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Geology and Origin of Mystery Cave
Forestville State Park, Minnesota

INTERPRETIVE REPORT

LCMR Mystery Cave Resources Evaluation

Arthur N. Palmer
Margaret V. Palmer
1993

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DEPARTMENT OF NATURAL RESOURCES
FORESTVILLE STATE PARK**

GEOLOGY AND ORIGIN OF MYSTERY CAVE

Interpretive Report

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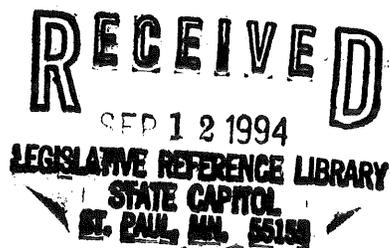
INTRODUCTION

This is the interpretive portion of the final report for the project **Mystery Cave Geology Resources Evaluation** (part of the Mystery Cave Resource Evaluation). This project concerns the geology, mineralogy, and origin of Mystery Cave. A summary of the technical aspects of the project is given in a separate Technical Report, and recommendations for further study and management suggestions are given in a separate Management Report. This Interpretive Report contains the main conclusions from the project, including background material, setting, general description of methods, a detailed description of cave features and their interpretation, and a discussion of the cave origin. This is the main document describing the results of the project in non-technical terms and is supplemented by the Technical Report, which contains quantitative details. Although these reports provide an adequate summary of the geology and origin of the cave, they are only preliminary. An expanded and updated version will be submitted in 1994.

Mystery Cave, is the largest cave in Minnesota (see topographic setting and cave map on Figures 1 and 2). The two entrances of the cave, plus the land around them, are administered by the state Department of Natural Resources at Forestville State Park, and interpretive tours are run for the public in both sections by DNR staff. The purpose of this report is to enhance the interpretive and management programs of the Park by providing a comprehensive reference to the geology and origin of the cave.

This study provides a descriptive inventory of the natural features within the cave and interprets how they formed. The cave is like a natural laboratory where a surprising number of features, rarely preserved on the surface, are left relatively undisturbed in a protected environment. The interpretation of these features helps to understand the evolutionary history of the entire surrounding region. For example, glacial sediment is poorly exposed at the surface, but there are well preserved and very old glacially derived sediments in Mystery Cave. Certain features that are actively growing in Mystery Cave are very rare, and studying them has helped to better explain these features in other caves elsewhere.

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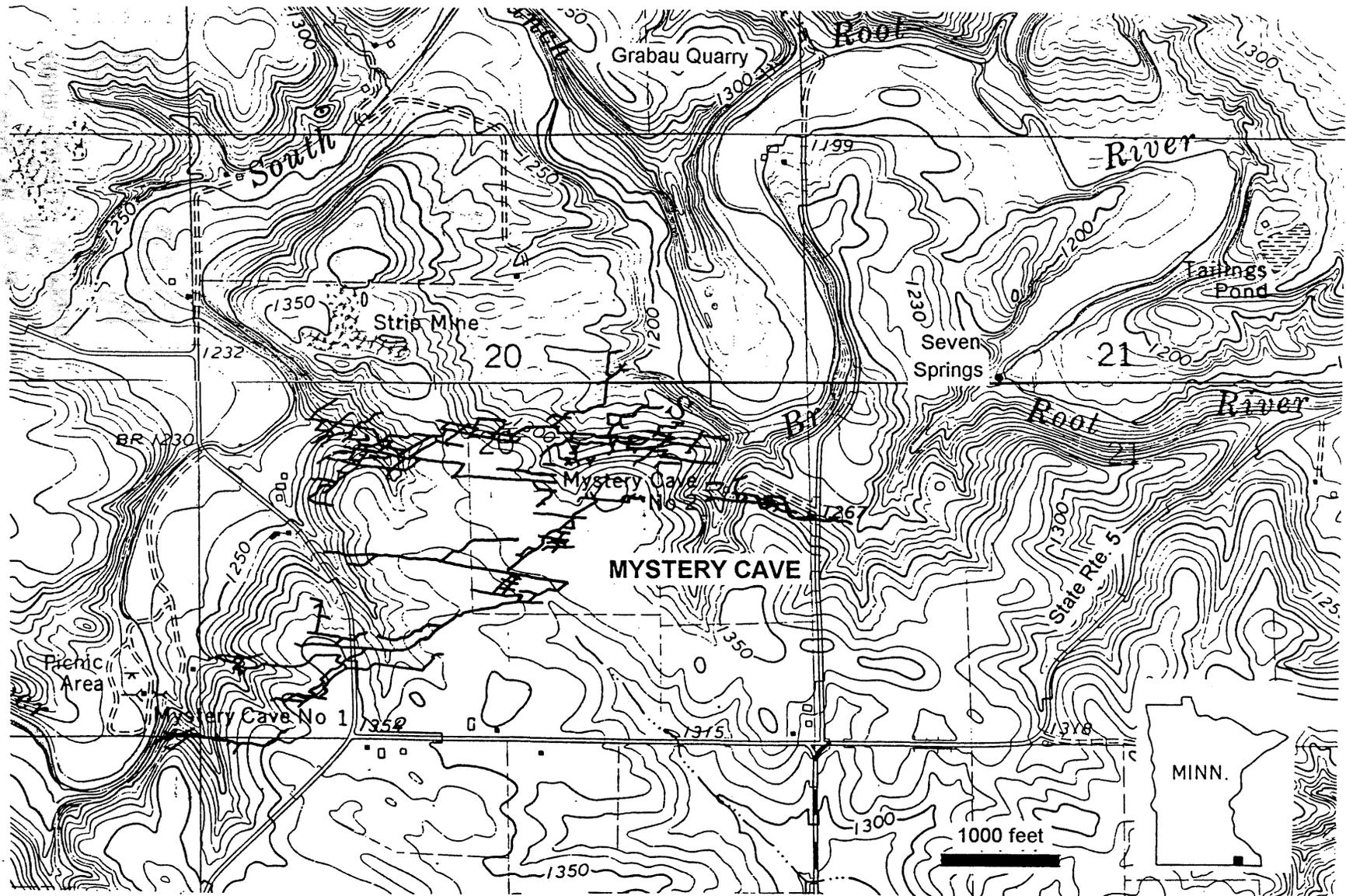


Figure 1: Location of Mystery Cave on the Cherry Grove and Wykoff USGS Quadrangles.

METHODS OF STUDY

Field and laboratory methods used in the preparation of this report are briefly described below, along with the major results. They are discussed in greater detail in the Technical Report.

Leveling Survey

To map the geology and its relationship to the cave, we leveled all the major passages in the cave (and some minor ones) with a tripod-mounted surveyor's level. This survey provided very precise vertical measurements, which are essential for a valid geologic interpretation. The horizontal layout of the survey was obtained from bearings measured with a SUUNTO compass, and distances were calculated from stadia readings made with the level. Where the passages were too small for the tripod-mounted level, a hand level and rods were used, along with a fibreglass tape and SUUNTO compass. Notes included continuous sketches of profiles plus and pertinent cross sections and descriptive information. At each station we measured upward or downward to the ceiling, floor, bedding planes, geologic contacts, sediment levels, water levels (past and present), and other noteworthy features. Bench marks were established in convenient places, mostly on natural features such as the tips of stalagmites. Where natural features were not available, an inconspicuous "+" was chiseled into the bedrock or on breakdown slabs, as requested by DNR. The 112 bench marks are listed in Appendix 1 of the Technical Report. Survey information is summarized in Appendix 2 of that report.

The geologic profile of the mapped passages is shown in the 20 sheets enclosed separately with these reports. For further details, see the section entitled Geologic Profile of Mystery Cave in the Technical Report.

Sampling of Bedrock, Speleothems, and Water

Loose chips of bedrock and broken speleothems were obtained in a non-destructive way, leaving no observable damage. Collecting in a cave should be done in the most discrete way possible, and only for projects that will provide a clear benefit to the interpretation of the cave. All strata in the cave were sampled, a total of 76 beds. In addition, 57 speleothem fragments and 4 sediment samples were obtained. The latter are relatively few, as the sediments had already been studied extensively by Milske (1982), and by Milske, Alexander, and Lively (1983). Sampling sites for rocks, minerals, and sediments for this study, plus sediment sampling sites of Milske (1982), speleothem samples used for U/Th dating by Lively (Milske, Alexander, and Lively, 1983) and for this report are shown in the Appendices of the Technical Report. A few water samples were taken for chemical analysis to correlate with our mineralogical observations. Water chemistry was the main focus of the LCMR Hydrology Project, and so our geochemical sampling and measurements were done simply to clarify a few mineralogical questions.

Mapping of the Rock Strata

Each bed in the limestone exposed in the cave was mapped during the survey. The stratigraphic section is shown in Figure 3 and is described in detail later in this report. Three rock formations are exposed in the cave: from lowest (oldest) to youngest, they are the Stewartville, Dubuque, and Maquoketa Formations. For convenience in mapping and identification, we identify individual beds with unofficial code names. Beds SX1 through SX3 are granular, crystalline beds near top of Stewartville. DT1 through DT4 are transitional beds at base of the Dubuque, with little or no

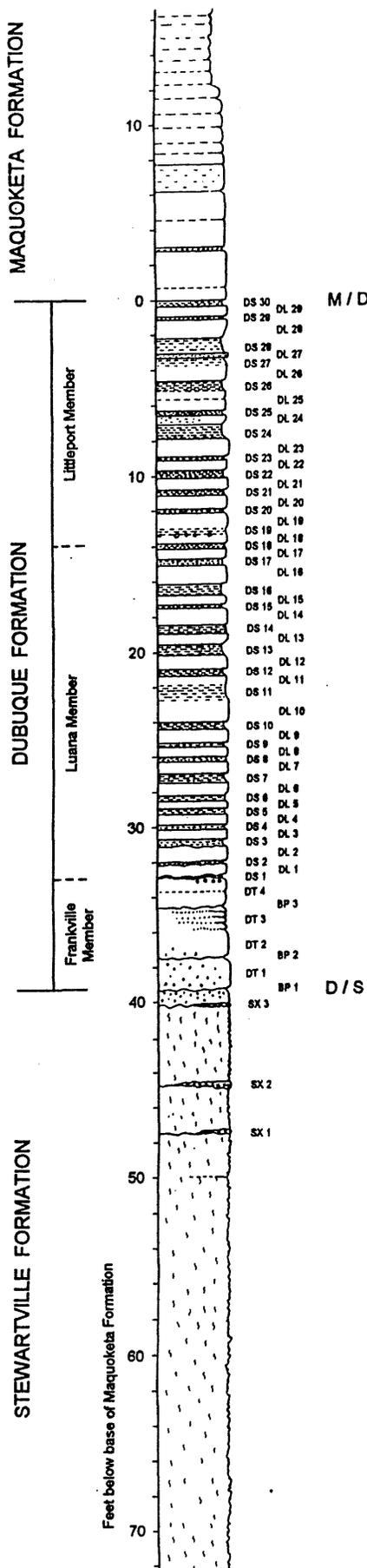
shale between them. BP1 through BP3 are major bedding planes near the base of the Dubuque. DL1 through DL29 are limestone beds in the Dubuque sandwiched between thin shale beds. DS1 through DS30 are the thin shale beds that separate the limestones in the Dubuque. Individual beds and contacts between beds are identified on the geologic profile by these code names. Contacts are indicated as in the following example: DS11/DL10 = contact between shale bed DS11 and the underlying limestone bed, DL10. The code names for the thin limestone and shale beds may seem awkward at first, but the advantage is that in the field it is possible to count quickly upward or downward from a known bed, using only the projecting limestones or the recessive shales, without having to keep track of every bed. It is appropriate to interpret each shale/limestone sequence as beginning with an influx of mud into the shallow sea, followed by a quiet period in which limestone is deposited. The alternation between shale and limestone therefore begins with DS1 (the first shale) followed by the corresponding limestone (DL1), then by the next sequence (DS2 and DL2), and so on.

The terms "limestone" and "shale" are used rather liberally in this description. As explained in the sections on interpretation of the bedrock, most of the limestones are highly dolomitic, and most of the shales are a combination of limestone and shale and so are technically limy shales or shaly limestones.

Refraction Seismology

A portable refraction seismometer was used to determine depths to bedrock in the valley of the South Branch of Root River near the Mystery I entrance, as well as a few other locations. To use the instrument, shock waves are generated at the surface with a sledge hammer on a thick aluminum plate. They are detected by a seismometer implanted in the soil at varying distances from the hammer. The travel time to the geophone for the first wave arrival is recorded on the seismograph. By comparing the travel time with the distance between the hammer and seismometer, wave velocities through the ground can be determined. At small distances the velocity is that of the soil (around 1000 ft/sec), but at larger distances the waves that arrive first are those that travel deeper into the ground through material that transmits the waves at a higher velocity (at Mystery Cave the weathered surface of the underlying limestone bedrock, which has a seismic velocity of about 10,000 ft/sec). The deeper waves can be detected because they refract back up to the surface, just as light is refracted through a lens, and because of the higher seismic velocity of the lower material, the deeper waves actually reach the seismometer first. (These are not waves that are simply reflected off the bedrock surface, as they would never reach the surface faster than the direct wave through the soil.) By calculating the wave velocities and the point at which both the direct and refracted waves arrive simultaneously, it is possible to find the depth of the bedrock below the surface -- i.e., the thickness of the soil or sediment on top of the bedrock.

The method of analysis is described in detail in the section on Refraction Seismology in the Technical Report. At Mystery Cave the depth of sediment in the valley of the South Branch of Root River is about 20-25 feet. Therefore, the valley was that much deeper before it was partly filled with sediment during glaciation. Most of the sediment appears to be wind-blown silt carried in from areas of exposed glacial sediment. It is interesting to note that the sediment in the valley is not saturated with water. The water table (the top of the zone in which all openings in the ground are filled with water) lies at or below the sediment/bedrock contact, at least 20-25 feet below the surface. This means that the South Branch is perched above the water table on the dry, rather impermeable silt. No wonder it loses its water to solutional fissures wherever it comes in contact with the limestone.



Maquoketa Formation: Shaly limy dolomite, incompetent, fossil-rich, and gray-brown, with a few beds of limy shale. Dolomite content is 50-90% in most beds. Approximately 17 feet of Maquoketa is exposed in Mystery Cave, mainly by breakdown into large near-surface rooms. Forms ceiling of Cathedral Room, the entrance rooms of Old Mystery and Old Still Caves, and the upper half of the cliff at the Grotto near the Mystery I entrance. Weathers to a soft silty muck in moist areas of the cave. Distinguished from the underlying Dubuque Formation by its general lack of rhythmically alternating limestone and shale beds.

Dubuque Formation: Competent beds of gray limestone alternating with thin interbeds of recessive limy shale. Total thickness at Mystery Cave is 39-40 feet. Limestone beds (labeled DL) are generally 8-12 inches thick; shale beds (labeled DS) average about 1-3 inches thick. A few shaly limestone beds reach thicknesses as much as 2 feet. One or two bentonite beds 1-3 inches thick near the middle and top of the formation. The Dubuque is sometimes divided into three members: The Frankville Member (lowest) consists of competent dolomitic limestone with prominent bedding planes and thin shale partings in places. The limestone beds are labeled DT (i.e., transitional Dubuque beds), and the prominent bedding planes are labeled BP. Dolomite content is 5-60%. The lower beds contain abundant small crinoid fossils. The Luana Member consists of alternating limestones and shales. Dolomite content is negligible in most beds but reaches 10% in a few. The Littleport Member (highest) is similar to the Luana, except that the limestone/shale alternation is not as regular and the dolomite content is much higher, varying from 5% to 40%. At other localities the bedding planes of the Littleport are wavier than those of the Luana, but this characteristic is not apparent at Mystery Cave. Contacts between the members are rather arbitrary. The dolomite content is a rational method for distinguishing the three members, although it requires laboratory analysis. The contact between the Dubuque and the underlying Stewartville Formation is a matter of debate; in this column the contact is placed at the upward change from rather massive limestone mottled with fossil worm burrows to well-bedded unburrowed limestone (generally equivalent to BP1).

Stewartville Formation: Massive gray-brown dolomitic limestone containing abundant mottling by fossil dolomitic worm burrows. Dolomite content ranges from 10% to 55%. Approximately 45 feet of Stewartville is exposed in Mystery Cave. In cave surfaces the dolomitic burrows either project from the walls or weather inward to form pockets, depending on the nature of the weathering and the dolomite texture. The burrows project outward mainly where the rock has been re-exposed after having been buried beneath cave sediment; the exact mechanism is still under study. A few thin beds of resistant, brown, crystalline limestone occur near the top of the Stewartville, which grade laterally into prominent wavy bedding planes. Apparently these horizons represent scouring by marine currents or wave action. The contact with the overlying Dubuque Formation is arbitrary. Here the contact is considered to be the clear break between burrowed dolomitic limestone and relatively pure granular limestone. This change causes a significant change in the weathered character of the cave walls. This contact is an approximate average of those designated by previous authors. The Stewartville is considered by some stratigraphers to be the uppermost member of the Galena Formation. Here the Stewartville is ranked as a formation within the Galena Group.

Figure 3: Stratigraphic column at Mystery Cave. See text for explanation of bed names.

Geochemistry

Water chemistry was not one of the primary goals of this project, since detailed information on the subject is available from the group undertaking the LCMR Hydrology project. However, the major geochemical concepts are described here, and a few measurements of water chemistry were made for this study, because they concern the origin of the cave and its speleothems. The results are summarized in the Technical Report.

In general, the drip waters entering the cave are highly supersaturated and have a high carbon dioxide (CO₂) content derived from the rich organic soil. The water rapidly loses CO₂ when it enters the cave, depositing calcium carbonate at a rate faster than in most other caves. During low flow, river water that enters the cave is saturated with both limestone and dolomite and is unable to enlarge the cave further. However, during floods, the river water and cave water derived from it are highly undersaturated and enlarges the cave.

Vibration Study

The seismograph was also used in the cave to measure the effect of surface disturbances in comparison with the background level of vibration. This study was rather preliminary, as our equipment and facilities were rather limited, but in general it showed that normal traffic over the cave produces almost undetectable vibration in comparison with background vibration from drips and other natural sources.

Laboratory Analysis of Samples

Rock and mineral samples were sketched, photographed, and described under a binocular microscope at magnifications up to 40X. Fossils, basic structure, and most minerals could be identified by this method. Some samples were immersed in mineral-specific stains that showed the distribution of certain minerals (mainly calcite). Most samples (73) were then cut by diamond saw into thin slabs and mounted on glass slides with epoxy, then ground to about 30 microns thick (0.03 mm), which is thin enough that they could be viewed by transmitted light through a microscope. These "thin sections" were interpreted and photographed with a petrographic microscope (magnification up to 630X), which uses polarized light to produce colors that help in the identification of minerals and their relationships.

Minerals that are too small to recognize under the polarizing microscope, or whose identity is ambiguous, can be identified by powdering a small sample and determining its X-ray diffraction pattern. A thin layer of powder is placed on a microscope slide and is slowly rotated within an X-ray diffractometer while it is exposed to a beam of X-rays. The rays are scattered by diffraction, and each mineral has a distinctive set of peaks at which the outgoing radiation is most concentrated.

The scanning electron microscope (SEM) is used to examine the surface characteristics of a sample. Combined with the SEM is an EDX (energy-dispersive X-ray) unit that is able to identify individual elements within selected parts of the sample. This information complements that from the X-ray diffraction unit. It does not identify the minerals but helps to narrow the range of possibilities and gives information about their impurities.

Results of these laboratory analyses are summarized in the Technical Report.

GEOLOGY OF MYSTERY CAVE

The results of the geologic study are summarized here, with emphasis on those aspects of the geology that pertain to the origin and layout of Mystery Cave and the features that it contains.

BRIEF GEOLOGICAL BACKGROUND

Mystery Cave is located in the southeast corner of Minnesota close to the Iowa border and shares the same regional geology as adjacent midcontinent states. The cave is developed in limestone and dolomite of the **Ordovician Period** (pronounced OR-do-VISH-ian), which are about 450 million years old. It offers fine exposures of bedrock, which nearly everywhere else in the region is buried under the much more recent glacial deposits. Although these rocks are also visible in a few outcrops, quarries, and road cuts, the rocks in Mystery Cave are much more continuous and are naturally weathered, rather than freshly blasted (as in the quarries), and therefore subtle textures and geologic features are much better displayed.

To put the geology of Mystery Cave into its proper context, a little background information is appropriate. The earth's hard outer crust is composed of rocks that fall into three groups: igneous, metamorphic, and sedimentary. Igneous rocks crystallize from molten lava and originate where mountains are actively forming. Metamorphic rocks are formed from preexisting rocks by heat and pressure. Sedimentary rocks consist either of chemical precipitates or fragmental material from the weathering of other rocks. At and near the surface in the Mystery Cave area, the rocks are all sedimentary. Sedimentary rocks are laid down in layers at the earth's surface at normal temperatures and pressures, and so they preserve many clues to the surface conditions that existed when they were deposited.

Rocks made up of weathered fragments of other rocks are called clastic rocks and were carried by water, air or ice before being deposited as layers. Clastic rocks are classified by the size and mineralogy of the grains. Microscopic fragments less than 4 microns (1/256 mm) in size are called clay. Clay minerals are complex compounds rich in silicon and oxygen that also include such elements as aluminum and magnesium. They are typically the weathering products of igneous rocks. Sedimentary rocks composed of solidified clay are called **shale**, a soft, flaky rock that is easily eroded. Particles between 1/256 and 1/16 mm in diameter are called silt, which forms the rock **siltstone**. Sand is between 1/16 and 2 mm in diameter and forms the rock **sandstone**. Siltstone and sandstone have the respective textures of very fine and coarse sandpaper. Sandstone is rather resistant and often forms cliffs. Siltstone is intermediate in characteristics between sandstone and shale. Larger eroded fragments are called gravel, which forms the rock **conglomerate**. The major mineral in silt and sand (and to some extent conglomerate) is quartz, which consists of crystalline SiO_2 . These sedimentary rocks are formed from their constituent sediments by compaction and by being cemented together by precipitated minerals.

Chemical sedimentary rocks include **limestone** (composed mainly of the mineral **calcite**, CaCO_3), **dolomite** ($\text{CaMg}(\text{CO}_3)_2$), and **gypsum** ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). These are the ones in which most large caves are formed. **Chert** is microcrystalline quartz, (commonly known as flint) which is usually deposited as a chemical sediment or replaces other rocks. A simple way to differentiate between quartz of any kind (including chert) and the other chemical sedimentary rocks is that quartz will scratch glass while the others will not. Dilute acid (e.g., 10% hydrochloric acid) will cause calcite to

fizz like a can of soda whose top has just been removed. Dolomite also fizzes in acid, but very slowly, and usually only if it is powdered first. Limestone and dolomite are usually gray and are fairly resistant to mechanical erosion. They are able to stand up as cliffs because of this; but they also form caves because they dissolve in water. Gypsum is a white to light gray rock so soft that a fingernail will scratch it. It is so soluble that it is normally dissolved away completely at the surface in humid climates.

Mystery Cave offers a fine chance to see limestone, dolomite, shale, and various combinations of all three rock types. It is immediately clear that the rocks were laid down in nearly horizontal layers, which are called **beds**. Each bed represents a rather continuous deposit of sediment. Contacts between beds are called **bedding planes**. These are formed by breaks in the deposition or changes in the type of sediments being deposited. Some bedding planes are nearly flat, whereas others have wavy relief indicating irregularities in the sedimentary deposit, or disturbance of the sediment surface, for example by erosion.

One of the most useful aspects of sedimentary rocks is that the layers deposited on top are always younger than those below. This is called the law of superposition. In the 1800s geologists were just beginning to recognize the different rock layers. They discovered that they could trace the beds laterally from one area to another, because some beds had unique features that could be easily recognized. These features included fossils, which are the remains of extinct organisms. Usually only the hard parts such as the shell remain. They could even trace rocks of the same age from continent to continent using fossils. Rocks all over the world could be separated into groups whose boundaries represented periods of erosion. Where the eroded surface of old rock layers is overlain by younger rocks, the irregular contact is called an **unconformity**. On the basis of these major groups of sedimentary rocks and the unconformities between them, a geologic time scale was devised. This time scale consists of several Eras and Periods, as shown in Table 1.

A continuous sequence of sedimentary beds having approximately the same character (such as sandstone) is called a **formation**. Each formation is given the name of the place where it was first described. For example the Stewartville Formation, which is seen in the lower levels of Mystery Cave, was named in the early 1900s for exposures near the town of Stewartville in Olmsted County, Minnesota. Rock types change their character from place to place, for example from limestone to shale, because of changes in the depositional environment changes. So the limestone and the shale would each be given a different name, although they were deposited at the same time. In this way a formation can change laterally to a different formation of the same age in another area. Furthermore, the boundaries are highly gradational. Thus the naming of a rock formation is not at all as simple as it might seem.

The rocks of the Mystery Cave area were deposited during the Ordovician Period, about 438-504 million years ago. Mystery Cave itself was formed by the dissolving of some of these Ordovician limestones by underground water over the past 0.5-1 million years, during the Quaternary Period. All but the last 12,000 years or so of the Quaternary Period consists of the Pleistocene Epoch, when large parts of the world were covered periodically by glaciers.

Dating geologic events such as the origin of rocks or the formation of a cave is one of the major tasks of a geologist. In most cases it is possible to work out the **relative ages** of geologic features and events by using clues and relationships such as the law of superposition. For instance, we know that Mystery Cave is younger than the rocks that it is in, because those rocks had to be dissolved

in order to form the cave. Likewise, we know that the sediment in the cave is younger than the cave. Beyond that, things get more complicated.

Absolute ages are harder to come by. These represent measurements or estimates of the actual age of a geologic feature or event. Radiometric dating is a major tool. Natural radioactive materials in certain rocks break down at known rates, so when the ratio of parent to daughter element is measured, it is possible to determine the age of the rock. The time scale is based mainly on radiometric age determinations and is revised as better dating techniques are developed. The geologic time scale was developed in Europe and initially reflected breaks in deposition, but because these rock breaks vary slightly from continent to continent, the time scale today does not necessary coincide with major rock breaks any more, but it is still useful as a yardstick to show us how old the rocks are.

Table 1: The geologic time scale.

AGE (millions of years ago)	ERA	PERIOD	MAJOR EVENTS
0-2	CENOZOIC	QUATERNARY	Glaciation, origin of Mystery Cave
2-70		TERTIARY	
70-230	MESOZOIC	CRETACEOUS	dinosaurs, first birds and mammals
		JURASSIC	
		TRIASSIC	
230-600	PALEOZOIC	PERMIAN	rocks at Mystery Cave deposited
		PENNSYLVANIAN	
		MISSISSIPPIAN	
		DEVONIAN	
		SILURIAN	
		ORDOVICIAN	
		CAMBRIAN	
>600	PRECAMBRIAN		Early evolution of the earth; simple plants and animals

Periods when rocks were being deposited were interrupted by mountain-building (tectonic) events, which caused uplift of the surface and partial or complete erosion of the rocks that had been deposited. The cause of these tectonic events and their recurrence through time was not completely understood until the 1970s, when geophysicists found that the rocky crust of the earth consists of hard blocks, or plates, that move about on in the more fluid underlying material as the indirect result of heat loss from the earth's interior. This is the concept of **plate tectonics**. Where plates collide, mountains form. In these areas, rocks are melted, altered by heat and pressure, uplifted and ultimately eroded to produce blankets of clastic sedimentary rocks around their flanks.

It was recognized long ago from their matching shapes that the present continents could have all originated from a single supercontinent called *Pangea*. Plate tectonics suggested that many of the continents are periodically joined into a large land mass, only to split apart once again into separate continents. Heat build-up under large continents causes them to split apart because of convective overturn in the underlying mantle of the earth. This cycle of continental buildup and breakup has occurred many times. Igneous and metamorphic rocks, metamorphism and the production of great sheets of clastic sediments indicates a time of tectonic events and plate collisions. Widespread layers of chemically precipitated sediments, such as limestone, formed mainly in areas far removed from the areas of active mountain uplift.

Mystery Cave shows us three major aspects of geology: its fine exposures of sedimentary rocks and fossils contain many clues to the environments in which the rocks were deposited back in the Ordovician Period; and the cave itself tells a complex story about the erosional, depositional, glacial, and climatic history of the region during the Quaternary Period. Finally, its cave "formations" (or *speleothems*) reveal a great deal about how crystals grow and what controls their shapes.

ROCK STRATA

Stratigraphy is the study of sedimentary rock strata. Although this may sound like the world's most boring topic, it involves no less a goal than discovering the history of the earth. Like a detective, a stratigrapher uses subtle clues hidden in rock layers to reconstruct events long past.

Sedimentary Environments

During large portions of the Paleozoic Era, the low-lying interior parts of the North American continent lay slightly below sea level. Much of the continent was submerged beneath shallow sea water (an *epeiric sea*). The continents are higher today and there are no longer any large-scale interior seas, which were so common in the past, so much of our knowledge of epeiric seas is found indirectly from the rocks that were deposited on their floors. After mountain-building events, large amounts of sediment were carried into the seas and spread out as blanket deposits over much of the continent. Between mountain-forming events, or far from the outlets of rivers that supplied the sedimentary material eroded from the land, chemical precipitates predominated. The Ordovician rocks at Mystery Cave were formed on just such a continental platform, and they consist of a mixture of both the eroded debris carried into the epeiric sea by rivers and chemical precipitates such as the limestone and dolomite in which the cave is developed.

The record of all the rocks deposited in the North American epeiric seas consists of rock layers separated by unconformities (breaks in the sedimentary record, when there was no deposition, or when erosion removed some of the earlier-deposited rocks). The unconformities usually represent

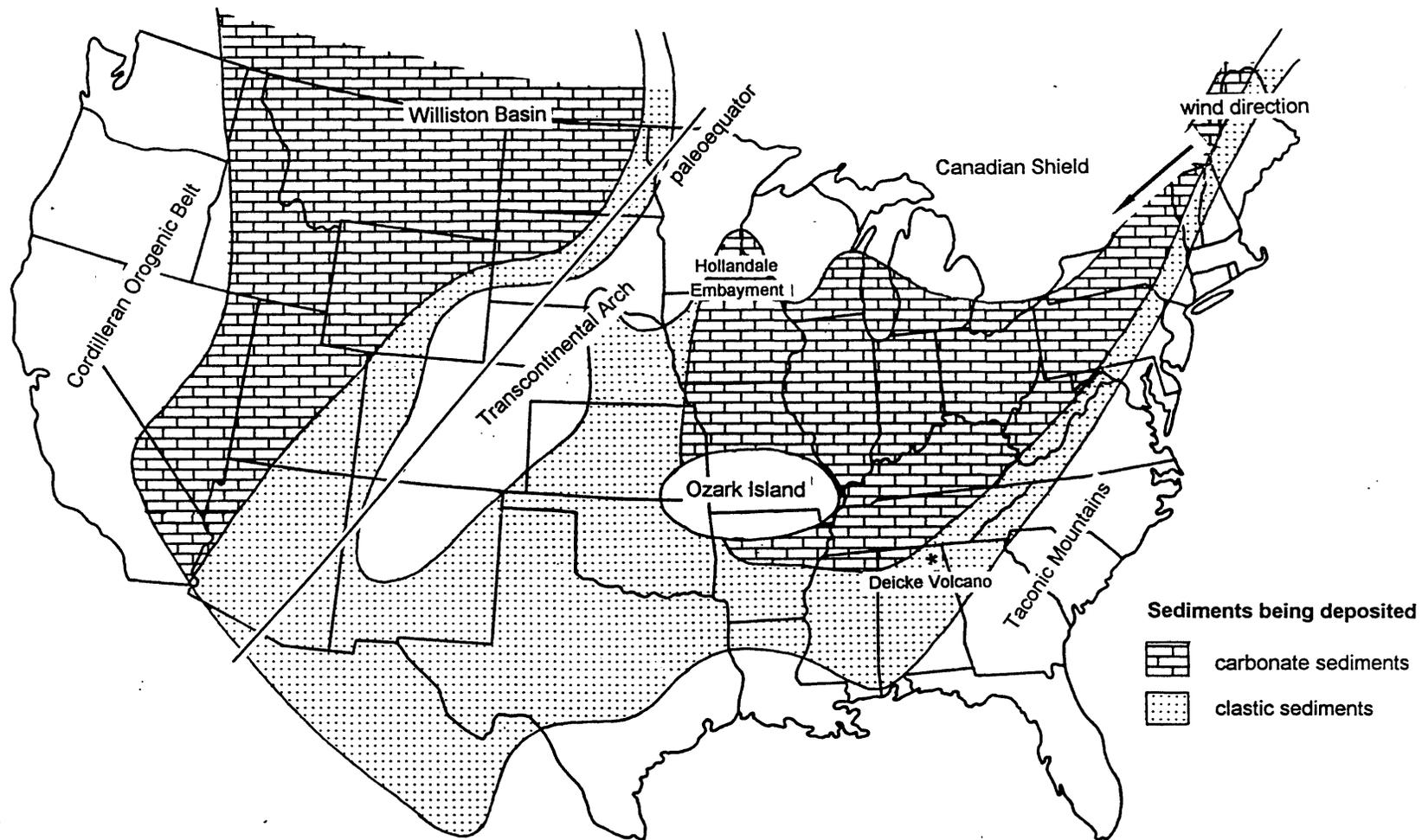


Figure 4: Map of what is now the United States during the Late Ordovician Period (modified from Sloan, 1987, and Seyfert and Sirkin, 1979).

major uplifts when the continents rose and the sea temporarily retreated from them. There were three periods in the Paleozoic Era when the sea retreated, and one of them was at the end of the Early Ordovician Period (see Figure 4). Retreats of the sea are called regressions, and advances of the seas, when sediments were deposited, are called transgressions. It is often difficult to prove what caused the sea to move in and out; it could have been either the continent rising or sea level falling. There is no consistent elevation marker than can be used to indicate which took place. In fact, if sea level is our standard measure of elevation, then the two events are equivalent! At least the effects are virtually the same.

