The Property of Limstone Caves

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Ⅰ. Introduction

Limestone caves are many times as numerous as those in other kinds of rock. They are also unrivaled in size and especially in the distances to which they extend underground. Some individual rooms in limestone caves are larger than any man-made room underground.

Mammoth Cave in Kentucky, for example, in the Flint Mammoth Cave System-the world's longest known cave-is part of a winding series of connected passages with a total surveyed length of over 300 kilometers. Carlsbad Caverns of New Mexico has one chamber whose area is 38,000 square meters-about 14 times that of a football field-and part of whose ceiling is 75 meters above the floor-about one and one-half times the height of Niagara Falls.

Chambers of such enormous volume as these are of course uncommon, and many interesting limestone caves are comparatively small. Nevertheless, these examples show what natural forces can do in the way of underground excavation when given sufficient time.

When engineers drive a tunnel or open a mine, they work as rapidly as they can, amid a deafening clatter of machinery punctuated by the detonation of powerful explosives. Nature, by contrast, hollows out limestone caves in almost complete silence, usually with no other tool than slowly moving, weakly acidified water.

However, nature has, so to speak, all the time in the world. Every large cave is probably at least a million years old. Human engineers do not have such periods of time to work with. Such lengths of time are necessary for the formation of caves, however, because of the slowness of natural processes.

Limestone and marble-the latter being limestone that has been recrystalized by heat and pressure-are composed of the mineral calcite($CaCO_3$). The limestone and marble that now contain caves were formed in ancient seas millions of years ago by marine animals and plants that extracted calcium carbonate from the sea water.

Sand grains composed of fragments of the skeletons of these organisms, together with extremely small grains produced by micro-organisms, were later compacted under pressure and cemented into firm rock. Finally. mountain-building forces uplifted these sedimentary rocks from the sea and exposed them to the air and to the dissolving power of fresh underground water.

Caves have been formed in limestone beds of widely differing ages. Researchers have long determined the relative ages of limestone formations and other sedimentary rocks by studying the fossils that these rocks contain.

It is now also possible to estimate the absolute ages of many rocks within a few thousands or millions of years. We estimate the ages of fossillferous rocks that contain uranium ores from the amount of lead that has accumulated in them through radioactive disintegration of the uranium.

We then infer that a rock containing the same fossils, but no uranium ore, is the same age. In this way we have learned that the limestone containing Mammoth Cave, for example, is about 325,000,000 years old, and that the limestone containing Carlsbad Caverns is about 250,000,000 years old.

The age of a cave, however, bears little relation to the age of the rocks that enclose it. Most caves are very much younger than their enclosing rock. In face, all the important limestone caves in the world, including some in rocks laid down hundreds of millions of years ago, are less than 10 million years old.

The limestone removed in producing a cave is not simply dissolved in water. In fact, limestone is only slightly more soluble in pure water than quartz, the chief mineral of sandstone, and is less soluble than most of the minerals in such rocks as granite and basalt, neither of which ever contains solution caves. Limestone caves are formed when acids attack calcite.

Even such very dilute acids as those in ground water can produce caves if given enough time. We can easily demonstrate the reaction between an acid and calcite in the laboratory by dropping a chip of limestone or marble into a beaker containing dilute hydrochloric acid. The chip will dance and bubble vigorously, and if sufficient acid is present it will finally disappear.

The acid chiefly responsible for the natural dissolution of limestone to form caves is carbonic acid(H_2CO_3), produced when carbon dioxide, the universal product of plant decay and animal respiration, combines With water. Carbonic acid is weak, even at maximum concentration. The outside atmosphere contains 0.03 percent carbon dioxide but the carbonic acid produced from this is too dilute to be very effective in forming caves. Most of the carbon dioxide responsible for creating the acid that dissolves limestone to produce caves comes from the soil, where decay of soil humus produces large amounts.

