H. H. Hobbs III

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VOLUME 31 NUMBER 4

Contents

OCTOBER 1969

Information for Contributors To the Bulletin

Papers in any discipline of speleology are considered for publication in the BULLETIN. The upper limit for length is about 10,000 words or approximately 40 pages of manuscript, typed double-spaced. At least one copy but preferably two copies of the manuscript (typed, double-spaced) should be submitted to the Editor, Jerry D. Vineyard, Missouri Geological Survey, Box 250, Rolla, Missouri 65401. Photographs and line drawings, if required, should be submitted with the manuscript. In general, prints and line drawings will be photo-reduced to the size necessary for use in the BULLETIN.

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Processes of Cavern Breakdown *

By Elizabeth L. White and William B. White

ABSTRACT

Breakdown occurrences have been studied extensively in the large cavern systems of the Central Kentucky Karst and in caves elsewhere in folded limestones. Rosettes of straight breakdown block edges show strong preferred orientation suggesting that fracturing occurs along pre-existing zones of weakness. Wide-span ceilings have a measurable sag.

Some processes activating cavern breakdown are: (1) loss of buoyant support by draining of galleries (2) undercutting of banks by floodwater stoping at the base level (3) removal of support by free surface stream action (4) crystal wedging and attack by sulfate mineralization (5) frost wedging (6) undercutting by later cavern development (7) undercutting and removal of material by vertical shafts and shaft drains (8) weakening of ceiling beds through attack by acid surface water.

One or more of the mechanisms of cavern breakdown are operative during all stages of development. Thus breakdown takes place continuously and plays an important role both in the initial enlargement of the cavern system and in its final degradation.

INTRODUCTION

The sediments that litter cave floors can be broadly classified into allochthonous and autochthonous types. Allochthonous sediments originate outside the cave and are usually composed of sand, clay, and rock fragments brought in by flowing water. Autochthonous sediments are derived locally and can be subdivided into chemical sediments, local detritus, and breakdown. The chemical sediments are locally deposited calcite, aragonite and gypsum. Local detritus is the weathering product of the limestone including clay minerals, chert, sand, and fossil fragments. The third sub-classification is breakdown. Breakdown is a general term for fallen bedrock fragments which have not traveled far from their point of origin.

Discussions of breakdown classifications and mechanisms in the European literature are sparse, although frequent mention is made of the existence of breakdown deposits. Kukla and Lozek (1959) include breakdown in their classification of cavern sediments and

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*Presented at the NSS-AAAS meeting, December 1962. This paper is also a contribution of the Cave Research Foundation.

Mugnier (1961) likewise distinguishes between breakdown and allochthonous sediment. In the United States Davies (1949) classified breakdown into block, slab, plate, and chip types. He has (1951) also analyzed cavern roof stability in terms of the mechanical strength of fixed and cantilever beams; an analysis based on methods used in calculating stability in mines.

In spite of the frequent mention of breakdown in the literature and its ubiquitous presence in most caves, very little attention has been paid to the processes which generate breakdown. Davies was mainly concerned with mechanics rather than geological processes acting in caves which might generate conditions which would result in breakdown. We have reconsidered breakdown mechanics and have outlined a number of geological processes which could set the stage for breakdown. Many of the field observations were made in the Flint Ridge Cave System and in Mammoth Cave, both in Mammoth Cave National Park, south-central Kentucky. Other observations have accumulated over the years. Most of the observations on caves in folded limestones were made in Appalachian Mountain caves of Pennsylvania and West Virginia.

Acknowledgements:

Support for the Kentucky field work in 1961 and 1962 was provided by the Cave Research Foundation. We are grateful to Mr. Michael Ehman for his services as field assistant on those two field sessions.

BREAKDOWN FEATURES

Perhaps the most common breakdown feature is the breakdown-littered cave floor. From this reference point one can distinguish small scale breakdown features which are the various types of breakdown blocks themselves, and large scale features which are cavern features consisting of — or generated by — breakdown processes.

Small Scale Features:

For the description of breakdown it is convenient to use Davies' (1949) classification in slightly modified form. Davies subdivided breakdown in block, slab, plate, and chip forms on a genetic basis. Block and slab breakdown can be produced by the same processes depending on the strength of bedding plane partings. Only rarely does a given collapse feature consist of a pure end member type. Secondly, Davies applied the term "plate breakdown" to types produced by a specific lithology, namely polygonally cracked shaley limestones. Chip breakdown was then said to be produced by spalling during release of tension in the rock. It seemed to us that this mixing of morphology and genesis makes the classification difficult to apply, particularly when taken out of the West Virginia karst area where it was originally developed. We have modified Davies' nomenclature to make the classification strictly on a morphological basis.

i. *Block Breakdown:* Rock fragments consisting of more than one bed remaining as a coherent unit.

ii. *Slab Breakdown:* Rock fragments consisting of single beds.

iii. *Chip Breakdown:* Rock fragments derived from the fragmentation of a bed.

The classification proposed above has the advantage that breakdown observed in the field can be properly classified without speculation as to its origin. It has the disadvantage of being also a function of limestone lithology. Thus limestone fragments of a given intermediate size might be blocks if derived from a thin-bedded limestone or be slabs if derived from a massively bedded limestone. In general, however, it has been found useful for the areas studied.

In the Flint Ridge cave system, slab breakdown is the most common and is distributed widely through all levels of the cave. Block breakdown occurs where major roof collapse has taken place and where divided walls have fallen between coalescing vertical shafts. The most extensive breakdown in the system is in the upper gallery of Great Salts Cave. This passage is floored with block and slab breakdown to a depth of 40 or more feet for a distance of more than a mlie. The largest breakdown block so far observed occurs in upper Salts Cave. It is a single block 63 feet in length, 15 feet in width and 4 feet thick.

Large Scale Features:

Although breakdown blocks form a variety of features in caves ranging from a few scattered blocks to major collapsed passages, only two breakdown features seem to be well characterizable. These are terminal breakdowns and breakout domes.

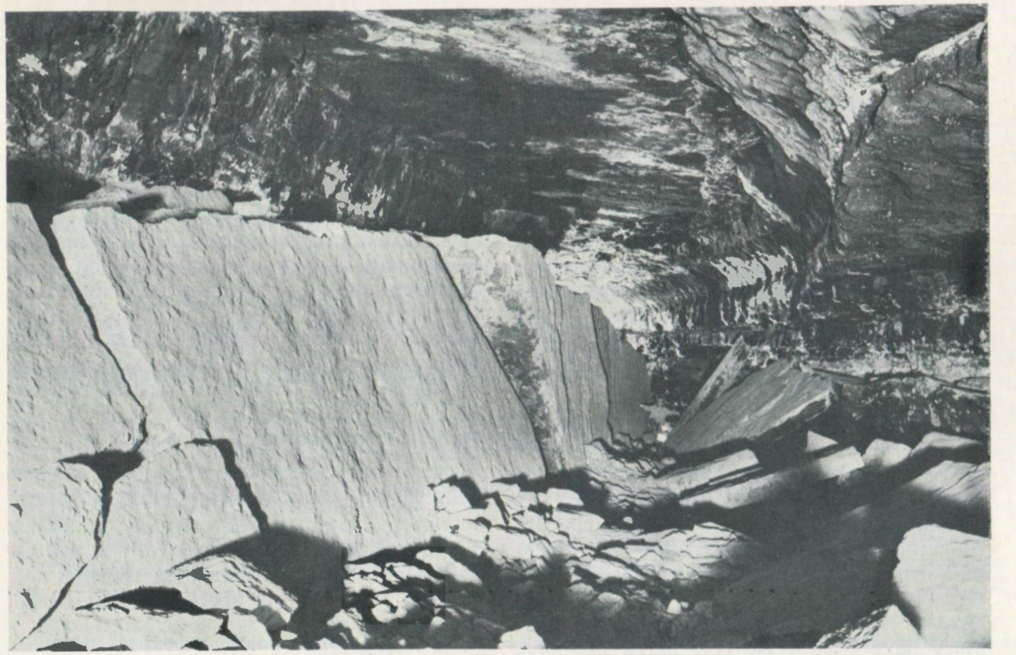


Figure 1.

Massive block breakdown in Great Salts Cave. Photo courtesy Cave Research Foundation, W. T. Austin.

Terminal breakdowns are the collapsed ends of major caves passages. In the Central Kentucky Karst, terminal breakdown is the most common terminator of passages. The terminal breakdowns often consist of sandstone as well as limestone fragments where the collapse has extended upward to overlying caprock. The importance of this feature has been discussed by Brucker (1966). Major trunk passages beneath the sandstone-capped plateau were once continuous feeder conduits carrying groundwater from the Sinkhole Plain south and east of the plateau to Green River in the north. These formerly continuous passages were truncated by ceiling collapse. Some are actual intersections of the passage with the surface, others have collapsed at depth. The present day configuration of the cave system is due in large part to these random features of collapse. Similar terminal breakdowns occur in many other caves in stratigraphic situations with and without caprock.

Among the most remarkable of cavern features are the huge rooms which form as a result of major ceiling collapse. Some of these, such as Chief City in Mammoth Cave, have floor dimensions of hundreds of feet and ceiling heights of nearly 100 feet. Davies (1951) ascribed the origin of these major breakdown rooms to tension dome collapse and described the mechanics of their formation. Careful examination of many breakdown areas reveals a continuum in sizes from very large breakdown rooms to small, roughly circular or elliptical breakdown areas in cave ceilings. The features at the small end of the scale are sometimes only 10 feet in diameter and involve only one or two beds. The morphological term, *breakout dome,* describes all such features regardless of their size.

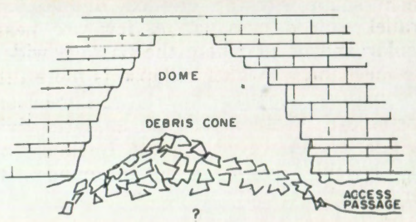


Figure 2.

Sketch showing the essential features of the breakout dome.

The essential features of the breakout dome are indicated schematically in figure 2. The debris pile varies in size from dome to dome but in those domes which are accessible, the volume of debris is much smaller than the enclosing volume of the dome. Since the bulk density of the debris cone is considerably less than that of the original bedrock, it is apparent that large quantities of material must have been removed. Large breakout domes must therefore have formed at a time when water was actively circulating near their base. The dome could then enlarge by a mechanism of solution of fallen blocks with concurrent stoping of the sides. The dome itself is usually circular or elliptical in contour. The top is often capped by a single massive bed.