Time breaks between the various periods of geologic time (like the one between the Cambrian and Ordovician Periods) were formulated in Europe and correlate with stratigraphic changes there. When paleontologists correlated the rocks in North America with those in Europe using fossils, they found that the rock breaks in Europe did not necessarily match those in North America. This does not make the geologic time scale useless, it merely means that it is independent of the major physical changes that took place in North America.

To aid in their interpretation, the sedimentary rocks of North America have been subdivided into four major rock sequences whose deposition was separated by periods of erosion, as shown in Figure 5 (Sloss, 1963). The rocks in the Mystery cave area are part of the Tippecanoe Sequence, the second major sequence of rocks deposited during the Paleozoic Era.

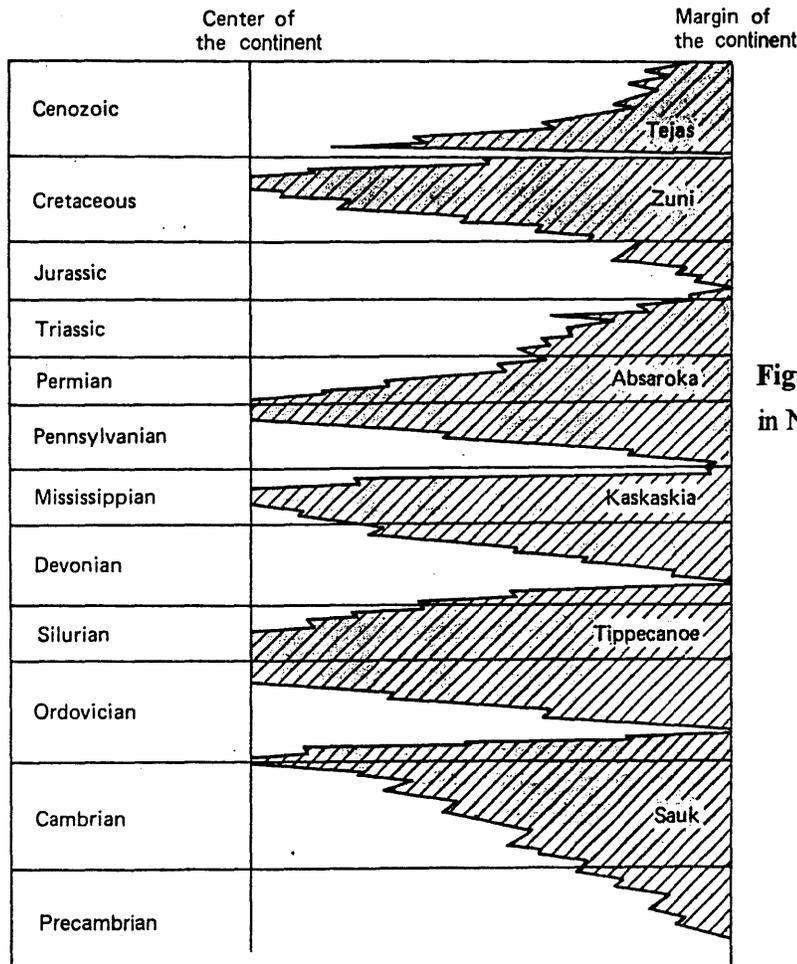


Figure 5: Major rock sequences in North America (after Sloss, 1963).

Ordovician Rocks of Southeastern Minnesota

During the Ordovician Period, the continental plates were not in the same position as they are today, because the plates have wandered through time over the surface of the earth. Midcontinental North America was 10 degrees south of the equator during the Late Ordovician. This rather startling information comes from studies of the orientation of magnetized particles in rocks that still retain the pattern of the earth's magnetic field when the rocks were formed. The topography was different also. The Taconic Mountains were forming along the east coast, and the midcontinent had low-relief, persistent structures that periodically rose and fell along very old, Precambrian zones of weakness. Southeastern Minnesota is in the Keweenawan rift valley, which subsided during the Late Ordovician forming a downwarped area, called the Hollandale Embayment. This caused deposition of sedimentary rocks to be continuous between the Stewartville, Dubuque and Maquoketa in the Minnesota area, although it was not elsewhere. To the north and west was the Transcontinental Arch, a northeast-southwest trending structure running through most of Minnesota and extending through Nebraska toward Colorado.

The Tippecanoe Sequence of sedimentary rocks was deposited on the North American platform after a long break in deposition that occurred at the close of the Early Ordovician Period (about 480 million years ago). This break must have been a lengthy one, because the fossils in the Tippecanoe Sequence are very different from those in earlier rocks, implying that organisms had a long time to evolve new forms. During the break in deposition, major uplifts formed the Taconic Mountains in a northeast-southwest belt along the eastern coast of North America. Evidence for this is found in the Middle Ordovician sedimentary rocks in neighboring areas. In the eastward direction the sedimentary rocks become thicker and more coarse-grained (e.g., they change from shale to sandstone to conglomerate), indicating that the sedimentary material had come from an eroding mountain range along the east coast.

During the Middle and Late Ordovician Period, clastic and chemical sediments were deposited over wide areas in the shallow sea that covered much of North America at that time. Figure 6 shows the sequence of rock units in the north-central United States. Erosion of land areas during the Middle Ordovician (460-480 million years ago) caused very pure quartz sand to be deposited in the sea throughout what is now the north-central United States. These high areas included the broad Canadian Shield to the north (mainly Precambrian igneous and metamorphic rocks) and the Transcontinental Arch to the west. This blanket of quartz sand, long since solidified into sandstone, is now known as the **St. Peter Sandstone**. It forms the bottom of the Tippecanoe sequence in the Mississippi Valley area. At Mystery Cave it is about 60 ft thick, but it is buried beneath younger rocks and so is not seen at the surface in this area. The well that supplies the Mystery I area obtains its water from this rock formation. ←

Above the St. Peter Sandstone, the **Platteville Formation** (about 20 ft thick) includes limestone and dolomite with interspersed shale and chert. The **Galena Group** that followed is rather similar. A 1000-foot uplift of the Transcontinental Arch exposed the arch to erosion, and the resulting clastic sediment spread into what is now the Mystery Cave area in early Galena time. The lower formations of the Galena Group include the **Decorah Shale** (about 30 ft thick), the **Cummingsville Formation** (about 50 ft thick), and the **Prosser Formation** (about 40 ft thick). See Mossler (1987) and Levorson and Gerk (1983) for details. The Cummingsville is composed of repetitive limestone and shale beds with more clastic material than the Prosser. The Prosser consists of finely crystalline, fossiliferous limestone with very thin shale partings and nodular chert layers. The stratigraphic names

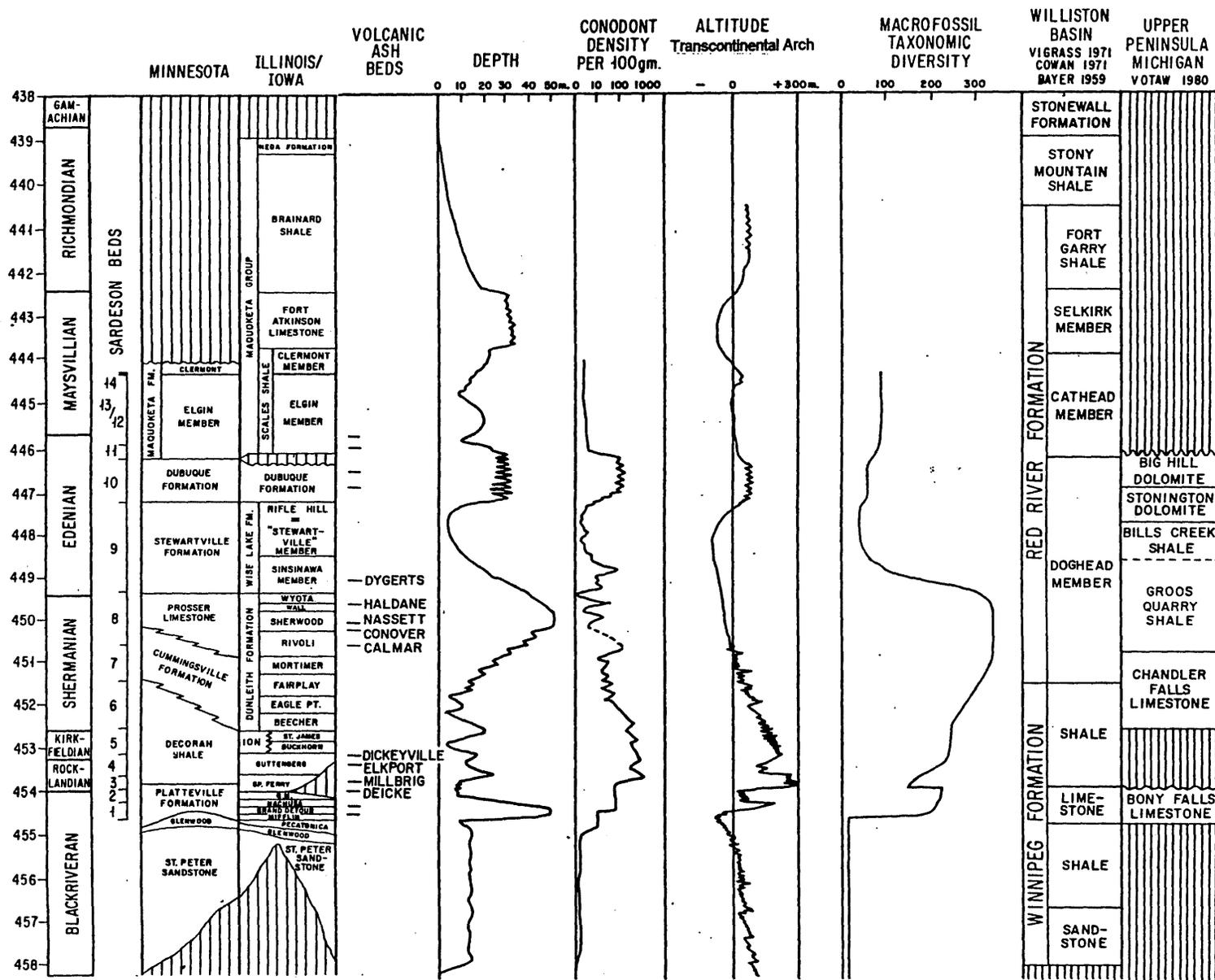


Figure 6: Middle and Late Ordovician rock strata in the Minnesota area and their relationship to sea-level change and to other rocks in the northern U.S. (from Sloan, 1987).

and boundaries in the Galena Group change from place to place and are often revised, so it is wise not to become too attached to any of them.

The **Stewartville Formation** (about 80 ft thick) is the uppermost rock layer in the Galena Group and is the one in which the lower levels of Mystery Cave are developed. It consists mainly of limestone and dolomite. Geologists have interpreted the Stewartville Formation in Minnesota as a shallowing-upward sequence ending almost at sea level (see Sloan, 1987). In other words, the depth of the sea was diminishing with time. The Transcontinental Arch had been completely eroded to below sea level by that time, and so the Stewartville contains relatively little insoluble material. Despite the shallowness of the sea, its floor was generally below low-tide level, as there are no raindrop marks or mudcracks on bedding planes. These quiet conditions were perfect for burrowing worms, whose fossil burrows are abundant throughout the top part of the formation.

Eventually the Transcontinental Arch was periodically exposed above sea level once again, and its eroded material was deposited in the Mystery Cave area as the interbedded shales separated by limestone beds, which form the **Dubuque Formation** (about 40 ft thick). The Dubuque was deposited in deeper water with periodic reductions in depth that correlate with deposition of the shale beds. Rates of deposition were roughly 12 mm per 1000 years (Sloan, 1987). The upper beds of the Dubuque were deposited in comparatively oxygen-poor conditions, as shown by the preservation of organic walls of microfossils, which would otherwise have decomposed.

Meanwhile, renewed uplift of the Taconic Mountains to the east caused shale and sandstone deposits to spread westward, covering the continental platform. By the Late Ordovician time (460 - 440 million years ago), this sediment reached as far as Iowa and Minnesota, almost 1000 miles away. The rhythmic alternation between limestone and shale was replaced by a more uniform accumulation of shaly limestone and dolomite, which formed the **Maquoketa Formation** (about 60 ft thick at Mystery Cave). The sea was even deeper (up to 150 feet) at the time, and abundant organic material, pyrite, and phosphate show that the water continued to be oxygen poor.

Sea level dropped, and there was a long interval during which no rocks were deposited and many were eroded away. The next rock layer to be deposited in the area was the **Cedar Valley Formation** (maximum thickness 150 ft) of Middle Devonian age (about 370-390 million years ago). It is separated from the underlying Dubuque Formation by an unconformity. This is composed mainly of shallow-water limestone and dolomite. It forms the tops of the hills over Mystery Cave, but the cave does not extend into it.

Periodically during the Middle and Late Ordovician Period, while the rocks above the St. Peter Sandstone were being deposited, thin but widespread layers of volcanic ash clay layers were scattered across much of the region. This material came mainly from the mountains along the east coast. The ash was quickly weathered to clay, mainly montmorillonite. Even though each bed is only a few centimeters thick, they can be traced over large areas, giving us an excellent tool for correlating rocks from one area to another. Each bed represents a very short time interval and is exactly the same age everywhere. These volcanic-derived clays are called bentonite, a gooey, porous, absorbent material. The bentonite at Mystery Cave has been altered so that it is better called **metabentonite**, which no longer contains montmorillonite, but which must be identified from trace minerals such as zircon, apatite, biotite, and garnet. At least 18 bentonites or metabentonites are known from the upper Mississippi Valley alone. Individual beds have been traced from Minnesota to Tennessee (Samson and

others, 1989). The largest of these, the Deicke bentonite, at the bottom of the Decorah Shale, coincided with a major biological extinction. That eruption caused a gigantic ash fall, twice the volume of the largest historic eruption (Sloan, 1987). Bottom-dwelling marine organisms were apparently unable to dig their way out of this ash.

Ordovician Fossils in the Mystery Cave Area

The preserved remains of plants and animals provide a clear interpretation of the kinds of environments in which the rocks were deposited. A fossil is any recognizable organic structure, or impression of such a structure, preserved from prehistoric time. Usually only the hard parts, such as shells, are preserved. The fossil record clearly shows that organisms have increased in kind and number with time as they adapted to new ways of life or new environments. The Ordovician climate was warm, favoring an abundant fauna, because North America lay near the equator at that time.

The sea that covered much of the North American interior platform was shallow enough that the floor was usually within the range of wave and current motion. Most often when animals died their shells were ground up by wave action or broken by scavengers and borers, forming a limy mud. It was less common for whole intact shells to be preserved, and they usually indicate deposits that accumulated below the base of the waves. Figure 7 (three pages long) shows some of the common types of animals whose remains are found today as fossils in the rocks of the Mystery Cave area.

Trilobites (pronounced TRY-low-bytes) were arthropods, as are insects. They were very abundant during the early Paleozoic Era but have been extinct a long time. Of all fossils, trilobites are especially interesting because they are among the most complex of early animals. Like other Arthropods, they had an external skeleton (exoskeleton) and a segmented body with paired appendages. Arthropods usually shed their shells as they grow, and these discarded exoskeletons are more often preserved in the rock record than the intact animals. They were scavengers, like modern lobsters. *Flexicalymene* (FLEX-ee-cala-MEENy) is a common trilobite found in the Dubuque.

Also very common in the Late Ordovician were **brachiopods** (BRACK-ee-o-pods), which had hard bivalved shells and attached themselves to some hard object by a muscular stalk. Some brachiopods survive today. The two parts of their shell are asymmetric, in other words the front shell is different from the back. They are most common in shallow marine water and derive food by circulating water through their mantle cavities, mainly eating marine phytoplankton. Brachiopod shells are distinctively layered, as can be seen under the microscope. The layers are laminated at angles to the shell surface like the shingles on a roof. Common brachiopods found in the Mystery Cave area include *Megamyonina unicosata* (MEG-a-my-OH-nia YOU-na-coss-TAHTa) and *Thaerodonta recedens* (THERRo-donta ra-CEED-ens), and *Paucicrura* (PAW-sa-KRURa, formerly *Resserella*) in the Dubuque; *Strophomena* (STRO-fo-MEENa) in the Stewartville and *Sowerbyella* (SOR-bee-ELLA) and *Rafinesquina* (RAFF-in-ESK-ina) in the Dubuque and Stewartville, which are both thin with long straight hinge lines, and *Rhynchotrema* (RINK-o-TREE-ma) in the Stewartville which has a sharp beak and is ornamented with radial pleats; and *Zygospira* (ZY-go-SPY-ra) in the Stewartville, which had helical structures that held up the soft internal organs.

Gastropods (GAS-trow-pods) are snails with coiled shells. In the Paleozoic Era they commonly lived along with brachiopods. They were bottom-dwelling scavengers that grazed on such food as algae growing on rock surfaces. *Hormotoma* (HORmo-TOE-ma), which has a helical spiral, and *Maclurites* (MAC-lur-EYE-tees), are found in the Stewartville in the Mystery Cave area.

Figure 7: Some Ordovician animals whose fossils are common in the rocks at Mystery Cave. Continued on next two pages.

Paleosynapta flaccida - a worm which left semi-vertical, dolomitized burrows.

Stewartville Formation

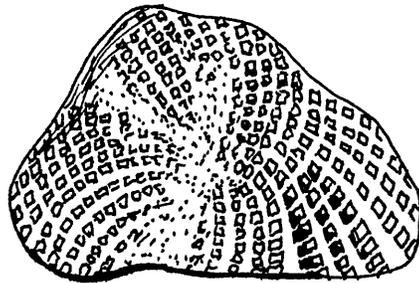


5 cm



dolomite rhombs

Fisherites reticulatus (formerly Receptaculites oweni) a dasycladacean green algae



Stewartville Formation

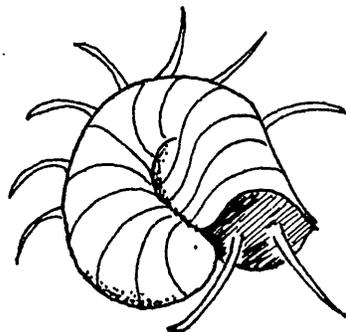
1 cm



Gastropods - Snails

Stewartville Formation

Maclurites



1 cm

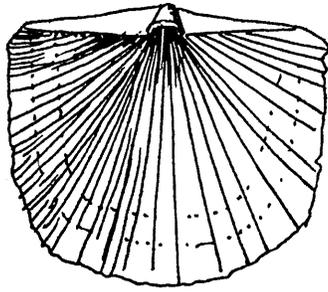


Hormotoma

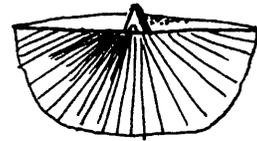


Figure 7 (continued): Some Ordovician animals whose fossils are common in the rocks at Mystery Cave. Continued on next page.

Brachiopods



Rafinesquina



Sowerbyella

1 cm
—

Stewartville and Dubuque Formations



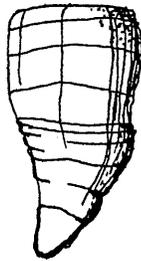
Zygospira



Rhynchotreta

1 cm
—

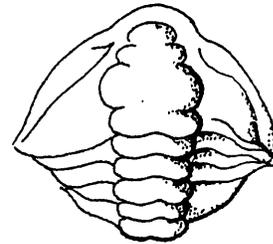
Horn Coral



Streptelasma

1 cm
—

Trilobite

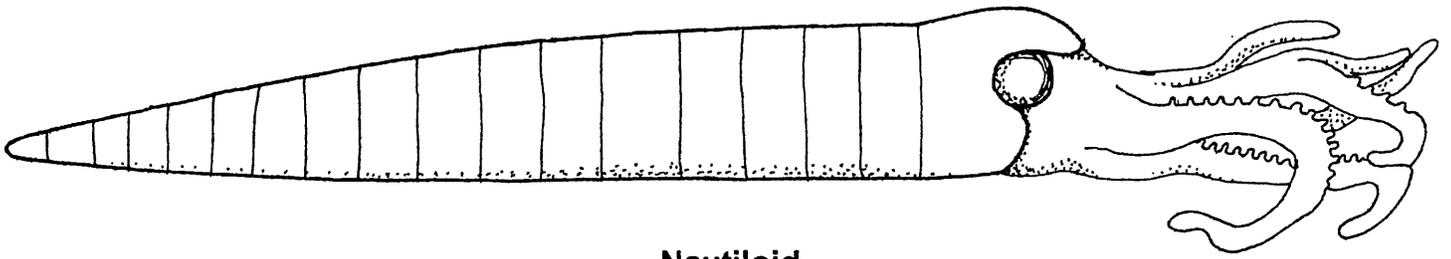


Flexicalymene

1 cm
—

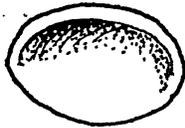
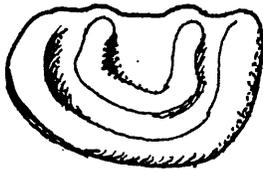
Figure 7 (continued): Some Ordovician animals whose fossils are common in the rocks at Mystery Cave.

Dubuque Formation



Nautiloid

30 cm

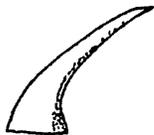


Ostracods

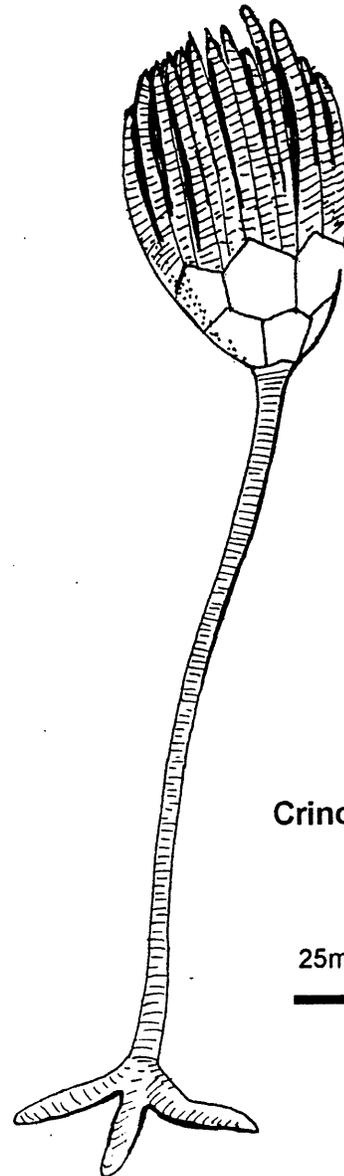
.5mm



Conodonts



.5 mm



Crinoid

25mm



Another scavenger was the nautilus, which is a **cephalopod** (SEFF-a-low-pod). Although most cephalopod shells are coiled, those of the Ordovician were straight, like elongate ice-cream cones. The most common living cephalopods are squids and octopuses. They have tentacles with suckers and live in chambered shells that give them buoyancy, but their most unusual characteristic is the way they move. They eject a stream of water that forces them backward through the sea like a projectile. The nautilus *Orthoceras* (or-THAH-ser-us or OR-tho-SERR-us) is found in the Stewartville and Dubuque Formations (Figure 8). Those visible in Mystery Cave are found mostly near the bottom of the Dubuque. These fossils range from a few inches to over six feet long, and living individuals at the time could grow to much larger size. They were the terror of the Ordovician seas.

Beds with abundant **crinoid** (CRY-noid) fossils are common near the Stewartville/Dubuque contact (Figure 9). Crinoids are echinoderms, a group that includes starfish and sea urchins. The echinoderms have five-rayed symmetry and their skeletons are made of calcium carbonate plates. When the animals die, their skeletons break into numerous plates which are scattered by the ocean currents and they were common debris on the sea floor. Under a microscope, in thin sections of rocks, the plates look like rectangular crystals and commonly are the nucleus for continued calcite overgrowths. Crinoids still grow today, although they are not as common as in the past. They live in vast gardens and look something like flowers with roots which attach to the ocean floor, a stem composed of superimposed circular plates, and a head from which arms branch out. The arms set up currents which sweep food toward the head, which contains the digestive tract and reproductive organs. The crinoid fossils in the Mystery Cave area are unusually small, usually no more than a couple of millimeters in diameter.

Corals are animals with soft bodies called polyps that have extended tentacles. The polyp lives in a cup-shaped skeleton full of radial partitions that separate the folds in its body wall. The fossil horn coral *Streptelasma corniculum* (STREP-ta-LAZ-ma cor-NICK-u-lum) is common in the Stewartville. Horn corals resemble conical horns and are common fossils in the shallow Paleozoic seas.

Bryozoans (BRY-o-ZO-ans) are colonial organisms common in shallow water. They are so similar to corals that they can be confused. Like corals, they consist of small fleshy organisms with tentacles that sweep microbes into their mouths. The organisms grow by budding, so when an animal divides, the new animal becomes encrusted with a wall. Under the microscope, many corals and bryozoans consist of vertical closely packed cylindrical structures divided into many individual compartments.

The Stewartville contains a distinctive fossil which has no living equivalent, but was apparently a form of green algae (Sloan and Kolata, 1987). It is *Fisherites* (FISH-er-EYE-tees), formerly *Receptaculites* (REE-sep-TACK-u-LIGHT-ees), which forms large hemispherical masses of small honeycomb-like compartments.

A large flabby worm called *Paleosynapta flaccida* (PALE-ee-o-sin-APT-a FLASSida) was also present in the Late Ordovician Stewartville mud and left many sediment-filled burrows that were eventually dolomitized. The worm itself is rarely preserved, but its dolomitized burrows are the dominant visible feature of the Stewartville.



Figure 8: Part of the shell of a nautiloid cephalopod *Orthoceras*, exposed in the ceiling of the route to Base Camp in Mystery II. Its diameter is about 6 inches.

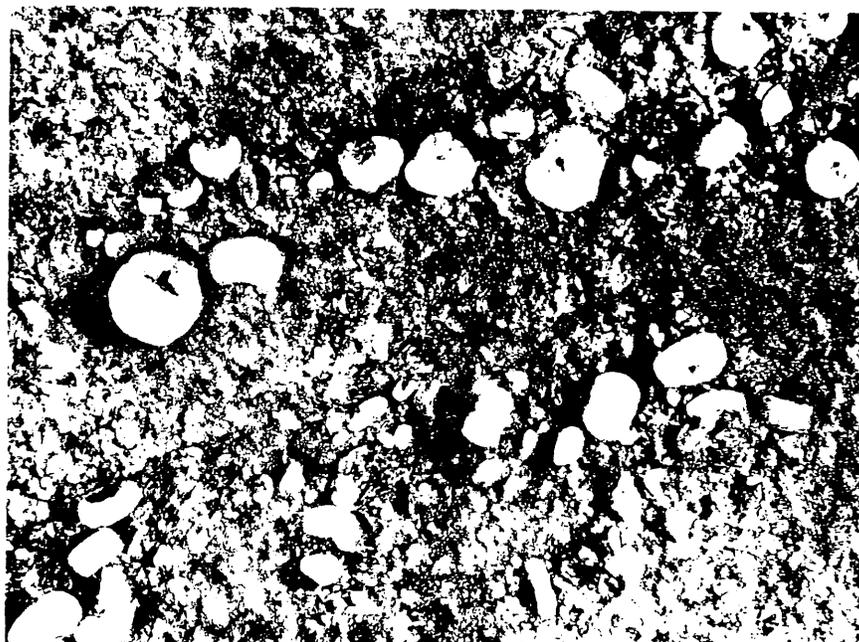


Figure 9: Fragments of crinoid stems are common in the beds near the Dubuque/Stewartville contact. Those shown here are located in Diamond Caverns, off Fourth Avenue in Mystery II. Each round segment is only about 2 mm wide.

A few less conspicuous fossils are the following: **Ostracods** (OSStra-cods), are crustaceans with tiny rounded shells usually 1-2 mm long, which swim near the sea floor. **Conodonts** (CONNo-donts) are microscopic structures of calcium phosphate that look like tiny teeth. They probably represent parts of the feeding apparatus of some unknown extinct animal. Both ostracods and conodonts frequently evolved new, distinct shapes and were widespread in distribution, so they are very useful for correlating beds over very large distances. Common in the upper part of the Dubuque, along with phosphate grains, are very tiny fossils of unknown affinity which look like cinnamon specks (Witzke, 1987). Among these are **Chitinozoans** (KITE-in-o-ZO-ans), which are extinct marine microfossils (150-300 microns long). They are thin walled and tapered like a flask, and are usually black, structureless and opaque but may be brown and translucent (Bates and Jackson, 1987).

Although their fossils are not found in the Mystery Cave area, fish first appeared in the Ordovician Period -- the first vertebrates with spines and a brain.

Rocks Exposed at Mystery Cave

The rock formations in which Mystery Cave is located are described here in rather general terms that emphasize the easily recognized features as seen in the cave. A more detailed discussion of the environments in which they were formed, based mainly on microscopic evidence, is given in the Technical Report in the section entitled Stratigraphic Interpretation.

Mystery Cave has formed in carbonate rocks deposited in shallow seas 446-448 million years ago (Sloan, 1987). The rocks exposed in Mystery Cave are the upper 45 feet of the Stewartville Formation, the full 40-foot thickness of the Dubuque Formation, and the lower 10 feet of the Maquoketa Formation. Refer to the fold-out stratigraphic column from the cave (Figure 3), and to the column measured in the Rifle Hill Quarry to the east of the cave by Levorson and Gerk (Figure 10, reproduced by Sloan and others, 1987).

The **Stewartville Formation** in Minnesota is the upper part of the Galena Group. It is distinguished from the underlying Prosser Formation by the absence of chert nodules, scarcity of fossils, and high dolomite content. Worm burrows are well exposed in all of the Stewartville seen in the cave. Bedding planes in the Stewartville are few and are hard to trace, because they do not contain shale interbeds and are discontinuous laterally, possibly because burrowing partially destroyed the bedding. Breakdown blocks of Stewartville often split into uniform slabs, however (as in 17 Layer Rock in Fifth Avenue), showing that many bedding planes are present but did not form partings wide enough to be enlarged by solution. The low-level crevices and stream passages in the cave are in the Stewartville. The mottled texture of the Stewartville was caused by burrowing by the rather fat flabby worms *Paleosynapta flaccida*. Although the worms were rarely preserved as fossils, their burrows are quite visible as curvilinear bodies about half an inch in diameter with roughly circular cross section and granular texture. The burrows are generally dolomite, whereas the surrounding bedrock is largely limestone. In many places the burrows weather inward, forming circular pockets (Figure 11). In other areas the burrows project outward and can form loops that extend from the wall like thick teacup handles (Figure 12). The projecting ones appear to have been weathered beneath a former layer of sediment fill in the cave.

The upper 10 feet of the Stewartville is interrupted by three beds of granular, crystalline limestone several inches thick at most (SX1 - SX3). In many places one or more of these beds is absent and its stratigraphic position is marked by an irregular bedding plane with a wavy appearance.