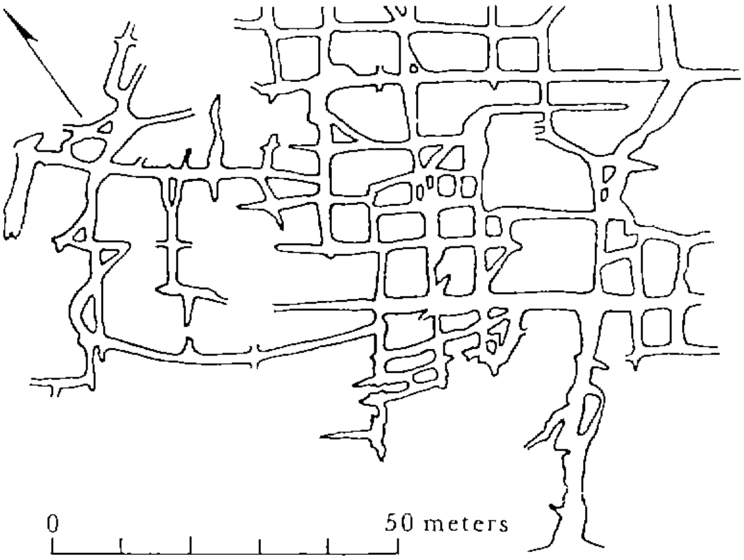
Carbon dioxide and water work together to remove limestone by means of this double reaction:

$$\overset{\text{carbon dioxide}}{CO_2} + \overset{\text{water}}{H_2O}$$

$$\downarrow$$

$$\overset{\text{carbonic acid}}{H_2CO_3} + \overset{\text{calcite}}{CaCO_3} \rightarrow \overset{\text{calcium bicarbonate solution}}{Ca^{2+} + 2HCO_3^-}$$

The carbon dioxide combines with water to produce carbonic acid, which in turn attacks the calcite and divides it into soluble ions. A cubic meter of water exposed to air containing 10 percent carbon dioxide, if kept in contact with limestone until the reaction ceases, can dissolve about 250 grams of calcite.



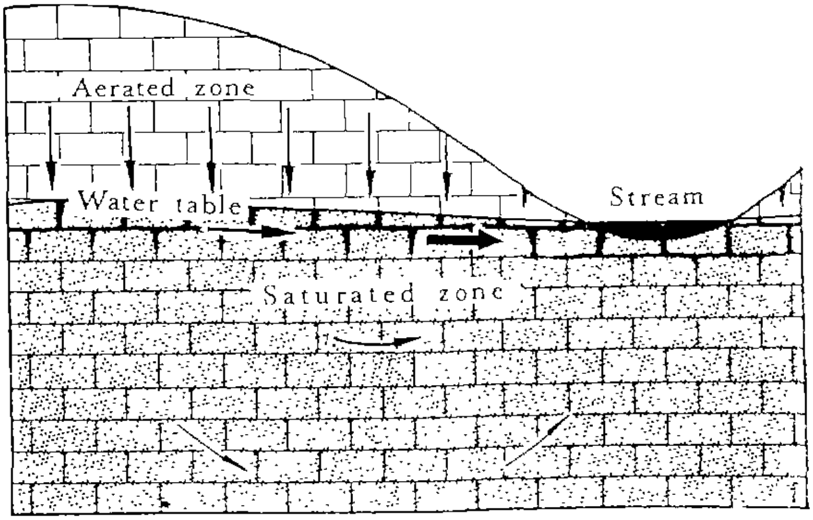
II. Formations by Slowly Moving Water

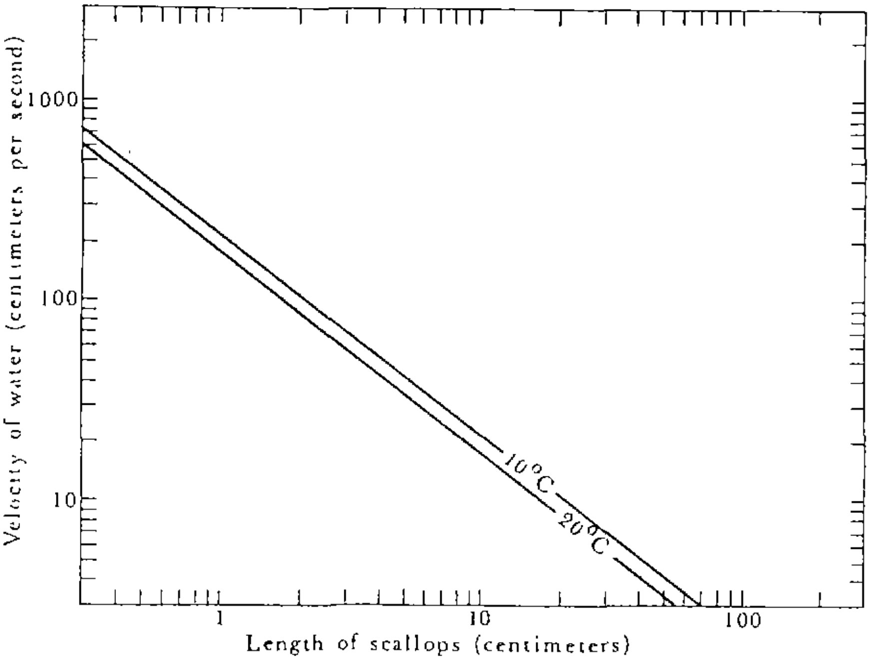
Until the Present century, scientists generally supposed that caves had been made by underground streams, just as valleys are made by surface streams. Compelling arguments against this idea, however, were offered by the Austrian geologist Alfred Grund, and by the American geologist W. M. Davis.

