of the drift lobe mapped as the Old Gray, and patches of this till remain on the upland areas west of the cave. These deposits are devoid of limestone, and many of the larger igneous and metamorphic rock fragments exhibit extreme *in situ* decomposition.

The presence of gravel deposits in Mystery Cave derived from the Old Gray drift places an absolute upper age limit on the till, currently mapped only as pre-late-Wisconsinan. Radioisotope ages obtained from flowstone overlying the gravel at Enigma Pit indicate that the gravel was deposited in the cave prior to 146 ± 10 ka. This long period of protection from surficial weathering processes accounts for the preservation of carbonate rock fragments in the gravel; consistent with this is the much lower abundance of carbonate rock observed in the Door-to-Door and Fifth Avenue West deposits, both associated with speleothem ages of <13 ka. The drift itself must be sufficiently older than 146 ka to allow for the interval of surficial weathering that produced extensive leaching of carbonate minerals from the limestone fragments. In the terminology of classical continental glacial chronology, the drift is clearly pre-Wisconsinan in age and probably pre-Illinoian as well, supporting the tentative correlation of these deposits with tills of Kansan age in adjacent Iowa (Wright, 1972). This correlation, however, will remain speculative until detailed study is given to the pre-Late Wisconsinan Quaternary geology of southeastern Minnesota.

Depositional History

The geologic history of the Mystery Cave system is a complex sequence of events for which the clastic sediments represent only a partial and incomplete record. Depositional processes within the cave occur in direct response to surficial geomorphic processes in the karst drainage basin, but the problem of stratigraphic correlation of cave deposits is complicated by the unique spatial discontinuity of this depositional environment. Flow of sediment-bearing groundwater through the cave may be vadose (free surface) or phreatic, and is always constrained to a pre-existing, three-dimensional network of channels. In addition, water and sediment must enter the system through discrete channels, so that the type of sediment deposited in the cave is a function not only of available source material and flow velocity, but also of the size, location, and density of surface connections.

The clastic deposits throughout Mystery Cave, however, appear to conform to a single, consistent depositional pattern. In composite, this pattern consists of a thick basal unit of finely laminated silt, overlain by breakdown, then by coarse-grained channel deposits fining upward into a second, thin, silt bed, with the entire sequence capped by flowstone and additional breakdown. The stream gravels are confined to several well defined channels, so throughout most of the cave the basal silt, variably overlain by breakdown and speleothem deposits, is the only unit present. Speleothems, where present, always overlie the clastic section; they have not been found below, within, or between clastic units of an individual section. The sediments are of allochthonous or mixed source, and clearly represent a late-stage depositional cycle within a well-integrated cave system. Within the chronologic framework provided by speleothem ages, it is possible to outline the major stages of this depositional phase of development; the morphology of the cave itself also provides evidence for at least a speculative reconstruction of the pre-depositional history.

Pre-depositional development. Although the age of the karst terrain of southeastern Minnesota is unknown, there is evidence that karstification began before the Pleistocene, possibly as early as Cretaceous time and, therefore, prior to establishment of the present drainage pattern of the Upper Mississippi Valley and its tributaries. This evidence comes primarily from the heavily glaciated carbonate terranes west of the cave, where burial of the bedrock beneath a thick mantle of drift has protected it from the present cycle of fluviokarstic activity. The bedrock surface beneath the drift is deeply weathered, with karst features such as solution-enlarged fissures and small caves, containing what appear to be primary deposits of Cretaceous sediments (Sloan, 1964). The relationship between this buried paleokarst and the active fluviokarst of the Root River basin is unclear. There is additional evidence of pre-Pleistocene karst on the surface of the Cedar Valley Formation, the uppermost bedrock unit in the vicinity of Mystery Cave. The surface of this limestone unit is deeply weathered and extremely irregular, with numerous shallow voids which contain the iron ore deposits of the lower Windrow Formation. The ore bodies are thought to be Cretaceous, possibly Tertiary, in age (Andrews, 1958; Bleifuss, 1972). Both geological and paleontological data indicate that the early Cretaceous in southeastern Minnesota was a time of warm, tropical climate and intense chemical weathering, conditions considered conducive to karstification of carbonate terranes. Mystery Cave may, therefore, represent a Pleistocene rejuvenation of a pre-existing cave system, although any record of preglacial deposits which may have existed has since been obliterated.