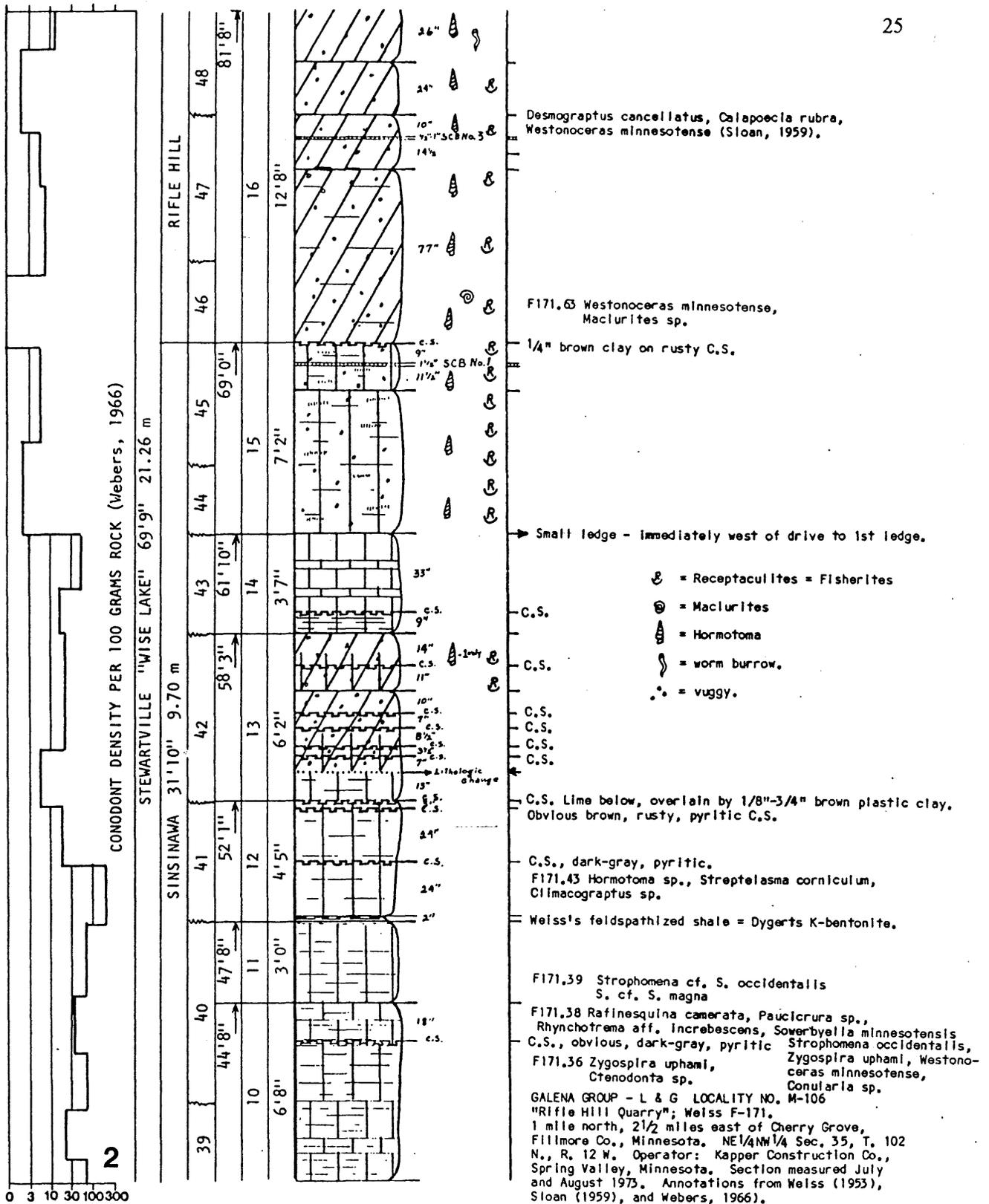


Figure 10: Stratigraphic column measured in Rifle Hill Quarry by Levorson and Gerk (from Sloan and others, 1987). Continued on next two pages.

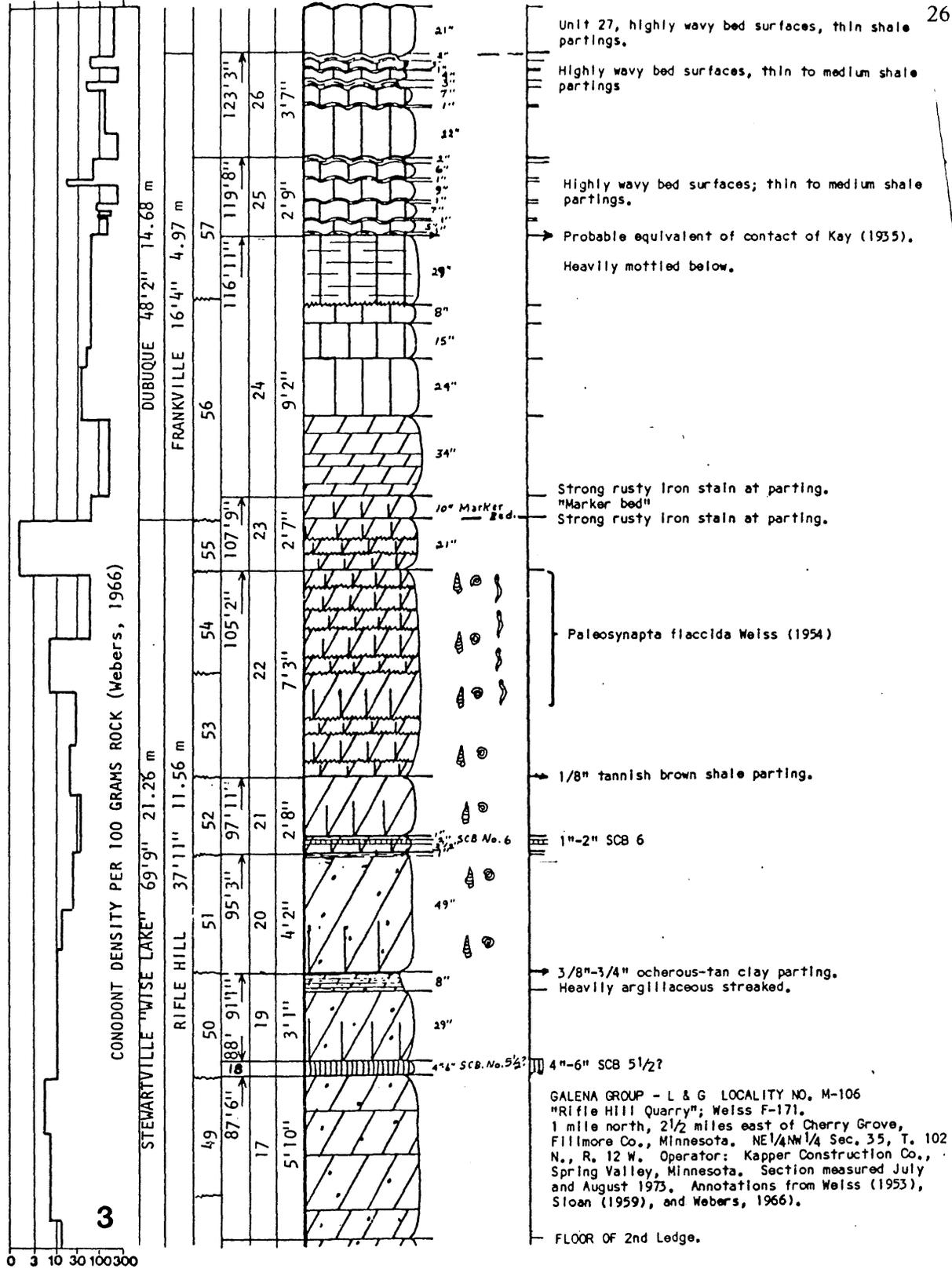


Figure 10 (continued): Stratigraphic column measured in Rifle Hill Quarry by Levorson and Gerk (from Sloan and others, 1987). Continued on next page.

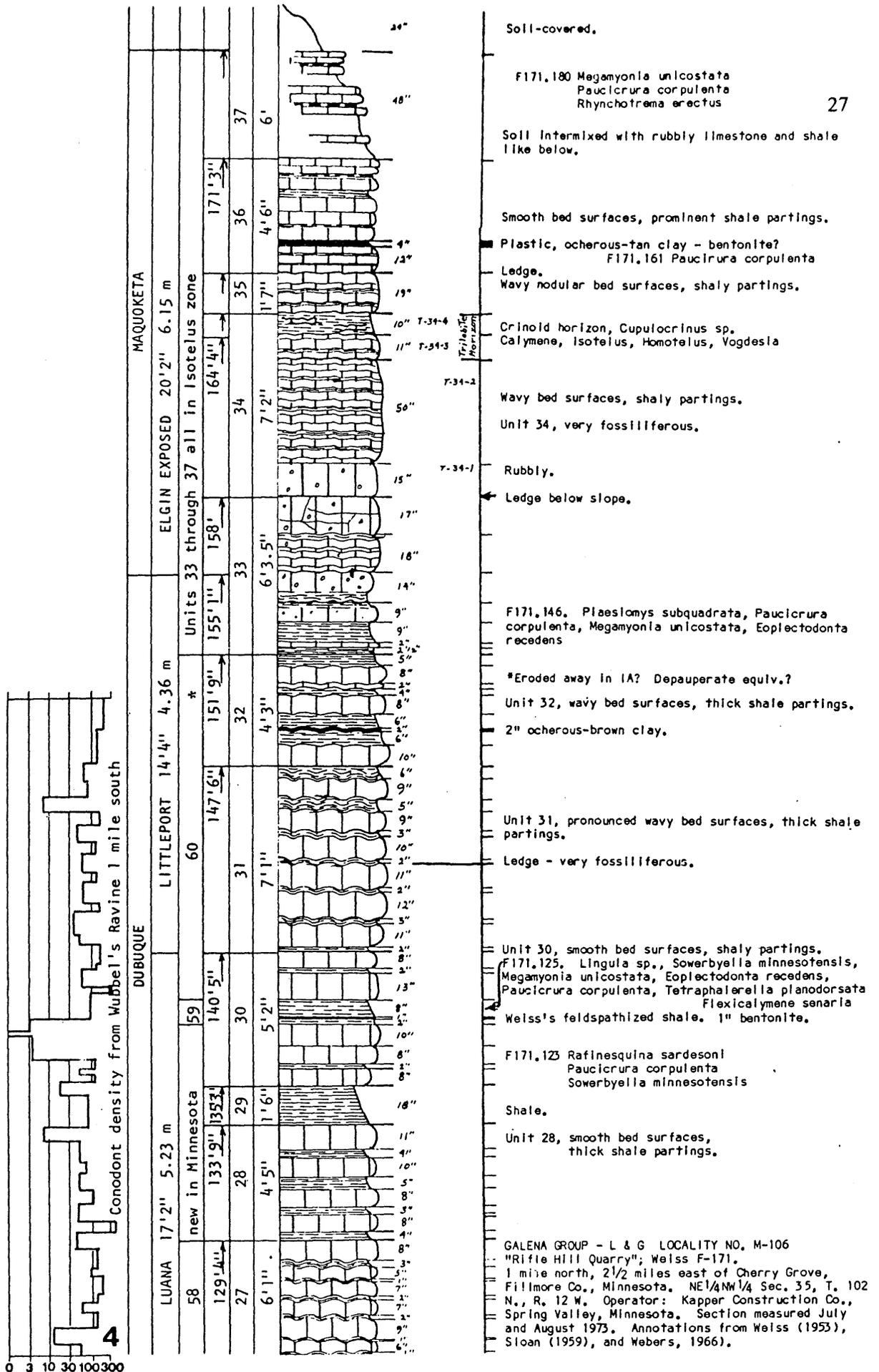


Figure 10 (continued): Stratigraphic column measured in Rifle Hill Quarry by Levorson and Gerk (from Sloan and others, 1987).

The amplitude of the irregularities is up to 4 inches, with a crest-to-crest distance of about a foot. The contact between the Stewartville and overlying Dubuque has been defined differently by various stratigraphers, depending on the criteria most important to the specific researcher. Since our concern is mainly with the effect on the cave, we prefer to define the contact as the boundary between the clearly bedded limestones and the underlying massive burrowed limestone and dolomite (see Figure 3). The only trouble is that the burrowing terminates upward in different beds from one location to another, so establishing a consistent contact requires measuring downward from distinctive beds in the Dubuque. In places the topmost Stewartville bed contains numerous fossil crinoid fossils, although these fossils are mainly limited to the transitional beds at the base of the Dubuque.

The **Dubuque Formation** is exposed in the wide upper-level passages with semi-rectangular cross sections. The upper 40% of the Dubuque is exposed in only a few places in the cave. The Dubuque is recognized by its alternating thin beds of shale and limestone, which produce prominent differential weathering, with the shale beds recessed. The basal 7 feet of the Dubuque contains little or no shale and is considered transitional with the Stewartville. Crinoid fossils are abundant in the lower one or two of the transitional beds. Former pyrite nodules (now largely oxidized to limonite) are abundant near the top of the transitional sequence. Weathering of pyrite nodules is most pronounced near the top of bed DT4, leaving rounded holes, many of which still contain bits of iron oxide. This horizon is so persistent and easily recognized within the cave that it is perhaps the most reliable marker bed in the entire sequence. From this bed it is easy to measure down to the correct bedding plane that represents the Stewartville contact. The top of unit DT3 contains four or five thin (one-inch) beds of limestone separated by prominent bedding-plane partings. The top of this sequence (BP3) is considered by many people to be the top of the Stewartville. This contact is not particularly distinctive from the standpoint of cave origin, though.

The main part of the Dubuque Formation is a relentless alternation of thin limestone and shale beds. The limestones average about 6-10 inches thick and the shales average about 1-3 inches thick (Figure 13). The shales weather inward perceptibly, although in passages exposed to recent solutional modification this differential weathering is considerably subdued. Certain limestone beds are slightly thicker than average -- up to a foot -- and persistently appear as the ceilings of passages modified by breakdown. The thinnest beds easily collapse into the relatively wide passages in the Dubuque, and the thickest limestone beds provide the most stable ceiling beams. Only rarely, and for short distances, is the cave ceiling composed of shale. The relatively thick limestones DL 10, DL14, and DL16 recur as the ceiling beds in many parts of the cave.

The Dubuque is divided into three members. From bottom to top they are the Frankville, Luana, and Littleport Members. At Mystery Cave the Frankville consists of the transitional beds with only very thin shale interbeds, labeled DT1 through DT4 on the stratigraphic column. There is no significant visual difference between the upper two members at Mystery Cave, although X-ray diffraction shows that the Littleport is significantly more dolomitic than the Luana. These distinctions are discussed in detail in the Technical Report.

Huge nautilus fossils with diameters of about 6 inches and exposed lengths up to about 6 feet can be seen in several places in the Dubuque, specifically in beds DT1, DL9, and DL10. Presumably they occur in all intervening beds, but these large creatures were few and far between. Three exposures are particularly good: (1) in the ceiling in bed DL9 just before Base Camp in Mystery II is a side view of a well-preserved nautilus. In the climb into the Formation Room in Mystery I, in bed DL 10, is a cross section of a nautilus, showing the internal structure. The largest fossil of all is in the



Figure 11: Dolomitized burrow of the worm *Paleosynapta flaccida* weather inward in areas of the cave that have not been protected by a cover of sediment when they were weathered. These are located in the Stewartville Formation in Fifth Avenue.

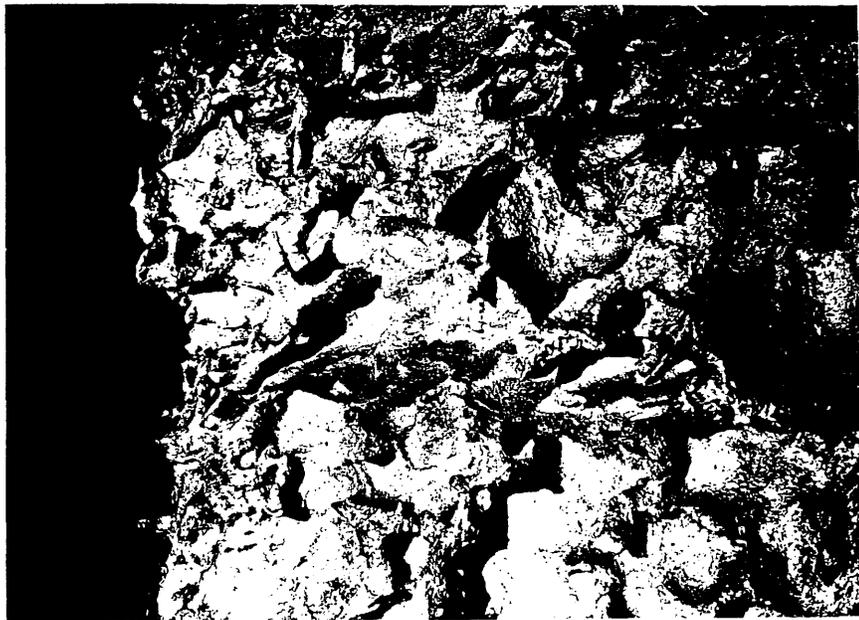


Figure 12: Worm burrows project outward where the cave walls have been weathered beneath a cover of former sediment. The process is still under investigation. These are located in the Angel Loop.

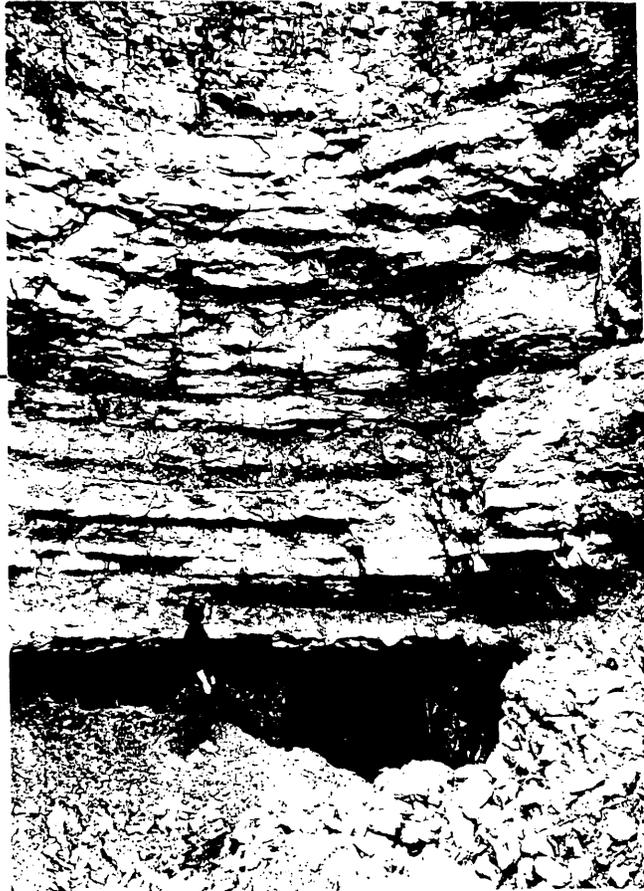


Figure 14: Entrance of Mystery I during construction of the present concrete entry-way (1991). The Maquoketa/Dubuque contact is visible in the cliff face above the entrance.



Figure 13: Alternating limestones and shales in the Dubuque Formation at the Hills of Rome in Fourth Avenue. Even though they are soluble, the limestone beds are structurally more competent than the soft shales, so they project outward slightly.

ceiling of the route to the Garden of the Gods, just before the "Texas Toast", where a 6-foot-long nautilus segment is exposed in the ceiling in bed DT1.

The **Maquoketa Formation** is a rather uniform shaly dolomite with prominent bedding and a few interbedded shales (Figure 14). Only the upper end of the Cathedral Room and the entrance rooms of Old Mystery and Old Still Caves extend into the Maquoketa, and only as the result of collapse. In the cave the Maquoketa forms a soft, crumbly, sandy-textured rock with little mechanical resistance. In Minnesota the top of the Dubuque is considered to be the highest conspicuous shale bed, because clay in the Maquoketa is uniformly distributed in the carbonate and does not commonly form discrete beds as it does in the Dubuque.

The **Cedar Valley Formation** is not exposed in Mystery Cave, but a remnant of it caps the hill over the Mystery I entrance. It is a dolomitic limestone containing coral fossils and many calcite-lined pockets (vugs). Although the total thickness of the formation is about 150 feet, only the bottom 10-20 feet remains. The rest has been eroded away.

The **Windrow Formation** consists of patchy deposits of sandy and gravelly clay thought to be of Cretaceous age (roughly 70 million years old) that was deposited over the eroded top of the Ordovician rocks. It contains massive blobs of iron oxide, which have been mined in places as iron ore. One remnant patch occurs above and slightly north of Mystery III.

Easily Recognized Beds in Mystery Cave

All beds shown on the stratigraphic column (Figure 3) are recognizable by eye without special training. It is rather difficult to tell one bed from another, however, and so it is useful to learn a few key beds that have distinctive features, and to count up or down to those that are less distinctive. The many thin beds of limestone and shale in the Dubuque are particularly vexing to keep track of. We eventually decided on the following code: S = Stewartville Formation; D = Dubuque Formation; M = Maquoketa Formation. Contacts between beds are indicated in the following manner: D/S = Dubuque/Stewartville contact, etc. SX1 - SX 3 = granular crystalline beds near the top of the Stewartville. DT1 - DT4 = transitional beds at the base of the Dubuque with little or no shale between them. BP1 - BP3 = major bedding planes near the base of the Dubuque. DL1 - DL29 = limestone beds in the Dubuque sandwiched between thin shale beds. DS1-DS30 are the thin shale beds in the Dubuque that separate the limestone beds. The codes for these thin limestone and shale beds may seem awkward at first, but the advantage is that in the cave it is possible to count quickly upward or downward from a known bed, using only the projecting limestones or the recessed shales, without having to keep track of every bed. It is traditional to interpret each shale/ limestone sequence as beginning with an influx of mud into the shallow sea, followed by a quiet period in which limestone is deposited. The alternation between shale and limestone therefore begins with DS1 (the first shale) followed by the corresponding limestone (DL1), then by the next sequence (DS2 and DL2), and so on.

The main part of the Stewartville Formation is a no-man's land in terms of finding distinctive beds. The massive rock mottled with worm burrows is exposed without a break throughout the lower-level fissures. Near the top, however, the three brown, coarse-textured, granular beds (SX1 - SX3), each no more than a few inches thick, project outward slightly from the cave walls. They are discontinuous, and where they are not present they are represented by wavy bedding planes. These beds are best seen in the Angel Loop and in the upper walls of the route to the Garden of the Gods. A fine example of a wavy bedding plane is seen in the junction area between Main Street and Lily Pad

Route in Mystery III (in place of bed SX3).

The bottom few feet of the Dubuque and (in places) the top bed of the Stewartville contain abundant crinoid fossil fragments, usually just isolated segments. These look like miniature buttons, and most are white or light brown. They produce a coarse, gritty wall texture. Excellent examples are seen in Diamond Caverns off Fourth Avenue.

A very persistent and recognizable bed is DT4, in which the top is highly pitted and stained red-brown where former pyrite nodules have weathered away. Above it is the lowest distinct shale of the Dubuque. This contact is easily seen a foot or two above the floor at the junction between Fifth Avenue and the route to the Smoking Chamber. It is visible in many other parts of the cave, such as the routes to the Needle's Eye and to the Formation Room in Mystery I.

Only a couple of beds are easily recognized in the alternating limestone-shale sequence of the main part of the Dubuque. The shale DS11 is highly limy and rather indistinct, so its combination with the underlying and overlying limestones (DL10 and DL11) forms a rather massive unit more than a meter thick that represents a conspicuous interruption of the thin shale-limestone sequence. This bed is seen near the ceiling in Fifth Avenue at the junction with the route to the Smoking Chamber. The underlying limestone bed (DL9) stands out very prominently because of its contrast with the weak shales that bound it (DS9 and DS10) and with the massive DL10 - DL11 sequence above.

Another conspicuous zone is the sequence DS13-DL13-DS14. Pyrite is (or was) abundant in this sequence, producing a yellow-brown iron oxide stain. The limestone DL13 is rather thin and composed of two separate beds, the lower of which is only about an inch thick. Oxidation of pyrite in this unit accounts for many of the iron-oxide-cored speleothems in the cave, such as the stalactites in the Formation Room.

A prominent resistant bed of limy siltstone near top of Dubuque (DL27) is only 2 inches thick, but it is easily seen about 3 feet below the Maquoketa/Dubuque contact. It appears as a thin but sharply defined ledge in the upper walls of the Cathedral Room, the entrance room of Old Mystery Cave, and in the Grotto just north of the Mystery I entrance.

GEOLOGIC STRUCTURE

Continents typically consist of two major parts: the active edges where mountain chains are forming, or have formed in the past (for example, the Appalachians) and a stable interior made of older rocks. The oldest area, the continental shield, is frequently bowed upward due to the accumulation of heat beneath the surface. Erosion of both the shield and rising mountain masses forms large aprons of sediment that cover the low-lying platforms between the mountainous continental edges and the domed interior. The bedrock at Mystery Cave formed in this environment between the earliest phases of the Appalachian mountains on the southeast and the Canadian Shield to the north. This continental platform has been warped into low-relief domes and basins many times in the past. Even the earliest of these features remain zones of weakness to this day, bounded by major fractures. Like cracks in a concrete sidewalk, even though we patch them they are likely to reopen next year, and the chance of new cracks forming in an uncracked area of cement is less likely.

The cave map clearly shows the pattern of fractures in the local limestone. East-west and northeast-southwest fractures are most prominent. A third fracture set oriented northwest-southeast

controls passage trends only in the northeastern part of cave. A few fractures are oriented north-south.

A simple fracture involving no visible movement is called a **joint**. A crack along which there has been movement, where one rock mass has slipped past another, is called a **fault**. Most joints and faults in the rocks in and around Mystery Cave are nearly vertical, cutting across the strata at essentially right angles. Most of the passages in the cave are solutionally enlarged joints and small faults, and that accounts for their straight patterns and angular intersections. They reflect the pattern of stress in the limestone caused by movements within the continental crust. Some cracks are merely separations between beds and are called **partings**. They are tilted at the same small angle as the beds and account for some of the low, wide passages in the cave. All three types of fractures are important to the origin of Mystery Cave, as they provided the original paths for the underground water to pass through the limestone (Figure 15).

Only a few faults are visible in the parts of the cave included in the leveling survey, and all are oriented east-west, parallel to the major joint trend. Their age is uncertain, but they relate to some period of early deformation of the rocks. The most accessible is in the fissure in line with the lower route to the Garden of the Gods (see Sheet 12 of the geologic profile). The south wall of the fault has moved upward about 8-12 inches relative to the north wall, so the beds do not match across the passage. Figure 15 shows this fault passage, although the apparent offset between the bedding plane in the photo is not the true fault displacement, since it is not the same bedding plane. Another large fault is located at the junction between Big Fork and the Door-to-Door Route (Sheet 5 of the geologic profile). The Door-to-Door Route follows it for a few hundred feet to the east. Other small faults appear in Sixth Avenue in the Fingers area of Mystery III and in the main Base Camp room in Mystery II. The first example is in the massive Stewartville Formation. The last three are in the lower Dubuque and clearly lose their identity as they are traced upward. Apparently the fault displacement is compensated for by differential compaction in the many shale beds of the Dubuque. The faults are also difficult to trace laterally from one passage to another. This may indicate that much of the movement was horizontal, and the offset is evident only where irregularities in the beds do not match.

The rocks of the Mystery Cave area have a **dip** (tilt) to the northwest of about 0.5-0.7 degree -- in other words, about 45-70 feet per mile. This tilting and warping was caused by stresses within the continent as the result of plate movements. The dip is easily seen on the enclosed geologic profile of the cave. Figure 12 in the Technical Report is a contour map of the Dubuque/Stewartville contact that shows the local variations in the dip. The contours are lines of equal elevation along the contact, and the dip is exactly perpendicular to them in the direction in which the elevation decreases (i.e., to the northwest). These lines define what is known as the **strike** of the beds. North of the cave, toward Grabau Quarry, the dip gradually changes toward the southwest. (Although from the contour map this change in dip direction would appear to be based on a single point, it was verified by actual measurements of the strike within the Quarry.)

In the cave the steepest dip is in Mystery III and the western part of Mystery II (about 0.8 degree), while the gentlest dip is in the eastern part of Mystery II (about 0.3 degree). The hinge line between the two areas is rather sharp. Apparently this flexing of the beds accounts for the fact that the northwest-southeast fissure passages in the cave are all located along or just east of the steepening of dip. Joints having this NW-SE trend appear throughout the cave, but they have been enlarged to cave size by solution only in the northeastern part of the cave. Local stress in the rock must have been greater along the hinge line, widening the joints to the point where the cave could utilize them as easily as the other joints.

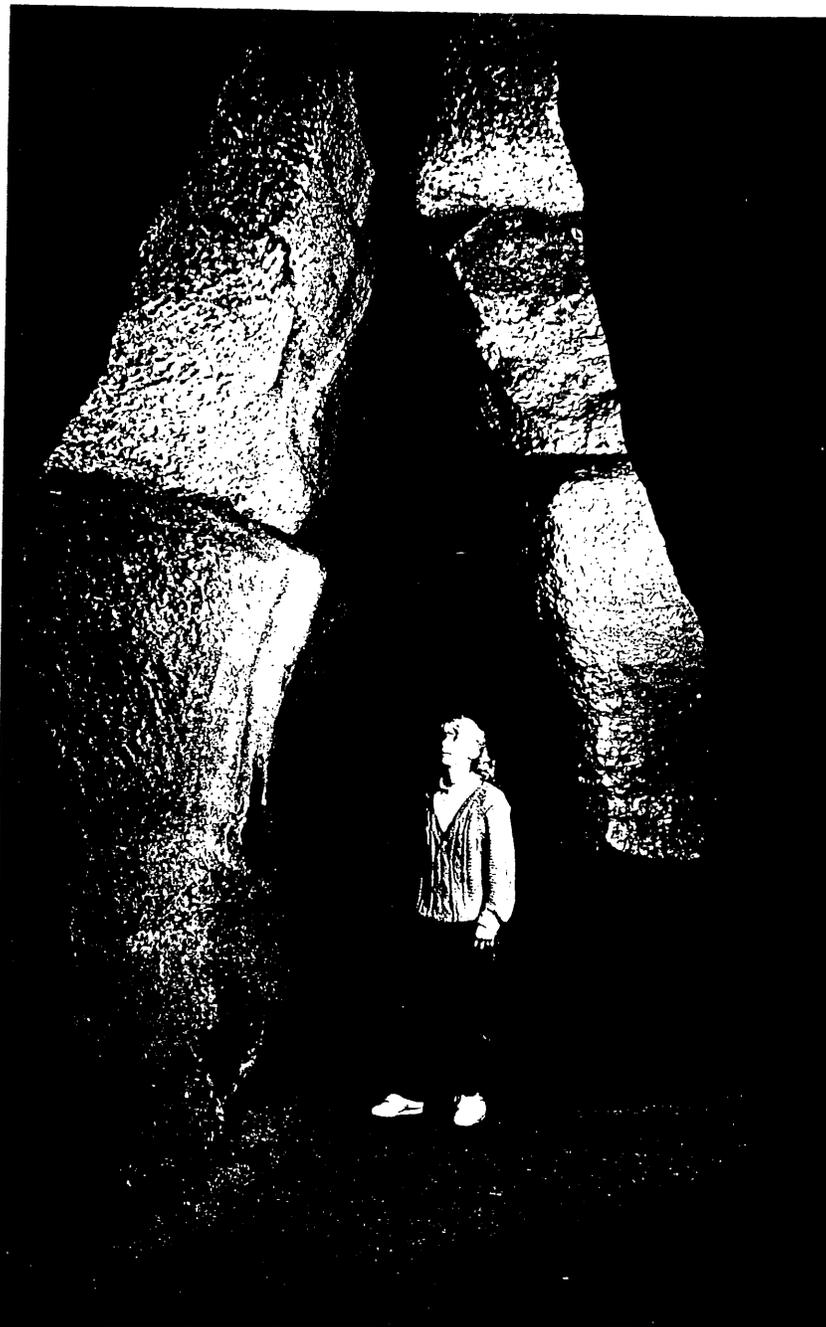


Figure 15: Most of the passages in Mystery Cave that have not been modified by breakdown are rather straight fissures that have developed along joints or faults. This passage, on the route to the Garden of the Gods, is located along a fault with about a foot of vertical displacement. Note the prominent bedding-plane partings in the walls, which have also been enlarged by solution, along with the vertical fractures. The apparent offset in the bedding plane is an illusion, because the one on the left is not the same as the one on the right. However, it is representative of the kind of offset that occurs along a fault. The left-hand block has actually moved up relative to the right-hand block. The faults and joints are much older than the cave

GEOMORPHIC SETTING

Geomorphology is the study of the configuration, origin, and developmental history of the land surface. The interpretation of caves is usually considered to be in the realm of geomorphology. A cave cannot be properly interpreted without considering the origin of the surrounding landscape. But what many geomorphologists fail to realize is that the landscape in a cave area cannot be properly interpreted without knowing the layout and history of the caves.