They point out that the shapes of cave passages do not resemble passages formed by downcutting streams. Cave passages usually form a network, so that cave maps often look like maps of cities with many intersecting streets. Such a grid is quite different from that made by many surface streams, where the pattern formed by tributaries joining the main stream is often like that of a branching tree.

Scientists now believe that most caves were formed by slowly moving water in the zone below the water table, which is the level below which the rocks are water-saturated.

A second line of evidence against the hypothesis that caves are formed by underground rivers is that cave walls generally are smooth or gently undulating. The beds of fast-moving streams on limestone are never smooth. In those places where surface streams flow on limestone, or Where a stream has entered a previously existing cave, the bed of the stream is always pitted with small solution pockets, known as *scallops*.





These distinctive indentations, which are usually a few centimeters to 1 meter across, have steep slopes on the upstream side and gentle ones on the downstream side. Scallops, therefore, are sometimes useful for determining the direction of flow of former cave streams, although they are usually present only in small parts of a cave system, or not at all. When scallops are present, they were formed by a stream that penetraed the cave late in its history, and they lie near the floor, below a definite high-water line.

The absence of small scallops in the greater part of most limestone caves supports the hypothesis that the caves were not formed by underground streams, but by slowly moving water, and thus, by implication, below the water table.

Ⅲ. Distribution of Cave Passages

Where a layer of limestone is interbedded with insoluble rock cave passages appear only in the limestone. If the limestone bed is thin, it is possible to predict the directions in which undiscovered passages might be found. Besides the distribution of soluble limestone, two other factors control the distribution of cave passages vertical to horizontal fractures in the limestone, and the water table, which forms a horizontal plane that determines the level at which many cave passages are formed.

The fractures occurring in limestone are of three types: (1) *partings*, which are parallel with the bedding; (2) *faults*, which cut the bedding and along which it has been displaced; and (3) *joints*, which cut the bedding but along which there has been no displacement.

Partings follow thin silt or clay layers laid down with the limestone. Faults are caused by mountain-building forces that fold the rocks until they break. Joints occur in both folded and nonfolded rocks. They are thought to be caused by Earth tides, which produce a gentle flexing of the rocks.

Earth tides have the same cause as ocean tides-the solid part of the Earth, like the water of the oceans, is attracted by the Moon and the Sun. Earth tides average only about 30 centimeters in height. The resulting joints may be compared with fatigue cracks that form in metal when it is repeatedly bent back and forth. Joints may take thousands of years to form, because the tidal flexing occurs only twice daily, and the displacement on each joint is very small.

Of the three types of fractures, faults are the least important to speleology, because in most cave regions they are rather rare and widely spaced. The shapes of cave passages are controlled chiefly by joints and partings that occur at least every meter in limestone. beds. When the limestone beds are horizontal, cave maps often show passages following two sets of joints intersecting approximately at right angles to each other. When the limestone beds have been tilted so that they dip steeply, the main cave passages are generally elongated along the strike-the direction of the line along which the limestone beds intersect the horizontal-and short passages extend along joints at right angles to these main passages.