Palmer (1975) devised a genetic classification of caves based on patterns of passage development and geohydrologic setting. In Palmer's terminology, the geometry of Mystery Cave conforms closely to that of a network maze, defined as 'an angular grid of intersecting fissures that is formed by solutional widening of nearly all major joints to roughly the same size within a given area of soluble rock . . . commonly restricted to areas of vertical or near vertical joint orientation' (Palmer, 1975). In Palmer's model, maze patterns are formed in either of two geohydrologic situations: 1) by diffuse infiltration of groundwater uniformly into all available fractures (a situation most commonly associated with young karst terrains); and 2) by floodwater recharge into caves fed by sinking streams (a situation more characteristic of mature karst containing well-developed, point-source groundwater recharge). Network development is most extensive in diffuse infiltration mazes, and tends to be somewhat rudimentary and less geometric in floodwater mazes.

The present geohydrologic setting of Mystery Cave is clearly that of a floodwater maze; recharge to the cave system is controlled primarily by direct input from the incised surface valley of the South Branch. The network maze pattern of passage development suggests, however, that initial development occurred by diffuse infiltration prior to incision of the surface valley. The accessible passages of the cave system are preferentially enlarged joints within a much more extensive solution network which, as a whole, bears little relationship to surface drainage. Both the upper and lower passage levels are primarily of phreatic origin; except where the natural ceiling has been secondarily altered by collapse, even the highest passages of the upper level exhibit solution features formed under water-filled conditions. The width and horizontality of these passages, as well as their discordant relationship to bedrock dip, suggest that the upper level represents a water table which existed prior to valley incision. The upper level is therefore an epiphreatic or water table cave, underlain by a network of deeper phreatic loops. Preferential enlargement of upper level phreatic conduits occurred in the zone proximal to the water table, where groundwater flow velocities and undersaturation are greatest. Where present, solution scallops on the walls of the upper level passages indicate a directional epiphreatic flow to the north and east, consistent with the present drainage pattern of the Root River basin.

Deposition of the basal silt. Deposition of clastic sediments in the cave began in the late stages of the phreatic phase, when the present surface drainage was well established and surface connections were large enough to permit direct influx of clay- to sand-sized particles. The phreatic network of both passage levels existed by this time, although continued enlargement of the upper level was probably directly influenced by sedimentation. The cave apparently lay at or below the water table prior to and during this early phase of sedimentation; no chemical deposits or other evidence of subaerial conditions have been found below or within the basal unit of the clastic section.

The major portion of this depositional cycle is represented by the basal silt, which fills both levels of the cave as a remarkably uniform blanket of fine, graded laminae. The laminae are thinnest in the crevice fills of the lower level, becoming gradually thicker and slightly coarser-grained in the deposits of the wider, upper level conduits. Ripple marks and other small-scale flow structures are also more prevalent in the upper level fills. As a whole, the basal silt bears a striking similarity to a surficial floodplain deposit; it is proposed that a similar mechanism produced cyclic deposition in the cave. In the case of the cave, however, sedimentation occurred by backflooding of the Root River, resulting in a temporary drop in flow velocity of sediment-bearing groundwater and deposition of sand, silt, and a small amount of clay. The deficiency of clay-sized particles in this deposit suggests that most of the very fine suspended load remained in suspension and was transported out of the cave system.

Deposition of sediment began in the lower, more stagnant levels of the cave, which resulted in increased shallow phreatic circulation and further enlargement of the upper level system. As infilling reached the upper level, the increase in flow velocity and the increase in both the volume and particle size of sediment influx resulted in the progressive deposition of thicker and coarser-grained laminae. Abrasion of the bedrock must have been a significant factor in passage enlargement throughout this depositional phase, as evidenced by the abundance of angular sand and silt-sized carbonate in the basal silt unit.