A landscape dominated by solutional features such as caves is called **karst topography**, or simply karst, named for a plateau in western Slovenia in which these features were first thoroughly studied. Besides caves, such features as sinkholes (depressions in the surface), sinking streams, and large springs are the dominant karst features. These are all found in the Mystery Cave area.

Southeastern Minnesota is a low plateau slightly dissected by stream erosion. The height of the uplands is only a couple of hundred feet above the valley bottoms. Streams in the area are all tributary to the Mississippi River to the east. Mystery Cave is located along the South Branch of the Root River, and the Root River flows directly into the Mississippi. When the Mississippi cuts its channel deeper, the Root River does the same. When the Mississippi valley becomes partly filled with sediment, the same happens in the Root River valley. Mystery Cave owes its origin mainly to underground diversion of the South Branch, and so the cave was made possible only when the streams in the region eroded down into the limestones in which the cave now lies.

Besides stream erosion, the area has been greatly affected by glaciation during the Quaternary Period (within the past million years or so). The latest glacial advances fell short of the Mystery Cave area, and that is the reason why the cave is not buried beneath thick glacial sediment. However, besides a few patches of old glacial deposits (called **glacial till**), the Mystery Cave area has been covered with at least 20 feet of wind-blown silt (**loess** -- pronounced "luss" or "lerse" -- take your choice). The loess was derived from extensive glacial sediment exposed in nearby areas, such as the Mississippi valley to the east and glaciated areas to the west.

The valley of the South Branch pre-dates the latest glaciation, the Wisconsinan glaciation, which took place about 12,000-50,000 years ago, because it is partly filled with loess derived from glacial sediment. The cave contains a great deal of the same material, and so the cave is also pre-Wisconsinan. However, in places there are thick silt beds covered by stalagmites that have been dated at more than 180,000 years old (see sections on Origin of Mystery Cave in this report, and summaries of speleothem dating in the Technical Report). In other words, the sediment in the cave is even older than the next-oldest glaciation (commonly referred to as the Illinoian glaciation), which took place about 100,000-150,000 years ago. When we consider that the erosion of the South Branch into the limestone at Mystery Cave must have taken place still earlier, that pushes the origin of the cave back into the middle Quaternary Period, perhaps more than 500,000 years ago.

Clearly the cave can tell us a great deal about both the erosional and glacial history of the region. A detailed discussion is given in the later section entitled Origin of Mystery Cave. Further information will appear in the 1994 update of this report.

High points in the landscape around Mystery Cave contain remnants of the Cretaceous Windrow Formation, which was deposited by predominantly westward-flowing streams. The Mississippi River did not exist at that time (at least in the Minnesota area). Because the Windrow lies

above the zone of cave formation, and because the drainage in Mystery Cave was apparently always to the *east*, the opposite of the Cretaceous drainage, it seems likely that the cave is post-Cretaceous. In Minnesota the Mississippi cuts through Cretaceous marine deposits, so its entrenchment is also post-Cretaceous. There is almost no record of what happened during the Tertiary Period, except for some frustratingly vague upland gravels scattered here and there in many central states.

The landscape that we see today is rather recent, geologically speaking -- about 1% of the age of the rocks. Most of its features are of only Quaternary age (see Table 1), which is the time when glaciers began their periodic advances into the region. The history of glaciations in the midcontinent is told mainly by sedimentary deposits left by the ice itself (glacial till), and by widespread sheets and valley deposits (outwash) left behind by meltwater from the glaciers. Wind carried the finer particles of till and outwash over the surrounding area and deposited them as blankets of loess (pronounced "lerse" or "luss" -- take your choice). Early studies seemed to distinguish four major glacial advances, called, from first to last, the Nebraskan, Kansan, Illinoian (note spelling), and Wisconsinan. Although the last one or two are still somewhat valid, it has become clear in recent decades that the picture is much more complex. Quaternary history is still poorly understood, because glacial deposits are very patchy, later glacial advances tend to disrupt and cover the deposits from earlier ones.

The Mississippi gorge contains "Kansan" till (>700,000 years old) overlain by younger (Illinoian) till in western Wisconsin (Wright, 1985), so the entrenched Mississippi valley was already well developed sometime in the early Quaternary. The latest glacial advances fell short of the Mystery Cave area, and that is the reason why the cave is not buried beneath thick glacial sediment. As shown on Figure 16, the headwaters of the Root River lie just to the east of a north-south moraine (mound of till) of suspected Kansan age (Sloan, 1985). It seems likely that the present course of the Root River and its tributaries was determined by the ice front that deposited this till. Figure 17 shows that Mystery Cave is located on the border between a thick loess-covered area on the east and a loess-deficient area on the west (Mason, 1992). The loess overlies several very old glacial tills (which have been called "Kansan and Nebraskan"), which also fill former stream valleys in Fillmore County (Hobbs, 1985). To the west of Mystery Cave, the loess blanket has been mainly eroded away, leaving a broad erosion surface ("Iowan erosion surface") on much older glacial tills.

The valley of the South Branch pre-dates at least the latest (Wisconsinan) glaciation, which took place about 12,000-50,000 years ago, because it is partly filled with loess. The cave contains a great deal of the same material, and so that cave is also pre-Wisconsinan. However, some of the speleothems in Mystery Cave have been dated at more than 350,000 years old, and so the cave is also older than the Illinoian glaciation. When we consider that the erosion of the South Branch into the limestone at Mystery Cave must have taken place still earlier, that pushes the origin of the cave back into the middle Quaternary Period, perhaps more than 500,000 years ago. Clearly the cave can tell us a great deal about both the erosional and glacial history of the area. A detailed discussion is given in the later section entitled Origin of the Mystery Cave.

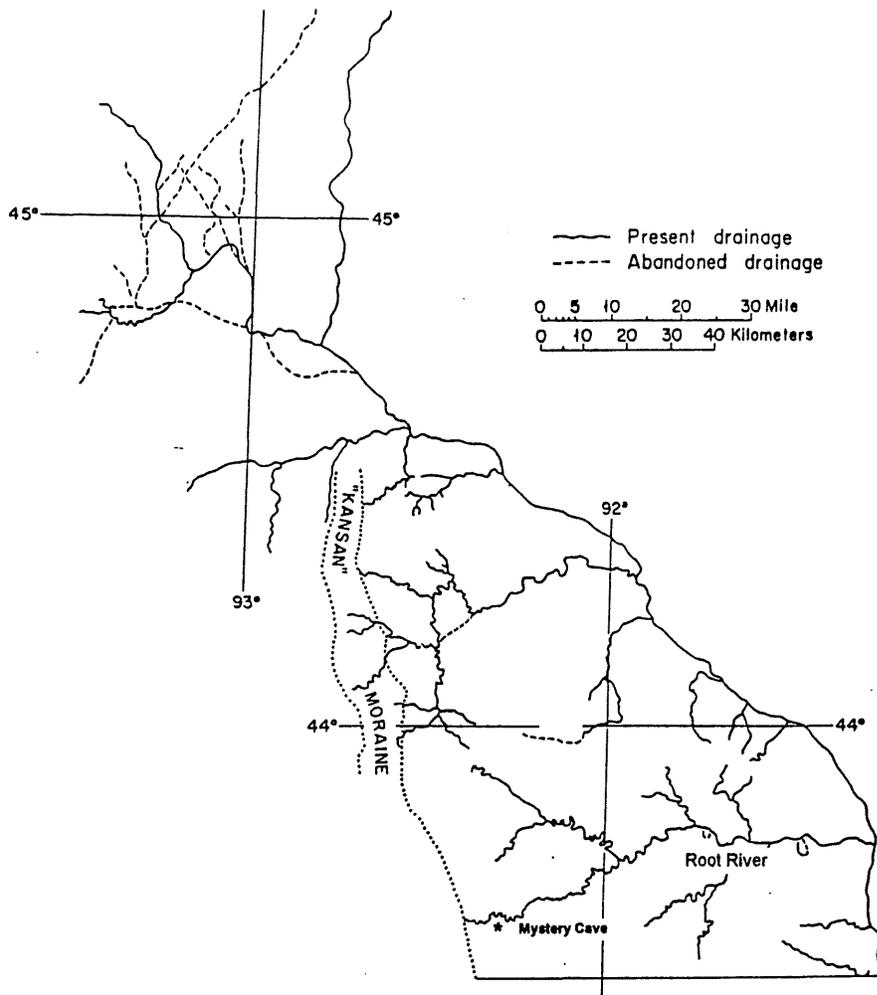


Figure 16: Map of the supposed "Kansan" glacial moraine and its relationship to the Root River (from Sloan, 1985).

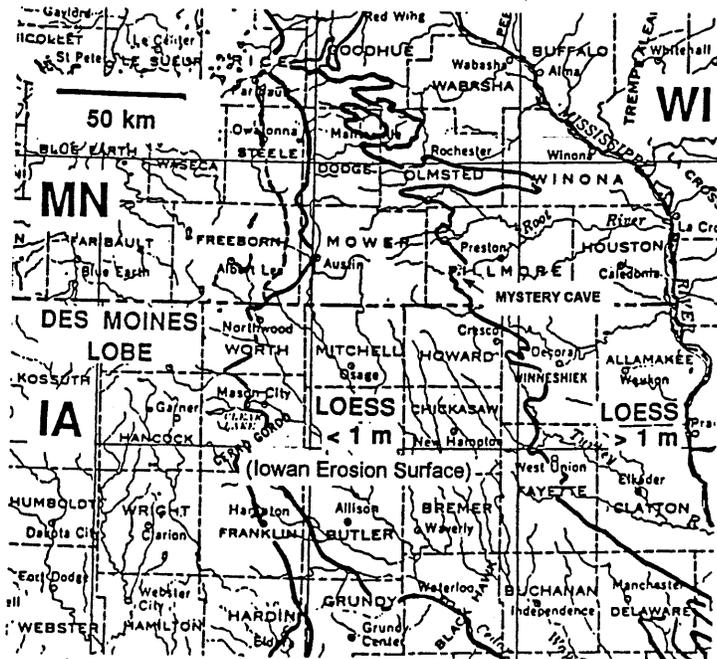


Figure 17: Map of loess deposits and the lowan erosion surface in the Mystery Cave area (from Mason, 1992).

WATER CHEMISTRY

Measurements of water chemistry give clues to the flow history of the cave water -- for example, what materials it has encountered along its path of flow -- as well as the ability of the water to dissolve or precipitate minerals. It is also the key to understanding the origin of speleothems ("cave formations"). The most abundant chemical constituents are described below; these are the important ones to measure in any full-scale water chemistry project.

Calcium is derived from limestone (CaCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$), and elsewhere from the sulfate minerals gypsum and anhydrite ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and CaSO_4), **Magnesium** is provided mainly by dolomite. **Bicarbonate** (HCO_3^-) is contributed in roughly equal amounts by dissolved carbon dioxide in the water and by dissolved limestone and dolomite (and to a lesser extent by the weathering of igneous and metamorphic rocks). **Sodium, potassium, and chloride** ions come from rock salt (mainly in deposits at considerable depth beneath the surface) and from road salt and other surface-derived contaminants. All but chloride can also be released in small quantities by the weathering of igneous and metamorphic rocks. **Sulfate** comes from the solution of gypsum or anhydrite, but in the Mystery Cave area it is mainly from contaminants and from oxidation of pyrite (FeS_2) in the bedrock. **Nitrate and phosphate** are mainly agricultural wastes (fertilizers, barnyard effluent, etc.).

The **saturation index** shows whether or not the water sample is saturated with a particular mineral. It is calculated in the following way: (1) the carbonate ion activity is calculated from the other chemical data available; (2) the ion activity product (IAP) is calculated -- for calcite, this would be found by multiplying (Ca^{++}) by (CO_3) -- note: activity is the concentration adjusted for various factors and is essentially an *effective* concentration; (3) the IAP is divided by the equilibrium constant for the specific mineral in question; and (4) the saturation index (SI) is the log of the result of step 3. A negative value indicates that the water is undersaturated with the mineral in question and can dissolve more of it. A positive value shows that the water is supersaturated with the mineral and cannot dissolve more of it; it has a tendency to precipitate the mineral instead. A zero value indicates exact saturation, at which the solution and deposition processes are in equilibrium. This is rarely observed, especially in the carbonate minerals such as calcite, aragonite, and dolomite, because saturation states are constantly changing as the water encounters different carbon dioxide levels, temperatures, and chemical environments. It is rare for a carbonate mineral simply to dissolve to saturation and remain at that state.

The Mg/Ca ratio (or any other similar ratio) must be in moles/liter or similar units, rather than parts per million or mg/liter, because the Ca atom has more mass than the Mg atom. Equal numbers of atoms of the two elements will give greater mg/l or ppm of calcium. Since most Ca comes from limestone and dolomite, and Mg comes mainly from dolomite, the Mg/Ca ratio indicates the approximate proportion of dissolved dolomite, compared to the total dissolved amount of carbonate rock. An Mg/Ca ratio of 0.25 therefore suggests that 25% of the dissolved carbonate bedrock came from dolomite. This estimate is somewhat idealized because both calcite and dolomite can have varying amounts of Mg in their structures, and both ions can be enhanced by other sources besides carbonate rocks.

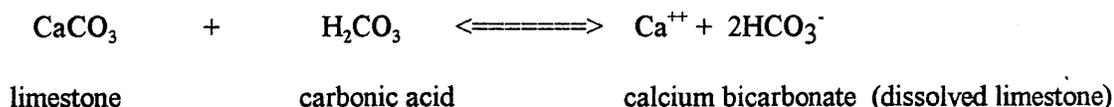
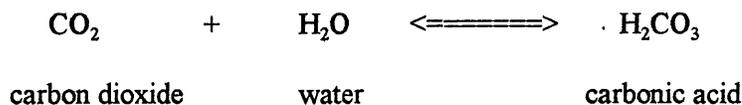
The P_{CO_2} (partial pressure of carbon dioxide) is useful in determining the source, history, and solutional potential of the water. The amount of calcite that can be dissolved in water determines the amount of limestone or dolomite that can be dissolved. The P_{CO_2} of the atmosphere is 0.035%, varying

slightly with altitude and degree of atmospheric pollution. In soil it is about 0.5-5% (usually about 1-3%). In caves the P_{CO_2} is about 0.05-0.5% (usually about 0.1-0.3%), depending on how well aerated the cave is. The greater the aeration the lower the P_{CO_2} . Surface streams usually have P_{CO_2} values similar to those of caves, because much of their water comes from groundwater seepage, and equilibration with the surface atmosphere is rather slow unless there is a great deal of turbulence or surface exposure, as in a waterfall.

Therefore, water that has infiltrated through the soil usually has a high P_{CO_2} and is able to dissolve a great deal of limestone as it encounters the limestone or dolomite bedrock. When it seeps into a cave, which has a lower P_{CO_2} , the water loses most of its carbon dioxide to the cave air. Since the amount of limestone or dolomite that can be held in solution depends on the level of carbon dioxide in the water, this loss makes the water less capable of holding dissolved limestone or dolomite, and so calcite (the least soluble carbonate mineral, and therefore the first to precipitate) is usually precipitated. Dolomite rarely crystallizes in caves because it is more soluble than calcite in dolomite-rich water, except at high temperatures, and because its rate of crystallization is very sluggish.

Aragonite crystallizes instead of calcite if the saturation level and Mg/Ca ratio are both high. Although aragonite contains only calcium carbonate (like calcite), it has a different crystal structure (needle-like) and is more soluble. In high-Mg water the calcite structure is inhibited and aragonite is able to precipitate if the saturation level rises high enough. That is why aragonite is common in Mystery Cave only where evaporation rates are high enough to drive the water well beyond saturation. In evaporative areas the water also loses much of its calcium as calcite, driving up the Mg/Ca ratio and providing the necessary environment for aragonite to precipitate. *← cave is this deposit*

Limestone and dolomite are the most common rocks that dissolve in underground water to form caves. Pure water has almost no ability to dissolve these rocks, but if the water contains some acid, as it almost always does, it dissolves them much more readily. The most common natural acid is carbonic acid, formed when water absorbs carbon dioxide from the atmosphere and soil. Carbon dioxide is a gas produced mainly by biological processes such as respiration and the decay of organic material. The solution of limestone by carbonic acid involves these reactions:



Dolomite dissolves in a similar way. The double-ended arrows show that the entire reaction can be reversed so that limestone is deposited instead of dissolved, creating crystalline features such as stalactites and stalagmites.

CAVE MINERALS

After a cave forms, it becomes the host for a variety of mineral deposits. These are the **speleothems** (popularly known as "cave formations") that give a cave much of its beauty. Speleothems are best classified in a two-fold manner: by mineral type and form (e.g., aragonite bushes). However, most forms are calcite, so the mineral name is omitted in favor of just the descriptive term. For example, stalactites are almost always calcite, and the dual name is needed only if they happen to consist of a different mineral (e.g. gypsum stalactite).

Speleothem shapes and mineral types depend strongly on local cave conditions, so it is convenient to arrange them according to the environment in which they form, in the air or underwater. Those in the same general grouping are most likely to occur together, and they can readily be used as clues to the past history of their host caves. Superposition of one type on another helps to document changes in the cave environment. This topic is discussed at length in the Technical Report.

Most speleothems are made of **calcium carbonate** (CaCO_3) that precipitates from water. This is the same material that makes up the limestone bedrock in which caves are located. Water passing downward through the soil absorbs a large amount of carbon dioxide, and water seeping slowly downward along narrow cracks becomes nearly saturated with dissolved calcite in equilibrium with this rather high CO_2 level. The air in most caves is much lower in carbon dioxide than that of the soil, because of exchange of air with the surface. If the descending water drains into an air-filled cave, it loses much of its carbon dioxide to the cave air. Some of the dissolved calcite may precipitate as crystals. This process is exactly the opposite of the solution of limestone. Thanks to exchange of air with the surface through entrances, air-filled caves contain much less carbon dioxide than do the overlying rock and soil. Water seeping into the ground picks up a great deal of carbon dioxide as it passes through the soil, enabling it to dissolve considerable amounts of limestone. However, if this water drains into an air-filled cave, the water loses much of its carbon dioxide to the cave air, reducing the amount of dissolved limestone that the water can hold. As a result, some of the dissolved calcium carbonate may precipitate as crystals.

The major carbonate minerals found in speleothems are **calcite** (CaCO_3) and **aragonite** (also CaCO_3 , but with a different crystal structure). Calcite occurs in a wide variety of crystal forms in three general categories: (1) prismatic, or columnar, like many-faced columns, (2) rhombic, box-like crystals in the shape of parallelograms, and (3) scalenohedral - a complex elongate shape with pointed ends. **Spar** is a term used to describe any calcite crystal with clearly visible faces. Aragonite almost always forms needle-shaped crystals. It is most often found in caves where there is intense evaporation. Speleothems composed of pure calcite or aragonite are white or transparent, but only a small amount of foreign material in the calcium carbonate can produce brilliant colors. Most colors are produced by iron or manganese oxides (producing opaque red and black colors), by organic muck (often black, very fine opaque coatings), organic acid (producing nice translucent yellow, orange to brilliant red colors), and clay or sediment that makes the speleothem look dirty brown.

Gypsum is hydrated calcium sulfate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), which crystallizes in very dry parts of a cave where there is considerable evaporation. It is a soft, white mineral that forms plates, needles, crusts, or flower-like growths on the cave bedrock. Some gypsum crystals grow in cave sediment. Dissolved gypsum is normally carried into a cave by water that seeps in small quantities through the limestone by capillary forces. Much of it is produced by oxidation of iron sulfides like pyrite. The

products of this reaction are red or yellow iron oxide and dissolved sulfate. Where the water reaches the wall of a cave in which evaporation is active, the sulfate becomes enriched enough to precipitate gypsum. The iron oxide tends to color the gypsum light brown.

For a more extensive discussion of cave minerals see Hill and Forti (1986).

SPELEOTHEMS IN MYSTERY CAVE

One of the unique aspects of Mystery Cave is the great number of unusual speleothems that it contains. In addition to the common decorations such as stalactites and stalagmites, there are many types that are very rare elsewhere, such as calcite rafts, raft cones, chenille spar, pool fingers, and folia. Many of these are known only from caves of the semi-arid west and similar areas, and their significance in Mystery Cave has not previously been recognized. Furthermore, the occurrence of these speleothems in Mystery Cave gives rare insight into their origin, since most of them are still actively growing, whereas very few are known to be forming elsewhere. This provides an opportunity to correlate pool chemistry with the speleothems found in the pools, giving evidence for why certain calcite crystals have distinct shapes, a topic that is now under considerable debate among geologists.

Speleothems can be organized into three major groups: those deposited underwater in pools, those formed by dripping or flowing water in air-filled parts of the cave, and those formed by capillary seepage in areas of high evaporation. Some show combined influences, such as those that form at the surfaces of pools or where the water level fluctuates. This seemingly simple classification is actually a bit ambiguous. Crystals growing in a drop of water, for instance, can have small-scale characteristics similar to those that form in a pool. Fortunately the overall crystal structure and speleothem shape shows the true origin.

The different speleothem types in Mystery Cave are described below, with their most typical locations. More detailed petrographic information from samples is given in the Technical Report.

Underwater Speleothems

Mammillary pool crusts

Layers of calcite crystals often coat the walls of cave pools. The crystals are columnar (prismatic) and grow perpendicular to the pool walls. Because the pool wall is not perfectly flat, wherever there is a small bump the crystals radiate out from it, forming larger mammillaries.

Botryoids

Calcite deposits can take on a knobby, grape-like shape called botryoids. In Mystery I botryoidal calcite consists of layered, subparallel to radiating, very long, needle-shaped crystals. The radiating masses form balls similar in appearance to cave popcorn, but on a larger scale. A large amount of inactive botryoidal calcite was hacked out of the route to the Bomb Shelter in Mystery I to extend the headroom during early (pre-DNR) commercialization. Botryoidal, needle-like calcite also borders Blue Lake in Mystery II, terminating upward at the level of the top of the raft cones. Broken material from Mystery I includes vertically elongated botryoidal masses covered with sediment and later coated with sheets of flowstone. Weathering of these deposits reveals flaky, layered interiors of

alternating flowstone and sediment.

Chenille spar

Chenille spar is a variety of botryoidal pool-lining calcite with vertical elongation, like drapes, usually found in association with shelfstone. The word chenille refers to cloth with vertical folds. Chenille spar occurs in the route to the Bomb Shelter in Mystery I and in a former ponded area in the western extension of Fourth Avenue in Mystery II. It consists of parallel layers of long calcite needles, typical of botryoidal calcite. A cross section of naturally broken chenille spar from Fourth Avenue shows that the layers of calcite cover the wall and any projections at a rather uniform thickness. In most cases these deposits seem to have coated thin organic filaments that grew down from a former water level, whose shape became greatly exaggerated by the thick layers of spar. Live filaments have been found on the tips of actively growing chenille spar in New Mexico. A sample of botryoidal crust (MY141) from the dump pile at Mystery I contains many filaments, although their relationship to the shape of the speleothem is not certain, since they are rather erratically scattered throughout the sample.

Pool fingers

Pool fingers are coated strands of organic filaments, apparently similar to chenille spar but thinner, often curved, and finger-like. The southern wall of Turquoise Lake, Mystery I, contains many pool fingers. Sample MY225, collected from this area by Warren Netherton (DNR) is coated with tiny clusters of subparallel to radial needles. The finger has a honey brown crystalline interior and a white crust of very fine needles. Because of recrystallization of the interior, it may be impossible to positively identify filaments inside, but we have found tiny strands less than 1/2 micron in diameter in a pool finger from a New Mexico cave. Unusual small pool fingers with prismatic sides occur at the end of Fourth Avenue West at the Yellow Flow. Some of these are curved. White organic filaments about 5 mm long are also visible in at least one of the rimstone pools in the Yellow Flow.

Calcite Shrubs

Calcite shrubs have not yet been described in the literature. They are a form of pool deposit generally lumped with other crystal pool linings. They consist of bladed crystals that grow in V-shaped twins whose arms are typically oriented at approximately 45 degrees to the main axis of the speleothem (and, where they form at a pool surface, at 45 degrees to that surface). This angle is dictated by the shape of the calcite rhombs of which they are composed. Shrubs often accompany rafts, shelfstone, or botryoids (sample MY135). They are very well developed in Mystery I in the route to the Bomb Shelter and in Fourth Avenue West (Figure 18).

Shelfstone and Rimstone

Shelfstone forms at the edges of pools and grows inward toward the center just below the water surface. Rimstone forms a dam of calcite where ponded water flows over a break in slope. Otherwise the two are similar. The shelfstone in Mystery is actually a composite feature. According to definition, shelfstone refers to the flat tops of the crystals that grow up to, and outward from, the water surface. Calcite shrubs crystals lining the pool floors can end upward as shelfstone, or mammillary crusts lining cave pools can jut outward as a horizontal bulge forming shelfstone at the pool surface. Shelfstone is common in Mystery I along the main tour route. The Rock Garden consists

of shelfstone that lines pools in a calcite coating over sediment. Lily Pad Lake in Mystery III contains shallow pools coated with needle-lined shelfstone and underlain by bladed pool crust (sample MY125).

Calcite rafts

Calcite rafts are paper-thin sheets of calcite that grow on the surface of still pools and float by surface tension. The calcite nucleates on dust particles on the water surface and grows both upward and downward from the sheet. Calcite starts as granular crystals and evolves to needle- or blade-shaped crystals in the majority of calcite rafts in Mystery Cave. The exception is that individual rhombs coat some rafts in Sugar Lake (MY20). Mounds of rafts occur in the walls of the crawlway leading out of the Bomb Shelter. Granular calcite crystals are actively forming on the water surface at the Rock Garden, Sugar Lake, and Turquoise Lake. They look like an opaque scum on the surface of the water.

Raft cones

Where water drops fall from the ceiling into a pool covered with calcite rafts, the rafts drop to the pool floor. The fallen rafts form a conical pile of debris below the drips with a drip hole in the center. These are called raft cones. Small raft cones can be seen on the floor of Sugar Lake and Turquoise Lake. Larger inactive cones are found in the route to the Bomb Shelter and on the Door-to-Door Route (MY33). Very tall raft cones are the central feature of Blue Lake in Mystery II (Figure 19). Their surface is lumpy but not flaky because they have been coated with a crust of calcite. Cross sections of naturally broken raft cones show that they consist of a porous network of stacked plates coated with sharply pointed calcite crystals, and so are clearly derived from raft material. It might seem that a horizontal plate would not fall vertically (judging from the erratic path that a falling leaf takes). However, actual observations show that the raft fragments fall nearly vertically, because they are too small to set up turbulent eddies.

Raft cones are common in strange caves like Lechuguilla, which has led some people to think that they are formed by hydrothermal fluids rising from depth. Mystery Cave is about as far removed from a hydrothermal origin as it is possible to get, and so its raft cones are extremely significant in distinguishing fact from fantasy.

Folia

Folia are horizontal growths of calcite like shelfstone, but with rounded, protrusions that have concave bottoms, like bracket fungus. They line the walls in a narrow band near the ceiling of the passage to Turquoise Lake, about four feet above the present lake level (MY30). The surfaces of the folia are coated with tiny calcite needles. The fungus-shaped protrusions consist of fans of subparallel layered crystals pointed outward and underlain by unlayered discontinuous blades. Folia apparently form at the edges of pools in which carbon dioxide is rapidly escaping, so that precipitation is very rapid. They are almost always found in association with calcite rafts. Their concave undersides have not been satisfactorily explained.



Figure 18: Calcite shrub consisting of bladed crystals. This sample was originally located on the route to the Bomb Shelter but was removed during early trail building.



Figure 19: Raft cones in Blue Lake. These are completely covered by water during wet periods.

Boxwork (the Mystery Cave Variety)

Where weathered shale (for example in the ceiling of the crawl in Fourth Avenue) is wetted and later dries out, the material shrinks, forming polygonal desiccation cracks. In rare circumstances these areas are again ponded, and calcite coats the walls and fills the cracks. When the areas dry out once again, the soft clay or shale tends to fall out from between calcite veins, leaving polygonal fins of calcite projecting from the ceiling or walls. This is a very rare occurrence, and the examples in Mystery Cave are the best we have seen. Most boxwork, as in Wind Cave, South Dakota, is formed by the replacement of gypsum veins by calcite early in the history of the rock layer.

Speleothems Formed by Dripping and Flowing Water

Dripstone and Flowstone

Dripstone consists of calcite (or rarely other minerals) deposited by dripping water, and **flowstone** consists of mounds or sheets deposited by water flowing over surfaces such as the cave walls (see Figure 20). Both require quantities of water sufficient to form discrete gravitational drips or flows. **Stalactites**, **stalagmites**, and **draperies** are the main forms of dripstone. **Stalactites** are the icicle-shaped speleothems that grow downward from the ceiling or from an overhanging ledge where water is descending. Thin ones, only a single water drop in diameter, are called **soda-straw stalactites**. Most, however, have enlarged in diameter as well as downward, by water running down the outside, or by capillary seepage out of the central canal along the crystal boundaries. **Stalagmites** grow upward from the floor where the water drops hit. Where the two grow together, a continuous **column** is formed. **Draperies** form where water runs down the sloping surface of an overhang and clings by surface tension. A fin of calcite forms along the trail of water, eventually growing into a drape-like speleothem. Mystery Cave contains many examples of dripstone and flowstone, most of which are still active. Inactive ones indicate that there has been a change in the character of seepage into the cave, possibly because of a drying climate or because of a change in land use at the surface that causes more water to be lost as evaporation and transpiration.

Speleothems Formed by Capillary Seepage

Helictites

Helictites are erratic growths of calcite (or rarely aragonite) that twist and branch like gnarled twigs. They resemble stalactites, except that they show little or no gravitational effect. They are formed by water seeping into the cave in quantities too small to form discrete drips, so capillarity is the main controlling force. They contain tiny central canals (less than 1/2 mm in diameter) that feed the growing tips. The canals are not oriented exactly down the center of the helictite, but wander erratically along a crudely spiraling path. In Mystery Cave, helictites are found mainly on the ceiling of the Helictite Route in Mystery III. They are about 1/4 to 1/2 inch in diameter and apparently have been enlarged from their original size by later coatings of calcite. Some have soda-straw stalactites growing from their tips, indicating an increase in the rate of water seeping into the cave.

Popcorn

Cave popcorn forms where evaporation is more important in precipitating calcium carbonate than CO₂ loss. Most popcorn consists of calcite or aragonite. It tends to grow on projections where evaporation rates are highest. Their fibrous crystals grow outward as concentric sprays, forming white coalescing balls that resemble true popcorn (Figure 21). The crystals are not constrained to grow within the boundaries of a water film, so they are irregular in length depending on where the evaporation rate is highest. Evaporation builds up the concentration of ions in the water, and in caves with very high rates of evaporation, less common minerals begin to precipitate in popcorn as discrete layers, such as hydromagnesite (a complex hydrated magnesium carbonate).

Aragonite Needles

Aragonite needles up to 1/4 inch long are common on the route to the Garden of the Gods (Figure 22). These white crystal growths are similar to popcorn, in that they form only in highly evaporative environments. Aragonite is favored over calcite where the water is highly supersaturated or has a large magnesium content (which poisons calcite crystals and prevents them from growing). Aragonite in Mystery Cave is found on the dolomitic Stewartville Formation, which is a ready source of dissolved magnesium. It forms mainly low on the walls, where the evaporation rate is highest. Evaporation pan studies by Roy Jameson, of the LCMR Hydrology group, have shown that the evaporation rate in the route to the Garden of the Gods is highest near the cave floor.