Ⅳ. Enlargement of Cave Passages

The rate of horizontal movement of water in the small fractures below the water table is commonly less than 10 meters per year, whereas in cave-sized conduits it averages 0.2 kilometers per hour. The water first moves downward through cracks to the water table, then collects in joints and partings below the water table, and finally moves through the limestone to points of discharge at springs.

When the fractures are small, the water becomes saturated with calcite soon after it descends below the water table, so the early stages of solution are very slow. During this period, flexing by Earth-tidal action along the joints may help to pump the water along. Acids produced within the rocks by oxidation of sulfide minerals in the limestone may accelerate the process of dissolution in places and permit it to operate at considerable depth below the water table.

The rate of flow is at first about equal through all the joints, but as some channels grow larger than others, they take in more water and therefore grow faster. When a channel reaches a certain critical size-about 5 millimeters in diameter-it subsequently grows at such a fast rate that it greatly outpaces adjacent channels, takes nearly all the water flow, and hence grows even faster.

We are not certain why a diameter of 5 millimeters is critical in the development of cave passages. One possibility is that at this diameter the flow of water in the channel becomes turbulent. When water is sufficiently undersaturated, the start of turbulence in a limestone channel greatly increases the effectiveness of the dissolution process. The action is similar to stirring sugar to dissolve it-fresh undersaturated solution is constantly being brought into contact with the solid.

William B. White has noted that among waters undersaturated with respect to calcite, a great acceleration in rate of dissolution occurs at a critical level of saturation. Water slightly undersaturated dissolves calcite very slowly, whereas water only a little more undersaturated dissolves it very rapidly. White's studies suggest that the critical level of undersaturation usually occurs at a channel diameter of approximately 5 millimeters-the same diameter at which turbulence also begins.

When these two factors affect a channel-critical undersaturation and the start of turbulence-the channel robs nearby fractures of their flow. The channel then being enlarged at an accelerating rate, ultimately grows into a cave passage, while its remaining neighbors never exceed 5 millimeters in diameter.

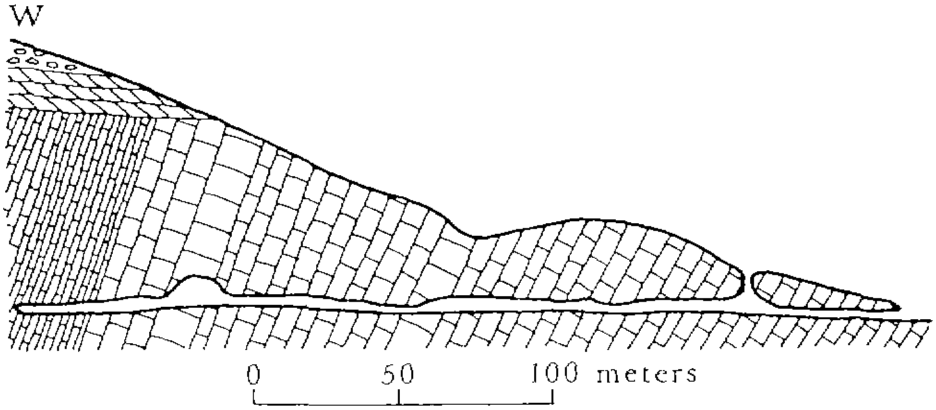
V. Origin at the Top of the Water-Saturated Zone

Although the characteristic network pattern and the absence of scallops on the walls show that most caves were formed by slowly moving water below the water table, the exact depths at which caves form are not shown by these types of evidence. However, another observation-that many cave passages are horizontal-suggests that the horizontal water table may have an influence on the origin of caves.

