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THE ORIGIN OF LIMESTONE CAVERNS

By W. M. DAVIS

PROFESSOR OF GEOLOGY, EMERITUS, HARVARD UNIVERSITY

INTRODUCTION

CAVERNS in massive limestones are usually more or less filled with dripstones, and thus exhibit the work of two contrasted processes: excavation and replenishment. The first process, as generally understood in the United States, is taken to be the solutional work of percolating vadose water (water descending from the land surface to the water table) associated with the corrasional work of vadose or water-table streams. No adequate explanation for the change of process from excavation to replenishment is usually given with this explanation.

Another explanation of caverns was proposed by Grund in 1903.[1] He suggested that they are the solutional work of ground water below the water table during a lower stand of the cavern region; and that when the water filling is withdrawn in consequence of regional elevation, dripstone deposition begins.

I have attempted to work out the consequences of these two rival explanations, with special attention to their application in regions of level-bedded limestones; and then to confront the unlike consequences with facts of observation in the hope of determining which explanation works best. A fuller discussion of the problem is presented in the *Bulletin* of the Geological Society of America for 1930. The statement here given is assertive rather than argumentative.

CAVERNS EXCAVATED ABOVE THE WATER TABLE

The joints and bedding planes in a mass of recently uplifted, level-bedded limestones are here assumed to be close-fitting. Minute water ways will be opened along them, especially on lines of intersection, and a complex, angular, three-dimensional network of tube-

[1] Alfred Grund, "Die Karsthydrographie." *Penck's Geogr. Abhandl.*, 7, 103–200, 1903.

like crevices will be thus developed. At an early stage the crevices may be water-filled nearly to the land surface, because their narrowness makes water movement through them very slow; and during this stage it is ground water rather than vadose water which occupies them. But as subaerial valleys are deepened and as the lower paths of the sheet-like crevices are enlarged to linear passages, the water table will sink to the levels of near-by valley floors. All the crevices and passages above it will thereafter be occupied only by vadose water and ground air.

When the passage diameters reach or exceed those of a stove pipe or a barrel the passages may be called shafts and galleries. Then vadose streams, running with free surface on gallery floors and carrying some sediment from surface sinks, will corrade as well as dissolve the bed rock. The streams in the higher galleries will be segmented wherever new shafts are opened, and the further enlargement of such galleries will be much retarded. But at the same time the lowest galleries, nearly coincident with the water table, will be actively enlarged by their growing streams. A process of natural selection then becomes operative, by which the three-dimensional network of water passages, earlier opened at various levels, will be reduced to a two-dimensional branchwork at the lowest levels; and the branch-work galleries will then be worn down to grade with respect to the valley floors into which their streams discharge. The subterranean branch-work will resemble that of a subaerial stream system in having many small and slender twigs near its divides, where the amount of water available for their maintenance is small, and in the down-stream union of many twigs and branches in a trunk.

As this work advances the high-level galleries, little enlarged, may be nearly filled by deposition of calcite. Furthermore, solution in the lower galleries will probably be exceeded by corrasion; for the streams will cut downward until grade is reached, and laterally thereafter. At the same time solution will be lessened, because with the development of surface sinkholes the shafts at their bottom will so promptly receive most of the rain water that it will be little carbonated. Besides, solvent action by vadose trickles ceases when they become saturated, but corrasion continues as long as sediment-bearing streams run. It seems therefore that the part played by carbon dioxide in cavern excavation has generally been exaggerated.

When good-sized, low-level branching galleries are thus excavated, their floors should be worn down to even gradients; rock falls from roof and walls may cause local and temporary irregularities. But the walls and roof should not show marks of stream wear, because early-made marks of this kind would be removed by rock falls during gallery enlargement. The side walls may, however, show flutings formed by the solvent action of vadose trickles; but such flutings are subject to intermittent removal by rock falls.

During all these changes the branchwork pattern of the streams and their galleries will be more and more perfected. The general acceptance of this view is illustrated in the following passage by Meinzer regarding the underground drainage of limestone regions:

> Percolating water gradually dissolves and removes the limestone and thus produces large underground channels [galleries]. By this process a system of underground drainage may be developed which is comparable to a surface drainage system in another [non-soluble] terrain. The underground streams, like the surface streams, become adjusted to some base level, such as the sea, a lake, or a major surface stream, into which they discharge, and they tend to become graded to this base level by the laws of stream gradation.[2]

In the meantime the general down-wear of the land surface, especially on the slopes of growing sinkholes, will convert the originally even upland into a mature or karst surface of deep hollows separated by sharp edges, peculiar to limestone regions. Then as such down-wear continues and the karst forms are subdued, the ever-enlarging, low-level galleries will be locally converted into open or blind valleys by the collapse of their roofs and the gradation of their walls. Eventually all the roofs will be removed, all the walls will be worn down, all traces of the caverns will vanish and a nearly featureless peneplain will result.

The opportunity for dripstone development offered by the main galleries of such caverns is not good, even at their maturity, because their ground air is moistened by the streams. It should be noted that, under this explanation of caverns in level limestones, their excavation is the work of only one cycle of erosion; indeed, of only the youthful and mature stages of one cycle, for during the older stages the previously excavated caverns are destroyed. Caverns thus formed are therefore at their best during the karst stage. However, if a limestone region in that stage of its cycle suffers regional elevation, in consequence of which new branchwork caverns are developed at a lower level than before, the first-formed, upper caverns will be deserted by their streams, and dripstone deposition will then, as Weller has shown,[3] go on apace before the upper caverns are unroofed by general surface degradation.