Gypsum Crystals

Gypsum is concentrated in dry areas of the cave on bedrock that contains (or once contained) pyrite. Oxidation of the pyrite produces sulfuric acid and iron oxide. The sulfuric acid dissolves the limestone, forming a solution of calcium sulfate, which precipitates as gypsum where water seeps into the cave and evaporates (Figure 23). Gypsum crystals are common in Diamond Caverns in Mystery II as soft, flaky brown plates a couple of millimeters in diameter. In that area the gypsum-bearing water has also been wicked from the bedrock into the surrounding sediment, where it precipitated as crystals up to an inch in length.

Moonmilk

Moonmilk is a white pasty material that consists of tiny crystals of various minerals such as calcite or hydromagnesite. The only example we found in Mystery Cave is in the Cathedral Room, on the ceiling at the terminal breakdown choke. It forms a popcorn-like crust that is very porous and consists of tiny calcite needles. X-ray analysis showed that it consists of very low-magnesium calcite. Only one other speleothem, a stalactite, was within this low range. The irony is that the moonmilk is developed on dolomite bedrock (Maquoketa), which is rich in magnesium. The bedrock is moist and probably the local evaporation rate is very low where the moonmilk is forming. The origin of the moonmilk is uncertain.



Figure 20: Stalactites, stalagmites, and columns on the Door-to-Door Route.

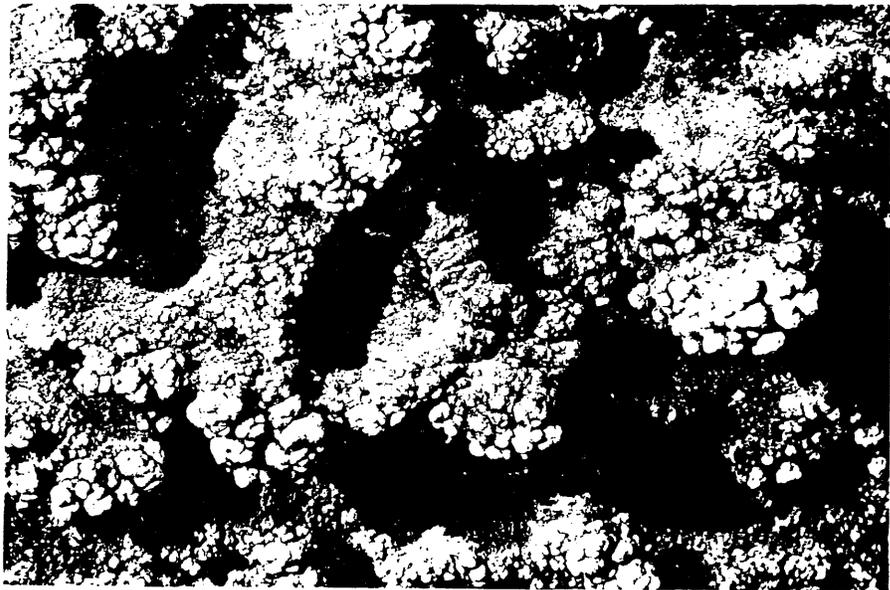
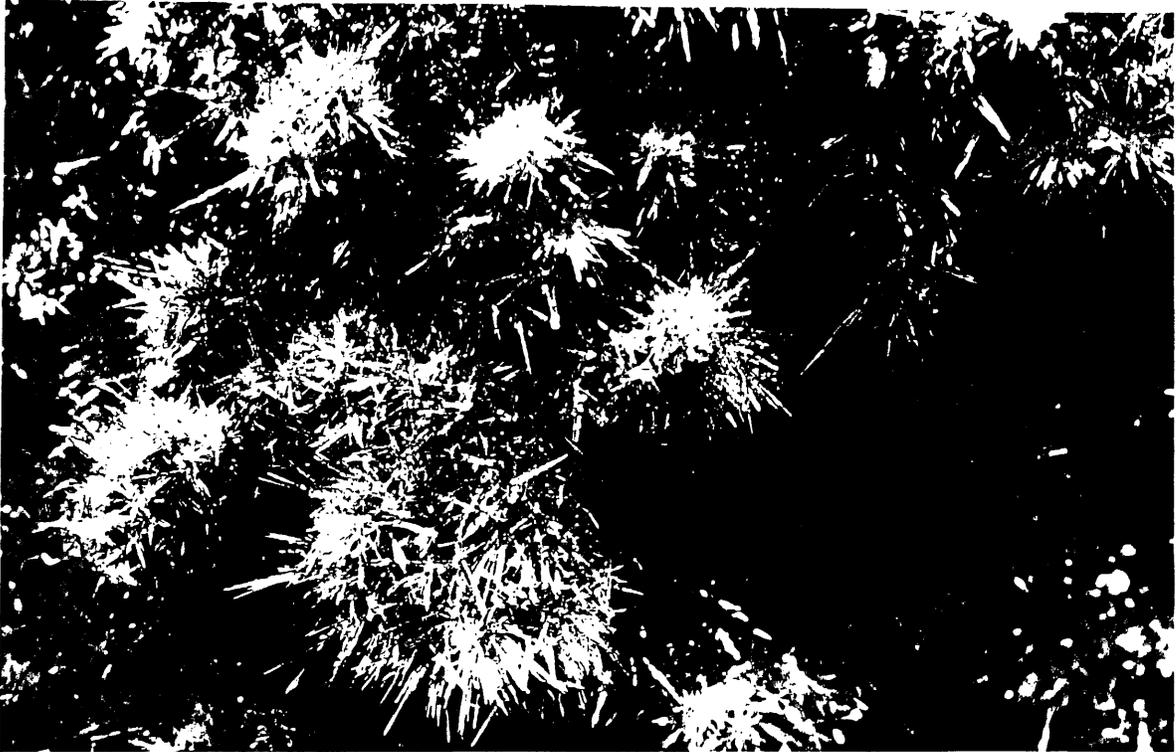


Figure 21: Cave popcorn at the eastern junction of the Angel Loop with Fifth Avenue. Width of photo is about 5 inches



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Figure 22: Aragonite crystals on the lower walls of the route to the Garden of the Gods. Each crystal is about 2-5 mm long.

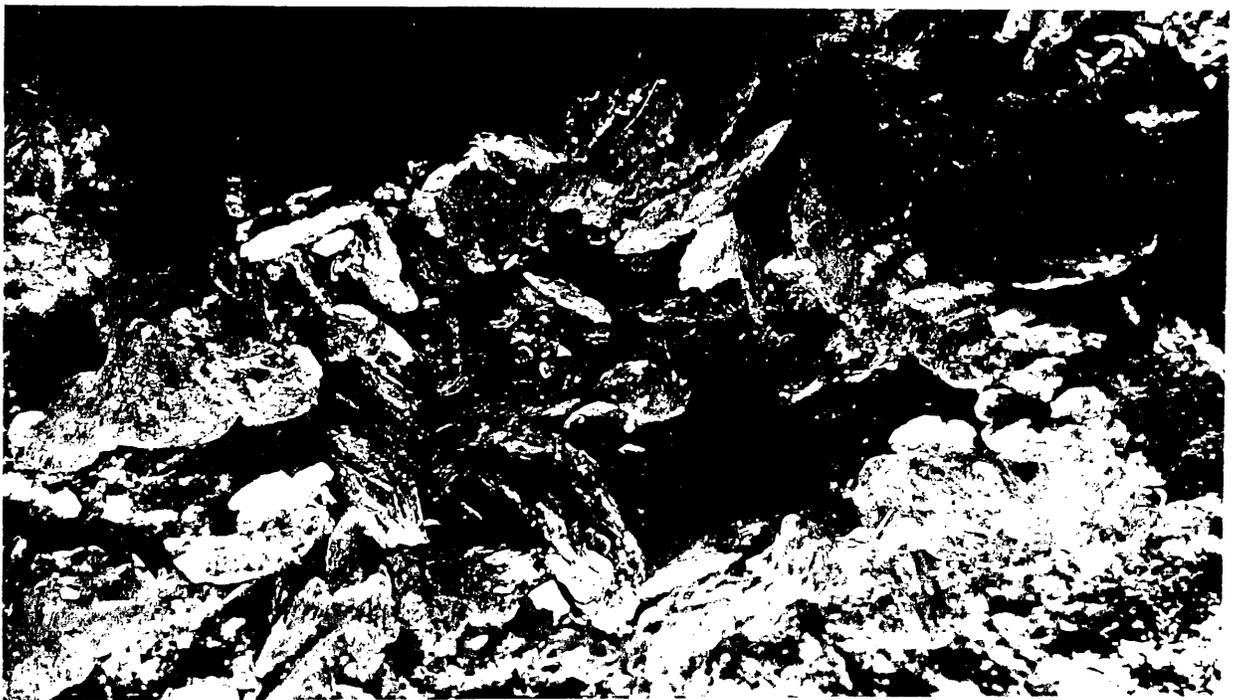


Figure 23: Gypsum crystals at the base of the Hills of Rome in Fourth Avenue. Each crystal is about 2-3 mm wide.

Speleothem Colors

Many of the speleothems in Mystery Cave are dark opaque brown, having been coated many times during their growth with layers of flood-borne silt and clay. Iron oxide also contributes to the dark red and brown colors of some speleothems, particularly where pyrite-rich beds are weathering. Those in the Formation Room of Mystery I are particularly good examples. White speleothems, like the calcite rafts in Turquoise Lake, have the color (or absence thereof) of rather pure calcite.

A few speleothems stand out from the rest, most notably the Carrot Sticks in the Angel Loop of Mystery II. The delicate translucent colors of such speleothems are generally attributed to organic acids carried in from the surface. There is certainly no lack of organic acids in water infiltrating into Mystery Cave, considering the richness of the soil. However, no analyses of these speleothems in Mystery Cave has been made, and so the exact source of the color remains uncertain. Whether the reddish orange of the Carrot Sticks is caused by iron oxide, by organic compounds, or a combination of both is not a serious enough question to justify breaking even a small piece!

Most of the dripstone and flowstone in the Tar Pits is purplish black, and hence the name. The black forms layers within the speleothems and coats the present surfaces. EDX analysis of a tiny bit of black flowstone crust (MY219) indicated that only calcium carbonate and clay are present. There were no peaks for iron or manganese, and so by default the only remaining likely source of the black color seems to be organic carbon. Organic muck carried into the cave by floodwaters coats many of the walls in the cave, but with a dusky, dull black rather than the shiny purple-black of the Tar Pits deposits. However, the black layers in another piece of the Tar Pits sample bubbled in hydrogen peroxide, which strongly hinted at the presence of manganese dioxide, which is a strong candidate for causing purplish-black colors. It appears that the black color in the Tar Pits formations is due to both organic carbon compounds and manganese dioxide. The Tar Pits are nearly beneath an abandoned strip mine in the iron-rich Windrow Formation (Cretaceous age), and manganese contained in the deposit may have been carried down into the cave. This subject bears more investigation.

Iron Oxide in Speleothems

Many speleothems in Mystery Cave are stained deep red by iron oxide, and several actually consist of interior bodies of iron oxide coated with calcite. There are two major sources of iron oxide: one is the oxidation of pyrite in the local bedrock, and the other is the iron oxide bodies in the Windrow Formation, which fills certain fissures in the limestone surface. Since the iron-oxide-rich speleothems lie on or a short distance below beds that are known to contain a great deal of pyrite and iron oxide, the former source seems to be the major (and perhaps the only) source. One series of beds in particular (DS13-DL13-DS14) is very rich in iron oxide derived from pyrite. The iron-oxide-rich stalactites in the Formation Room of Mystery I are growing on this sequence. Bright yellow iron oxide (limonite) has fallen from the ceiling in the western extension of Fifth Avenue from just below these beds.

Two major speleothems contain iron oxide cores: the Bird's Nest in the Formation Room, a large shattered column north of Sand Camp on the Door-to-Door Route (Figure 24). They are fundamentally dripstone columns, but with truncated oval tops. The Bird's Nest is rather flat on top, with a raised rim of calcite and a calcite covering on the surface of the indented interior, which was formerly exposed iron oxide (judging from shattered fragments on the floor). The other has a sloping top with exposed iron oxide surrounded by a thin coating of calcite. X-ray analysis of the central part

of the Door-to-Door Route formation showed it to consist of a combination of hematite, goethite (both common forms of iron oxide), calcite, and gypsum. The presence of gypsum helps to support the role of pyrite as the source for the iron oxide. Iron oxide is very unstable and often changes its composition, becoming hydrated and expanding in the process. The warped stalactites in the Formation Room have been disturbed by this process. The tops of the Bird's Nest and the Door-to-Door Route speleothem apparently shattered and fell away because the thickest parts of the iron oxide core expanded.

Chalky Crusts on Desiccated Speleothems

White chalky crusts appear on many speleothems that are now inactive (such as those that were buried during early trail building in Mystery I). Even under 600 X magnification a sample from the dump pile at Mystery I (MY132) showed no clear change in crystal structure or mineralogy between the interior and the chalky surface. The white crust is only a few microns thick and may be simply a weathering of large calcite crystals to finer-grained ones. A chalky white crust on flowstone near Sugar Lake in Mystery II (MY152) showed this relationship more clearly. The surface had been converted to very tiny calcite crystals. Work on this topic will continue with the aid of the scanning electron microscope.

Bacterial Filaments in Speleothems

Microscopic organic filaments, about half a micron in diameter, are very common in pool deposits especially those in Mystery I (for example, MY9-MY10). They are probably bacterial, although a positive identification has yet to be made. Filaments usually occur in layers subparallel to the speleothem surfaces, as though they had been caught up in the calcite growth. However the filaments usually cut across crystal boundaries, which may indicate that the filaments were endolithic - in other words, eating their way into the crystals. This seems unlikely. Bacterial filaments play a more active role in speleothem growth in the pool fingers (and possibly chenille spar), as described in previous paragraphs.



Figure 24: Calcite drapery with an iron-oxide core, in the Door-to-Door Route north of Sand Camp. The top of the speleothem broke off naturally, probably because of expansion of the iron oxide by hydration.

NON-CHEMICAL DEPOSITS IN MYSTERY CAVE

Certain cave deposits do not fall into the category of speleothems. These consist of material carried into the cave or that has fallen from the cave roof. Although not as glamorous as speleothems, they still can tell us a lot about the developmental history of the cave.

Sediment

This topic was purposely downplayed in our study because it has been the main topic of earlier work (Milske, 1982). In general, however, the sediment fill in Mystery Cave consists of a combination of insoluble material carried in by streams from the surface plus weathered debris from the bedrock in the cave. Where the water velocities have been large, gravel and sand is deposited (provided there is sufficient source for this material). The gravel and sand that caps the sediment banks in Mystery I were clearly deposited by swiftly moving water entering the cave from the South Branch of Root River. Finer grained sediment, such as silt and clay, was deposited by slow-moving water, such as that which ponds up in backwater areas of the cave during floods. Much (and probably most) of this material has been carried in from the surface, but some is derived from weathering of the bedrock, particularly the shale beds in the Dubuque. Some of the latter consists of bits of weathered limestone and dolomite.

The general sedimentary sequence in the cave consists of thick silt overlain by sand and gravel, which in turn is cemented by flowstone. The silt probably came from the wind-deposited material that so thickly covers the land surface (as described earlier). The sand and gravel were deposited by free-flowing streams on top of the silt fill. This topic is discussed further in the next section on the origin of Mystery Cave.

Organic Debris

Floodwaters from the South Branch of Root River occasionally carry in large concentrations of vegetal matter and dark soil from the surface. This dark organic material coats the walls in several places in the cave, most notably the southwestern end of the Door-to-Door Route in Mystery I and the western end of Main Street in Mystery III near the junction with Rimstone River. Oxidation of this organic material probably boosts the carbon dioxide content of the cave air, although the actual amount is uncertain. In certain dead-end caves the build-up of carbon dioxide from this source reaches dangerous levels. This is apparently not a problem in the well-aerated Mystery Cave.

Breakdown

Breakdown consists of bedrock that has fallen from the ceiling or walls. It ranges from minor chips and flakes to large slabs and blocks. The size and shape of the blocks depends on the nature of the rock (e.g. bedding thickness), the size and shape of the passage, the amount of space remaining in which breakdown can occur. Many of the large passages and rooms in Mystery Cave owe almost their entire present shape to breakdown. Large rooms separated by nearly blocked sections (as at the Hills of Rome) are usually caused by local removal of breakdown by a lower-level stream, which dissolves the blocks and carries away the sediment that encases them. Breakdown terminates many of the passages in the cave, especially where a passage approaches the surface.

When did the breakdown occur? The fact that most of the breakdown is cemented together by silt and clay shows that most of it is fairly old. Breakdown has been observed in other caves mainly when there are fluctuating water levels. Water will dissolve the contacts between blocks, and when it recedes, the loss of buoyancy causes blocks to fall. This is a nice scenario, because it does not pose any danger (since we would not be in the cave at such times). However, blocks do fall even today in unstable areas. Earthquakes can bring down rocks, but their effect is much smaller than would be expected. In general, they affect only those rocks that are about to fall on their own. Most of the ceilings in the cave are fairly stable now, as most of the breakdown that is likely to fall has already done so.

ORIGIN AND DEVELOPMENTAL HISTORY OF MYSTERY CAVE

Mystery Cave is very much a product of its surroundings. For that reason, it provides a great deal of evidence for the landscape evolution of the entire region. Earlier researchers (for example, Milske, Alexander, and Lively, 1983) have laid a great deal of the groundwork by examining the geologic setting and sediments in great detail and determining the relative and absolute ages of many of the cave features. Their article provides the best published introduction to the cave and its origin. Our own interpretation of the cave origin differs in some respects but is still compatible with that of Milske, Alexander, and Lively.

In comparing our views to those of earlier researchers, two differences stand out: (1) It has been traditional to consider the earliest cave development to have been widespread solutional enlargement of fractures by preglacial region-wide groundwater flow at and just below the water table, and that the present cave is simply an enlargement of those early fissures by more rapid flow contributed by water sinking underground from the South Branch of Root River. We give less emphasis to widespread early solution and attribute virtually all the significant cave development to underground flow from the South Branch. In our view, water from the South Branch of Root River formed the cave, rather than simply modifying it and using it as a convenient underground pathway. (2) Earlier workers tended to subdivide the evolution of the cave into many discrete phases, such as a phreatic stage followed by a vadose stage. We view these phases as having very indistinct overlapping boundaries, with recurring episodes that modified the cave by similar processes on many different occasions. Rather than viewing the cave origin as an orderly progression from phreatic to vadose, we interpret Mystery Cave as a dynamic floodwater cave in which the cave-forming processes are still going on, with enlarging and filling events that recur over and over, like remakes of the same movie plot. These differences certainly do not mean that the earlier interpretations were wrong. In fact, the two approaches complement one another. Also, it is still important to organize the developmental history of the cave into some kind of sequence, even if the boundaries *are* indistinct.

Calvin Alexander, of the University of Minnesota, has kindly provided us with a detailed account of his interpretation of the cave origin (September 4, 1991), a copy of which is located in the Mystery Cave files. His interpretation is based partly on work by others but is his own synthesis from many years of mapping and geologic study in the cave. The following discussion on cave origin represents our own views so far, but we repeatedly refer to Dr. Alexander's work and note any agreements and differences of opinion.

Exact dates for the different stages of cave development are very difficult to pin down. However, most of the sequences and controlling factors are fairly clear, so perhaps it is not critical to know exactly how old each feature is, as long as a general time frame is available. In addition, in order to present a coherent picture of the development of Mystery Cave, it is necessary to speculate about certain items. Most geologic interpretations are subject to revision and re-evaluation -- it would be a pretty boring science if the earliest papers on a subject were absolutely correct in every detail, leaving nothing more for the future! For those who wish for hard facts and exact dates, just consider the tremendous uncertainty and speculation that shrouds much of *human* history -- even modern events during our own lifetime! So in the following discussion, what we consider to be "facts" are stated without qualification, but speculations are given in various shades of gray.

1. **Deposition of the limestone beds.** The Stewartville, Dubuque, and Maquoketa Formations accumulated on the floor of a shallow continental sea about 450 million years ago during the Ordovician Period of geologic time. Many features in the cave owe their appearance to the differences in rock texture and composition that date from this time. For example, the distinct difference between the massive, mottled Stewartville and the prominently bedded Dubuque dominates the wall character in the cave.
2. **Origin of fractures.** The age of the joints and faults is extremely difficult to determine in the Mystery Cave area. It is probable that they were formed not long after the original soft sediment became brittle rock, Region-wide stresses within the continent were probably responsible, as shown by the fact that they are widely distributed and vary in trend in only a gradual way over large distances. These stresses were probably related to the Ordovician-age warping of the eastern part of North America, which formed the Taconic Mountains. Observation of newly deposited limestones (e.g., those in Bermuda and the Bahamas, many of which are only a few tens of thousands of years old) shows that jointing begins very early, even in nearly stable areas in which there are few stresses. Faults require considerably more stress to form, and again it is likely that they date from the Taconic mountain-forming events of the late Ordovician Period.
3. **Exposure of the limestones above sea level; earliest solutional phase.** Below the sea floor, limestone is generally stable and does not dissolve, although much recrystallization can take place that slightly alters the mineralogy and texture. Furthermore, water in the material below the sea floor has essentially zero hydraulic gradient and cannot move. Without the through-flow of fresh water, caves cannot form. The limestones at Mystery Cave were apparently first exposed above sea level for a significant length of time in the Cretaceous Period, about 100 million years ago, when the land uplifted and overlying rock layers were eroded off. Many near-surface fractures were solutionally enlarged into fissures at that time, most of which were later filled with sediment and iron oxide of the Cretaceous Windrow Formation. Sloan (1964) described buried solution-enlarged fissures and small caves filled with Cretaceous sediment beneath the thick glacial till to the west of Mystery Cave. Topographic relief was apparently very low at that time, so significant cave development was sparse or absent. Undoubtedly some of these early fissures have been enlarged further during the origin of Mystery Cave. The limestone has lain at or near the surface since the Cretaceous Period, so there was no major geologic interruption between the origin of the early fissures and of Mystery Cave.

From the pattern of Cretaceous deposits in the north-central U.S., it is clear that Cretaceous drainage in the Mystery Cave area was toward the west. Today it is eastward, toward the Mississippi River. The Mississippi developed sometime during the Tertiary Period, apparently as the result of tensional rifting of the central part of the continent.
4. **Entrenchment of the Root River.** Mystery Cave itself began to form only when the South Branch of the Root River deepened its valley, forming an entrenched valley in the limestone surface. The trigger for this important event was apparently the onset of glaciation during the Quaternary Period. As glacial ice advanced and retreated just north of the cave area, abundant meltwater deepened the channel of the Mississippi River, to which the Root River is tributary. Deepening was probably greatest when water drained from large glacial lakes with very little sediment load, which made the water highly erosive. The picture is not perfectly clear,

because the great amount of sediment eroded off the glaciers at other times caused the meltwater to deposit material and fill up the valleys, rather than erode them. Things are further complicated by the fact that the continent is depressed by the weight of glaciers, enhancing the tendency for valleys to fill with sediment. The opposite is true during the interglacial stages. The drop in sea level caused by the tying-up of seawater as ice during glacial advances resulted in deepening of valleys around the coast. These valleys tended to fill with sediment as sea level rose during glacial retreats. Located in mid-continent, the upper Mississippi valley was probably not affected significantly by sea-level fluctuations.

Deepening of the Root River valley took place mostly by headward erosion (since there was no systematic eastward tilting of the land to cause simultaneous entrenchment all along the valley). This mode of valley erosion is similar to that at Niagara Falls, where a deep gorge is being eroded by headward erosion at the waterfall -- but much less dramatic in the Root River, in which there is no single massive, resistant bed, as at Niagara Falls, so headward erosion in the Root River was more likely produced by a number of small rapids that worked their way headward from the Mississippi valley.

Mystery Cave is located exactly where the gradient of the South Branch is steepest (see Figure 25). This condition is not only true today, but it has persisted for a long time, because the bedrock floor of the valley, located beneath sediment fill more than 20 feet deep, has roughly the same gradient. This steepening is probably caused in part by the resistance of the massive Stewartville Formation in comparison to other nearby rocks above and below. In any event, cave origin by underground piracy of surface streams is favored most by steep gradients. An even more appropriate way to measure river gradient from the standpoint of potential cave origin is to consider the drop in elevation over the straight-line distance between meander crests. The local gradient across the meander loops at Mystery Cave is nearly 0.069 ft/ft, or 360 ft/mile, a very steep gradient by groundwater standards. The present straight-line gradient from Mystery I to Seven Springs is even greater, at 420 ft/ft. (This path is slightly shorter than the full crest-to-crest meander length.)

Meanwhile, the entrenchment of the South Branch and other rivers below the limestone upland enhanced the tendency for sinkholes to develop in the land surface and for surface infiltration to be channeled underground at discrete points. Mystery Cave shows no evidence for significant passage development from such water, but it was an important factor in the development of certain other caves in the region. However, the large amount of carbon dioxide carried into Mystery Cave by this water may have enhanced the rate of solution by water fed by sink points in the river. It also accounts for the large number of speleothems that formed in Mystery Cave later in its history, when the cave was mainly air filled.

5. **Earliest passage development in Mystery Cave: upper levels of Mystery II and Mystery III.** The first parts of Mystery Cave to form were the large west-to-east passages such as Fourth Avenue and Fifth Avenue. Entrenchment of the South Fork took place earliest in this downstream area, and so it is likely that subsurface diversion and cave-passage development would have been initiated there first. This idea is supported by the fact that these passages are highest in elevation of any in the cave (except for a few that have migrated upward by collapse), and that they are highest above the present cave streams. Also, by far the oldest speleothem dates have been measured in these passages. Most of the passages show considerable breakdown modification, so their original pattern is not clear.

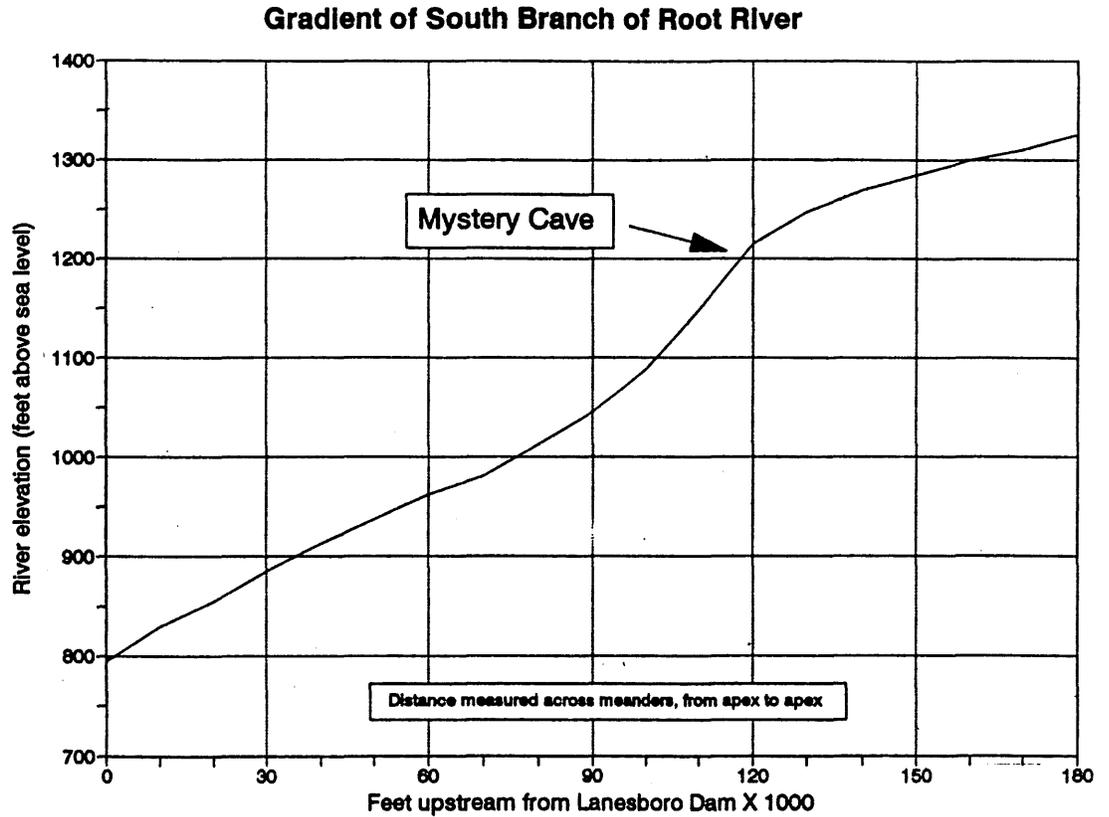


Figure 25: Graph of the gradient across meanders in the South Branch of the Root River, upstream from the Lanesboro Dam, calculated from the elevation drop in the river over the distance from the crest of each meander to the crest of the next. Mystery Cave is located along the section of river that has the steepest gradient.

Fifth Avenue consists of a high, wide set of fissures dissolved in the topmost beds of the Stewartville Formation. It is likely that all of these passages formed at or near the Dubuque/Stewartville contact and have been enlarged downward by solution and upward by The water that formed these passages probably came from sink points in the bed of the South Branch just west of Mystery III. This is a promising spot, similar in character to the present Mystery I area, where limestone is exposed in a steep bluff on the outside of a sharp meander bend. Infiltration from the surface is not a feasible source of the cave-forming water, either now or in the past. Infiltrating water is almost invariably supersaturated and is depositing speleothems. This water is too diffuse to have caused the cave to form -- it is dispersed among many narrow fissures. The passages in Mystery Cave show no tendency to emanate from surface sources the way sinkhole-fed cave passages do. Instead, the passages are laterally continuous with no vertical shafts or canyons. (Enigma Pit is a possible exception, but its water seems to be simply clearing away sediment rather than forming new passages.) The headward parts of passages such as the main passage of Mystery I and Eureka Avenue originate full-blown right at the river valley (although most of them actually terminate in breakdown and fill near the valley edge). It is clear that the cave-forming water emanated from the river.

But where did the water exit? This is a significant question, as its answer will determine where additional undiscovered passages may lie. The present outlet at Seven Springs is a possibility, but there is no evidence that they were active during the first phases of cave development. A promising location is the western wall of a prominent abandoned meander scar south of where Route 5 crosses the South Branch east of the cave (Figure 26). This was formed by an old upper-level meander in the river and has since been abandoned in favor of a more northerly route. The old meander left a low-relief bench at about 1150-1180 feet, which is an appropriate outlet level for the old Mystery III and Mystery II passages, which cluster at about 1200-1220 ft. It is also located directly in line with the main trend of Mystery III and Mystery II. The Stewartville Formation is exposed there as well. The western wall of this old meander bend would be an ideal place to search for cave passages, or at least to look for evidence of former spring outlets, such as collapse zones or erosional alcoves.

The prominent bedding planes above and below the Dubuque/Stewartville contact are particularly favorable zones for solution, especially where they are intersected by joints. These beds are limestones and dolomitic limestones with low insoluble content, and they are not interrupted by shale beds. The bedding planes form prominent partings that are susceptible to solution and generally form the widest parts of the passages that intersect them (see examples on Door-to-Door Route, Diamond Caverns, Angel Loop, and Fifth Avenue). In many places the bedding-plane partings contain anastomoses, which are little mazes of intersecting tubes an inch or two in diameter. These are best observed in the Door-to-Door Route (see profile for examples). Anastomoses are most commonly formed by flooding after the initial development of a cave, and so they take their place along with ceiling pockets and joint indentations as floodwater injection features. However, they usually form only along the most prominent bedding planes and are good indicators that those were the bedding planes along which the cave passage began to develop.