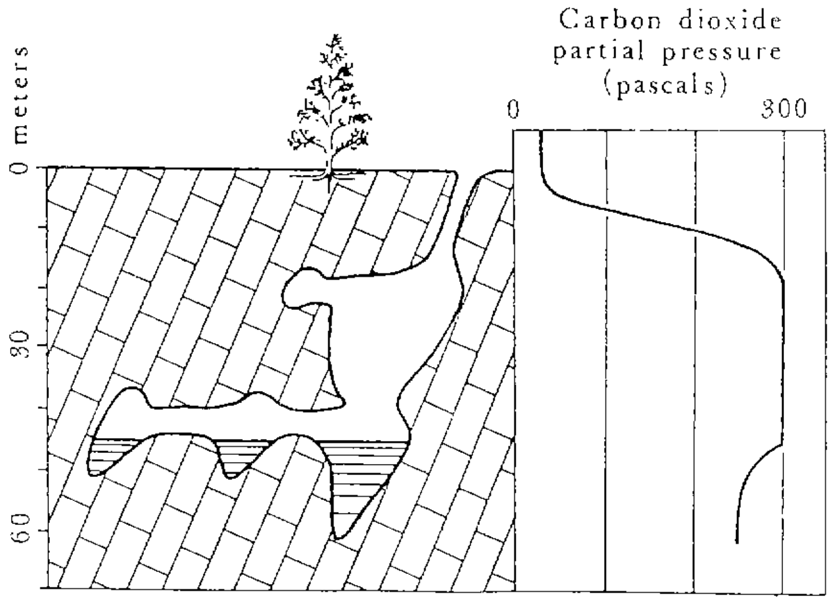
In caves where the limestone beds themselves are horizontal this might seem to be a sufficient reason for the horizontality of the cave passages, but cave passages are horizontal even in areas where the limestone beds are folded or steeply dipping. Moreover, recent work in very large cave systems in nearly flat-lying limestone, where speleologists formerly thought that the cave passages merely followed the most soluble beds, has shown that even here the passages cut slightly across the bedding of the limestone.

These passages are controlled by a nearly horizontal plane that is not precisely parallel to the bedding. In view of this evidence, many modern investigators agree that most limestone caves have been formed in a relatively thin horizontal zone directly below the water table.

We believe that cave passages form directly below the water table because of a combination of several factors: (1) the carbon dioxide content in this zone is relatively high; (2) unlike the down-ward-moving water above, the water below the water table is in contact with the limestone long enough to become fully saturated with calcium carbonate; and (3) because of a nonlinear relation between carbon dioxide content and calcite solubility, mixed down- ward-percolating water and ground water has a greater dissolution capacity than either of these waters alone.



Many caves are nearly horizontal, as shown in this profile of Lehman Caves, Nevada. Such caves are thought to have formed directly below a horizontal water table.

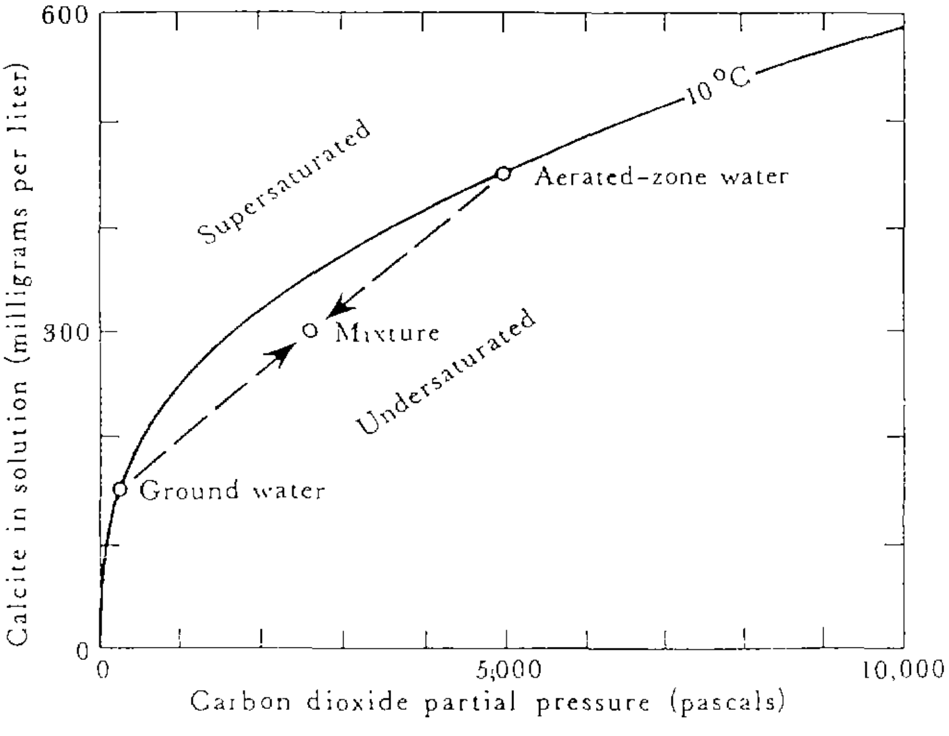


Carbon dioxide content of the water and air in Black Chasm Cave, California, and of the air above the cave, in May 1962. The underwater samples were collected by a diver. The carbon dioxide of the water, and therefore its carbonic acid content, is greatest near the water surface.