The termination of this phreatic depositional phase and the beginning of the present erosional phase of fluviokarstic activity occurred when headward incision of the surface valley, in response to regional base leveling, initiated draining of the cave system toward the river. Draining of the upper level had begun by 161 ± 14 ka, the oldest speleothem age as yet obtained from the cave. As the incising river encountered the downstream edge of the cave system, surface flow began to be diverted from the bedrock valley into underground flow paths containing only soft, unconsolidated sediments which could be easily eroded by the downcutting stream. By progressive development of upstream sinkpoints, this headward entrenchment of vadose streams progressed westward, then southwestward through the cave. As a consequence of this diversion of flow into underground channels, the surface stream gradually lost competency to incise its valley. At present, although the valley gradient from upstream sink to resurgence is very steep, it is partially and sometimes completely dry under low flow conditions, and the river level upstream from the sinkpoint of the Disappearing River is perched nearly 20 m above the stream level in the cave.

Deposition of the stream gravels. Re-excavation of the cave system by headward erosion of the sediment fill has occurred during the period from about 160 ka to the present, but erosion was apparently not continuous over this interval. At least 2 intervening episodes of vadose deposition are recorded by the Enigma Pit gravel and the Door-to-Door and Fifth Avenue West gravels. These channel deposits lie 15 to 26 m above the present cave stream level, delineating a system of upper level, paleoflow paths that approximately parallels the present lower level vadose system (Fig. 14). As previously discussed, the gravels are entirely of allochthonous origin, derived primarily from pre-Late Wisconsinan glacial drift and from local deposits of Windrow gravel and iron ore.

Two assumptions are inherent in the interpretation of these gravel deposits. First, it is assumed that the radioisotope ages of flowstones directly overlying the gravels represent the approximate ages of the clastic deposits; second, that the gravels were transported into the cave from the river, and that the level of these deposits within the cave, therefore, corresponds approximately to the elevation of the surface valley feeding the cave at the time of deposition.

The earliest episode of stream deposition is represented by the Enigma Pit gravel, deposited approximately 146 ka in an east-west trending upper level passage 25 m above the present vadose level (defined as the level of Rimstone Creek, the lowest measured free-surface stream of the present vadose system). The east end of the Enigma Pit passage terminates beneath the west flank of a small tributary valley which joins the main valley of the South Branch 100 m to the north; the surface connection, however, is now blocked. The stream apparently either entered or exited the cave system at this point, and, although the path and direction of flow cannot be determined unambiguously from the single exposed section at Enigma Pit, the gradient of the passage floor suggests an east-to-west flow direction. A second episode of stream deposition occurred about 13 ka. During the intervening period, 146 to 13 ka, the primary points of stream capture progressed upstream to sinkpoints located along the west flank of the entrenching meander, and direct surface connections then existed to several of the large, east-west trending phreatic conduits that terminated against the east edge of this section of the valley. Gravel washed into the cave from the surface valley was deposited in the upper level passages of Fifth Avenue West and the Door-to-Door Route 15 to 20 m above the present vadose level.