The age of the early passages in the cave is conjectural. The oldest speleothem dates exceed the limits of the U/Th dating technique (350,000 years). The only recourse at present is to

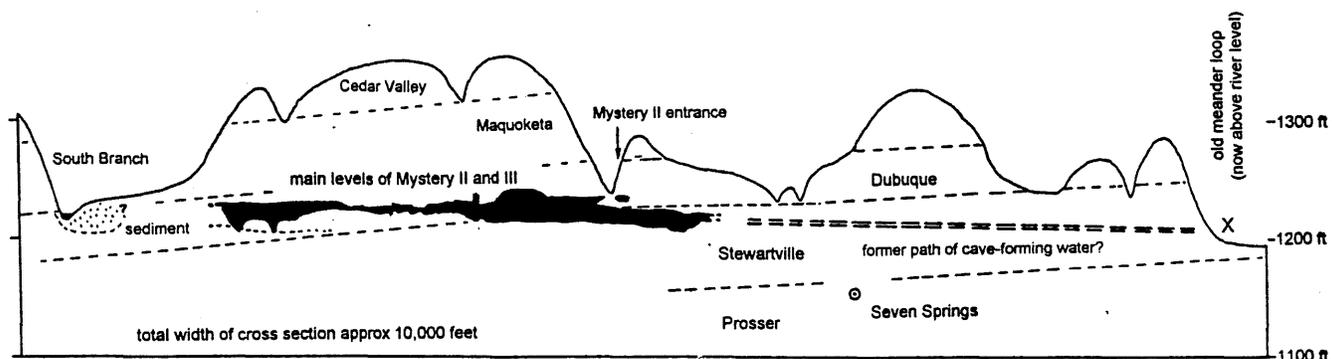
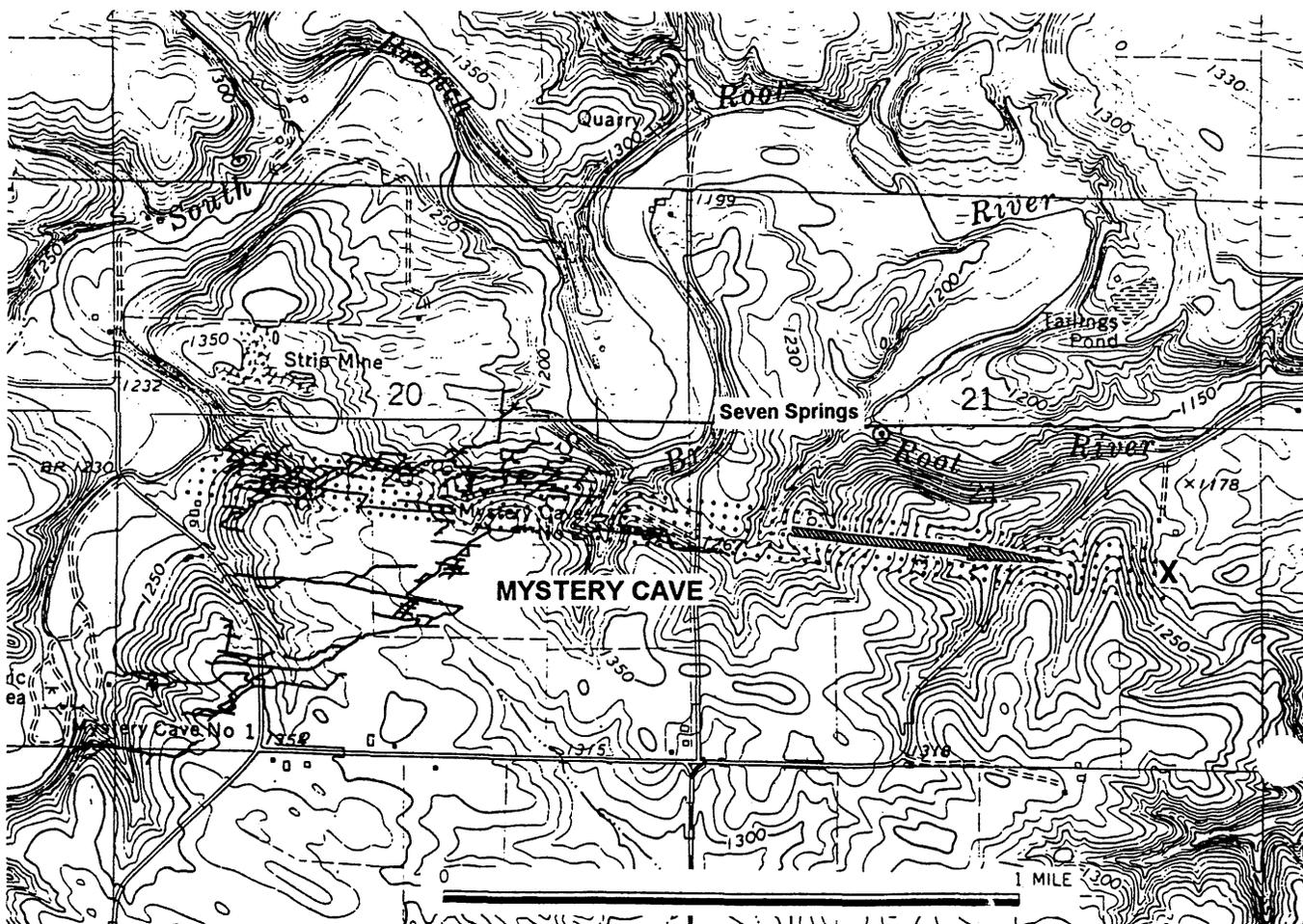


Figure 26: Map and cross section showing the probable route of the earliest passages to form in Mystery Cave. The profile shows the main levels and their possible outlet in a now-abandoned meander loop (X). They are now blocked by fill and breakdown beneath the small valley east of Garden of the Gods. Seven Springs is the present outlet for the cave water and may be perched on chert beds at the top of the Prosser Formation. (The springs are located to the north of the line of cross section, slightly down-dip, so the top of the Prosser is lower there than shown on the cross section.)

relate the cave origin to the entrenchment history of the river, which itself is uncertain. Entrenchment of the Mississippi River probably began during the earliest phases of glaciation, about a million years ago. Entrenchment of the South Branch must have been later. The broadest limits to the earliest stages of cave development are therefore between 1.0 million years and 0.35 million years. However, the passages must be considerably older than the speleothem dates. They are among the most recent deposits in these passages, and many of them post-date considerable breakdown modification. A date of more than 0.5 million years is probable. This places the origin of Mystery Cave somewhere in the middle (or even early) Quaternary Period. It is evident from the speleothem dates that these passages pre-date at least two major glaciations (commonly known as Illinoian and Wisconsinan).

6. **Second phase of passage development: Mystery I and Door-to-Door Route.** As the South Branch continued to entrench its valley, new sink points developed farther upstream. As a result, the southwest-to-northeast series of passages began to form. These include Mystery I and its connection with Mystery II by the Door-to-Door Route and related fissures (many of which are too narrow to traverse -- including the Door-to-Door Route for some people). Other likely inputs fed Big Fork and other nearby passages in the western end of Mystery I. Speleothem dates in Mystery I are no older than 12,000-13,000 years, although these figures can be misleading. This is a very active part of the cave that still floods frequently, and it is probable that the passages are much older, but that speleothems were unable to survive in this area until relatively recently. Some speleothems on the Door-to Door Route north of Sand Camp are too recrystallized to date, and they are undoubtedly older than the rather young dates given above.
7. **Development of lower levels.** This is where the clear sequential progression of events begins to break down. Lower levels probably began to form in Mystery II and III well before the Mystery I passages took shape, and they continue to form and enlarge today. The major related event was that the spring outlets at Seven Springs were established. These were probably not the original outlets for the cave water, since they are right at river level and may have once been below the present river level. Seven Springs today is a series of small solutional openings along a favorable bedding plane, apparently near the base of the Stewartville Formation. The amount of solutional enlargement is very small, and it is clear that these specific openings have not served long as the outlet for Mystery Cave. Considering that the river valley was filled with at least 20 feet of silty sediment late in the Quaternary Period, it is probable that the spring was once at a lower elevation and has simply moved upward to a new stratigraphic level as a result of sediment blockage of the lower outlet.

The present spring location is near the cherty top of the Prosser Formation. Could the chert be acting as a resistant lower boundary to karst development at Mystery Cave? Chert is nearly insoluble, so it retards cave development. In east-central states like Kentucky, similar chert beds are perching zones for groundwater, but to a limited degree. Chert exposed well above river levels is easily breached by cave passages. Near river level, chert is a more formidable barrier.

8. **Sediment fill.** Sediment fill in Mystery Cave cannot be attributed to a single stage, since some sediment accumulates even while a passage is forming, and much sediment is deposited by floods even today. In general, the work of Milske (1982) shows that the main bodies of sediment in Mystery Cave consist of thick silt covered by sand and gravel (Figure 27). The

silt in the cave is tentatively interpreted by Alexander (1991) as a change from deep phreatic to shallow phreatic cave development. He notes that wherever the bottom of the silt is exposed, it sits directly on a solutional bedrock surface. No breakdown has been observed beneath the silt.

Silt deposits as uniform as those in Mystery Cave are rare, however, and it is more likely that the main cave silt correlates with the silt cover on the surface, which is mainly wind-deposited loess carried in from areas of extensive glacial sediment. This sediment cover formed a rather uniform blanket over most of the Mystery Cave area, rather like a layer of dust in an old house. It even partly filled the river valleys to depths of 20-30 feet, despite the erosional capacity of the flowing water. River water entering sink points apparently carried a great deal of this material into the cave. The cave silts seem to be related to the loess blanket on the surface, in which case it must have a rather narrow range of dates. It is hard to imagine that there is no correlation between the cave silt and that in the river valley, since they occupy the same elevation range, have similar thicknesses and textures, and appear to have the same relationship to the evolutionary history of the cave. In keeping with other cave events, the fill dates are not exactly known. However, the surface loess is commonly thought to be of Wisconsinan age, which limits it to the last 50,000 years or so. This does not agree well with the dates of 117,000-183,000 years for speleothems that cover the silt in Enigma Pit (Figure 28). The silt in that part of the cave must then be Illinoian age or even older. Could this be loess derived from Illinoian glacial deposits? Is there more than one silt deposit? Some speleothems in Mystery II are more than 350,000 years old, and they speak of even phases of cave development (Figure 29). It is probable that the cave can shed considerable light on the glacial history of the area. Further investigations will require a great deal of teamwork with glacial geologists.

The silt is overlain in most places by sand and gravel. Some of the gravel cobbles are up to 20 cm in diameter, indicating very rapid flow. Speleothem dates on these deposits in Enigma Pit are as old as 146,000 years. On the Door-to-Door Route they are all about 12,000-13,000 years. This would correlate well with the latest phase of Wisconsinan glaciation in the region. This was the Des Moines Lobe, which terminated 40-50 miles west of Mystery Cave.

9. **Recent modifications of the cave.** The cave continues to be modified by water sinking in many places along the bed of the South Branch. During low flow the water has little effect. However, during high flow it carries in a great deal of quartz sand into active stream channels, swirling it into backwater areas, in some cases more than 30 feet above the low-flow stream floor. In many other passages the water rises slowly and has no perceptible current, depositing silt and clay instead of sand. Where it overflows into high-level passages the water attains a variety of local velocities, depending on the passage configuration, and causes considerable erosion and deposition.

The most important aspect of floodwater input to the cave is that it is highly undersaturated with respect to limestone and dolomite. Nearly all the cave water is supersaturated most of the year, but during floods, even relatively static pools fed by the river water are undersaturated and are able to enlarge the cave by dissolving the bedrock (see Figures 16 and 17 of the Technical Report). The cave has most of the features of a typical floodwater cave, including an irregular network pattern, enlarged ceiling pockets and dead-end joint fissures, and highly varied sediment grain size (Figure 30).

FIFTH AVENUE WEST

ENIGMA PIT

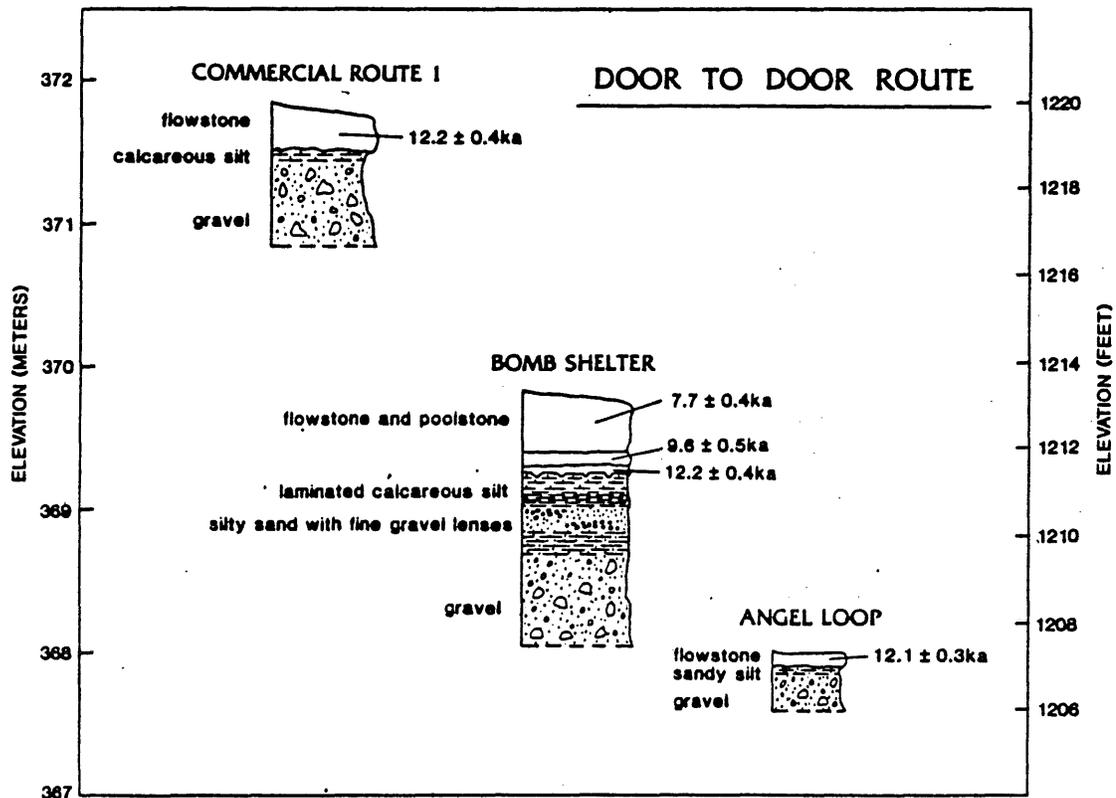
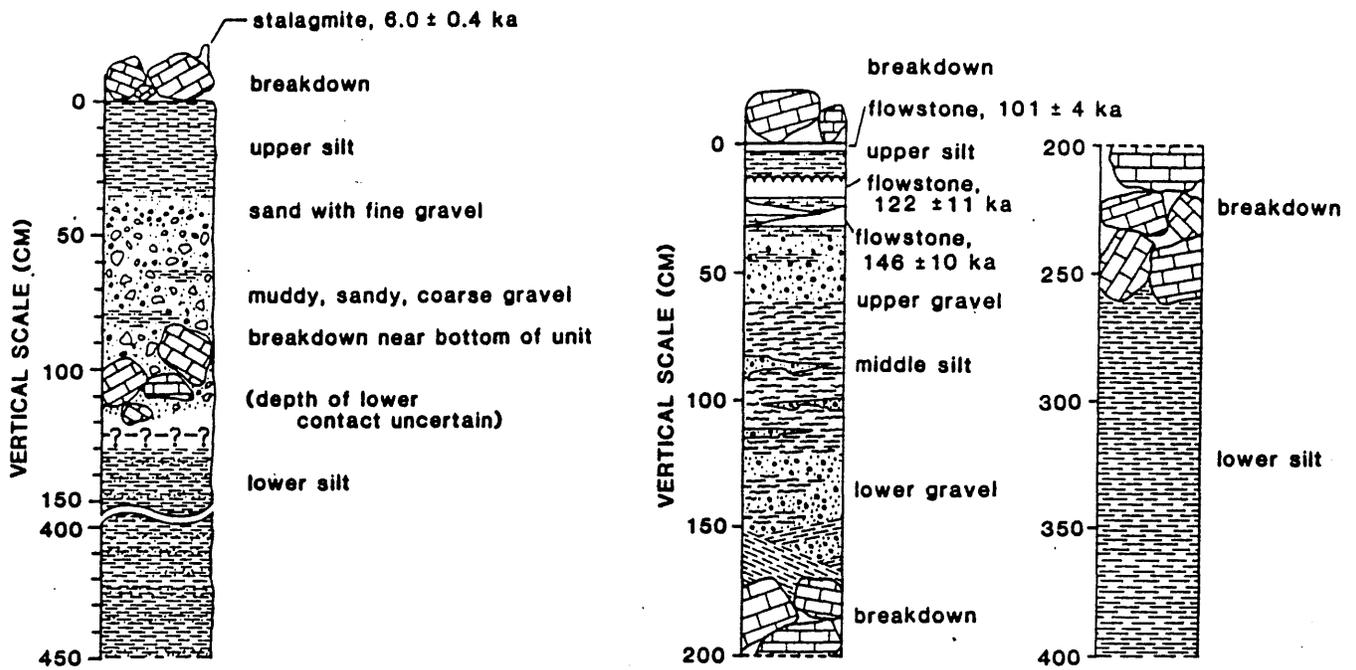


Figure 27: Typical sedimentary deposits in Mystery Cave (from Milske, 1982).

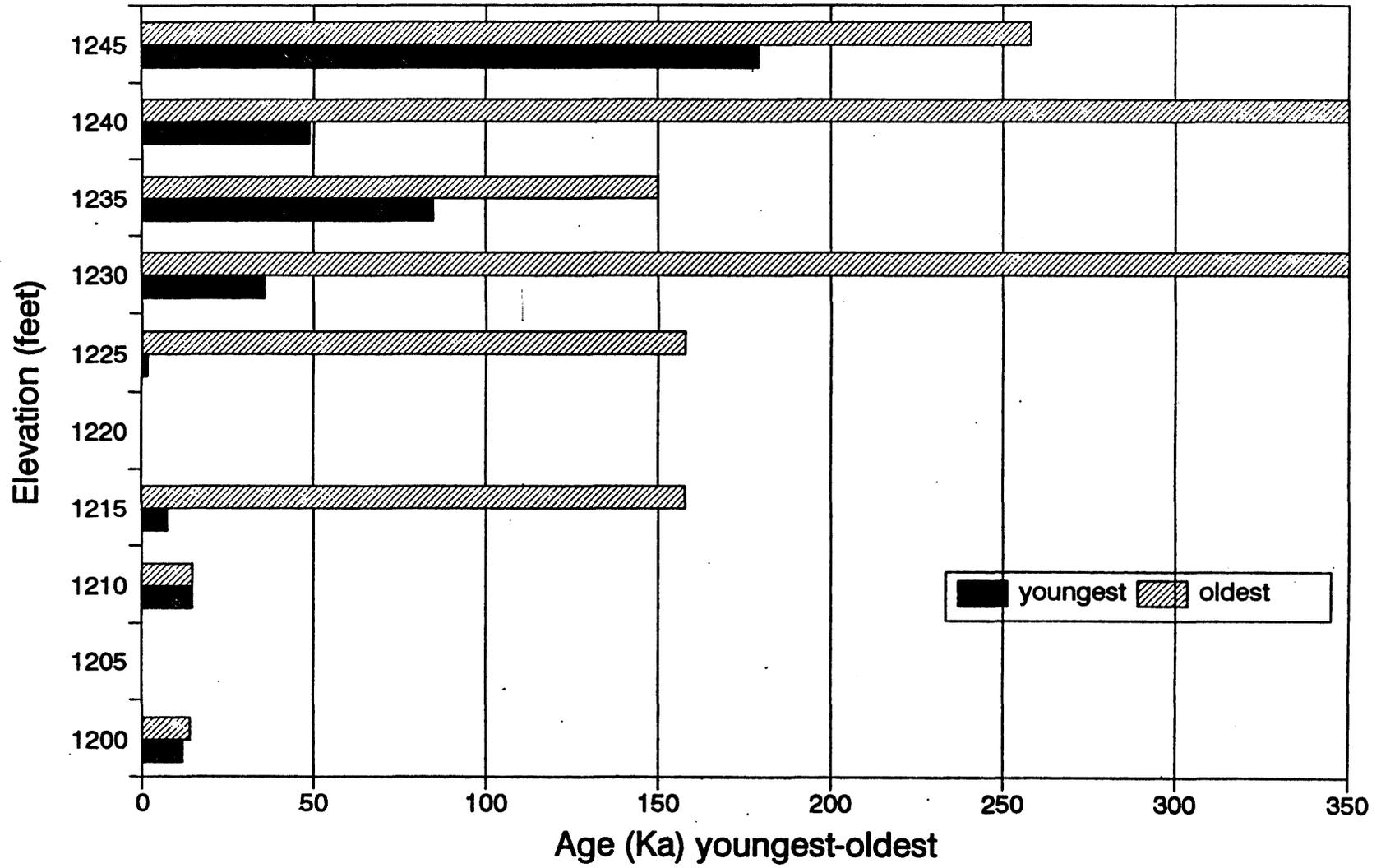


Figure 28: Speleothem ages in Mystery Cave (from Richard Lively, Minnesota Geological Survey).

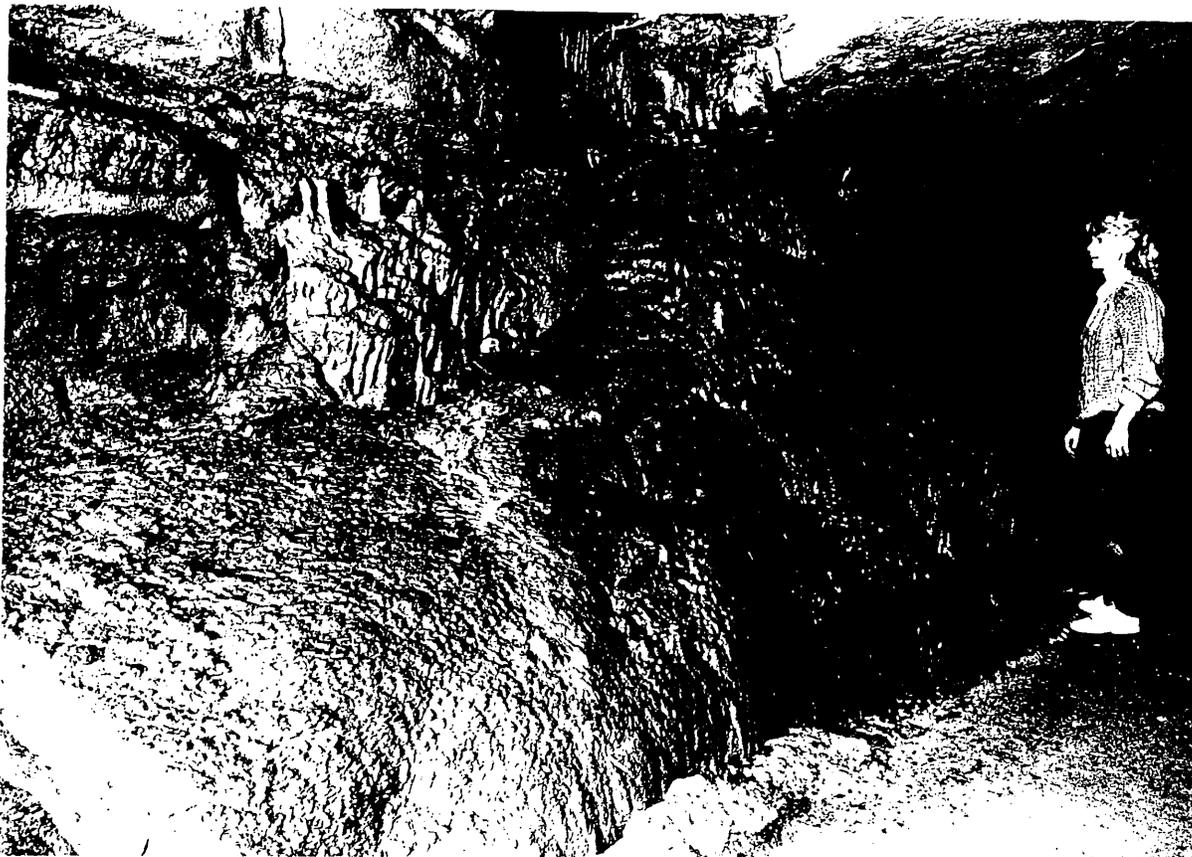


Figure 29: The flowstone mound near Blue Lake in Fourth Avenue contains calcite of several different ages. The outer few inches of the main mass range from 49,000 to 78,000 years old. Botryoidal calcite from the underside of the formation is about 89,000 years old. The dull, slightly lighter gray material is older flowstone and shelfstone (179,000 to more than 350,000 years old) partly engulfed in the more recent flowstone. The "Mushroom" formation on the far side of the mound is part of the older flowstone that peeled away from the wall before being cemented in place by the younger flowstone.

Speleothems have been deposited throughout most of the cave passages, once they have undergone their major phase of solutional enlargement. Supersaturated seepage water capable of depositing speleothems is always available, but in most an actively forming passages the effects of this water are overwhelmed by the solutionally aggressive water coming from the river. It is unlikely, for example, for speleothems to be deposited near the stream level of Flim Flam Creek. Once a passage becomes air filled most of the time, however, calcite speleothems can begin to grow and can survive occasional influxes of undersaturated water. There is no sharp cutoff between passage origin and speleothem deposition, even within a single passage.

The speleothem dates cluster around times that correspond with interglacial stages, although there are no clear breaks between deposition and non-deposition. Evidently the times of maximum glacial advance were not conducive to speleothem deposition because of freezing conditions. Many of the older speleothems in the cave have been naturally broken. Some stalagmites (for example, those at station D622) are still in position but have been fractured. Freezing and thawing in a glacial environment is one of the few ways in which such breakage can occur. It is possible that the shattering of the Bird's Nest and other iron-oxide-cored speleothems also date from freeze/thaw cycles during glaciation. Ordinary winter freezing only penetrates the ground a few feet at most. Speleothems continue to be deposited today, while many of the lower-level passages continue to be enlarged by solution.

Although sediment continues to be deposited in certain areas of the cave, present-day conditions favor a net removal of sediment. The many active vadose passages with their high-gradient, rapid flow are routes by which much of the thick sediments are being carried away. Steep sediment banks at such places as Flim Flam Creek and the Great Depression show how extensive the sediment fill is, and how much has been carried out of the cave by streams. Perhaps the most significant removal of sediment has been from Fifth Avenue. There is evidence for at least 10-15 feet of sediment fill in the passage, which has been almost completely removed by later stream action. This removal was probably the work of water flowing from the Door-to-Door Route following the latest glaciation (last 12,000 years or so).

Most interesting are the features associated with the former sediment. At intersections with side fissures, solution grooves rise upward in the walls of Fifth Avenue. This gives the impression that phreatic water was entering through the side fissures and mixing with water in Fifth Avenue, creating an aggressive mixture (Alexander, 1991). That would imply that the fissures were contemporaries with Fifth Avenue. Another example of a solution groove is in the Mystery II entrance passage, in the wall where the steps turn to the right as they enter the narrow fissure that leads to Fifth Avenue. Our interpretation is that these grooves were formed by periodic flooding while Fifth Avenue was partly filled with sediment. As the floodwaters receded, they drained down the walls into the side fissures along the sediment contact. This would account for the fact that the grooves all extend above the fissure openings. Now that the sediment has been removed, the grooves seem puzzling at first. Similar features are seen in caves in which the sediment remains in place (e.g., Mammoth Cave, Ky., and Cumberland Caverns, Tenn.)

The keyhole cross section of certain passages can be attributed to partial sediment filling of fissures (Figure 31). The part above the sediment continued to be enlarged by solution, while the sediment-filled part remained a narrow fissure. These are common in the walls of Fifth Avenue, supporting the idea of a former sediment fill.

The sediment fill in this part of the cave also seems to have determined whether the dolomitic burrows in the Stewartville project outward or weather inward. Below a certain undulatory contact, the burrows show a distinct change from weathering inward (above the contact) to projecting outward (below the contact). This contact does not coincide with the bedding, nor does it seem to match the level of highest sediment. It appears to be determined by a former sediment level. However, the chemical and mineralogical reasons for this difference are still under investigation.

Among the most recent events in the evolution of the cave is the accumulation of local pool deposits. Mystery Cave is a marvelous repository for unusual pool deposits because of abundant high-CO₂ seepage from the surface and the highly irregular passage floors, which contain many natural basins sealed rather tightly by silt and clay. In many places the basin shape has been determined by breakdown piles, and silt and clay have cemented the breakdown into rather tight pool linings. Pool deposits do not correlate in level, except on a very local scale, as they are perched above the water table. For that reason, features such as shelfstone and raft cones cannot be correlated from place to place. Most of them do correspond roughly in time, dating mainly from since the last glaciation (last 12,000 years or so).

Breakdown has played a major role in modifying the original passage configurations, especially those in the Dubuque and Maquoketa. Its activity continues today. Alexander (1991) considers the breakdown modification of the large passages in Mystery Cave to post-date the silt, and to date mainly from the initial draining of the cave (transition from phreatic to vadose conditions). He attributes the draining of the cave to the entrenchment of the South Branch, and considers this to be the first time that floodwaters could enter the cave and modify it. In contrast, our view is that most of the cave-forming events are contemporaneous with entrenchment of the river, and that floodwater processes have been important to the origin and modification of even the earliest of the true cave passages. Alexander (1991) concludes that "the hydraulic role of Mystery as an underground meander cutoff for the surface drainage is therefore a coincidence." But he adds the interesting comment: "I do not like coincidences!" Note that we are often our own worst critics.

Written words may sound like inflexible law, but in the search for better understanding we often end up repudiating our own earlier work. Over the two-year span of this project we have come across many more questions than we have had time to answer. The 1994 update of this report will concentrate on interpretation of the data collected so far. However, in future years it will take teamwork with many other colleagues to help answer the many remaining questions.



Figure 30: Solutional ceiling pockets along joints are typical in caves formed or enlarged by water whose level fluctuates a great deal. Undersaturated floodwater is forced into all available fissures under pressure, enlarging them by solution.

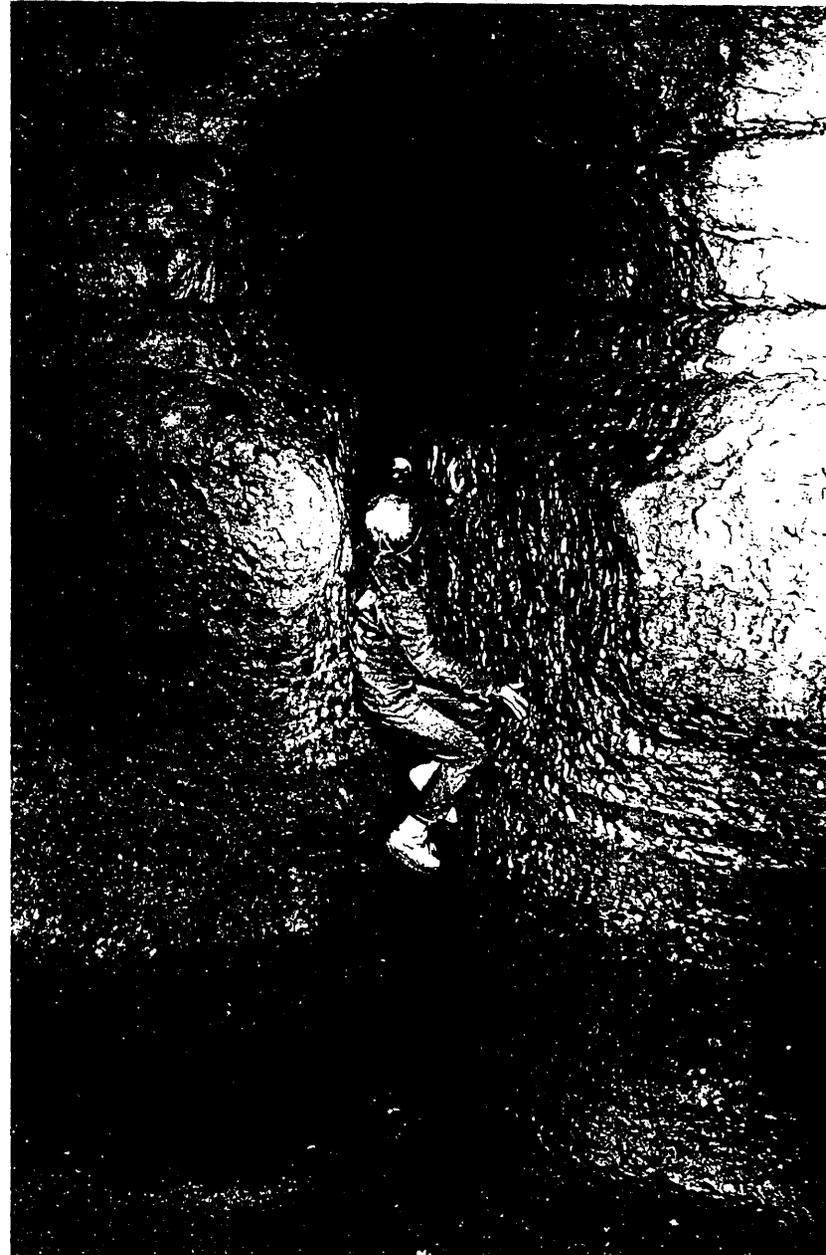


Figure 31: A passage with a keyhole cross section across from the junction of Fourth Avenue with Fifth Avenue. This passage was formed by the enlargement of a fissure whose lower part was once filled with sediment.