To clarify these factors further: Water containing carbon dioxide derived from the soil moves downward so rapidly in the aerated zone that it may dissolve only a small fraction of the limestone that it could dissolve if given enough time. When this water discharges into the main body of ground water below the water table, it may still contain unneutralized carbonic acid.

But even if the water from the aerated zone is saturated with calcite, and the water below the water table is too, their mixture has the capacity to dissolve more limestone. That is, the mixing of two waters that have different carbon dioxide contents, both saturated with calcite, leads to an undersaturated mixture that has excess carbon dioxide and thus is capable of dissolving more limestone. This phenomenon results from the fact that calcite dissolution is more sensitive to an increase in carbon dioxide content at low carbon dioxide levels than at high levels. Therefore, any mixing enhances dissolution.

As a result of the excess carbon dioxide in water near the water table, the small cavities directly above the water table acquire a high and uniform carbon dioxide content. The carbon dioxide diffuses downward from these cavities into the upper layer of the ground water, imparting an almost constant dissolving capacity to the water near the top of the water-saturated zone-a capacity much greater than that of the water far below the water table.



Master channels therefore tend to form in a limited vertical zone directly below the water table. As they become larger, nearly all the water movement below the water table is in this zone. The dissolved calcium carbonate is carried along a very gentle slope at the top of the saturated zone, sometimes for a distance of many kilometers, to outlets along stream valleys.

Water which enters a sinking stream at the surface usually has a low content of dissolved limestone and a low concentration of carbon dioxide (equal to that in the surface atmosphere). In this state the water can dissolve little more limestone. When it enters a water-filled conduit that is insulated from the outside atmosphere, however, it absorbs more carbon dioxide from the main ground water body, and the amount of limestone that it takes into solution is greatly increased. This helps the throughgoing conduits to grow much faster than the intervening narrow solution cavities.

This cave-forming process may continue for thousands of years. Only two things can stop it-a lowering of the water table, or the formation, by surface erosion, of air passages into the cave system, The lowering of the water table drains the cave, which means that dissolution either must cease or must continue at a lower level, perhaps until a lower system of cave passages has formed. The opening of a cave entrance or other air passages usually marks the end of the cave-forming process.

Because the entrance allows ventilation to begin, the high partial pressure of carbon dioxide can no longer be maintained in the cavities above the water table. The excess carbon dioxide is dissipated, the water quickly becomes saturated or even supersaturated with calcite, and the dissolution process ceases. Usually, in fact, this change marks the beginning of a reverse process, the deposition of calcite in the form of stalactites and other characteristic deposits.

At approximately the moment when a cave becomes accessible to people, therefore, it begins to be decorated by the features that mean most to the average visitor. But that moment is only the beginning of the process: the elaborate decorations in our most beautiful caves have been forming for thousands of years and will continue to form as long as water continues to percolate downward from the surface.

Ⅵ. Stages of Limestone-Cave Evolution

The formation of limestone caves is directly related to the development of the overlying land surface. Many instances of nearly horizontal cave passages occur in areas of modern mountain-building activity, where earthquakes are common and young sediments have been noticeably tilted. For example, the caves at Lehman Caves National Monument have nearly level passages, even though the mountain range in which they lie has been conspicuously tilted within the past 5,000,000 years.

This shows that limestone caves are, geologically speaking, very young and short-lived. Never more than a few million years intervene between the initial stages of a cave and the time when it is destroyed by the collapse of its roof.

Limestone caves usually develop in four stages: (1) the initial enlargement of joints and partings by ground water in the water Saturated zone: (2) the development of master channels directly below the water table during a period when the altitude of the water table is relatively stable and a high partial pressure of carbon dioxide exists at the top of the water-saturated zone; (3) a transitional stage, in which nearby streams have cut down to the point where their seasonal fluctuations strongly affect the level of the water table in the cave, sometimes introducing river silt into the cave system; and (4) the further lowering of the water table and downcutting of the surface until an opening to the surface is created, the carbonic acid content of the cave water consequently becoming so low that the water ceases to dissolve the limestone.