The stream gravels appear to represent

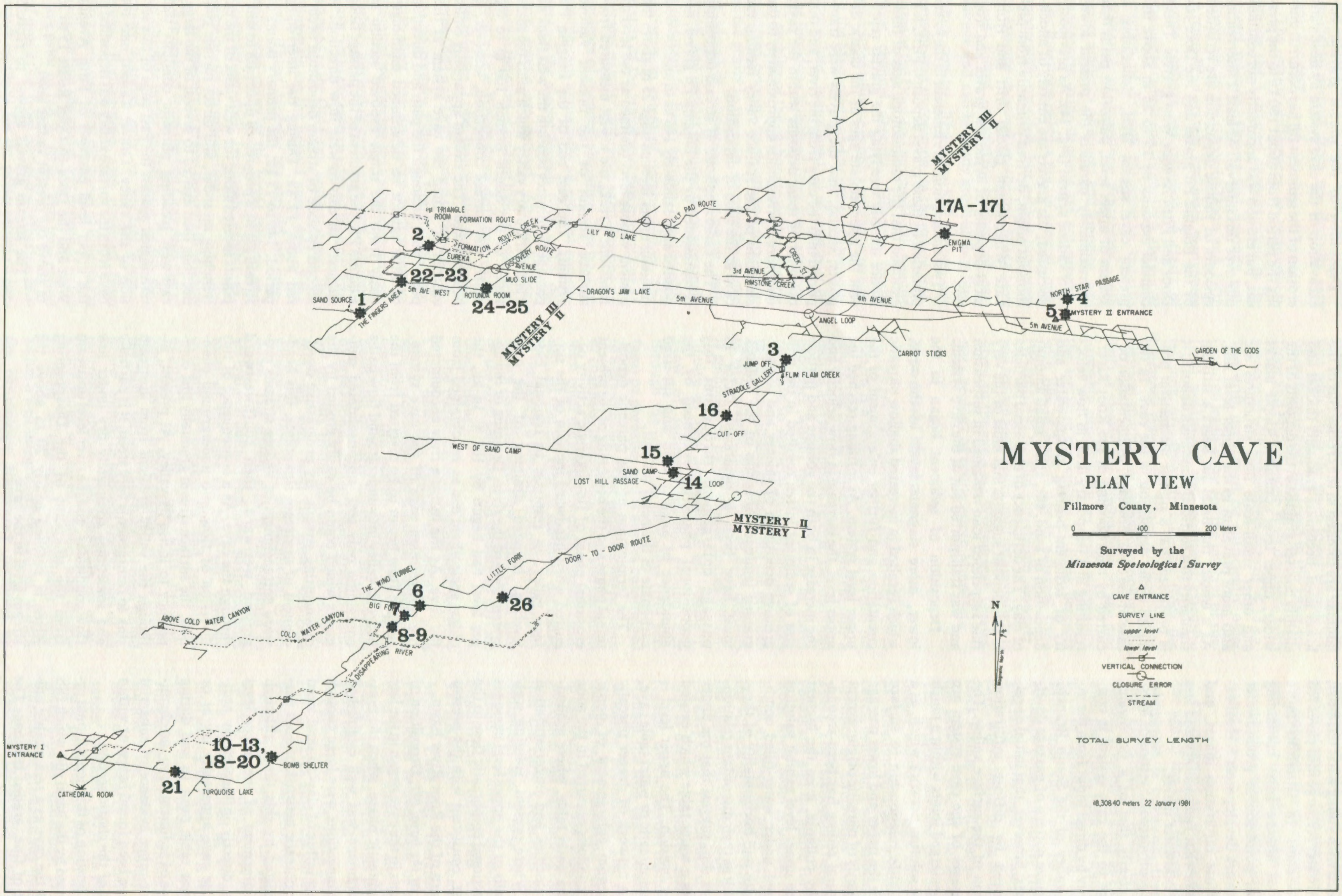


Figure 14. Groundwater flowpaths through Mystery Cave. Present flow paths are shown by solid arrows; paleoflow paths are shown by dashed arrows.

short-lived episodes of rapid channel aggradation during the otherwise predominantly erosional fluviokarstic cycle of the past 160 000 years. Both depositional events were immediately followed by periods of flowstone deposition which correspond closely to the onset of major cycles of speleothem growth throughout the cave from 161 ± 14 ka to 101 ± 4 ka and from 13.0 ± 0.6 ka to the present. Periods of speleothem growth are interpreted to represent interglacial or interstadial climatic conditions, and a number of studies have recently begun to delineate a Pleistocene chronology for the past 400 000 years based on radioisotope ages of cave deposits (*e.g.*, Harmon, *et al.*, 1977, 1978b, 1979; Atkinson, *et al.*, 1978; Thompson, *et al.*, 1976; Lively, 1983). Although a large number of ages have been determined from caves in North America and Britain, these studies have focused exclusively on chemical cave deposits and, until now, there have been no attempts to correlate speleothem ages with clastic cave sediments.