COMPARISON WITH OTHER CAVES

As a floodwater maze formed by the underground diversion of water from a surface river, Mystery Cave has many similarities with other caves of that type. It is most similar to caves in other parts of the glaciated north-central and northeastern states. The greatest similarity is with the caves near Watertown, NY (Glen Park Caves, etc.) and Ontario, which are located in rocks of roughly the same age, which have been glaciated, and which are highly fractured. These caves are located along the banks of rivers and have been formed (or at least greatly enlarged) by floodwater entering the limestone during high river flow. Moira Cave in Ontario is a meander-cutoff cave very similar in origin and character to Mystery Cave. Similar meander cutoff caves are well documented elsewhere, such as in Indiana and Kentucky.

The chemical processes that formed Mystery Cave are similar to those that formed Mammoth Cave and others fed by surface infiltration through sinkholes. However, the cave patterns are quite different. Instead of a network maze, as in Mystery Cave, the passages in such caves form a branching pattern. There may be local floodwater mazes superimposed on the branching pattern, as at Blue Spring Cave, Indiana. The maze pattern of Mystery Cave is superficially similar to those of sandstone-capped mazes. Water entering limestone through overlying sandstone enlarges virtually every fracture in the limestone at uniform rates over large areas, forming widespread network mazes like Anvil Cave in Alabama. However, the network pattern of floodwater caves like Mystery is less regular, and individual passages tend to be less uniform in size.

The origin of Mystery Cave is least similar to caves of arid or semi-arid regions, such as Carlsbad Cavern, New Mexico, which were formed by rising water rich in hydrogen sulfide. Such caves have very little relationship to surface water inputs. Strangely, many speleothems in Mystery Cave are most similar to those of the arid-zone caves. Calcite rafts, raft cones, folia, chenille spar, pool fingers, and iron-oxide speleothems are salient features in caves such as Lechuguilla, and it is widely believed that these rather rare features are related to the deep-seated origin of the caves. But that similarity can be misleading: chemical conditions in the cave pools are similar (for example, with high carbon dioxide content and rapid deposition of calcite and aragonite), but for different reasons. Pools in the dry-climate caves may be enriched with carbon dioxide from depth, whereas the high carbon dioxide content of the water in Mystery Cave is caused simply by the close proximity of thick organic-rich soil, through which the water must pass to feed the pools (except during flood periods, when river water fills some of the lower pools such as Turquoise Lake).

NOTEWORTHY FEATURES ALONG THE TOUR ROUTES IN MYSTERY CAVE

Only the most important and unusual features are described here. In the 1994 version of this report the entire cave will be described in a detailed geologic guide.

Mystery I

The Grotto, located on the left of the walkway to the Mystery I entrance, is a cave opening that is blocked by breakdown. It doesn't lead to known passages in Mystery Cave. The Maquoketa/Dubuque contact is seen just below the top of the entrance arch (upward change from thin-bedded, shaly limestone to thicker-bedded, more uniform limestone. (This contact is also seen near the ceiling of the Cathedral Rm.)

The Pipe Organ and Frozen Falls are fine examples of flowstone draperies, where drip water entering the cave loses most of its carbon dioxide to the cave air, depositing calcite. Shelfstone and calcite rafts in the Rock Garden show what happens when drip waters become ponded. Turquoise Lake is fed by a rapid inflow of water through the overlying soil and contains rafts, raft cones, and chenille spar. These are depositing rather rapidly because of the high rate at which carbon dioxide is being lost from the water. Folia near the ceiling in the passage leading to Turquoise Lake were deposited by this same water when the water level was higher. These are extremely rare features, and this is the only known occurrence in Mystery Cave. Raft cones and calcite pool linings are abundant in the route to the Bomb Shelter. These indicate more extensive ponding in the cave than at present -- a former extension of Turquoise Lake.

The Formation Room contains a number of significant features. In the wall overhead, where the stairs enter the room, is a fossil nautilus shown in cross section. Thick deposits of sand on the left were carried into the cave early in its history by flooding of the South Branch. (There is not enough information yet to relate it to the rest of the cave.) The erratic stalactites at the far end of the room are rich in iron oxide (rust) from oxidation of pyrite in beds DS13-DL13-DS14. Hydration of the iron oxide has warped the beds and tilted the stalactites. This series of beds is a suspected bentonite zone (still under investigation).

Mystery II

The most conspicuous aspects of Fifth Avenue are the burrows in the Stewartville Formation, which project outward in the lower walls and are weathered inward in the upper walls. (They seem to project in areas that were once covered with sediment; further information will be forthcoming.) Note how the intervening walls around holes created by the indented burrows are covered with white aragonite needles near the junction of the entrance passage with Fifth Avenue. Aragonite is deposited only where evaporation is high, and so it is limited only to the most exposed areas low in the walls.

Popcorn is another deposit that requires evaporation, but in this case the mineral is calcite, and there is more seepage coming out of the walls. It is most common around the junction with Angel Loop.

Raft cones in Blue Lake are among the best known examples in any cave. This may be the only cave in which they can be viewed on a tourist trail, and certainly is the only chance for visitors to see them actively forming in a pool.

Gypsum crystals in Diamond Cavern and at the bottom of the Hills of Rome are formed only in very dry conditions and where there is a source of sulfate. The sulfate source is oxidation of pyrite in the beds near the Dubuque/Stewartville contact. That contact is best seen at the western junction between Angel Loop and Fifth Avenue, where the tour route rises into Fifth Avenue. The transition from mottled, burrowed limestone to bedded limestone is quite clear.

PRESENTATION OF GEOLOGIC INFORMATION TO TOUR GROUPS

Visitors to Mystery Cave should come away with a basic understanding of how the cave formed and why it is significant. Portraying geology to a tour group can be difficult because the concepts are not simple, and each answer only leads to more questions. Furthermore, most interpreters are not specifically trained in geology and are perhaps uncertain of many details themselves. It is necessary to walk a fine line between giving too little information (which gives the impression that the cave has little to offer) and too much information (which tries the patience of visitors and may put the interpreter out on a limb). It is best to discuss only a few major geologic topics, but in a convincing way. Each interpreter should find a personal approach with which he or she is comfortable, but here are a few suggestions:

It is best to start with a few simple facts: Mystery Cave was formed by underground water that dissolved the limestone bedrock. Limestone is a type of rock that dissolves easily in fresh water. It consists of layers of calcium carbonate deposited on the sea floor. The limestone at Mystery Cave was deposited in a shallow sea that once covered much of the continent about 400-500 million years ago.

Mystery Cave was formed when the South Branch of Root River passed underground through cracks in the limestone. By doing so, it took a shortcut through the limestone, bypassing a long, winding section of its valley. The cave began to form about 500 thousand to a million years ago, and so it is much younger than the limestone. Water still goes through the lower levels, so the cave is still enlarging today.

Meanwhile, some water drips down through tiny cracks in the overlying rock, but in too small a quantity to help form the cave. Instead, the limestone it has picked up from the overlying rock is deposited as "cave formations" (speleothems).

This is about all a tour group can absorb in one discussion, and perhaps even this should be spaced out a bit. From this basic introduction it is possible to go in any of a number of directions: (1) Fossils in the rock indicate its marine origin (show burrows, etc.). (2) The cave consists of solutionally widened cracks (joints) -- note how long, straight, and fissure-like they are. (3) Sediment in the cave was mainly carried in from the surface, although some is insoluble material left over from dissolving of the bedrock. (4) Speleothems come in various shapes and mineral types, depending on the drip rate and amount of evaporation (calcite, aragonite, and gypsum, in order from wet to dry). (5) Different levels in the cave represent successive stages of deepening of the underground channels as the South Branch cut its valley deeper. (6) What does this tell us about groundwater quality? Can we afford to let wastes seep into the ground, where they are out of sight and out of mind?

Any one of these topics can lead to further discussion, and which ones are chosen depends on the interests of the interpreter and the response of the tour group. It is much better to focus on a few promising ideas, rather than go through a fixed routine that tries to cover all topics in an even-handed way. A little information sparks the visitors' interest more than a long-winded discussion. There is no quiz at the end of the tour.

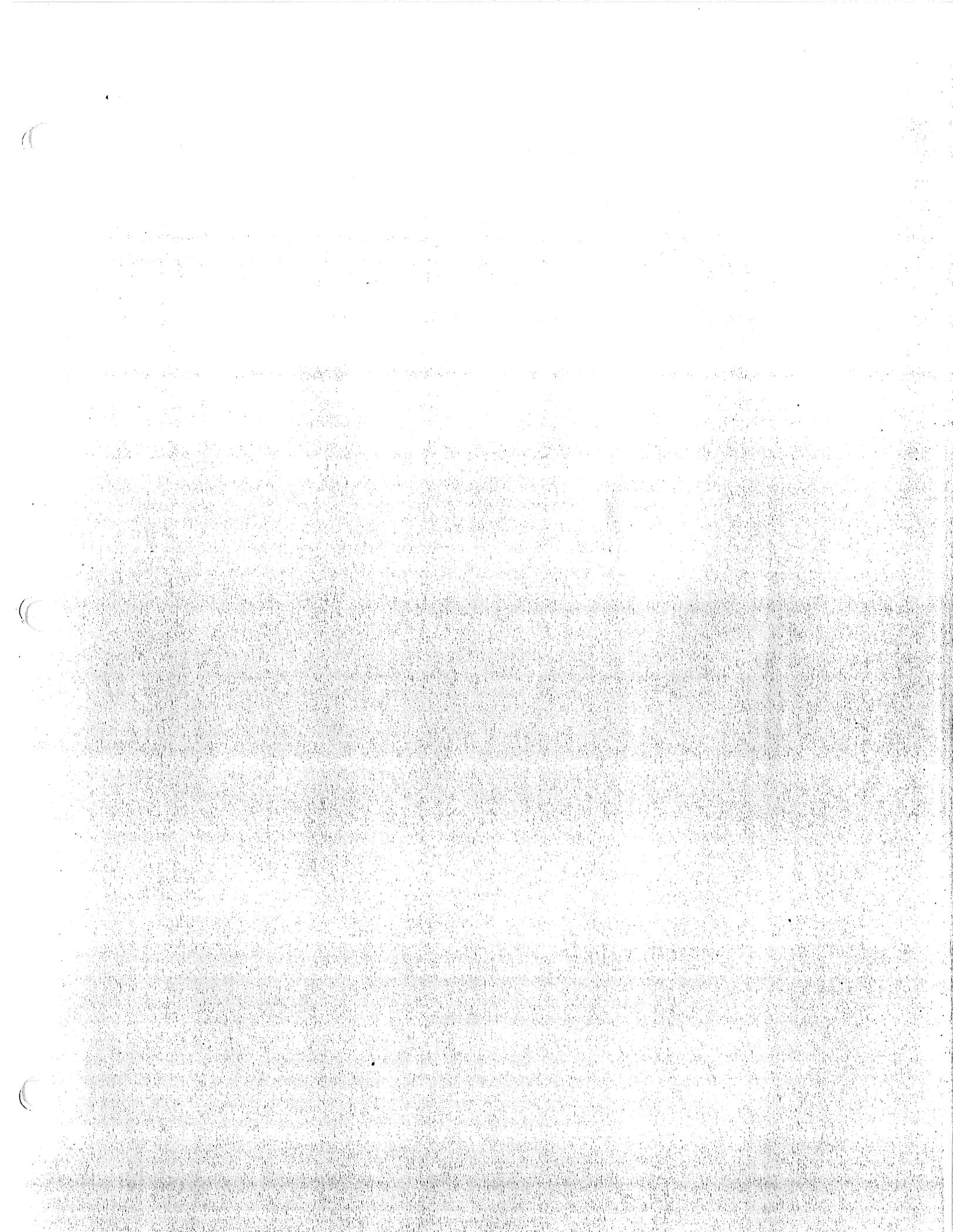
Your tours will be exciting to the visitor only if you yourself are interested in the topics. And the only way to become interested is to know something about those topics. Read about them, and try to make observations on your own. Personal involvement automatically leads to enthusiasm, and subjects that originally seemed boring can come alive.

CONCLUSIONS

Mystery Cave is not well known outside of Minnesota, but it takes its place as one of the most significant caves in the country in terms of what it can tell us about past glacial and erosional history and the growth of speleothems. It is also perhaps the finest example of a floodwater maze in the United States. It is especially significant because nearly all of the processes that formed the cave and speleothems are still active today, and their many complex interrelationships can be studied in the field. The cave and its contents should be protected to the fullest extent possible. Interpreters can take great pride in presenting it to the public.

REFERENCES

- Alexander, C.A., 1991, Geologic history and speleogenesis of Mystery Cave, Forestville State Park, MN: unpublished draft included in letter to A. and P. Palmer, on file at Mystery Cave, 9 p.
- Bates, R.L., and Jackson, J.A., 1987, Glossary of geology: American Geological Institute, Alexandria, VA, 3rd ed., 788 p.
- Hill, C.A., and Forti, P., 1986, Cave minerals of the world: Huntsville, Ala., National Speleological Society, 238 p.
- Kendall, A.C., and Broughton, P.L., 1978, Origin of fabrics in speleothems composed of columnar calcite crystals: *Journal of Sedimentary Petrology*, v. 48, p. 519-538.
- Milske, J.A., 1982, Stratigraphy and petrology of clastic sediments in Mystery Cave, Fillmore County, Minnesota: M.S. thesis, University of Minnesota, St. Paul, MN, 111 p.
- Milske, J.A., Alexander, E.C., and Lively, R.S., 1983, Clastic sediments in Mystery Cave, southeastern Minnesota: *National Speleological Society Bulletin*, v. 45, p. 55-75.
- Mossler, J.H., 1987, Paleozoic lithostratigraphic nomenclature for Minnesota: Minnesota Geological Survey, Report of Investigations 36, 36 p.
- Samson, S.D., Patchett, P.J., Roddick, J.C., and Parrish, R.R., 1989, Origin and tectonic setting of Ordovician bentonites in North America: isotopic and age constraints: *Geologic Society of America Bulletin*, v. 101, p. 1175-1181.
- Sloan, R.E., (ed.), 1987, Middle and Late Ordovician lithostratigraphy and biostratigraphy of the Upper Mississippi Valley: Minnesota Geological Survey, Report of Investigations 35, 232 p.
- , 1987, Tectonics, biostratigraphy and lithostratigraphy of the Middle and Late Ordovician of the Upper Mississippi Valley in Middle and Late Ordovician lithostratigraphy and biostratigraphy of the Upper Mississippi Valley: Minnesota Geological Survey Report of Investigations 35, p. 7-20.
- Sloan, R.L., and Kolata, D.R., 1987, The Middle and Late Ordovician strata and fossils of southeastern Minnesota, in Field trip guidebook for the upper Mississippi Valley Minnesota, Iowa, and Wisconsin, Balaban, N.H. (ed.): Minnesota Geological Survey, prepared for the 21st annual meeting of the Geological Society of America, north-central section, p. 70-95.
- Witzke, B.J., 1983, Ordovician Galena Group in Iowa subsurface in Ordovician Galena Group of the Upper Mississippi Valley - Deposition, diagenesis, and paleoecology, Delgado, D.J. (ed.): Guidebook for the 13th Annual Field Conference, Great Lakes Section SEPM, p. D1-D26.



APPENDIX -- Frequently Asked Questions about Mystery Cave

During our visits to Mystery Cave, members of the interpretive staff were encouraged to submit questions about the origin and geology of the cave and its features. Many of the following questions are typical of those asked by visitors, while others are questions that are frequently pondered by the interpretive staff. The answers are given in terms that non-technical persons can understand.

Q: *What is the overall developmental history of the cave?*

A: a. The South Branch of the Root River was flowing on the limestone in a very broad valley early in the Quaternary Period (about 1-2 million years ago), before glacial advances affected the area significantly. Topographic relief was rather subdued, and cave development was minimal because the water table was close to the surface and there was little tendency for water to go underground.

b. Rapid entrenchment of the Mississippi River took place early in the Quaternary Period, somewhere around 500 thousand or a million years ago, in response to glacial activity. This entrenchment may have been triggered by the large amounts of meltwater coming from glaciers or glacial lakes, or by readjustment of drainage lines by glaciers. Root River is a tributary and so it cut downward also, forming a sharp-walled but not very deep gorge in the limestones. Valley deepening took place mainly by headward erosion, so there was a fairly steep gradient in the entrenching part of the river.

c. As the area of entrenchment worked its way upstream to our area, a steep gradient was established across the long meander loop that encloses what is now Mystery Cave. Although most of the water at first followed the surface valley, progressively more water passed underground through the limestone across the meander to springs farther downstream. The shallowness of these groundwater paths ensured that there would be many relatively wide joints and bedding-plane partings in the limestone for the water to follow. Some of these joints had probably been slightly widened by earlier groundwater flow, but there is no evidence that the present cave has been significantly affected by such earlier phases of solution.

d. The joints and partings with the most flow enlarged into cave passages in the following sequence: First, water passed through the ground along the path of Mystery III to Mystery II, more or less west-to-east. The oldest flowstone in the area is more than 350,000 years old, so this part of the cave must have originated earlier. This pre-dates the Illinoian (next-to-last) glaciation. Later, much of the water sank farther upstream, forming Mystery I and linking it to Mystery II. The oldest flowstone dates in this area are only about 12,000-13,000 years, which is post-glacial -- much too recent to represent the age of the passages themselves. The passages probably pre-date the Wisconsinan (latest) glaciation, and it is possible that earlier flowstone was removed by solution, or that the aggressive floodwaters entering this part of the cave did not allow flowstone to accumulate.

e. As entrenchment continued, the specific paths of groundwater flow varied. Today, for instance, water continues to sink all along the meander and come out at a number of springs (some not even on South Branch). Sinking of water continues to progress farther upstream with time. Groundwater infiltration into the uplands also forms minor passages tributary to

those formed by the underground paths fed by the South Branch (although almost all of the water from the overlying surface seeps into the cave slowly and forms speleothems instead of dissolving new passages), so the total drainage picture is quite complicated.

f. The maze-like pattern is due not just to the abundance of large open joints susceptible to solution, but also to the flood-prone nature of the inputs. The water of South Branch is saturated with calcite most of the year, but during floods it is undersaturated. Flooding fills many cave passages with water that is under pressure and highly aggressive, so all significant joints and partings in the area are enlarged, rather than just a few favorable ones. The most favorable path of flow is near the top of the Stewartville (Galena), where intersecting joints and bedding planes are abundant. From there, upward solution (aided by collapse) enlarge the wide galleries, and downward entrenchment forms lower-level fissures.

g. Gravel and sand were (and still are) deposited along the paths of fastest water flow, and silt and clay in areas of stagnant backwater flooding (abandoned passages temporarily reactivated). During glacial advances in the nearby areas, however, a great deal of sediment became available from glacial meltwater. The deep valleys of the Mississippi River and its tributaries were partly filled, and it's likely that most of the sediment in the cave is related to these glacial events. The main filling seems to have been an approximately 20-foot surface cover of wind-blown silt derived from vast expanses of nearby glacial sediment. This is called loess. The soft powdery surface soil and cave fill are mainly this material. It is probably Wisconsinan in age -- within the last 50,000 years. Much of it has been removed by post-glacial erosion, but the many silt-choked passages attest to the great extent of the filling.

h. The cave is still enlarging today, almost exclusively in the lowest levels during periods of high flow.

Q: *Are there any indications of the rate of water flow at various times?*

A: Solutional scallops and sediment are the best indicators of water velocity. The asymmetry of the scallops indicates the direction of water flow -- just like ripples or sand dunes -- and the average length of scallops indicates the flow velocity. As a crude rule of thumb, the velocity of the water that formed the scallops (cm/sec) is 350 divided by the average scallop length in centimeters (measured parallel to the direction of flow). The scallops in Mystery Cave range in size from about 0.5 to 6 inches, indicating velocities of roughly 1-10 ft/sec. The smaller scallops indicate faster velocities, but below about 0.5 ft/sec scallops don't form at all. Some rocks, such as shaly limestone and the burrowed Stewartville, don't usually form scallops because of interference from their own internal texture. Sediment ranges in size from cobbles near the Mystery I entrance to the ubiquitous silty mud, indicating velocities of several ft/sec all the way down to nearly standing water. This huge range in velocities is typical of a floodwater cave like Mystery. During low flow the velocities will be moderate, since the velocity depends mainly on the slope of the passages the water follows. As a flood begins, the velocity increases, and large cobbles can be carried into the cave, although they don't usually make it very far. Then some unexpected things begin to happen. In the narrow parts of the main stream passages the velocity keeps increasing, often to the point where no sediment is deposited at all and scallops can't form because they are eroded off by the rocks being carried by the water. But the narrow places transmit the water inefficiently and cause the water to pond upstream. This ponded water occupies such a large cross-sectional area that it moves

more slowly than the low-flow water does. So during a flood, some areas are exposed to very fast water, and others are exposed to slow flow. When water overflows into higher levels, it usually stands around with almost no flow. That's where most of the mud (fine-grained material like clay and silt) accumulates. As a result, it is common to have sand and gravel in stream passages, with mud on the sides. In upper levels, mud deposited by late-stage flooding usually covers sand and gravel deposited when the passages contained an active stream. Because they are enlarged and modified by slow-moving water, the upper levels are muddy and have almost no scallops.

In summary, it isn't possible to relate velocity of flow to any particular stage in the cave's history, since the cave has been subjected to flooding all through its history. Only during the initial phases of solution, when water was flowing through narrow cracks, was the water flow consistent -- it was very low in all the cracks, but varied according to the square of the crack width. If you consider two initial cracks, one twice as wide as the other, the water velocity would be 4 times faster in the wider crack, all other factors being equal.

Q: *When water was flowing through the cave at various times while the cave was forming, where did it exit?*

A: Throughout the history of the cave, including today, the water follows a complex pattern of routes that change with the water level. During floods today, for instance, water overflows into older, higher levels that are normally dry. So no single route handles all levels of water. Today all the water in Mystery Cave apparently exits through Seven Springs, but there may be higher-level overflow springs that are activated during high flow. Also, there are nearby springs that may take water from parts of the cave that have not yet been tested with dye tracing.

The northernmost passages probably formed first, followed by the southeastern passages as the South Branch sank at progressively headward locations. In the past, the water probably followed paths similar to those of today, if we can judge from the pattern of older cave passages. But the original springs must have been higher than those of today. Old spring outlets usually appear as indentations or small valleys in the sides of plateaus, and it is likely that the old spring outlets for Mystery were somewhere in the vicinity of the old meander scar at an elevation of 1150-1180 feet, south of where Route 5 crosses the South Branch. This location is in direct line with the old passages in the cave and is located in the Stewartville Formation, so there would have been no impediment to flow to that point.

Q: *What effect did glaciation have on the cave?*

A: The answer to this question is essential to correctly interpreting the evolutionary history of the cave. Unfortunately the history of glaciation in this area is very poorly known. Even the people who have spent their lives studying glacial history admit this. So it's difficult to be precise in answering this question. However, it's safe to say that the earliest cave passages pre-date the last two glacial advances. Much of the fill in the cave dates from when large amounts of wind-blown silt covered the land around here during advances in glacial ice into this area. Cave enlargement into deeper levels, accompanied by erosional removal of sediment, therefore seems to be most common during the interglacial periods. During glacial advances, sediment is carried into the cave, and the upper levels tend to enlarge further. Work on this

topic must continue for many decades before a clear view of the subject is available.

Q: *Why are there such prominent cracks in the limestone, and why are they oriented the way they are?*

A: The fractures (joints) in the rock layers in southeastern Minnesota are particularly prominent, and almost all the local caves are joint controlled. This is typical for caves in the Ordovician limestones all through the north-central and northeastern states. The limestones are thin and rather flat lying, and they have been subjected to many different kinds of stresses over their long life span. The first and probably most important event was a major episode of mountain formation to the east (Taconic Mountains) late in the Ordovician Period. At that time there were also minor uplifts in the central states. Just west of here was a broad linear arch that compressed the rocks along its flanks, and the pattern of joints formed in this way were east-west and northeast-southwest, ideally with an intersection of about 60 degrees. The limestones are very brittle and easily break along joints. The joints are so regular because they are controlled by the pattern of stresses in the rock -- sort of the way the pattern of cracks in a sheet of plate glass is predictable. However, exact details of what exactly caused the joints at Mystery Cave, how old they are, and why they have the orientation they do are still very poorly known.

Q: *Why is there such a close similarity between the angles of jointing in the limestone and the angles of cleavage in calcite crystals?*

A: There is no connection between the two. The acute-obtuse angles in the joint pattern are typical where there is directional stress in any type of competent bedrock. Squeeze a rock with pressures from both west and east (for example), and you get intersecting fractures oriented NNW and NNE with an angle of about 60 degrees. This is roughly the same as the cleavage angle in calcite, which is caused by the packing of atoms in the calcite structure. There is no genetic connection between the two. Although the limestone contains mainly calcite, it is in randomly oriented grains that don't influence the joint pattern. Many things that look alike have quite different origins.

Q: *Is the general northeasterly trend of the cave affected by the dip of the limestone bedrock?*

A: No. It is controlled by the hydraulic gradient between the sink points and springs in the South Fork. The dip is about half a degree to the northwest, in the opposite direction to the trend of the cave. This discordant relationship between cave trend and dip is not common and requires intense fracturing in the rock, which in this area is quite abundant.

Q: *How much undiscovered passage may exist at Mystery Cave? Will there ever be a Mystery IV?*

A: Cavers would love to know the answer to this one. Floodwater caves such as this are very unpredictable, with large passages connected by narrow ones. Obviously many are too small to enter, and they may lead to big areas that will remain inaccessible. The way to predict the location of new passages is to interpret the paths of water from input to outlet, both today and in the past. Look for extensions of the presently known big passages. Note how Dragon's Jaw Lake leads to an extension of Fourth Avenue, separated from the main part of Fourth Avenue

by breakdown. Interruptions like that are most typical beneath valleys (as at the Mystery II entrance, where the valley has separated 5th Ave. from the entrance passage). Also, there will be new passages discovered in the lower levels, mainly narrow nasty fissures.

There are large areas of plateau northwest of Mystery III that contain underground drainage, so that is a promising area to check. Also, the area east of Garden of the Gods is prime territory for discoveries, because that seems to be the path followed by the original cave-forming water. Outlying caves that were once connected to Mystery but which have since been truncated by breakdown or erosion can also be used as a guide to where the cave extends. There's plenty of space around the connection route between I and II, but the layout of the South Branch makes it unlikely that water once passed through that part of the plateau in great quantities. There could be as much as 20 miles in the cave -- eventually -- but it will take lots of hard work, including digging. There's more potential in other areas, like the huge underground flow systems north of the South Branch leading to Moth and Grabau Springs.

Q: *Are all limestone regions karst?*

A: It's a matter of degree. A humid climate, relatively pure limestone (or other soluble rock), and exposure at the surface are all necessary for the typical kind of karst, with caves, sinkholes, and underground drainage. However, even in arid regions and in limestones buried deep beneath the surface, many karst processes still operate, although the results are often subdued. Minor solution features are found in virtually all limestones.

Q: *What is the origin of solution domes in the cave?*

A: There are two kinds. The most common formed along joints in passage ceilings (as in the Angel Loop). They result from fluctuating water levels, which are especially common in caves subjected to flooding from nearby rivers (which certainly applies to Mystery). Flooding was most common late in Mystery Cave's geologic history, after the main passages had formed. If a passage is filled with water year round, the water in neighboring small cracks stays saturated with dissolved limestone and can't enlarge the cracks by solution. But after the water level drops and the cracks become air filled, periodic floods from the surface river fill the passages with water under pressure and force water into all the surrounding air-filled cracks. This water has come directly from the surface through big passages and is very capable of dissolving limestone. The water injected under pressure into cracks enlarges them into fissures, pockets, and domes (see Figure 30).

A second kind of solution dome is rounder, more like a true dome. These are common in the well-bedded rocks like the Dubuque. Slabs of breakdown fall from the ceiling where passages are wide, until the ceiling stabilizes. Often a rather circular "breakout dome" is formed. Repeated flooding of the cave late in its history modified the breakdown by solution, so what may appear to be a purely solutional dome, with smooth rounded contours, was actually initiated by breakdown. The breakdown blocks may now be obscured by sediment, further clouding the origin of these domes. Swirling water can help to round them, but it is not necessary. Much of the late-stage solution is caused by low-velocity floodwaters rising from lower levels.

The first type of solution dome is often attributed (incorrectly) to water descending through

the narrow ceiling fissure and mixing with the water in the main passage. (Two sources of water, both saturated with dissolved limestone, can produce an undersaturated solution when they mix, if they contain different amounts of carbon dioxide.) This origin for solution domes is favored by most Europeans. The idea is valid in some situations, and some caves are formed almost entirely by mixing; but the process does not account for solution domes, at least the kind we see in Mystery Cave. The problem with the idea is that if water descends along the narrow cracks, it would be saturated with dissolved limestone and would be able to dissolve only after it had emerged into the passage and mixed with the main flow. Also, when the water level dropped in the main passage, the drips coming from the narrow crack would begin to deposit stalactites, which are found in only a small percentage of solution domes.

Q: *What causes the conical indentations in the walls at the junction between Fourth and Fifth Avenues?*

A: These are floodwater injection features formed by solution along joint/bedding-plane intersections when flooding injects water into all available crevices under high pressure. The large fissures extending off Fifth Avenue are formed in the same way, except that they had larger joints available. The shape of the conical holes has also been affected somewhat by the worm burrows.

Q: *Why are injection features (solution pockets, etc.) more concentrated around Frozen Falls bridge than in most other areas?*

A: These features are common where flooding is most intense, and where the water is solutionally most aggressive. Flooding is most intense upstream from constrictions, and the water is most aggressive right where it first enters the ground. Frozen Falls fits at least the second criterion, and perhaps both.

Q: *Are keyhole passages located at about the same level throughout the cave?*

A: They are concentrated at the Dubuque/Stewartville contact, where prominent bedding planes intersect major fissures in the Stewartville. They are therefore controlled mainly (but not exclusively) by the strata, rather than by elevation. They don't indicate a stable water table. In fact, the water table in the cave has always been very unstable due to its being fed by the river, which undergoes frequent flooding.

Some keyhole passages, like those in the walls of Fifth Avenue, may have been controlled by former sediment levels (Figure 31). Partial filling of fractures would allow the non-filled upper portions to enlarge, forming keyhole passages at roughly the same elevation, if the top of the sediment fill is rather uniform.

Q: *Does air fill the cavity above the water surface in a cave as the water drops, or does carbon dioxide fill the openings until an entrance forms?*

A: The air will be rich in CO₂, but it contains all the ingredients of outside air. There are two reasons: (1) air is able to seep into the cave through fissures and pores in the rock; and (2) all the gases in the outside atmosphere become dissolved in water before it infiltrates into the ground, so cave water contains much dissolved oxygen, nitrogen, etc., as well as CO₂. When

the water level drops in the cave, creating an air-filled void, the atmosphere in the void equilibrates with the dissolved gases in the water, producing a mixture similar to that of the outside air but richer in CO₂, which is contributed mainly by the soil.

Q: *How can we determine the age of a specific rock formation?*

A: Many rocks can be dated because they contain radioactive elements that begin to break down as soon as the rocks are formed. By measuring the amount of remaining radioactive material (for example, uranium) and comparing it to the amount of material produced by the radioactive decay (for example, lead), and knowing the rate at which the material decays, we can calculate how old the rock is. Many rocks do not contain material that can be dated in this way, but they contain fossils that can be compared to those in the rocks that have been dated. A few rocks contain neither fossils nor datable material. In this case it's necessary to examine their position with respect to those rocks whose ages are known. For example, overlying rocks are generally younger, and underlying rocks are older.

Q: *How old is Mystery Cave?*

A: Dating of flowstone by the Minnesota Geological Survey gives a maximum age of more than 350,000 years for those deposits. The sediment that the flowstone overlies must be older, and the cave is even older than that. An age of at least half a million years for the earliest cave passages seems appropriate.