Very large domes known to the writers are Chief City in Mammoth Cave, Rothrock's Cathedral in Wyandotte Cave, the entrance room of Hellhole Cave, West Virginia and the entrance room of Marvel Cave, Missouri. Another candidate would be Devil's Sinkhole in Texas. In this cave the details of the enlargement mechanism are less clear, although the beehive-shaped room and the gigantic debris cone are certainly typical of other breakout domes.

BREAKDOWN MECHANICS

Mechanics of Beams:

The mechanical model used by Davies (1951) and by most treatments of mining problems (see for example Merrill, 1957) is the simple beam model. If the cave (or mine) is in flat-bedded rocks, small elastic sags will separate the individual beds of the roof. These then act as beams with a span equal to the passage width, and a thickness equal to the bedding thickness. Since the width of the beam does not enter the final formulae, the extent of continuous bed along the passage is immaterial. If the roof span is intact it is treated as a fixed beam. If it is broken or strongly jointed it may be treated as a cantilever beam. The main assumption is that the strength of the rock within a bed is much larger than the strength of the bedding plane parting. Ceiling beams are also clamped by the weight of bedrock behind the passage walls. The beams are not free to rotate and so simple jointing in a thick bed will not necessarily transform a fixed beam into a cantilever.

The resistance to fracture at the point where the beam is attached to the wall is determined by the maximum flexural or bending stress of the limestone. The bending stress is given by:

$$S = \frac{Mc}{I} \qquad (1)$$

where for fixed beams:

$$I = \frac{bt^3}{12}, \quad c = \frac{t}{2}, \quad \text{and } M = \frac{wl^2}{12}$$

Since $w = \rho bt$, then $M = bt\rho l^2$

The critical beam thickness that will just support its own weight is given by:

$$t = \frac{\rho l^2}{2S} \qquad (2)$$

Where:

S = Flexural stress in the extreme fiber (lb/in^2)
c = Distance to outermost fiber (in)
I = Moment of inertia of beam (in^4)
b = Beam width (in)
t = Beam thickness (in)
M = Maximum moment (lb-in)
ρ = Density of beam material (lb/in^3)
l = Beam length = roof span (ft)

The analogous formula for a cantilever beam is:

$$t = \frac{3\rho l^2}{2S} \qquad (3)$$

Because of the uncertain effects of joints and other flaws in the limestone it is difficult to assign a value to the bending stress. An approximation to the maximum roof spans which can survive is given in figure 3 for an assumed bending stress of 2300 psi. A 100 foot span, large by cave standards, requires a 2-foot thick ceiling bed to be stable. This relationship provides an explanation for the observed maximum width of cave passages of about 100 feet. Only in exceptional circumstances would the limestone be sufficiently massive and free of flaws to support a wider span of ceiling. Indeed, most cave passages begin to suffer collapse long before they enlarge to 100 foot widths.

Mechanics of Plates:

Small breakout domes are common in Mammoth Cave and the Flint Ridge cave system. These usually involve the failure of only one or two beds and are typically elliptical in shape with the long axis of the ellipse parallel to the passage. A few are nearly circular and occur where the passage widens. The mechanics of such collapse is more difficult mathematically, since two-dimensional stresses are involved, and an analysis giving the relationship between plate thickness and critical yield stress could not be found in the literature.

Such plates do, however, provide a possible test of whether the beds fail by brittle fracture or whether there is some elastic sag before failure. A particularly favorable case occurs in the Flint Ridge system near the intersection of Pohl Avenue and Lower Crouchway. Here a wide expanse of ceiling is roofed with several thin beds, some of which have failed, and the remainder of which have an apparent sag. The exact shapes of these beds were mapped using a hand level technique to generate an arbitrary horizontal reference plane. The distance to the ceiling was measured on a 3-foot grid using a steel tape. The ceiling is shown in figure 4. The hatchured lines are edges of beds with the hatchures on the edge of the bed. Contour interval is 2 inches.

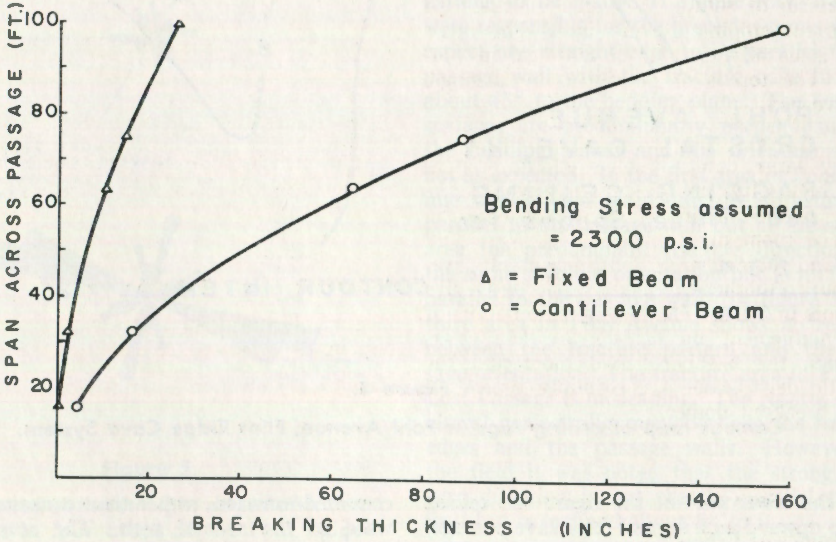


Figure 3.

Relationship between critical breaking thickness and passage width for fixed and cantilever beams.

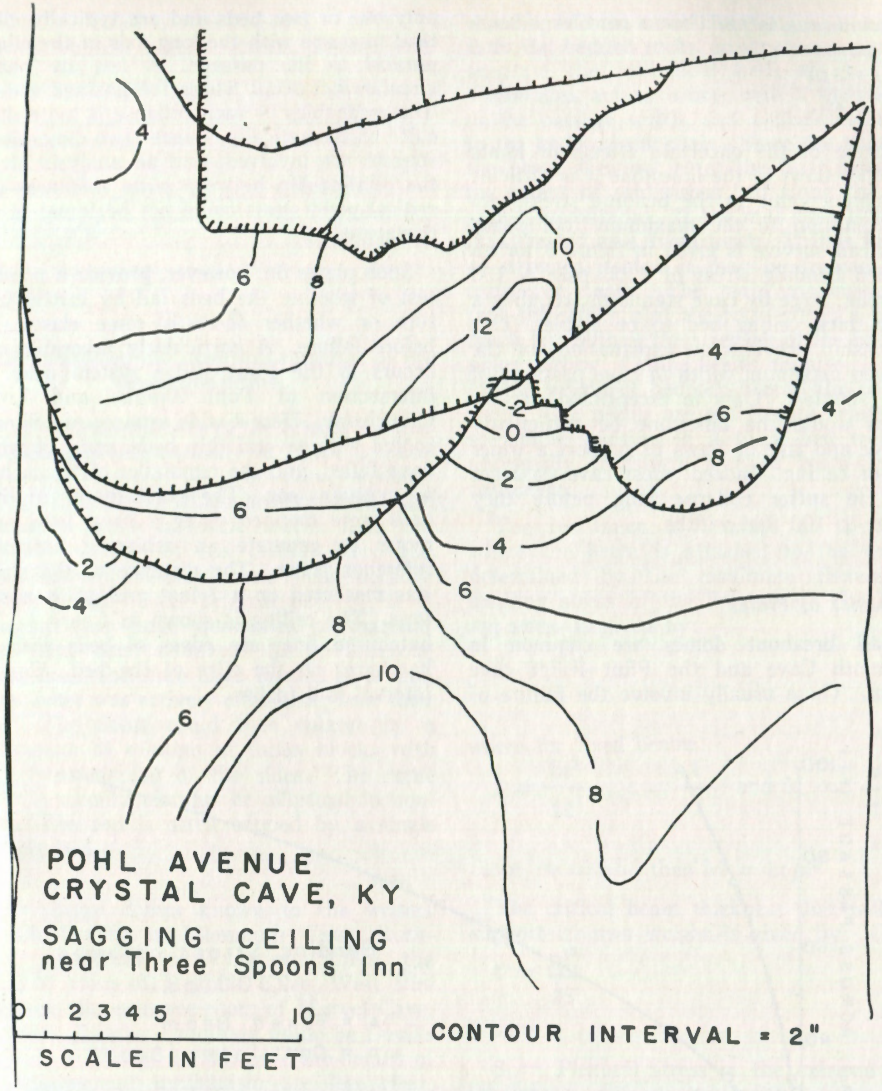


Figure 4.

Contour map of ceiling sags in Pohl Avenue, Flint Ridge Cave System.

In the lower part of the figure the ceiling has an upward arch normal for a cave passage. Near the center of the figure is a spur of the lowest bed which juts out with a measurable sag. The total sag is almost 12 inches and the curvature of the spur is reversed, being convex downward, rather than concave downward of the normal arch. The reversal of curvature suggests that the sag is genuine and not just an irregularity in the solutional surface. The large measurable sag indicates that the assumption commonly made that the shear modulus and rigidity modulus are equal is not quite correct. Elastic or plastic deformation of the rock does take place under simple gravitational stresses.

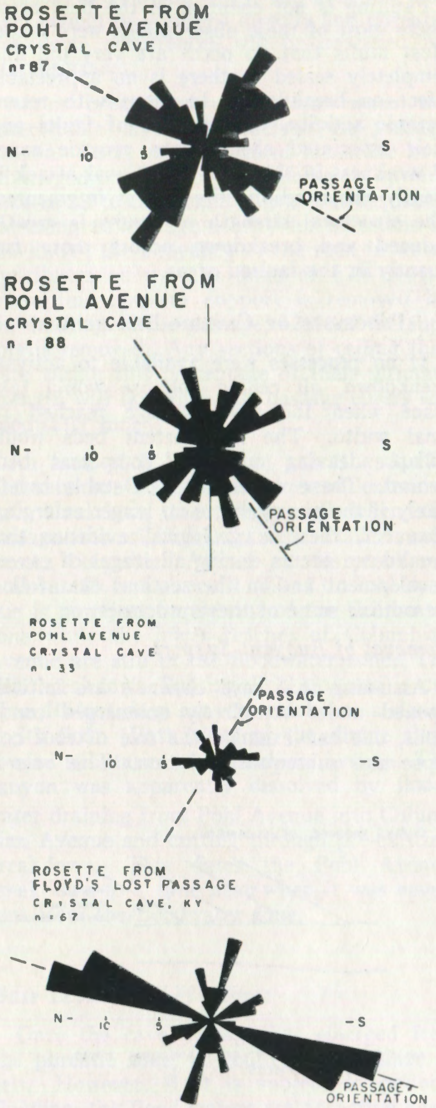


Figure 5.