The groups of speleothem ages obtained from Mystery Cave record nonglacial climatic conditions from about 160 ka to 100 ka, from about 59 ka to 35 ka and from about 13 ka to the present. The youngest age group appears to represent the end of the Wisconsinan glaciation and the present interglacial period. These ages correlate well with speleothem ages in Britain (Atkinson, *et al.*, 1978), Vancouver Island (Gascoyne, *et al.*, 1981) and the Rocky Mountains (Harmon, *et al.*, 1977) and also correspond to the beginning of the retreat of the Des Moines Lobe about 14 ka based on ^{14}C dating (Ruhe, 1969). The growth period from 59 ka to 35 ka is interpreted as representing the major interstadial that preceded the late-Wisconsinan glacial advance in southeastern Minnesota (Lively, *et al.*, 1981). The oldest age group is somewhat more difficult to interpret. The onset of speleothem growth about 160 ka corresponds to speleothem deposition hiatuses in caves in West Virginia (Thompson, *et al.*, 1976) and Kentucky (Harmon, *et al.*, 1978b) and with a minimum low-sea level stand associated with the Illinoian Glaciation (Gascoyne, *et al.*, 1979). This interval of speleothem growth does, however, correlate with ages obtained from Britain and the Rocky Mountains and encompasses periods of high sea level stand on the Bermuda platform (Harmon, *et al.*, 1978a) and the Huon Peninsula, New Guinea (Bloom, *et al.*, 1974). Speleothem deposition in Mystery Cave apparently began during the late Illinoian and continued through the Sangamon Interglacial, which ended in southeastern Minnesota at approximately 100 ka. The stream gravel deposits which have occurred in Mystery Cave during the past 160 000 years appear to correspond to the late stages of the Wisconsinan and Illinoian glacial periods of southeastern Minnesota. This interval was one of periglacial conditions, for there is no solid evidence that glacial ice ever advanced as far west as Minnesota in the Illinoian, and the late Wisconsinan Des Moines Lobe terminated 100 km west of the cave. The stream gravels therefore represent late glacial alluvial terraces deposited beyond the area covered by glacial ice or directly fed by glacial meltwater.

Frye (1961) studied the relationship between cycles of Pleistocene glaciation and depositional cycles in drainage systems located beyond the margins of glaciers in central and south-central United States. According to his model, valley alluviation occurs during phases of glacial retreat, while erosion predominates during glacial advance, and interglacials are characterized by depositional equilibrium and soil development. The pattern of fluvial deposition observed in Mystery Cave supports such a model, although the interglacial soils developed on the alluvial terraces of surface valleys are represented in the cave environment by periods of speleothem growth. If this interpretation is correct, it provides a possible means of determining the ages of alluvial terrace gravels in karst drainage basins by correlation with cave terraces, although this correlation has not, as yet, been attempted between Mystery Cave and the Root River.

The preceding discussion of the depositional history is admittedly very generalized and undoubtedly overly simplified. Many details have been intentionally omitted in an attempt to provide a broad and cohesive interpretation that will serve as a basis for future, more detailed stratigraphic studies, both in Mystery Cave and in the hundreds of other caves in the karst region of southeastern Minnesota. It is important, also, that future studies be directed toward the interpretation of the long-neglected surficial deposits of the pre-Late Wisconsinan Quaternary in this area of the state.

CONCLUSIONS

Mystery Cave in a joint-controlled, network, maze cave that developed in the shallow phreatic zone proximal to a water table which pre-dates valley incision. Clastic sediments in the cave record the following depositional history: **1)** deposition of finely laminated silt by backflooding of the Root River and accumulation of autochthonous carbonate; **2)** lowering of base level, beginning approximately 160 ka, resulting in gradual draining of the cave, onset of speleothem deposition, and headward erosion of the basal silt by capture of vadose flow from the surface valley; **3)** deposition of stream gravels about 145 ka and 13 ka at levels 15 to 25 m above the present vadose level in the cave.

Paleoflow directions indicated by the stream gravels are consistent with the present pattern of vadose flow. A primary source of the gravels is the pre-Late Wisconsian Old Gray Drift, which places an upper limit of about 145 ka on the age of this glacial deposit. The till clearly predates the Wisconsinan and probably also predates the Illinoian glacial period.

Speleothem ages obtained from the cave indicate major periods of chemical deposition from about 160 ka to 100 ka, from about 60 ka to 35 ka, and from about 13 ka to the present (Lively, *et al.*, 1981; Lively, 1983). The intervals are interpreted as representing, respectively, the late Illinoian glacial and Sangamon interglacial, the pre-Late Wisconsinan interstadial, and the end of the Wisconsinan glacial stage in southeastern Minnesota. The climate of the late Illinoian was, in the area of the cave, apparently mild enough to permit speleothem growth.

The stream gravels associated with the early phases of speleothem growth intervals appear to represent late-glacial alluvial terrace deposits of the Wisconsinan and Illinoian stages. This interpretation is consistent with Frye's (1961) model of Pleistocene depositional cycles in drainage systems which lie beyond the areas covered by glacial ice. If correct, it may provide a method for dating the surface valley terraces in the karst basin by correlation with cave terraces.