Meanwhile, the acid content in the aerated zone between the soil and the cave remains high.

In the final phase of this stage, therefore, surface sinkholes enlarge by dissolution until some of them join, and the roof of the cave progressively collapses and is eroded away.

Ⅶ. Vertical Shafts

Late in the history of a limestone cave, after the water table has been lowered and air has largely replaced the ground water, some sculpturing may take place. It is during this period that a surface Stream may enter the cave, carve notches on its walls, and leave a record of scallops and stream sediment. During this stage, also, underground vertical shafts may be cut through the horizontal cave passages. Such vertical shafts are often called domepits because from below you look up at a dome, and from above you look down into a pit.

Domepits are usually between 1 and 10 meters in diameter, with vertical extents of up to 50 meters. Their walls are characterized by vertical grooves, which contrast sharply with the smoother walls in most other parts of caves. Unlike most horizontal cave passages, which bear little relation to surface topography, domepits generally lie under the heads of stream valleys, beneath the centers of sinkholes, or along a line where a layer of impermeable non-carbonate rock cover has been eroded off the limestone.

Water often showers down inside a domepit. Even the casual observer gets the impressthat these features are younger than the main cave system, and that their formation often has no relation to the position of the older main cave passages. Commonly only a narrow slot connects a domepit with an older main passage. And domepits often extend to the present water table although the main cave passages may be high above it.

E. R. Pohl has shown that domepits are cracks or joints that have been enlarged through dissolution by water which moves rapidly from the soil down toward the water table. The distinctive vertical grooves on the walls of the shafts are caused by a film of water modest carbon dioxide flowing down the walls. The water retains a content, usually acquired during lateral flow in noncarbonate material, and it has not been in contact with limestone long enough to exhaust its capacity to dissolve.

Most domepits are still being formed today by solution under aerated conditions, a process quite different from solution at or below the water table by which the main passages of most caves were formed.

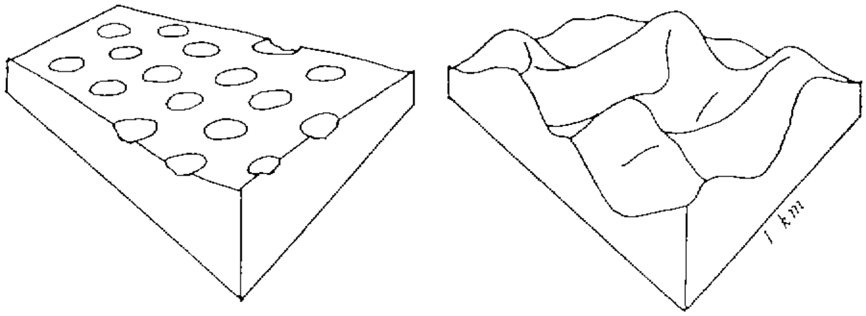
Ⅶ. Karst

Rock dissolution, which is so important to the origin of limestone caves also affects the land surface in cave areas. and this leads to a distinctive topography known as karst. The word *karst* is derived from Slovenian, either from *kar*(rocky) or *hrast*(oak), and was first used by Austrian map makers in 1744 as a name for the rocky oak-forested karst and cave region that lies in northwestern Yugoslavia and northeastern Italy.

The word has since been generalized to mean any terrain where the topography has been formed chiefly by the dissolving of rock.

Karst areas commonly have inward-sloping depressions at the surface, and the drainage is subterranean through caves. Bare rock in karst regions is usually covered by U-shaped solution grooves or channels, from about 1 millimeter to 1 meter across, separated by sharp ridges. Where the rock is covered by soil, or where the soil has recently been removed, rounded fissures may occur along joints,

Karst is characterized by several different types of large-scale topographic features that are gradational with one another. Within cave areas of the humid-temperate parts of the United States and Europe, the usual type is *sinkhole karst*, characterized by funnel-shaped depressions. These sinkholes have dimensions most commonly measured in meters or tens of meters. The upper level of sinkhole karst forms an otherwise continuous surface, interrupted by the sinkholes, which in many places impinge against one another.