Rosettes of the straight edges of fallen slabs in four areas of the Flint Ridge Cave System. These data were taken in areas where rotation or slumping of the breakdown pile had not taken place.

Influence of Structure:

Much breakdown in the long galleries of the Mammoth Cave area is of the slab type. Slabs of rock have the same thickness as the beds, namely from a few inches to a few feet. The tops and bottoms are roughly planar and the edges are usually straight so that the breakdown is composed of polygonal slabs rather than irregular fragments. The thicknesses of fallen slabs are of the right order of magnitude to have fallen by simple fracture. However, the straight edges of the fragments indicate that failure may have taken place along pre-existing zones of weakness in the rock.

This possibility was checked by plotting the orientation of the edges of breakdown slabs in areas where the slabs have not rotated on falling. The rosettes shown in figures 5a - 5d are plotted in the usual manner in which the number of straight breakdown edges with orientation is a given 10° sector is plotted radially. There are several interesting observations to be made. If simple rock fracture were responsible for the breakdown one would expect one straight edge to be parallel to the passage wall with the fracture edge inclined about 45° to the bedding plane. The fracture surfaces are predominantly perpendicular to the bedding planes and the orientations are not as expected. In the first area in Pohl Avenue one of the main fracture directions is parallel to the passage wall but at the second area the predominant fracture direction has the same absolute orientation but is no longer parallel to the passage wall. In figure 5c the third area in Pohl Avenue shows no relation between the fracture pattern and the passage orientation. The fracture area in Floyd's Lost Passage is misleading. The rosette shows almost perfect alignment bewteen the fracture edges and the passage walls. However, in the field it was noted that the strong fracture direction is not exactly parallel to the wall but is inclined about 5° to it.

This analysis indicates that failure of the ceiling takes place in accordance with the simple fracture model; however, the observations of the slab orientation indicate that failure takes place along the existing zones of weakness in the rock. Clamping of the segments maintains the fixed beam configuration.

The influence of folding is to change the relationship between bedding planes, joints, the cave passage, and gravitationally induced stresses. Caves in folded limestones typically exhibit different patterns of breakdown development than those of caves in flat-lying limestones. Many cave passages are oriented along the strike in folded limestones. Beds are tipped at high angles, strike joints tend to be perpendicular to the bedding and are thus inclined at a high angle in the opposite direction. Under these conditions, the zone of weakness is ideal for dropping blocks. The weight of the block is oriented in such a way that both bedding plane and joint face are in tension. The gross strength of the bed is much less than the strength of fixed beams where the joint faces are in compression.

One does not, however, find breakdown very commonly in strike-oriented passages. Many strike-oriented Applachian caves are remarkably free of breakdown — at least at the surface of the clastic sediments. It is concluded that breakdown is so rapid under these conditions that most of the available material falls during the initial excavating stages of cavern development and has been removed by solution.

The most intensive later stage breakdown occurs where the passage cuts across the bedding planes. Penn's Cave in central Pennsylvania, and Wild Woman Cave in eastern Oklahoma are particularly good examples. Both are mainly strike-oriented caves. In both caves the strike-aligned sections of the passage are free of breakdown. In Penn's Cave at one point the passage is offset about 50 feet across the beds and at this point there is an extensive rockfall with blocks 5-10 feet thick. In Wild Woman Cave there are extensive rockfalls at each place the passage crosses the bedding planes of the 20° dipping Arbuckle limestone.

Apparently during the initial stages of development the triangular beams oriented parallel to the passage fell. Later development of a zone of weakness would cause the perpendicular blocks to drop out and be responsible for the pattern of breakdown observed (fig. 6).

Faulting is not common in the field areas where most of these observations were made. Most faults that do occur are very old and completely sealed so there is no appreciable effect on breakdown. In areas with recent tectonic activity, the presence of faults and their associated shear zones provide zones of weakness in the rock. Solutional attack is greatly enhanced and the rock is fragmented. The structural strength of beams is greatly reduced and breakdown occurs more frequently in the faulted areas.

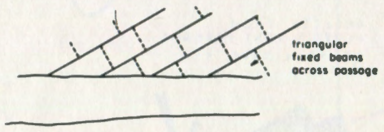
PROCESSES OF CAVERN BREAKDOWN

If no processes were available to activate breakdown, all ceiling collapse would take place when the cave passage reached its final width. The incompetent beds would collapse leaving only the competent beds behind. These would then be stable indefinitely if the passage were no longer enlarging. However, there is geological evidence that breakdown occurs during all stages of cavern development and in the sections that follow we outline some of these processes.

Removal of Buoyant Support:

Assuming that cave channels are initially opened under completely submerged conditions, one can examine the role of roof collapse and subsequent solution. This role is difficult to evaluate since sub-aqueous passages cannot be observed directly and phreatic breakdown occurrences will be obscured by later processes.

DURING PASSAGE DEVELOPMENT



FOLLOWING DEVELOPMENT OF TRANSVERSE ZONES OF WEAKNESS

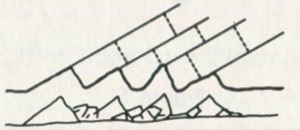


Figure 6.

Sketch showing the development of breakdown in passages cutting the bedding in areas of steeply dipping limestone.

Major breakdown must occur when the water table is lowered below the passage horizon. Each unit volume of limestone in a submerged cavern roof experiences an upward force equal to the weight of water it displaces. Assuming an average density for limestone of 150 lb/ft^3, the buoyancy of the rock in water contributes an upward force of 62.4 lb/ft^3. When this buoyant support is removed by the draining of the passage, 42% of the support is removed. Any sections of ceiling that were within this percentage of their ultimate strength will fall when this passage enters the floodwater zone.

An area of Pohl Avenue near the Austin Entrance to Crystal Cave has an extensive slab breakdown that likely fell when the passage was originally drained. Pohl Avenue crosses Columbian Avenue at this point and is about 10 feet above it (fig. 7). Pohl Avenue is now just barely out of the floodwater zone while the lower reaches of Columbian Avenue are still in the floodwater zone. The slab breakdown flooring Pohl Avenue is cut by a 10-foot deep canyon which has a divide in its floor. Both sides of the divide slope toward tributaries of Columbian Avenue. The canyon was apparently dissolved by floodwater draining from Pohl Avenue into Columbian Avenue and cutting through pre-existing breakdown. This dates the Pohl Avenue breakdown to a time near when it was emergent from the floodwater zone.

Base Level Back Flooding:

Once the cave passage has emerged from the phreatic zone, it would soon stabilize itself. However, if it is subject to periodic flooding, the flood waters are an active agent that can further open zones and cause further roof collapse. An example of this mechanism is provided in downstream Columbian Avenue in Crystal Cave. The sediments here are alternating layers of sand and clay. Breakdown blocks occur buried in these deposits. Ceilings above the blocks are rounded indicating additional solution since the blocks fell. This particular area seems to represent a clear case of rockfall activated by solutional attack by floodwaters. While this machanism may be of particular importance in the Mammoth Cave area because of its proximity to the Green River, the same machanism could be active in any cave subject to seasonal flooding.

Undercutting by Free-surface Streams:

As base level is still further lowered, it becomes possible for the passage to be used as a route for a free-surface stream draining some other part of the area. Since free-surface streams often have higher gradients than subwater table streams, they may carry a coarser load of sediment and can remove the fills deposited by earlier processes. Free-surface streams can activate breakdown in two ways: as the fill is removed, partially supported ceiling beams are exposed to additional load and may fall; secondly, the walls may be undercut, effectively increasing the length of beams and cause additional collapse. The process is particularly effective if the stream meanders, giving it a cutting edge against the walls. A portion, at least, of the very extensive breakdown in Great Salts Cave was apparently activated by this mechanism. In places one can climb down between the breakdown and the walls of the main gallery and find a smaller passage meandering in and out of the main gallery with considerable undercutting of the walls. The breakdown slabs are interbedded with coarse sand and quartz pebbles — a sediment derived from the basal Pottsville Conglomerate and common to most upper levels of the cave system.