But how can we date an event such as the beginning of cave origin, which doesn't leave a datable deposit? The best way is to relate the cave to the surrounding landscape. The cave was initiated by the entrenchment of the South Branch below the plateau surface. Only when the limestone was exposed in the section of river around the cave was it possible for enough water to flow through the ground to form the cave. The history of the cave therefore parallels that of the erosional history of the region. And the erosional history is in turn partly controlled by glaciation -- which is poorly known in this area. Superficially, the rivers in the north-central states deepened their channels by erosion during the periods between glacial advances, and they filled up their channels with sediments during glaciations. Therefore cave probably began to form during the period of erosion following one of the earlier glaciations. The extensive sediment fill in the cave probably accumulated during glaciation. Meltwaters from the ice probably messed things up by removing and rearranging the sediments and enlarging some passages.

Q: *What should we tell a person who doubts the age of the rock, fossils, glacial deposits, and cave, and who attributes all geologic phenomena either to the original creation or Noah's flood?*

A: For everyone's sake, it is best to try to de-fuse the issue as gently as possible. Here are several comments that may help. However, it is better simply to accept whatever each individual believes. The following items should NOT necessarily be used verbatim, because they would only lead to arguments. Try to find a compromise. If none is forthcoming, let the person have his or her way. You will have the sympathy of the rest of the tour group (or at least most of it).

a. Most (or at least many) scientists find that the more they learn about the world, the more awed they are at its complexity and beauty, and their faith increases as a result. For example, most astronauts return with stronger religious convictions.

b. Science and religion can coexist without contradiction if many of the early events in the Bible are considered allegorical, to cover the topics in the most direct way, so as to get quickly to the more important topics such as faith and salvation.

c. For those who favor a literal interpretation of the Bible: It has been shown that the measurement of time differs according to where you are. For example, time in a space craft passes more slowly. On a celestial scale, time passes very slowly. Note that the first 7 days of Genesis are described from God's standpoint, not ours. Only when Adam and Eve appear does time revert to the human scale. So it is possible that a single "day" of creation actually represents billions of our years.

d. The concepts that you describe on your tour, such as the formation of rock layers over millions of years and the interpretation of fossils, have been determined independently by scientists all over the world from all sorts of cultures and faiths, and their basic findings agree. The rock layers we see here were laid down one on the other in the sea that once covered most of the continent. This happened many times, not just once, but it can be accepted as a version of Noah's flood if desired. The complexity of the fossils increases with higher (and therefore younger) layers, and each layer, wherever it is found in the world, always has the same types of fossils in it. These layers are dated with many different techniques, and they all agree fairly well, with just a little uncertainty. There are many tales of dating that has gone wrong, or fossils that are all mixed up, but these are few, and when examined in detail they turn out to have been the work of inexperienced people or faulty lab procedure.

e. The cave is not the result of Noah's flood because it is limited to the small area of the Root River where the water goes underground across a steep meander. A world-wide flood would not produce a cave so well adjusted to the local river pattern.

f. Good luck.

Q: *Why is the cave a constant 47-48 degrees?*

A: Daily and seasonal temperature fluctuations die out downward within about 10 or 20 feet of the land surface. A cave deeper than that will generally have a temperature close to the mean-annual surface temperature. Mystery Cave takes a large amount of water from the South Branch, which heats or cools local parts of the cave, depending on the season, and the effect is most noticeable along active streams in the cave. Air currents do the same, but to a smaller degree. Also there are small fluctuations caused by tours, lights, etc. So the cave's temperature is really constant, but the fluctuations are rather small, except around entrances and water inputs.

Q: *Is there an instrument that can detect underlying caves from the surface?*

A: Large shallow caves can be detected, but not reliably. Deep ones are almost undetectable. Gravity surveys can detect voids on the basis of locally low gravity readings, but the cave has to be very large and shallow to be detectable. Mystery doesn't qualify. Seismic surveys aren't

well suited to detecting cave passages. Electrical resistivity or conductivity should work (higher resistivity over caves), but the results are difficult to interpret and are susceptible to distracting influences. Ground-penetrating radar shows potential, but it works only for very shallow caves. Recently there have been some advances in using spontaneous potential caused by underground water movement, but again the results are difficult to interpret. In summary, there's no instrument that can reliably find caves, except under ideal circumstances, and usually the results are ambiguous. Cave explorers are still the best means for finding caves!

Q: *Is limestone deposited only in tropical seas?*

A: Mostly, but not entirely. Some is being deposited today in cold climates, but it is rare. Nearly all limestone is formed at low latitudes and shallow depths, where the water is warm. Not only is this conducive to the growth of plants and animals that use calcium carbonate for their shells, but calcite is also most stable in warm water. At depth, even in the tropics, calcite is unstable due to colder temperatures. At the time the limestone was deposited around here, Minnesota was located very near the equator. It isn't any more!!

Q: *How do the rock layers in Mystery I correlate with those in Mystery II and III? Are there any beds that are easily traced?*

A: The rocks in the two major parts of the cave match exactly, with almost no differences in rock type or thickness of beds. The topmost shale bed inside the gate at Mystery I is the same as the second shale bed from the top in the high point in Fourth Avenue between the Smoking Chamber and Fat Man's Misery. Thus Fourth Avenue correlates almost exactly in its stratigraphic position with the main passage in Mystery I.

Several beds are readily identifiable, even to non-geologists. Most obvious is the upward change from massive mottled limestone/dolomite of the Stewartville to the bedded limestone of the Dubuque, for example at the stairs into Fifth Avenue from Angel Loop. Five feet higher is a 1.5-foot bed (DT4) that is rather resistant, with a faint recessed bedding plane along its middle, whose top parts contain much yellow limonite (iron oxide from the weathering of pyrite) and solutional holes about an inch in diameter caused by solution of limestone around the pyrite blobs. It is overlain by the first obvious shale bed (DS1).

Fourteen feet above the top of the massive mottled limestone (Dubuque/Stewartville contact) is a very prominent bed (DL9) about 0.8 ft thick, overlain and underlain by prominently recessed shales (DS9 and DS10). Above this bed is a 3.5-foot-thick sequence of limestone and shale with no prominent bedding planes within it (DL10-DS11-DL11). This sequence shows up about 2/3 of the way up Fourth Avenue between the Hills of Rome, and is just beneath foot level at the flowstone mound before Blue Lake.

Q: *What is the proper term for the rock type in the Stewartville?*

A: At Mystery Cave it is appropriate to call it a dolomitic limestone. Calling it a dolomite is acceptable too, since most rocks that are referred to as dolomite are actually a combination of the two rock types, rather than pure dolomite.

Q: *What are the "crinkly beds" that are supposed to represent the top of the Stewartville Formation?*

A: Start in the Angel Loop, and notice the bed near the floor with the mottled appearance. This is near the top of the Stewartville. Near the ceiling are one or two bedding planes. Now climb up the stairs into Fifth Avenue and notice that bedding becomes more prominent and the mottling disappears. A one-foot-thick bed above the mottling is overlain by a 3.5-foot-thick layer, the top foot of which is divided into thin irregular beds, which are the "crinkly beds." There are usually 4 of these, but in places there are 5, depending on what you call a bed. Thin shales separate them, but they are hardly noticeable. In some areas of the cave, such as Mystery III, the layer directly above the Stewartville also contains 4 or 5 irregular beds, so the presence of the "crinkly beds" is not a good criterion for the bottom of the Dubuque. The problem is that thin shale layers, which determine whether a prominent bedding plane will be formed, are deposited rather irregularly and are not present everywhere. They don't represent a major change in the environment. The change from massive burrowed limestone to more uniform crinoid-rich limestone is a much better criterion, because it represents a major change in environment, from static, muddy conditions to freely circulating water. This change is reflected in the types of animals that occupied the area. Unfortunately, it appears that even the burrowing and other animals didn't change simultaneously all over the area -- they persisted longer in some areas than in others. We prefer to use the top of the massive burrowed limestone as the Dubuque/Stewartville boundary, because it has the greatest importance to the character of the caves. Many geologists argue about where the contact should be, but it's obviously gradational and changes character from one area to another. There is a problem with trying to impose an artificial kind of order on a system that is inherently disorderly with fuzzy boundaries.

Q: *Was the Stewartville Formation formed in a shallow or deep ocean? Why is it dolomitic rather than just limestone?*

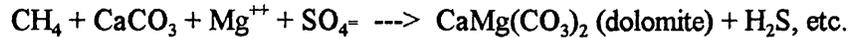
A: The rocks of the Stewartville have no indication of wave activity, so they formed beneath wave base -- in other words, below about 5 meters. There are a few minor beds (SX1-SX3) that represent rare bottom scouring by storm events, so the depth wasn't much more than this. These beds can be seen on the route to Garden of the Gods and in the Angel Loop: they are brown granular, crystalline beds only a few inches thick that project slightly from the cave walls near the top of the Stewartville. Fossil types also indicate a depth ranging from 2 to 50 meters.

Q: *How is limestone converted to dolomite?*

A: This is accomplished by addition of magnesium to the original limestone. At surface temperatures this takes place very slowly, so even though sea water is saturated with dolomite, calcium carbonate forms instead, because it crystallizes much more quickly. If Mg-rich water seeps through the limestone it slowly changes it to dolomite. This doesn't normally happen on the sea floor, because the water in the limestone of the sea water is not moving. There are several ways to accomplish this: (1) Raise the limestone above sea level and expose it to sea spray (rich in Mg), so water enriched with Mg seeps into the limestone and converts it to dolomite. (2) Raise the limestone above sea level and allow evaporation to take place, drawing sea water upward through the limestone and changing it to dolomite. (3) Convert the

limestone to dolomite at high temperatures deep beneath the surface, where dolomite is much more stable than limestone (this requires that the water be high in Mg). (4) Convert limestone to dolomite in reducing zones where there is no oxygen and where organic compounds or methane can convert calcite to dolomite by reactions described below.

#4 is probably how the burrows in the Stewartville were dolomitized. Organic materials cause reducing conditions that produce methane (CH₄), which reacts with sulfates in the rock to change calcite to dolomite:



This reaction can be shown to work well in other similar areas.

Q: *In general, the worm burrows in the Stewartville are less resistant than the surrounding limestone, forming recesses. however, in places the burrows stand out as resistant projections, as at Enigma Pit. Why the difference?*

A: The burrows are mostly dolomite, which doesn't dissolve as rapidly as limestone. (The porous, sandy material that filled the burrows more easily transmitted the magnesium-rich water that converted the limestone to dolomite.) Because dolomite dissolves less rapidly than limestone, we would expect the burrows to stand out as projections. This is the case in many areas, and the resulting cave walls have a texture like Velcro, which delights cavers in narrow passages. However, if the dolomite is sandy textured and not well cemented together, the contact points between the crystals dissolve, leaving a loose sandy material that easily washes out, producing hollows rather than projections.

The nature of water movement and the water chemistry also affect the way rock weathers. Fresh water that contains very little dissolved limestone or dolomite will dissolve both rocks rather evenly. Water that is nearly saturated with either rock will dissolve dolomite much more slowly. High-velocity water will erode loose, granular material more readily, which probably includes the dolomite burrows. Also, the projections that appear to be resistant burrows may actually be the final remnants of the intervening limestone between the burrows, rather than the burrows themselves.

Finally, walls that contain projecting burrows show evidence for having been covered by sediment fill at some time during the past history of the cave and have since been re-excavated. Note in Fifth Avenue that the indented burrows are higher in the walls than projecting ones, and that the relationship is not inverted anywhere in the cave. Furthermore, the contact between the two modes is highly irregular, not following the beds. We are still working on this question and will have a clearer interpretation in the final (1994) version of this report.

Q: *Does the extreme mottling and roughness of the walls in the Angel Loop and on the way to Garden of the Gods (particularly under ledges) represent former water levels?*

A: The mottling and roughness is present only in the Stewartville Formation, which is exposed in the lower walls in both areas. However, the roughness tends to be planed off by rapidly

moving water, so the extreme roughness was probably caused by slow-moving water, probably floodwater rising from lower levels.

Q: *Why are there strata in the Dubuque Formation?*

A: In the shallow sea that covered most of the continent during the Ordovician Period, limestone was deposited rather continuously. Occasionally there was an increase in the amount of sediment washed off the land areas to the north and east as the result of cyclic changes in climate. At these times, the mud carried by rivers draining off the land accumulated faster than the limestone could, creating layers of shale or shaly limestone. Many of these layers were just thin dustings of mud that interrupted the limestone and formed bedding planes. Others were substantial layers almost as thick as the limestone beds they interrupted. The amount of time represented by each layer (or bed) is not known exactly, and must have varied a great deal; but since the fossils didn't change significantly from bottom to top in the Dubuque, we can assume that there was not a great deal of time involved in its deposition. Each layer may represent hundreds, thousands, or tens of thousands of years. Occasionally a layer can be deposited in a single day (as during a storm). A single bedding plane may represent a long period of time when nothing much was happening.

The Stewartville doesn't have such prominent bedding because little sediment was being carried into the sea at that time, and burrowing animals (worms?) disrupted the bedding. The Maquoketa Formation doesn't have such good bedding because mud was being carried into the area rather continuously, rather than in cycles. All three formations probably represent a progressively wetter climate, with increasing amounts of water running off the continent, accompanied by a rising of mountains to the east (now the Taconic Mountains of New England and the Maritime Provinces of Canada), the erosion of which served as a source for the sediments deposited in the central states.

Q: *Where did the silt and clay come from that make up the shale layers in the Dubuque Formation, and why do they alternate so regularly?*

A: Almost all this material came from the transcontinental arch, which formed a periodic land area to the west of here. A small amount of volcanic ash was also added from the Appalachians to the east. The regularity of the layers was apparently caused by changes in climate, which caused sea level to rise and fall slightly, which also happened in the last few million years during glaciations. These fluctuations periodically exposed the transcontinental arch to erosion, providing a source for the sediment. The arch was apparently below sea level all during the Stewartville deposition and mainly above sea level during Maquoketa deposition.

Fossils show that the average rate of deposition was 12 - 13 mm per 1000 years. Thus it took an average of about 24,000 years to deposit one foot (300 mm). However, any single bed may have been deposited at a much faster rate, because there were lengthy times (totaling about 25% of the time) when virtually no sediment was being deposited.

Uplift of the transcontinental arch was periodic, and only when the arch rose above sea level was silt carried into our area. It is more likely that the so-called "uplifts" were actually slight decreases in sea level, which exposed the arch to erosion, caused by changes in climate similar

to those that produced glacial cycles in more recent times.

The cyclic nature of the shales in the Dubuque Formation suggest that they may be controlled by climatic variations affected by cyclic changes in the amount of energy received from the sun, as the result of variations in the eccentricity of the earth's orbit (Milankovitch cycles). These cycles have a period of about 23,000 years, with longer cycles of 41,000 and 100,000 years. Glacial advances and retreats during the couple of million years match the longest Milankovitch cycles fairly well. It is probable that the cyclic Dubuque deposits were controlled by the same process. Growth and retreat of ice caps around the poles cause small fluctuations of sea level by tying up varying amounts of sea water as ice. Such fluctuations could easily have caused the transcontinental arch to be periodically exposed to erosion, producing the shale beds in the Dubuque. Although the match is not perfect, the approximate deposition rate of one foot per 24,000 years in the Dubuque roughly matches that of the shortest Milankovitch cycles. An exact match with the Milankovitch cycles is difficult to verify because of uncertainty in how the rates of deposition varied with time.

Q: *Is there a map designating where the rivers were that brought in the silt that is now in the Dubuque?*

A: No. The rivers were on land (the broad, low, Transcontinental Arch, a structural warp in the rocks west of here) and that land area was eventually eroded away. The silt was distributed quite uniformly throughout the Mystery Cave area and shows no delta pattern, since it is located far from the original shore.

Q: *What is bentonite, and what do the bentonite layers in the limestone mean?*

A: Bentonite is a concentrated deposit of the clay mineral montmorillonite. It is a weathering product of various materials, such as volcanic ash. This sticky material can be identified only by special lab equipment (X-ray diffractometer, etc.). However, much bentonite has been so weathered that it can be recognized only by certain trace minerals such as zircon, biotite, and apatite. Geologists are excited about bentonite because it represents a layer that was undeniably formed at one single time, so the layer represents a time marker: anything above it is younger, anything below it is older. Furthermore, it indicates intense periods of mountain formation at the time the ash was deposited.

Thin bentonite layers occur in various parts of the rock section exposed in Mystery Cave. The most accessible one (possibly more than one) occurs in the upper walls of Mystery I (beds DS13-DL13-DS14). It represents periodic volcanic ash carried into the area from the mountains forming to the east.

Q: *How were the iron nodules formed?*

A: Certain layers in the limestone contained pyrite (iron sulfide) formed only in stagnant, reducing conditions where organic materials were abundant. Pyrite forms knobby masses, or crystals of cubic shape. When it is exposed to oxygen and water (as in the cave atmosphere) it oxidizes in the following way:

iron sulfide + water + oxygen \implies iron oxide + sulfuric acid

The acid is usually rather dilute and is quickly neutralized as it reacts with the limestone. This produces little circular pits in the rock. Notice, for example, the layer just above floor level at the junction of 5th Ave. with the route to the Smoking Chamber: Near the top of the layer are many pits, some of which are filled with yellow or red iron oxide. These are the "iron nodules," and they represent former pyrite blobs. Iron oxide forms the minerals limonite (yellow) and hematite (red). The original pyrite accumulated in areas starved for oxygen, such as at the mucky bottom of stagnant water. The organic carbon reacts with any oxygen present, using it all up and forming carbon dioxide. When all the available oxygen is used up, the carbon starts using up the oxygen in sulfate (available in sea water), reducing it to hydrogen sulfide. Hydrogen sulfide produces a rotten-egg smell and is found in water from wells that penetrate areas with poor circulation of water. Any iron in the vicinity readily reacts with hydrogen sulfide to produce pyrite. So the pyrite nodules, and therefore the iron oxide nodules, represent a temporarily foul environment with poor circulation and usually a lot of organic material accumulating.

Q: *How deep is the breakdown in Fourth and Fifth Avenues?*

A: This is an important question, because its answer affects our interpretation of the age and sequence of passages. The original passage ceilings were obviously much lower, and they have migrated upward by breakdown during later stages of cave enlargement. Solutional domes occur in the ceilings, even where there has been a lot of breakdown, so almost all the breakdown predates the latest stages of solution. On the basis of passages that have no breakdown, the most favorable location for passages to originate is in the non-shaly bedded rocks of the lower Dubuque Formation, at and just above the Stewartville. This rock is most soluble and cave origin is not impeded by a lot of impermeable shale. The passages that extend above this level are mainly the wide broken-down passages like Fourth Avenue. Assuming that they all formed at or near the Stewartville contact, they must contain as much as 30 feet of breakdown in places, but very little in some areas.

Fat Man's Misery between 4th and 5th Avenues is at the favorable level for cave origin, so at that point the Avenues might be expected to contain very little breakdown. This may be true for Fourth Avenue, but not far to the east Fifth Avenue drops into the Stewartville, which suggests that at least some of the early cave development was deeper than the "ideal" location described above. Upward enlargement of such passages into the Dubuque is probably accompanied by passage widening and breakdown, which obscures the original shape and may even roof over the original fissure with slabs of breakdown. (Note that the slabs that cover the floor fissures along the trail routes were laid down by the early developers to keep visitors from disappearing into the cracks.)

What about the places where the ceiling height is very large, where the breakdown seems to have been removed in some way (like at the Hills of Rome)? In these places the breakdown may have fallen into a lower level that crosses beneath the upper one, or it may have been dissolved away by a lower-level stream. At the bottoms of the big rooms (Hills of Rome, Great Depression, etc.) there's almost always a drain to a lower level, indicating either or both of the two possibilities above.

Q: *What is the origin of the "Mushroom" formation?*

A: Next time you are at the flowstone mound next to Blue Lake, stand on the opposite side of the passage to get a broad view. The "mushroom," as well as the shelfstone on the left of the flowstone mound and the corroded curtain of flowstone on the left side of the mound, are all older flowstone deposits (more than 350,000 years old) that have been weathered to a dull gray-brown (Figure 29). Compare them to the shiny red-brown of the main mound of flowstone, which is still forming today. The older flowstone formed a thin sheet on the wall: note the layering in the "mushroom" parallel to the wall. But its base was apparently on a mud bank, and eventually the weight of the flowstone caused the mud to settle, causing the entire flowstone bank to subside a short distance. Part of the thin flowstone curtain pulled away from the wall a foot or so, and the "mushroom" is part of this. Later flowstone about 50,000-77,000 years ago cemented these remnants into their present positions. Note that the younger flowstone separates the curtain on the left from the limestone wall. Note also that the irregularities in the back sides of the "mushroom" and old flowstone curtain match exactly with the irregularities in the bedrock walls behind them. The older flowstone did not stick well to the shaly limestone of the walls and easily pulled away when the rest of the flowstone bank subsided. Apparently there was a long period of weathering, and probably flooding and solution, between the two phases of flowstone deposition. The old flowstone is highly corroded, compared to the later flowstone. It is not clear whether the shelfstone on the wall is younger or older than the corroded flowstone, since both are older than the limit of the U/Th dating technique (350,000 years). The flowstone could not have been deposited at the same time, because the shelfstone, which is higher, represents an old water level, and the downward-oriented drapery remnants were deposited above water.

What accounts for the mushroom or cross shape? The flowstone that forms the feature was deposited on an irregular wall, so it spread out in some areas and formed a narrow band in others. Corrosion later enhanced the difference in width and obscured many of the characteristics that are typical of flowstone. The crude putty-like base around the "mushroom," which gives the impression that someone stuck it up on the big flowstone mound with mud, is a remnant of the original flowstone that has been corroded and fractured.

Q: *In Fifth Ave. the popcorn is most dense in the area just before the Angel Loop. It is gradational horizontally but terminates abruptly upward. Why?*

A: Popcorn can form in drips of water, or by evaporation of water from the limestone walls; the popcorn in Fifth Avenue is the evaporative type. Air movement increases the rate of evaporation from the cave walls, and moisture in the porous bedrock is drawn out and precipitates dissolved limestone as popcorn. The knobby popcorn shape is caused by the fact that evaporation is greatest on projecting surfaces, so capillary moisture on the wall will tend to precipitate calcite more readily on knobs, enhancing the knob shapes. The abundance near the Angel Loop is caused by the prominent air movement there, where air from the door-to-door route meets air in the larger passage. The relative humidity is apparently lower in this area because of the mixing of different air masses, although it will be necessary to check the data from the meteorology team to clarify these relationships (see forthcoming 1994 update of this report). The abrupt vertical termination is caused by stratification of air, where cold, drier air is overlain by less dense, moist air. The dry air encourages popcorn to form, but the moist air does not. This process has been well documented in certain other caves (e.g. Carlsbad).

The popcorn is probably still forming, although we can infer this only by measuring the relative humidity of the air. Popcorn forms too slowly to measure its rate of growth on an annual basis.

Q: *Why is Blue Lake blue?*

A: We have heard that the blue/green color of Blue Lake and Turquoise Lake is caused by refraction/absorption of certain wave lengths of light by molecular calcium carbonate dissolved in the water. Most of the calcium carbonate is in ionic form as calcium and bicarbonate ions (Ca^{++} and HCO_3^-). Dissolved molecular CaCO_3 is very dilute, but is still the most abundant uncharged chemical constituent in the water and is responsible for the apparent color of deep cave water.

Q: *Why doesn't the water in Blue Lake deposit uniform horizontal layers as it rises and falls?*

A: The water rises and falls too rapidly to form distinct shelfstone ledges at specific levels. Note the tremendous fluctuations in lake level throughout the year at the bridge over Blue Lake, from nearly dry to less than a foot below the bridge. However, calcite is deposited all over the exposed surfaces, including the raft cones. The layers are more numerous and thicker on the lower parts of the walls and floor because the water covers those areas a greater percentage of the time.

Q: *Why do the cones in Blue Lake form in lumps instead of uniform mounds?*

A: This is typical of all raft cones. They consist mainly of loose flaky raft material piled up beneath the water surface where drips hit the water surface when it is covered with calcite rafts. (This condition apparently no longer exists). So the original shape is like a pile of corn flakes, with irregular sides. Meanwhile, the mass of rafts is cemented together by calcite deposited beneath the water surface, forming the lumpy appearance. Today the underwater calcite deposition appears to be continuing, which enhances the original irregularities. Popcorn may also grow on the sides when the cones are exposed above the water, and this increases the irregularity (true for some raft cones but not necessarily for those in Blue Lake).

Q: *Small crystals of gypsum form in the cave walls by evaporation – but how can large beds of gypsum be deposited on the sea floor, like those around Ft. Dodge, Iowa?*

A: Where sea water is exposed to evaporation and has limited circulation (as where the water is shallow or nearly separated from the main ocean by an arm of land), the water becomes supersaturated with gypsum and it can precipitate in beds. This requires a fairly arid climate.

Q: *What is the white deposit above the popcorn in Fifth Ave.?*

A: Mainly aragonite. It indicates evaporation, as does the popcorn itself. The apparent stratification of speleothem types does not indicate former water levels, but is generally controlled by stratification of air of different moisture contents. Aragonite forms only if the water seeping out of the cave walls is rich in magnesium (typical of seepage from dolomitic rocks). Although aragonite does not contain Mg, abundant Mg prevents calcite from precipitating. It is interesting to note that limestone that is deposited in the ocean (which is

rich in Mg) generally starts out as aragonite, which later converts to calcite.

Q: *In Diamond Caverns there is gypsum along both walls, but not on the ceiling. Why?*

A: Pyrite is more abundant in the rock layers along the walls than in those in the ceiling. The pyrite (iron sulfide) oxidizes to iron oxide (the yellow blobs and stains) and sulfuric acid. The sulfuric acid immediately reacts with the limestone, dissolving little pockets and producing calcium sulfate. Evaporation causes the calcium sulfate to crystallize as gypsum (hydrated calcium sulfate) in areas near where the original pyrite was located. Gypsum "flowers" form where the calcium sulfate is most concentrated -- often right around a pre-existing pyrite crystal.

Q: *What is the origin of the Bird's Nest in the Formation Room?*

A: This is not an easy question, because the only way to tell would be to take a slice from it! From comparison with other areas, however, it appears that this is a body of iron oxide from oxidation of pyrite in the limestone, which is now coated with calcite flowstone. Iron oxide (rust) is very unstable and often changes its composition, becoming hydrated and expanding in the process. The warped stalactites in the Formation Room have been disturbed by this process. It is probable that the top of the Bird's Nest shattered and fell away as the iron oxide in its core expanded. Fragments of thin calcite rind lie below it, many of which have blobs of iron oxide attached. These are probably the shattered fragments of the original formation top. The top (both the resistant rind of calcite and the soft, recessed inner core of iron oxide) have since been coated with a more recent deposit of calcite from the same drip source, forming the hollow "birdbath" structure. A similar but larger feature occurs a few hundred feet north of Sand Camp on the door-to-door route; its shattered upper part is not covered by a later calcite coating, and it shows clearly the outer calcite rind with iron oxide interior.

Q: *Is there any correlation among the raft cones?*

A: There is no correlation in the levels or ages of raft cones, except over short distances. However, they all represent some of the last events in the history of the cave. They occur in standing pools of supersaturated water fed by dripping water that has passed through the soil and is rapidly losing carbon dioxide, and since the pools occur at a variety of elevations, the raft cones do not match in elevation. Even the old ones in Mystery I are relatively recent, although their pools no longer exist and they have been covered with mud from recent flooding, just like everything else in the cave.

Q: *Much of the Mystery I wall flowstone is in thin layers that break apart easily. Were they deposited in some kind of cyclic pattern?*

A: Yes, their sheet-like texture was formed when the calcite deposition was interrupted by thin layers of mud deposited during floods. Although a calcite layer will tend to infiltrate and cement the mud layer below it, the bond with the underlying calcite is disrupted if the surface is not clean.

Q: *As the limestone and speleothems become weathered, what is happening?*

A: When limestone beds or calcite speleothems are exposed to air for a long time, they tend to acquire a white chalky surface rind. The thickest we've seen is about half an inch in porous limestone exposed to moist air for about a million years. Most of the material that makes limestone dark gray is organic carbon, and this oxidizes slowly in air, producing carbon dioxide and a thin bleached surface rind. This process seems to be enhanced by water seeping through the walls into the cave. The whiteness of the rind is also largely due to recrystallization of the calcite into smaller crystals, and the action of microorganisms may be important here. In Mystery Cave the walls and speleothems show only a very thin altered layer of finely crystalline calcite only a fraction of a millimeter thick.

Q: *What's the origin of the calcite vugs (or geodes) in the Angel Loop?*

A: These are small cavities lined with calcite crystals, which predate the cave. Most (or all) were small bodies of gypsum in the limestone that were gradually dissolved away, leaving a hollow space that became lined with calcite. The dissolving of the gypsum actually promotes the simultaneous deposition of calcite, because as calcium is released by the very soluble gypsum it forces the less soluble calcite to precipitate because of the rise in the calcium content of the water. This sort of thing usually happens when fresh water (not sea water) first starts flowing through the rock layer. The calcite vugs are most common near the top of the Stewartville Formation around bedding plane 1 (BP1).

Q: *Why are the stalagmites and draperies in the Tar Pit area of Mystery III purple?*

A: Apparently this dark color is mainly manganese dioxide. Organic material from the surface has probably contributed. The origin of colors in minerals can be very elusive.

Q: *Are the helictites near the Bar formed by air flow from Mystery I to Mystery II?*

A: No. Helictites require small amounts of seeping water, not enough to form gravitational drips. Evaporation of water in the area due to air flow may reduce the amount of water and therefore help to form helictites, rather than stalactites, but air movement is not the cause of the twisting shapes.

Q: *In 5th Ave. between Angel Loop and Smoking Chamber the walls and ceiling are always very wet; so why are there so few speleothems in these areas?*

A: We have no concrete evidence but can venture a few possibilities: (a) it may be condensation moisture formed where the moist air from Mystery I enters the cold upper levels of Mystery II; (b) the water may have begun to enter only recently, due to changes in land use above -- e.g., deforestation -- and just hasn't had enough time to precipitate visible amounts of flowstone; (c) the carbon dioxide in the descending seepage may have been depleted before it reached the cave, as would be the case if it passed through a material like sandstone before encountering the limestone (so when the limestone dissolved there would no longer be a source of carbon dioxide available to recharge the water) -- this is not the case at Mystery Cave, however; (d) the water may be descending rapidly enough that when it reaches the cave it has not had enough time to approach saturation with dissolved limestone. Any or all of these

factors are known to cause this phenomenon in other caves.

Q: *At the bottom of the Hills of Rome, why are the walls dry on one side (with gypsum crystals) and wet on the other (no gypsum)?*

A: Water seeps into the passage more vigorously on the north side of the passage, because the source of water feeding Blue Lake is on that side. Gypsum cannot grow in moist areas (unless the water contains an unusually high content of dissolved gypsum). Much less water enters the other side, and so gypsum is able to grow in that dryer area, where the dissolved gypsum content can be enriched more readily by evaporation.

Q: *How did Devil's Kitchen form?*

A: It is a room with a high ceiling formed by upward solution along major joints at times when the cave was filled with water. Dripping water probably had little to do with its origin. The susceptibility of these joints to enlargement was probably due to their proximity to the surface. Blocks of limestone between the joints must have dropped out at various times, and these have either been dissolved away, buried by sediment, or moved during trail building.

Q: *What caused the vein filling in the limestone in Fourth Avenue between the Lake and Diamond Caverns?*

A: It is a calcite vein that filled an early fracture in the limestone. Deep beneath the surface, water usually deposits calcite in pockets and fractures, because calcite is less soluble at the higher temperatures that exist at depth. Similar vein filling can be seen in the Angel Loop near where the route to the Bar joins the main part of the loop.

Q: *Where does the radon come from in the cave?*

A: Shale tends to collect many materials that are dissolved in the water that passes through it, including tiny amounts of uranium compounds. They are trapped by the shale or precipitate within it. For example, oxidized uranium is soluble, but in the reduced state (in the absence of oxygen) it precipitates. Organic material in the mud that makes up shale help to reduce (and therefore precipitate) the uranium compounds, and these are the chief emitters of radon.

Q: *What effect does acid rain have on the cave? Will it have a significant effect over the next few hundred years? Are any studies being done on the subject?*

By the time the water reaches the cave, it is already nearly saturated with dissolved limestone, and adding acid to the rainwater will not significantly affect the cave. Instead, the rate of limestone solution at and near the surface will increase. Even this effect is small over the short time intervals involved. Water in the soil naturally picks up so much carbon dioxide that the pH drops to about the same level as that of average acid rain, and so the effect of the acid rain on water that passes through soil is less than on surface water.