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APPENDIX

The ^{234}U/^{230}Th dating technique assumes that the sample being dated was initially free of ^{230}Th or that the initial ^{230}Th can be determined. Calcite speleothems often contain significant amounts of initial ^{230}Th associated with detrital impurities in the $CaCO_3$. Detrital impurities also contain the long-lived isotope ^{232}Th. The initial or detrital ^{230}Th content of a sample is normally approximated by multiplying the measured ^{232}Th content by a detrital ^{230}Th/^{232}Th ratio. Schwarcz (1980) discusses in detail the problems associated with such corrections. The problem is, therefore, to determine the detrital ^{230}Th/^{232}Th ratio appropriate for a particular sample, cave, or region.

The initial results of age determinations on speleothems collected from three widely separated locations along the Door-to-Door Route indicated that all three samples were deposited contemporaneously. The measured ^{230}Th/^{232}Th activity ratios indicated that different quantities of detrital material had been incorporated into each sample. These data provided an opportunity to use an isochron analysis to obtain a more accurate age for the deposition of the Door-to-Door gravels and to determine a ^{230}Th/^{232}Th activity ratio for the Mystery Cave system. There is no *a priori* reason that the detrital ^{230}Th/^{232}Th activity ratio is constant from place to place within a cave or region or is even constant through time at a given place. However, evidence that the detrital ^{230}Th/^{232}Th ratio is indeed reasonably constant in a system simplifies the analyses and increases the degree of confidence to be placed in the resulting ages.

Figure 15 illustrates the U and Th isotopic data from three samples (MC-1, MC-7, MC-27) which cap Door-to-Door deposits. It is an isochron diagram, on which samples with the same age and detrital ^{230}Th/^{232}Th ratio will form a linear array whose slope is a function of the sample's age and whose ordinate intercept is the present day value of the detrital ^{230}Th/^{232}Th activity ratio. The Door-to-Door Route samples form an excellent linear array. The listed slope, intercept, and associated errors (1 σ) result from a correlated error, least squares regression (York, 1969) of the 3 data points. The array is actually more precise than would be expected based on the error bars on the individual data points, and the formal error limits are unreasonably small.

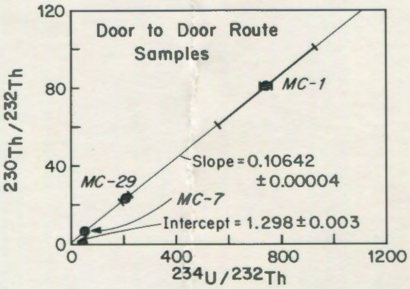

***Figure 15* (above).** Isochron diagram of the uranium and thorium activity data from Door-to-Door Route speleothems.

***Figure 16.* (below).** The ^{230}Th/^{234}U activity ratios of the Door-to-Door Route speleothems as a function of the present day value of the detrital ^{230}Th/^{232}Th ratio. The stippled region is the area with the 1 δ error limits of all three data.

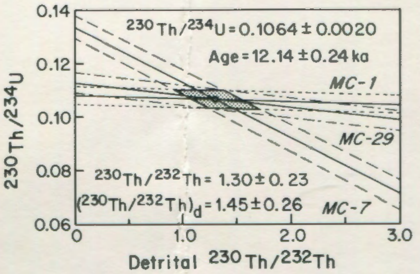

Figure 16 illustrates the individual sample's ^{230}Th/^{234}U ratio dependency on the present day detrital ^{230}Th/^{232}Th ratio. It was used to estimate more realistic errors for the slope and intercept of the isochron in Figure 15. The error envelope on each sample's ^{230}Th/^{234}U ratio is shown as the dashed lines parallel to each solid line. The values of the slope and intercept from Figure 15 plot as the dot at the intersection of the three lines in Figure 16. The stipled region is the locus of values which lie within the 1 σ error envelopes of all three data. Based on the size of the stipled region, we estimated the errors listed in Figure 16.

The present day ^{230}Th/^{232}Th activity ratio of 1.30 ± 0.23 decay corrects to an initial detrital ^{230}Th/^{232}Th activity ratio of 1.45 ± 0.26. The latter value was used (with appropriate decay corrections in a iterative fashion) to correct the ages in Table 4 and Lively (1983) for detrital ^{230}Th.

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