Mineral-Activated Breakdown:

A chemical mechanism by which gypsum replaces limestone and causes breakdown by a combination of chemical attack and crystal wedging plays an important role in some of the breakdown occurrences in central Kentucky. The source of sulfate minerals in the Central Kentucky Karst has been shown (Pohl and White, 1965) to be the pyrite which occurs in the upper Girkin limestone and Big Clifty sandstone. The pyrite is oxidized and the sulfate bearing solutions percolate into the cave. The geochemistry of the reactions is such that no reaction with the limestone takes place until the solutions move into the vicinity of a cave passage. The reaction of the sulfate-bearing solution with

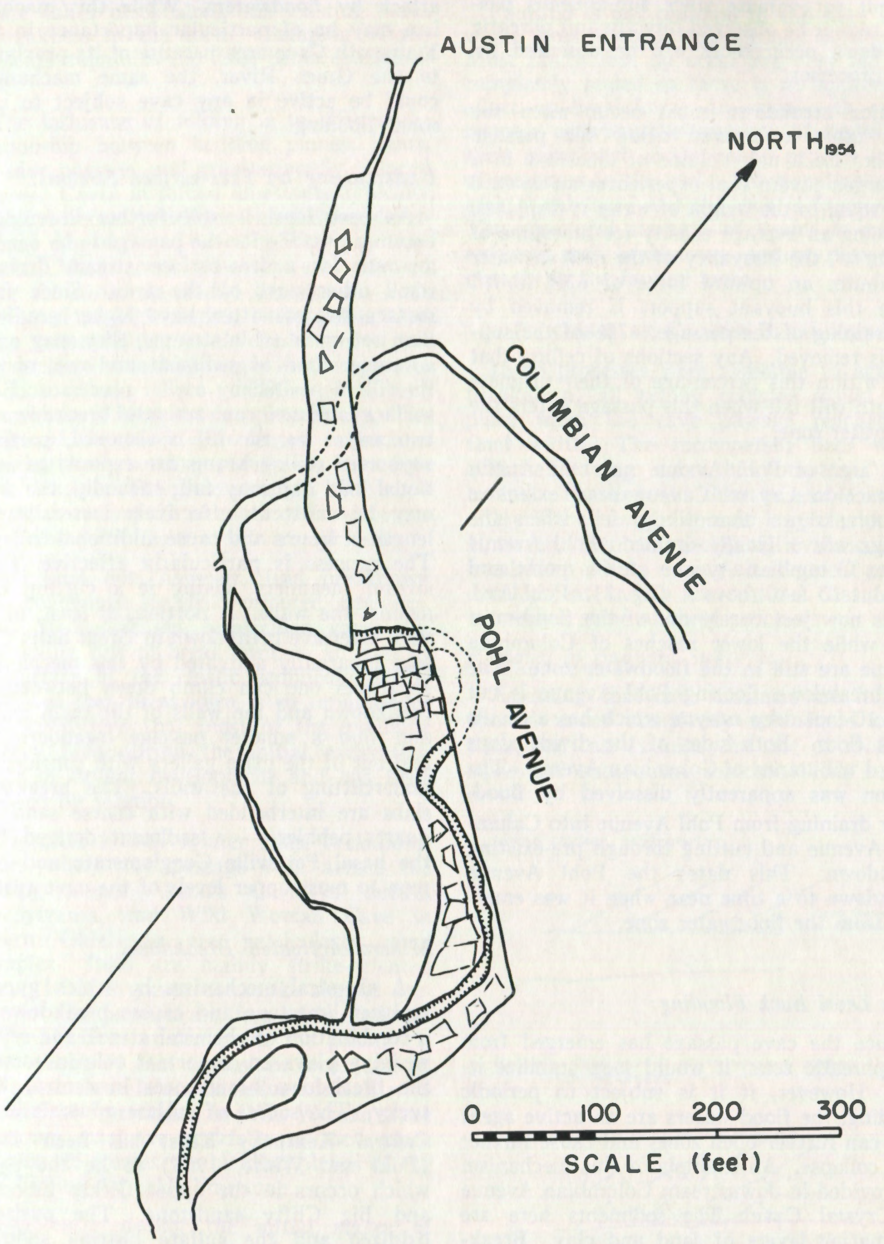


Figure 7.
Map showing relationship between Pohl and Columbian Avenues, Flint Ridge Cave System. Canyon is incised in pre-existing breakdown.

limestone produces carbon dioxide which is discharged into the cave passage and there is a gradual replacement of limestone by gypsum. This replacement is on a mole basis but the molar volume of gypsum is higher than the calcite it replaces and thus there is a physical expansion force in addition to the chemical attack. Crystal wedging from growing gypsum crystals in the passage walls and ceilings forces off chips of rock and generates an extensive chip breakdown in many of the upper level passages. This process is discussed in another paper (White and White, in prep.) Mineral activation will function only in the caves with gypsum deposits but these appear to occur in many of the Mississippian limestone caves of eastern United States. The process is only active during the intermediate history of the cavern when the passages are high above the floodwater zone and well protected by an overlying caprock.

Breakdown Activation by Shafts and Shaft Drain Development:

In caves such as the Flint Ridge Cave System that are protected by a resistant caprock there is an intermediate dormant stage in cavern development between the time the gallery is raised well above the floodwater zone and loses its free-surface streams and the time the caprock is breached. When the caprock is either breached or removed by valley slope retreat, fresh acid surface water of local origin is admitted to the limestone and solution processes begin again. The first process to affect the underlying cavern is the development of vertical shafts and their network of drains (Pohl, 1955; Merrill, 1960). They form near the edge of the caprock and usually bore down all the way to baselevel. If the shaft passes near a cave passage beams can be weakened or changed from fixed to cantilever beams. Shafting action also removes pre-existing breakdown and thus removes support from the ceiling.

At Three Spoons Inn in Pohl Avenue a vertical shaft has removed more than 1000 cubic feet of pre-existing breakdown and is currently sawing its way through a large breakdown block which had tilted and slumped into the hole (fig. 8). At many places in the Mammoth Cave area, vertical shaft development has cut through piles of breakdown causing further collapse.

Attack by Fresh Surface Waters:

Breakdown plays a leading role in the final stages of degradation of the cavern system. When the caprock is removed or the land surface is degraded to the point where surface weathering attacks the cave walls, gullies and valleys cut more deeply than the surrounding landscape and gradually dissect the cave system into fragments. The ends of the truncated sections are usually blocked by terminal breakdowns against encroaching valley sides (Brucker, 1966).

A terminal breakdown in the making may be observed in Overholt Blowing Cave in Pocohontas County, West Virginia. A 0.25 mile long gallery, 25 feet or more in diameter is nearly blocked at both ends by rockfall. Both rockfalls are bypassed by low stream passages and the large gallery is continuous in both directions beyond the breakdowns. Surveys show that the main cavern is parallel to the side of a long ridge and both breakdown areas are directly beneath surface gullies on the sides of the ridge (fig. 9).

Frost Wedging:

Frost wedging is included in the list of breakdown processes primarily for sake of completeness. In caves in temperate climates frost wedging is an effective factor in prying loose blocks only near the entrance. Frost wedging is also a very late stage process and is effective only after other degradational processes have created cave entrances. In Alpine caves at high altitudes and under periglacial conditions frost wedging could play a very important role.

The breakdown resulting from frost wedging is somewhat different in appearance from breakdown caused by other processes. At Aitken Cave, central Pennsylvania, frost action — water freezing and expanding in open cracks and joints — has resulted in a rubble of angular, equidimensional fragments usually not more than 4 inches in thickness. Thus frost action like crystal wedging tends to reduce the breakdown to a more fine-grained material than other processes.

Effect of Earthquakes:

It has often been proposed in the older literature that breakdown is caused by earthquakes. To some extent this must be a hang-

Figure 8.

Breakdown being removed by action of vertical shaft. Pohl Avenue in the Flint Ridge Cave System. Photo courtesy W. T. Austin.

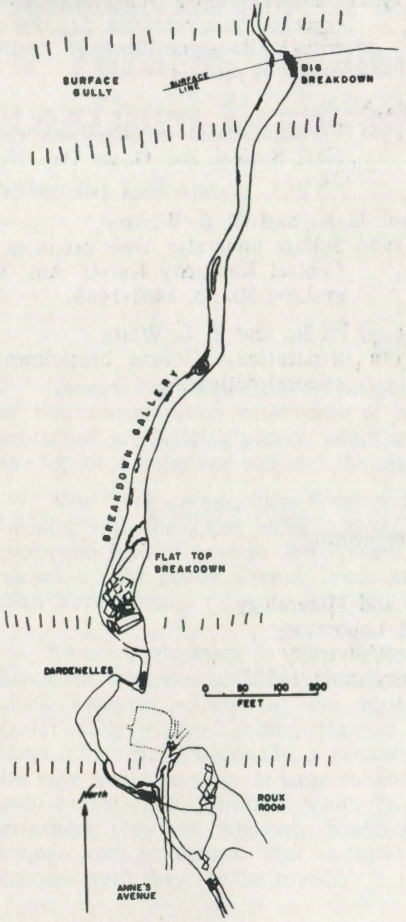


Figure 9.

Map showing relation of incipient terminal breakdown to surface gullies in Overholt Blowing Cave, West Virginia.

over from the old catastrophism school of geological thinking but perhaps it contains some grain of truth. A number of earthquakes have occurred since caving has become an active sport. Various accounts in newsletters indicate that rocks do fall although major roof collapse has not been observed.

It seems from the foregoing analysis, that earthquakes would be at best a triggering mechanism. If a set of ceiling beams has nearly reached their critical limits due to other processes, an earthquake would trigger collapse. It seems unlikely that all observed breakdown is triggered by earthquakes. The various processes of attack weaken ceiling beams until collapse would eventually take place even without the intervention of a triggering mechanism. It also does not seem likely that a mild tremor would do more than release blocks about to fall under their own weight. Blasting in caves is observed to do little damage outside the immediate blast area.

CONCLUSIONS

In conclusion the following significance to cavern breakdown is suggested. The thickness and distribution of breakdown indicates that Davies' mechanical model is approximately correct. However, the straight and well oriented edges of fallen blocks suggest that failure occurs along pre-existing zones of weakness in the limestone and thus that the observed beam thickness-passage width relations are a measure of the overall average strength of the limestone, rather than the strength of a simple homogeneous limestone specimen.

Some seven processes responsible for cavern breakdown have been delineated and suggest that rockfall in the cave is not a random event but is a result of specific geological process triggered by specific geological forces. Breakdown is active in all periods of cavern history but is most intensive in the very early and very late stages of development. Breakdown processes are at their mildest during the intermediate mature stages of cave history when the caves are most visited by explorers.

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Origin of Caves in Eastern New York as Related to Unconfined Groudwater Flow

By Stephen Jay Egemeier

ABSTRACT

Caverns are linear rather than planar features. They form at the intersections of flow concentration with zones of solvent concentration. Surfaces of flow concentration are bedding planes, joints and faults. Zones of solvent concentration are the top of a limestone bed and the upper phreatic zone within a limestone.

New York caverns have developed along the intersections of faults, joints, and bedding with the upper phreatic zone. Faults, joints and bedding each determine a particular type of passage development. The influence of the upper phreatic zone is shown by the gently sloping floors and the accordant stream junctions found in New York caves.

Karst development in New York seems to be a continuing process. As the limestones were exposed an integrated drainage system within the limestone developed along fractures intersecting the upper phreatic zone. Simultaneously, "cutters" (solutionally enlarged joints; Howard, 1963), developed on the surface along the same fractures. Occasionally, a connection between the surface "cutter" system and the cave would develop. If large volumes of debris were washed underground through such a connection, fill might result. In some cases, filled passages may be reopened; in others, they are bypassed. Karst development may be a continuing process of change and adjustment that operates in soluble rocks from the time they are exposed until they are destroyed.