Temperate-karst sinkholes (left) average about one-tenth the diameter of tropical-karst cockpits (right). The cockpit karst requires an average temperature of at least 18°C, a rainfall of 1200 millimeters, and rapid mountain uplift

Humid-tropical cave areas, such as Puerto Rico and southeast Asia, are distinguished by two related types of karst. The first, *cockpit karst*, consists of a terrain made up of conical hills alternating with polygonal or star-shaped depressions, the whole resembling a molded egg box.

The second, *tower karst*, consists of more widely separated steep-walled hills rising from flat valleys or plains. Such tower-like hills, with rocky overhanging cliffs, usually have caves at their bases, and have often been depicted in the art of southern China.

The lowland flats in the tower karst of tropical regions are perhaps related to large basins in temperate karst regions known as *interior valleys*. An interior valley is an enclosed depression several kilometers in diameter that has a flat floor and steep walls. During the rainy season, springs feed streams that cross the fertile alluviated floor of the valley and sink into caves on the lowest side.

During especially heavy rains the caves may not be able to handle the runoff, and within a few hours the interior valley becomes a lake. Later, at the end of the rains, the lake may disappear as quickly as it formed.

The presence of soil, and its nature and distribution in different climatic zones, is believed to be an important factor in the development of the various types of karst. The cliffed walls of karst towers and of interior valleys are clearly related to rapid solutional erosion under a soil blanket in the valley and at the foot of the cliffs. This alluvial blanket forms a cover that holds in carbon dioxide which combines with surface water to form weak carbonic acid that speeds the process of dissolution.

The development of karat features requires that the process of dissolution be faster than other types of erosion that affect all rocks. Where moisture is sparce or temperatures usually low, the distinctive karst landforms develop only poorly. Hence, in cold and arid lands, where dissolution is slow, limestone forms mountains, whereas in warm and humid areas, where dissolution is rapid, it forms lower topography than other types of rock nearby.

The speed of erosion in typical karst areas is such that karst tends to be ephemeral, because limestone in humid climates tends to erode rapidly to base level. As a consequence, the great karst and cave areas of the world are in two settings: regions of rapid mountain uplift, and regions where limestone beds are being exposed by the erosional retreat of a nonsoluble rock cover.

Ⅸ. Caves not in Limestone

Three types of caves besides limestone caves are important to speleology-sandstone caves, sea caves, and lava tubes.

Sandstone caves were widely used for shelter by early peoples, who liked them all the better for their being shallow. Deep limestone caves were too wet, cold, and dark for comfortable habitation. Sandstone caves are formed at the bases of cliffs, where certain parts of the rock are less well cemented than other parts.

Surface water moving down the cliff dissolves away the cement in those areas and causes the sand grains to fall apart and be removed. At the same time, upper sandstone surfaces get harder because additional cement is deposited there from water drawn to the surface by capillarity. Good examples of sandstone shelter caves are those that contain the famous cliff dwellings at Mesa Verde National Park in southern Colorado.

Sea caves are somewhat similar to sandstone shelter caves, except that they occur along the shore. They are formed at the base of sea cliffs at places where one part of the rock is more easily eroded than the adjacent rock, allowing wave attack to remove it more easily. Sea caves are usually formed along vertical zones of weakness, such as faults or steeply dipping beds of softer rock.

Since the waves can attack only the base of the cliff, the weak zone retreats faster there than it does higher up; the higher part of the cliff therefore remains as a roof for the cave. The Pacific coast of the United States has an especially large number of sea caves, some of which, like Sea Lion Cave in Oregon, are tourist attractions.

Lava tubes occur in areas where basaltic lava has recently flowed from volcanoes. A tube forms when a tongue of lava. flowing down a marked slope, solidifies on its outer surface, while the interior remains molten and continues to flow. When the liquid lava has drained out of the interior of the tongue, a tubular cavity remains.

A newly formed lava cave does not have an entrance at the level of the floor, but a thin part of the ceiling commonly collapses after the lava has cooled, and thus forms an opening through which the cave can be entered. Lava caves can be many kilometers long and can branch in both the upstream and downstream directions of lava flow.

Almost all areas of young basaltic rocks contain some lava caves, and many of those in the western United States and Hawaii are visited by tourists.

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