INTRODUCTION

Cavern passages are far longer than they are wide. They appear to be linear, rather than planar features. Generally linear features develop along the intersections of surfaces. This appears to be generally true of caverns. The surfaces involved are the zones of maximum solvent concentration and the surfaces of maximum flow concentration. The zones of solvent concentration are usually nearly horizontal and depend on the chemistry of subsurface waters. The surfaces of maximum flow concentration generally are not horizontal, but are steeply inclined. At the intersection of these two types of surfaces there is not only maximum flow, but maximum solvent concentration as well. This results in maximum solution and maximum probability of cavern development.

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The conclusions in this paper are the author's and are not necessarily subscribed to by those mentioned above.

Zones of Solvent Concentration in Dense Crystalline Limestone

It is well known that although limestone is nearly insoluble in pure water, it is fairly soluble in water containing carbonic acid. Carbonic acid, which forms by the addition of carbon dioxide to water, occurs in nearly all waters, although in small amounts. As the formation of carbonic acid is an equilibrium process, the concentration of the acid in a water body depends on the partial pressure of carbon dioxide in contact with that body. In the atmosphere this partial pressure is 3.0×10^{-4} atmospheres whereas in soil air, the pressure according to Holland and others (1964) may run as high as 2.5×10^{-2}. The mean is about 1.0×10^{-3} atmospheres. As a result, when downward percolating subsurface waters contact limestone, substantial solution is possible. This solution is concentrated at the surface of limestone units and decreases exponentially downward as a solvent groundwater approaches saturation. This source of solvent water can solutionally modify the surface of a limestone, but becomes saturated before reaching sufficient depth to form a cave.

Several mechanisms that can produce undersaturated subsurface waters within a body of limestone have been proposed. (For a detailed treatment of this problem see Thrailkill, 1968). Of these, the so-called "temperature" and "mixing" effects appear to be the most effective.

As the solubility of calcite is inversely related to temperature, a decrease in the temperature of a saturated solution will result in undersaturation ("temperature effect"). Thus, during warm weather the cooling of water entering the groundwater reservoir should produce an undersaturated solution. During the winter the converse would be expected. At first glance it appears that no net solution should occur. However, during the warm months carbon dioxide generating processes in the soil, such as decay, are far more active than in colder months. As a result, the solution that results when warm water is cooled during the summer exceeds the precipitation that results when cool water is warmed during the winter. Hence, significant net solution does occur within a limestone, as a result of the "temperature effect."

The "mixing effect" produces undersaturation by the mixing of any solutions that became saturated under different conditions of carbon dioxide partial pressure. To oversimplify, mixing results in undersaturation because the saturation concentration of calcite is non-linearly related to the partial pressure of carbon dioxide. A complete treatment of this process is in Thrailkill (1968). Mixing of this type would be expected to occur in the upper phreatic zone, where downward percolating waters join the groundwater reservoir. It is clear that processes producing unsaturated solutions within a limestone unit should be far less significant than those producing unsaturated solutions at the top of a limestone unit. Petty (1968) was able to show that this is indeed the case in an area he studied in Great Britain. Solution in the upper phreatic zone, and therefore caves, represents only a fraction of the solutional loss in a limestone terrain.

Chemically, then, solution is probably greatest at the top of a limestone body and in the upper phreatic zone within the body. As the elevation of the upper phreatic zone changes a substantial zone within a limestone body will be subjected to solution over time. Temperature and carbon dioxide concentration gradients are likely in the upper phreatic zone if mixing is slow, resulting in possible solution well below the water table. Solution has occurred at depths of almost 200 feet below river levels in Tennessee according to Moneymaker (1941). Most caverns probably develop at fairly shallow depths below the water table.

Surfaces of Flow Concentration in Dense Crystalline Limestone

Limestones are aquifers with very low primary porosity and permeability. Davis (1966), Howard and Howard (1967) and many others have concluded that the primary permeability of limestones is too small to develop caves in a geologically reasonable time. Secondary permeability due to fractures is considered necessary for cavern formation. Davis (1966) feels that permeability along joints is insufficient to produce caves. He proposes that joint movement due to earth tides is necessary to "pump" water through favored joints to speed up the solution process by increasing solvent flow volume.

Howard and Howard (1967) investigated the solution of limestone between parallel boundaries in laboratory experiments. They determined that solution rates increase exponentially with spacing between blocks of limestone. Kaye (1957) determined that there is a strong dependence of solution rates on solvent velocity. Because velocity is dependent, among other things, upon crack width, it follows that the larger a crack initially, the faster it will grow. Once a crack enlarges sufficiently for turbulent flow to start, the effective solvent velocity increases suddenly resulting in a rapid increase in the rate of enlargement. As a result large cracks become larger and small cracks hardly change. Thus initial surfaces of maximum flow increase their lead over competing surfaces and dominate further solutional development.

Because solution depends upon crack width and the availability of solvent it follows that maximum solution will occur where both conditions are most favorable. The maximum solution would be expected where cracks intersect the surface of a limestone unit and also where cracks intersect the upper phreatic zone within a limestone unit.

Of all the features in a limestone that may add to permeability, probably the least known is bedding. It seems to be generally recognized that there is a tendency of caverns to be more common in thin bedded limestones than in thicker bedded units provided bedding is thick enough to span a cavern without excessive ceiling failure. A reduction of limestone thickness near major valleys in Tennessee was noticed by Sterns (1967) and attributed to groundwater sapping. For this to have occurred a substantial amount of solution must have taken place along bedding planes. This indicates that solution along bedding may be far more significant than is generally realized.

The dip of a limestone helps determine the strike of caverns within. The dip has little effect on the strike of segments of a cave passage but it does seem to control the general direction of an entire cave or major passage. A study of the literature on Appalachian caves showed that the apparent dip of the bedding along the mean strike of major cave passages was between zero and 15 degrees. The mean was 4 degrees.

In gently dipping rocks (4 degrees or less) passages might, and do, form with nearly any strike. In more steeply dipping limestones there are two planes with apparent dips of 4 degrees along which caverns might trend. Typically cavern passages slope and drain in the direction of the apparent dip.

The reason for this relationship is not clear. It is probable, however, that this relation only holds for caverns formed under conditions of unconfined groundwater flow.

Joints, being so commonly present, probably control the development of the majority of cavern passages. Water enters a joint from above and flows vertically down the joint (fig. 1a) until it intersects the upper phreatic zone, where it becomes unsaturated (mixing effect) and subsequently dissolves part of the joint wall. The resulting solution then flows slowly toward the groundwater outlet. Commonly, cavern development occurs along joints with different strikes, resulting in passages with many angular turns. Anderson (1961) plotted the passages of Gage's Cave, Schoharie Co., New York, on polar coordinates and compared this to a similar plot of joints in nearby outcrops. An excellent correlation was obvious.

Lattiman and Parizek (1964) examined wells near and along surface fracture traces and found that subsurface solution openings are encountered more often in wells along fracture traces than in those drilled in between. This indicated that the passages follow fracture traces formed along the same cracks as the surface fracture traces. Hence, "cutters" (solutionally widened joints) at the surface might be expected to correlate with passages below.

Because cracks along fault planes usually are wider than those along bedding planes or joints, faults would be expected to have a greater influence on cavern development than joints or bedding. Krinitzsky (1947) and Ford (1965) mentioned faults in a few caves. Others have discounted their importance saying that they are rare, hence have little or no influence on cavern development. It is true that in comparison to joints, faults are rare. This is especially true in New York state. However, in New York, faults seem to have controlled the development of nearly all the largest cavern passages. Preliminary trips to other states around the country have shown that this is not a local occurrence. Faults are important in cavern development. Faulting not only produces larger initial cracks than jointing but their orientation may allow them to capture greater water flow. A low angle fault such as in figure 1c may intersect several joints. If the fault opening is wider than openings along the joints the fault will capture the water from these joints. The resulting increased water flow along the fault results in more solution when the fault waters join the upper phreatic zone. In a fault plane cavern, water entering the cavern along the fault plane often deposits flowstone on the footwall side of the cavern testifying to the quantity of water brought into the cavern along the fault plane. High angle faults (fig. 1b) capture water from fewer joints than do low angle faults in areas with vertically dipping joints. As a result high angle faults may have less influence on cavern development. However, the large initial size of a fault opening usually is sufficient to strongly influence or control cavern development. Typically fault-plane cavern passages are straight and have a cross section as shown in figure 1c.

Folding produces joints and may enlarge cracks between bedding planes and, hence, exerts a strong influence on cavern development. In the Appalachian cavern areas, flexural slip folding is fairly common. During folding of this type there is slippage along bedding on the flanks of folds and tensional joints develop, especially near the fold crest. Joints parallel the fold axis and dip inward slightly, toward the centers of anticlines (fig. 1d). The joints are widest at the land surface and tend to pinch out with depth. Hence folding adds joint sets and opened bedding planes to whatever previous secondary permeability may have been present. Fold limbs act in many ways like low angle faults. Water flowing down joints is captured by the open bedding planes and conducted toward the phreatic zone much as it would be by a fault (fig. 1d). On reaching the upper phreatic zone solution enlarges the bedding plane. In folded limestones, caverns are typically found along the limbs of folds. However, if joint openings are larger than bedding openings, many points in a fold crest may enlarge producing an intersecting maze of passages at the crest of a fold.

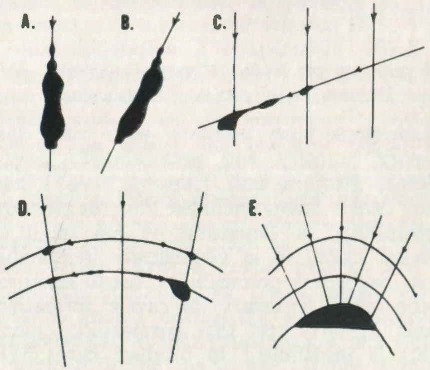

Figure 1.

Passage cross sections showing groundwater flow leading to their development. A. Joint passage. B. High angle fault passage. C. Low angle fault passage. D. Large fold. E. Small fold.

In the case of small folds with joints arranged in a fan (fig. 1e) water flowing down joints will collect below the crest, resulting in passage development along the fold axis. Because small folds are rarely continuous over long distances usually only a few side passages in a cavern system will develop in this manner. In larger folds the joints are rarely inclined enough to produce this effect.

GENERAL KARST DEVELOPMENT

When erosional processes expose a limestone terrain, several solution processes start simultaneously. The top of the limestone just below the soil mantle is attacked by vadose waters charged with carbon dioxide absorbed from the carbon-dioxide rich soil air. This water starts to dissolve channels called "cutters" in the limestone surface, and a subsoil drainage network is developed (Fellows, 1965). Generally, very small dendritic networks feed water into much larger channels developed along joints. When the limestone between these channels protrudes above the soil mantle, karren is said to have developed. Typically "cutters" are not expressed at the land surface. Subtle shadings in plant growth over "cutters" due to the changes in soil thickness results in readily discernible "cutter" patterns on aerial photographs. Simultaneously, while "cutters" form near the surface groundwater deep in the limestone flows slowly toward the discharge areas gradually dissolving out an integrated drainage system along fractures that intersect the upper phreatic zone. The integrated system may enlarge headward from system outlets. A discussion by Rhoades and Sinacori (1941) suggests this, as do some electrical analog studies by the author. An integrated system in Hershey Valley, Pennsylvania, was studied by Foose (1953). Groundwater behavior was similar in many respects to that of a normal non-karst aquifer. Cones of depression in the water table were observed after extensive pumping. When the water table fell below the level of surface streams, the streams sank. When the water table returned, streams flowed on the surface again. Although the aquifer appeared to have a well integrated solution network, it had not developed caverns. Solution openings were generally only a few inches wide. This is an unusually uniform integrated solution network.

An integrated groundwater drainage system is usually not homogeneous. Certain areas, due to greater recharge, lower outlets or both, have steeper groundwater gradients, hence greater flow. Thus, open channels enlarge more rapidly in these areas and pirate water from smaller, nearby channels. Because steeper groundwater gradients are more common near the headwaters of surface streams than they are further downstream, caverns should be somewhat larger and more common in these areas. Davies (1960) noted this general tendency in areas he studied. If, through stream erosion, groundwater outlets change, caverns should have floor levels corresponding to their past outlet levels. A study of cavern elevations and related river terrace levels done by Davies (1960) showed such a correlation.

Between the surface and the upper phreatic zone some solution does occur. From time to time a "cutter" dissolving downward will intersect a cavern system below. Typically this occurs at the upstream ends of caverns where cavern-to-surface distance is minimum and groundwater gradients are steepest. At first only water flows through the narrow connections, which usually form along fracture intersections where flow is unusually high. As the connection enlarges and the "cutter" system channels more water to the new low point, increasing amounts of soil and other surface debris wash downward, producing a conical sink above the connection. Often the opening of surface connections leads to filling of underground conduits. The temporary base levels of surface streams are suddenly lowered when they are captured and diverted underground. This causes them to start vigorous erosion, which may choke the streams below with surface sediments. As the surface streams' gradients decrease, the amount of inwashing sediment decreases. As a result, underground streams may begin to reopen sediment choked channels. If this is the case, then filling should be more common in the early history of a cavern when underground streams are smaller and less competent. Sedimentation may also result from the ponding of cavern streams by landslides, or glacial till (blockage of an outlet). Internal rock falls may also cause ponding and local sedimentation. There are several cases of ponding for each of these reasons in New York. In areas where many connections develop between surface "cutter" systems and underground cavern systems, a cavern may develop mazes of joint passages capturing the seepage from the "cutters" above. This is most common at the upstream end of a cavern system, where caverns are near the surface. Many caverns in New York appear to follow this pattern.

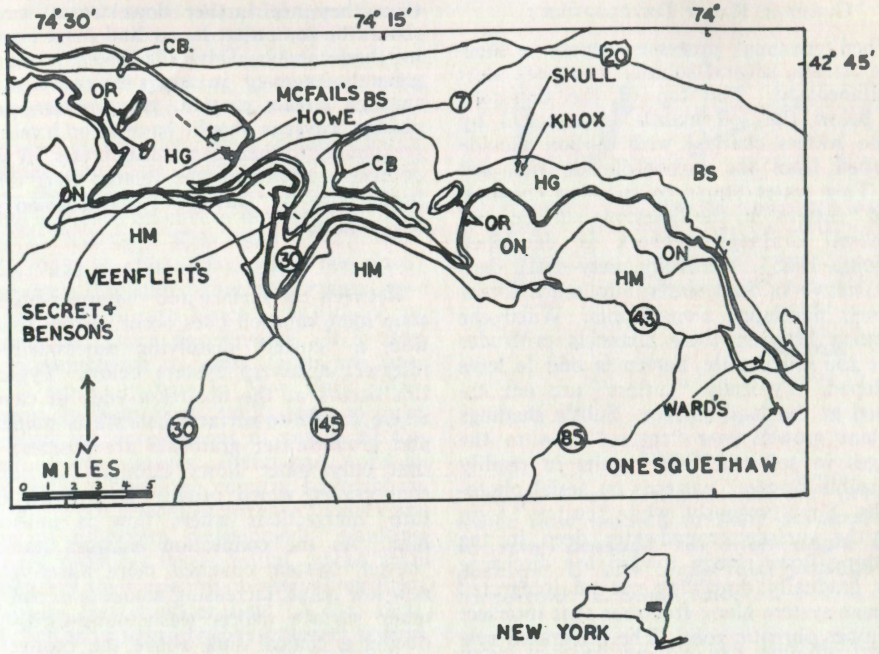

Figure 2.

Eastern New York cavern region. Geology after the geologic map of New York (Fisher, D. W., et al., 1961).
KEY: HM Hamilton Group; ON Onondaga Limestone; OR Oriskany Sandstone; HG Helderberg Group, Becraft-Chrysler Formation; CB Cobleskill Limestone; BS Brayman Shale and Schenectady Formation.

As solution proceeds and passages enlarge there comes a time when the drainage conduits can carry more water than enters them although they may be below the water table. At this time outside air begins to enter and circulate in a cavern system. The entry of air is not a sudden event caused by regional uplift, but simply the consequences of passage enlargement. At first air circulates only during the dry season, but further enlargement may allow air circulation during floods as well. Once outside air has entered a cavern stalactites and stalagmites begin to form and decorate the passages, and man may be able to enter parts of the cavern without diving gear.

When erosion exposes a limestone terrain it not only enables cavern forming processes to start but it also starts processes eventually bringing destruction to caverns as well. Cavern collapse has been presented as a means of destruction of limestone caverns. If this is the case, collapsed caves should be evident in some areas or collapse sinks indicating the beginning of this process should also be evident. In New York, at least, such features are fairly uncommon. However, one cavern destroying process that is also evident is escarpment or slope retreat along major river valleys. Possibly this process should be given more consideration in other cavern areas as well.

Cavern Development in New York

Caverns generally seem to develop according to the patterns outlined above. Those in New York were chosen as examples, because of my familiarity with them through three summers of work in Schoharie and western Albany Counties (fig. 2).

Table 1.
Stratigraphy

Age	Unit	Significance	Thickness Feet
DEVONIAN	Hamilton Group (shales)	Aquiclude	
	Onondaga Limestone	Impermeable chert layers impede cavern formation; this unit contains several known caves.	116
	Oriskany Sandstone, Esopus Shale and Schoharie Grit	Aquiclude	100
	Becraft Limestone	Rarely forms caves	25
	New Scotland Limestone and Kalkberg Limestones	Shaly limestone, no known caves	115
	Coeymans Formation, Ravena Limestone Member	A massive, prominently jointed cave-forming limestone	40-50
	Manlius Formation, Thacher Limestone Member	The main cave-forming limestone; jointed and thin bedded	40-50
SILURIAN	Rondout Formation, Chrysler Dolomite Member	Caves predominantly in the overlying limestones, sometimes extend down into this unit. There are a few caves exclusively in this unit	7-30
	Cobleskill Limestone	Dolomitic limestone, floors many caves	0-9
	Brayman Shale	Aquiclude	

stratigraphy after Rickard, 1962

The main cave-forming limestones in New York are the Thacher, Ravena and Onondaga (Table 1). Bedding dips 2 to 3 degrees to the south-southwest throughout most of the area. The strikes of joint sets are around 20 and 95 degrees. There is some minor folding in the eastern part of the area. Faults are rare and where present, have displacements of a few feet at most. Generally the limestone areas are drained by streams that flow south into larger streams that flow north or east into the Hudson or Mohawk

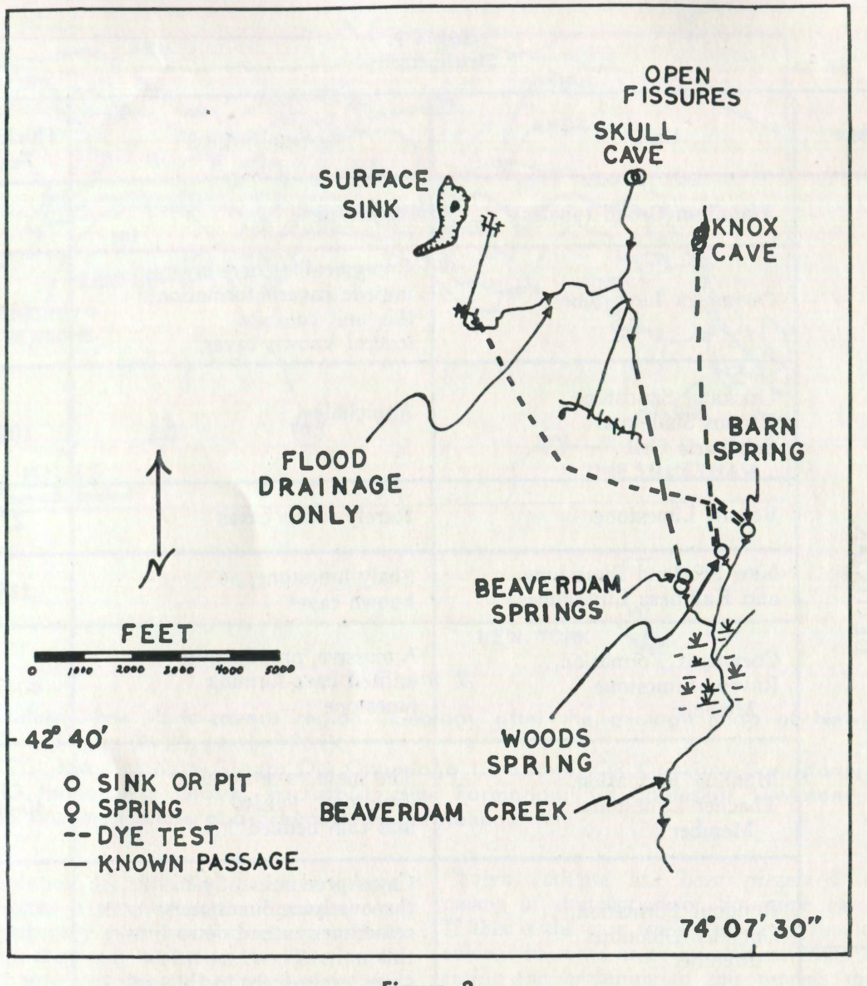

Figure 3.

Hydrologic relations of the Skull-Knox Cave System.

Rivers, along glacially modified valleys.

The Skull-Knox System: Skull-Knox is one of the few large cavern systems in New York state. The caves are in homoclinal beds of the Ravena, Thacher, and Chrysler limestones which dip 2 to 2½ degrees south-southwest. The underground pattern of cavern drainage has been determined by dye tests (fig. 3). Just north of the Skull entrance the ground is scored by intersecting joint-developed "cutters", a few of which are 10 or more feet deep. Nearly all runoff is lost into these fissures and channeled into Skull Cave. This close relationship of the "cutter" and associated cavern systems is typical near cavern entrances, and results from control of both systems by the same fractures. The cavern entrance is located on the Ravena-Thacher contact because the more massively bedded Ravena provides a roof for the cave (Howard, 1963). The northern part of the cave is developed along joints and has a profile similar to that shown in fig. 1a. The water that enters the passage flows along the joints. Further downstream from the entrance the passage has dissolved down into the Chrysler Formation. As this unit is soft and easily removed by corrosion as well as solution, the cave is developed downdip almost entirely in this unit for several thousand feet. The passage, wide and low, can be followed from joint to joint. Joint control is obvious and the even slope of the floor and ceiling indicates solution occurred at one level within the upper phreatic zone determined by the outlet. The lower part of this passage, as well as the rest of the passages in the cave are also joint-controlled. Passage junctions are accordant which may indicate headward development from the outlet within the upper phreatic zone. Well logs in the area indicate that the cave is nearly 50 feet below the present water table in the limestone. To the west there is an extensive maze of passages. This set of passages, entirely roofed, appears to collect water from an analogous system of "cutters" developed above the cave, probably along the same fractures. Another maze, in the southern part of the cave, may have developed in a similar manner. Today this second maze is fairly dry and inactive. Nearby Knox Cave (fig. 3) appears to be a part of a maze developed to feed the Skull system. An electrical resistivity survey revealed a "cutter" system hidden by soil over Knox which corresponded with the passages below, again showing that surface and subsurface solution is controlled by the same fractures, in this case, joints. Today there are no traversable interconnecting passages between Skull and Knox although dye tests indicated that a stream in Skull and one in Knox resurge at the same springs.

The Skull-Knox drainage system is fairly complex. Dye was injected into underground streams at various points in the system to determine their outlets. Curiously enough, the stream in the western part of Skull resurged through springs to the east of the resurgence of Skull's eastern stream. Obviously the two streams must cross at different underground levels. The stream in the western part of Skull disappears into a gravel-choked channel in the Thacher Formation. The main or eastern stream has reached the level of the Roundout Formation where it disappears. Apparently a change in outlet elevation has left one stream perched above the other. In time the upper stream may dissolve down into the lower stream and thus be captured. During the annual spring flood the western stream overflows and runs eastward through an explored passage of Skull Cave into the main stream. This route is labelled "flood drainage only" on figure 3. Probably this drainage route predates the one currently used by the western stream. The new route then must be lower and, hence, probably crosses beneath the main or eastern underground stream. In the future this lower route of flow will enlarge and become able to handle floods as well as base flow.

The close correspondence of surface and subsurface solutional development in the Skull-Knox area shows the strong influence exerted on cavern development by surfaces of maximum flow, mainly joints in this case. The accordance of ceiling and floor levels, and even passage gradients toward outlets, testifies to the importance of the upper phreatic zone in controlling the vertical location of the cave. Presently a new lower outlet has pirated part of the flow to the old outlet. Perhaps this represents headward development of a new passage related to the new lower outlet. A cavern's outlet not only affects the elevation of the upper phreatic zone, but also seems to determine the elevations at which passages form within that zone.

The Ward-Gregory System: Just south of Clarksville is the Ward-Gregory System, a simple fault-plane cavern system developed in the Onondaga limestone (fig. 4). Normally many narrow solution tubes develop in the Onondaga, separated by hard, intercalated cherty layers. Thus, the impermeable chert layers make it rather difficult for a substantial cave to develop. Ward-Gregory did form, however, and is substantial apparently because the chert layers were cut by a low-angle fault striking south-southwest. The cave has developed almost exclusively along the fault. In several places fault striations are present on the ceiling. Nearly all passage cross sections throughout the cave resemble figure 1c. Anastomosing solution channels are common along the fault plane in the cave indicating that it has transmitted a substantial amount of water. Almost all flowstone in the cave is found on the west wall of the cave (footwall) — more evidence of water transmitted into the cave by the fault. The

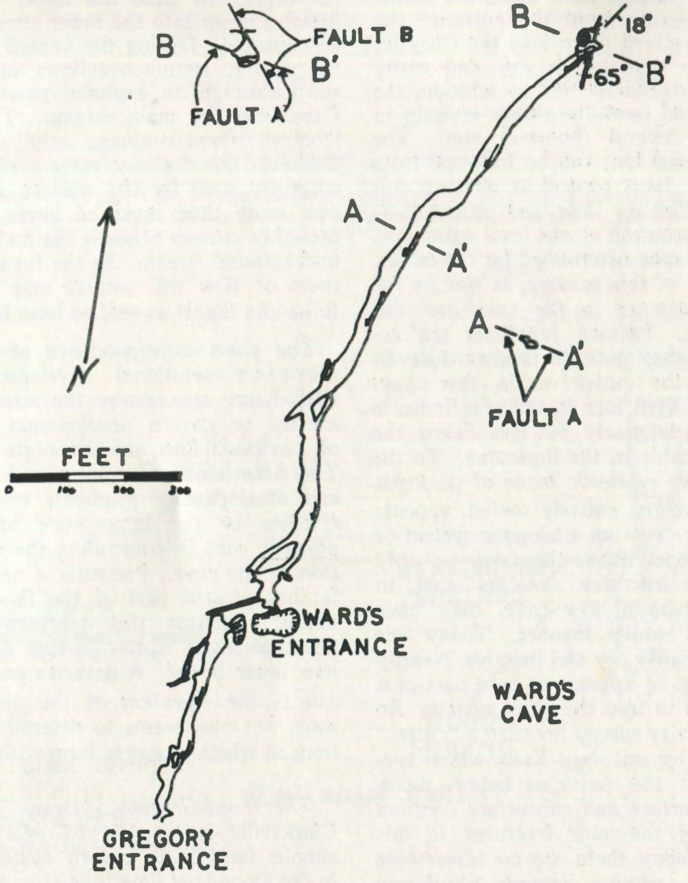

Figure 4.

Faulting and the Ward-Gregory Cave System.

size of the passage, large by New York standards, reflects its importance in cave development.

A second fault crosses the northern end of the cave. This is a high angle fault which produces a passage cross section like that diagrammed in figure 1b. The passage extends to the surface at this point. This fault acts much like a very prominent joint as it does not collect as much water as do low-angle faults. Water in the Ward-Gregory system flows southward down a nearly constant slope along the fault from this point, the upstream end of the cave, southward emerging at a spring on the bank of Onesquethaw Creek. The cave is almost exclusively developed along these two faults. Thus, this cave is an excellent example of a cavern developed at the intersection of a surface of flow concentration, faults in this case, and the zone of solvent concentration or upper phreatic zone.

VeenFleit's Cave: VeenFleit's Cave is developed almost entirely along a fault in the Chrysler Dolomite and Thacher Limestone. This particular fault, dipping 14 degrees southwest and striking northwest, also has several other caves developed along

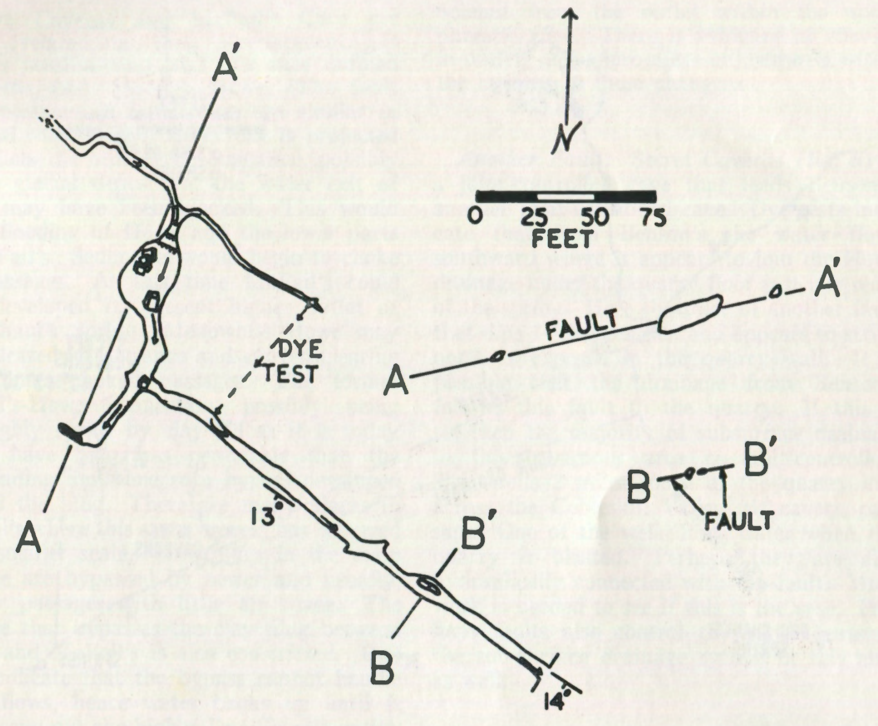

Figure 5.

Map of VeenFleit's Cave showing faulting and hydrologic relations.

it as well (fig. 2 and 5). VeenFleit's has the typical fault plane cavern profile as shown in figure 1c. The northeast side of the cave, or footwall of the fault, contains nearly all the flowstone found in the cave, which testifies to the effectiveness of the fault in transmitting water into the cave. The fault plane is marked by a vein of strontianite. In many places striations are present on the ceiling.

Inside the cave, away from the entrance or water exit, the cave splits into two passages, both of which are along the fault plane but at different levels. Both the upper and lower levels have even slopes and probably represent a change in the elevation of the upper phreatic zone due to a change in the elevation of the outlet. The cavern development is restricted to the intersection of the fault with these two levels of the upper phreatic zone.

Other Caves Along the VeenFleit Fault: The VeenFleit fault extends northwestward from VeenFleit's Cave. Southeast of Howe Caverns the fault is exposed on a quarry face. Several solution tubes are evident along the fault in the quarry face. One of these is part of Howe Caverns. Although one cannot get close to the fault in the quarry due to loose rock, it can be seen that fault movement was a matter of only a foot or two. Due to the thinness of bedding and the disruption of bedding near the fault the direction of motion is not apparent.

Howe Caverns' main passage is developed entirely along the fault. The passage cross section is typical and matches figure 1c. As usual, almost all the flowstone decorating the passage is found along the northeast wall of the cave, or the footwall of the fault, indicating the importance of the fault in bringing water into the cave. A joint-controlled passage, called the "Winding Way," joints the cave from the north. At the northwest end of Howe the fault passage is plugged

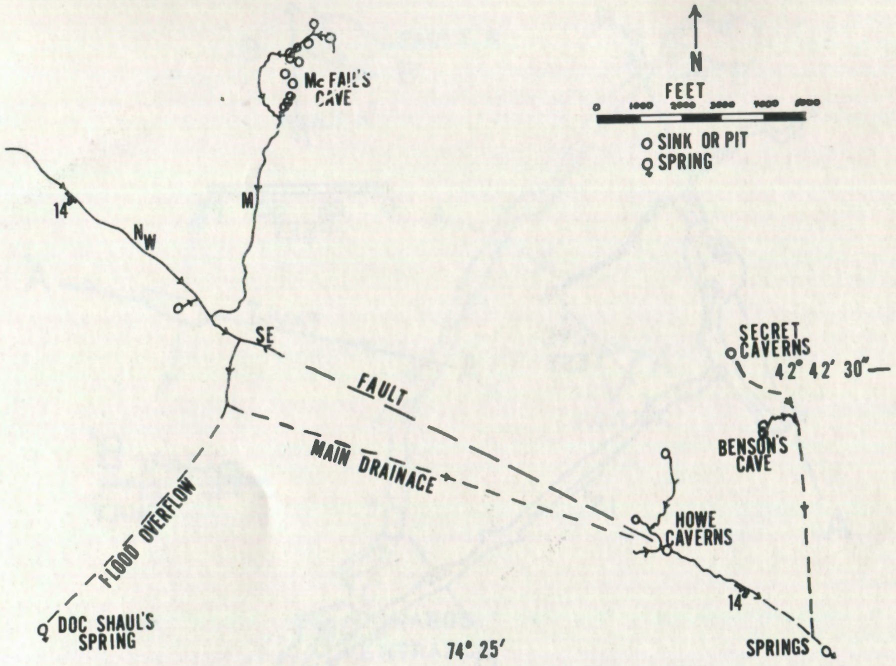

Figure 6.

Structural and hydrological relation of Secret Caverns, Howe Caverns, Benson's Cave, McFail's Cave and Doc Shaul's Spring, eastern New York.

with broken rock and fill. At one time it probably extended as far as McFail's, the next known cave along the fault.

Howe and McFail's are particularly interesting because they both developed along joints and a fault. The obviously greater influence of the fault may well result from its having had a larger initial crack width. The important ability of the fault to collect water from nearby joints is again evident. Control of cavern development was not just a case of faults and joints, but of the upper phreatic zone as well as shown by evenly sloping passages with accordant junctions.

The upper parts of the McFail's system are developed along joints in the Thacher and Ravena limestones. The main stream, designated M on fig. 6, follows the joint sets to the fault plane developed northwest and southeast passages. In the upper reaches of the cavern system in the north, surface "cutter" systems have dissolved down into the caverns below along favorable joints. Nearly all the vertcial drop in the cavern system is near the entrance where the "cutter" system has dissolved down into the graded cavern below. Downstream from the entrance, stream gradients are even with the exception of occasional riffles or small waterfalls held up by less soluble beds. At its southern end the joint-controlled main stream passage has an accordant junction with the immense fault-developed northwest passage. The tremendous size difference between the two passages clearly shows the importance of faults in cavern development. This is expected since faults have greater initial permeability than joints and because of their ability to capture water from several joints thus increasing the amount of solvent available for solutional enlargement.

Howe Caverns and McFail's Cave are closely related in their development. It appears possible that McFail's once drained along the fault through Howe. The fault plane passages in both caves are similar in size and shape and if either one is projected it predicts the other. At some time, possibly due to glacial deposition, the water exit of Howe may have been blocked. This would cause flooding of Howe and the lower parts of McFail's. Sediments would begin to choke the passages. At this time McFail's could have developed its present higher outlet at Doc Shaul's Spring. Meanwhile Howe may have cleared its entrance and started clearing its sediment-choked passages. The former McFail's-Howe connection, possibly being thoroughly sealed by clay fill as it is today would have been less permeable than the surrounding limestone so a bypass developed around the plug. There are many places in McFail's where this same process has occurred on a smaller scale. Clay plugs in the main passage are bypassed by newer and usually, smaller passages with little air space. The passage that bypasses the clay plug between Howe and McFail's is also constricted. Dye tests indicate that the bypass cannot handle flood flows, hence water backs up until it can escape out the higher Doc Shaul's outlet. The bypass will gradually enlarge eventually allowing it to handle floods as well as summer flow. Gradually, the cave is adjusting to its new outlet.

Howe and McFail's are particularly important because they have developed along a fault as well as along joints. This allows a comparison of the relative importance of these features. It is clear, by the sheer size of the fault-plane passages in these caves, that faults are more favorable sites for cavern development than joints. There appear to be two main reasons for this. First, faults are usually more open than joints, allowing greater flow when solution starts and second, faults tend to capture water from joints, by virtue of their larger size, and conduct it along the upper phreatic zone. Hence, more solvent is produced along faults as well.

The relationship of these caverns to fractures is not the only relationship observed. Passages generally show even slopes and accordant junctions indicating vertical control which is probably due to the headward development from the outlet within the upper phreatic zone. There is evidence of changes in outlets and appropriate adjustments within the caverns to these changes.

Another Fault: Secret Caverns (fig. 6) is a joint-controlled cave that feeds Benson's, another joint-controlled cave. Dye tests indicate that from Benson's the water flows southward where it appears to join the Howe drainage under the quarry floor just upstream of the spring. Here the trace of another fault that dips 14 degrees east and appears to strike north is exposed in the quarry wall. It is possible that the drainage from Benson's follows this fault to the quarry. If this is so, then the majority of subsurface drainage in this cavernous area is fault-controlled. Two wells 2 miles south of the quarry and across the Cobleskill Valley hit cavern passage. One of the wells loses water when the quarry is blasted. Perhaps they are also hydraulically connected with the fault. More work is needed to see if this is the case. Perhaps faults also control the major parts of the sub-surface drainage system in this area as well.

Onesquethaw Cave: Onesquethaw Cave is unusual in the area studied because it is formed in folded limestone (fig. 2), which has influenced the formation of the cave. One passage within the cave has developed along the limb of an open anticline. Cracks along bedding planes, possibly enlarged by slippage along them during folding, appear to channel water down the limb of the fold. Joints carry water down into these bedding planes much as they carry water into a fault plane (fig. 1d). In another part of the cave the crest of a tight anticline has dissolved out to form a passage. Here it appears that joints radiating from the fold crest channeled water to the crest, producing the passage as shown in fig. 1e. Davies (1965) has mentioned that in some cases caves on the crests of open folds may develop mazes of interconnecting joint-controlled passages. Probably this type of development is along joints opened during folding. A preliminary look at caverns in Virginia and West Virginia has revealed that these tendencies are not local to Onesquethaw.

Summary

Geochemical considerations suggest that cavern development is favored in the upper phreatic zone. Physical considerations, such as accordant stream junctions, and the gentle gradients of streams suggests vertical control of cavern development. One would not expect such features if caverns developed by random solution beneath the water table and later were entered by surface streams. Where the level of the outlet has changed, caverns show obvious signs of adjustment. In some cases such adjustments were found to be incomplete as in Skull and McFail's.

The caverns studied show clear relationship to faults, joints and bedding, as well as to the upper phreatic zone. The elevation of the outlet may determine the level within the upper phreatic zone along which a passage develops. Fault plane passages tend to be substantially larger than joint passages due to their larger initial size and, hence, their ability to collect water from joints. This feature of a fault was illustrated by the occurrence of flowstone mainly on the footwall side of faultplane caverns. Joint-controlled caverns generally are smaller and more complicated in plan, sometimes forming mazes below surface "cutters" as in the cases of Skull and Knox. Folds, because they produce joints and may open bedding planes, also influence cavern development. Fold limbs act much as low-angle faults while joints at fault crests are more likely to produce mazes. Sometimes the joints associated with smaller folds channel water to the crest producing a passage there. Onesquethaw, the only cave studied in folded limestone showed many of these features. Preliminary study of caves in Virginia and West Virginia shows that these trends are general.

Karst development seems to be a continuing process. It is non-random and hence generally predictable. Future study should make it possible to better predict subsurface water channels and will lead to a better understanding of the processes that formed them. Although many of the ideas presented here may have general application to cavern formation under conditions of unconfined flow in dense crystalline limestones, it is obvious that specific areas may require a different analysis.

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