[2] O. E. Meinzer, "Relations of Ground Water Conditions to Leakage of Reservoirs." *Am. Inst. Min. Engrs. Tech. Pub.*, 215, 1929.

[3] J. M. Weller, "The Geology of Edmondson County . . . [Kentucky]." *Ky. Geol. Surv.*, 1927.

CAVERNS EXCAVATED BELOW THE WATER TABLE

Following King's results[4] it would seem that, at an early stage in a cycle of erosion, ground water may make a deep descent beneath uplands before its ascent toward discharging springs in valley floors is begun. But when maturity is reached in a limestone region, much underground water may flow as water-table streams without making so great a descent. Yet even then some of it must circulate slowly at greater depths. This is assured by the depth at which water is encountered in deep wells. For example, Bain mentions[5] a well 1,750 feet deep in a valley that is 750 feet below the adjacent limestone uplands in southern Missouri, and infers a circulation to a depth of 2,500 feet beneath the uplands. It is the solvent action of this deep and slow moving ground water that is now to be examined.

As with vadose water the movement of ground water must be at first chiefly along intersections of joints with each other and with bedding planes. A complex, angular, three-dimensional network of fine crevices will therefore be developed in this case also, but more slowly than by vadose water, because deep-lying ground water is almost stationary; also because deep-descending water will be partly charged with calcite at the beginning of its descent. The fine crevices will, however, be gradually widened into shafts and galleries, all of which must remain water-filled, to whatever size they grow. Unlike the high-level crevices and passages in the network above the water table, none of the low-lying crevices below the water table will be deserted, however small they are, by the withdrawal of water to lower and larger ones. All will continue to grow. Hence the three-dimensional network will here be preserved, instead of being converted into a two-dimensional branchwork. But like the vadose branchwork, the ground-water network should be of smaller dimensions near the divides and should increase in size toward the main valleys. Yet unlike the vadose branchwork, gallery floors here will not be graded; they may ascend and descend somewhat irregularly.

Narrow and deep galleries may be dissolved out along master joints, but their angular turns from one joint to another need not be rounded off, as they should be if similar joints are followed by vadose streams at higher levels. Broad and low galleries may be dissolved out on especially soluble layers; and several such galleries may be developed simultaneously at different levels. Their breadth will be determined largely by the strength of their roof. Rock falls from roof and walls may take place as galleries are enlarged; hence both roof and walls may have forms of two kinds: forms of solution, whatever such forms may be, and forms of fracture. The fallen blocks will be gradually dissolved away, and the first-fallen, lower members of a slowly growing heap should be most rounded by this process. In large galleries the later fallen blocks should rest on a floor of clay, the insoluble residue of the dissolved limestone; and when such a floor cover is well developed, further enlargement of the gallery should be only upward and laterally. No dripstones can be formed while the water-filling is present; but if the solvent power of a saturated water-filling is diminished by any cause, crystals of calcite may be deposited on the walls, thus making the cavern resemble an immense geode.

The time factor is here of great importance. The excavation of deep-lying caverns in a limestone region by ground-water solution may continue during an entire cycle of erosion, during which so much of the upheaved limestones as stand above peneplain level will pass through all the changes of surface and cavern forms described above, until peneplanation is reached. As calcite is soluble in about 70,000 times its volume of non-carbonated water, the increasing volume of ground water in a growing cavern must be changed many thousand times during the cavern growth. But as the duration of a cycle of erosion may well be several million years, the time available for these changes in a cavern beneath a peneplain is enormously long. At least several months may be allowed for the supply and withdrawal of the water in crevices an inch in width, and in passages of knitting-needle or stove-pipe size during early stages of growth; and one or more centuries in great galleries at late stages of growth. Such periods of time would seem long enough for the ground water to become saturated. In the tomb-like stillness of large galleries, solution in slow-moving water may be aided by diffusion and also by a slow convection, due to the sinking of saturated water in contact with roof and walls and its replacement by less saturated water from below. Moreover the quick descent of rain water down sinkhole shafts during maturity will be changed in the later stages of a cycle, when the land surface is subdued to low relief or worn down to a peneplain, to a slow percolation through the residual soils, and the descending water will then have a good chance of becoming carbonated. Furthermore, the water table then lies so little below the surface that the descending water need not have become saturated when it reaches that level, and will therefore continue its solvent action at lower levels. On the other hand small differences of head beneath a peneplain will retard ground-water circulation and thus lessen its solvent power; but with increasing size of shafts and

[4] F. H. King, "Movement of Ground Water." *Nineteenth Ann. Rep. U. S. Geol. Surv.*, 1899, Pt. 2, 59–294.

[5] H. F. Bain, "Lead and Zinc Deposits of the Ozark Region [Missouri]." *22nd Ann. Rep. U. S. Geol. Surv.*, Pt. 2, 23–227, 1901.

galleries a given head will cause a less sluggish circulation.

In case some of the ground water, coming from deep sources, is more or less charged with carbon dioxide, as Emmons has suggested in his study of ore-filled cavities in the limestones of the Mississippi Valley,[6] the rate of cavern excavation would be accelerated; and in such cases, the escape of some of the carbon dioxide in consequence of diminution of pressure with ascent might provoke deposition of calcite crystals on the cavern walls, as has been noted.

The withdrawal of the water-filling from ground-water caverns may be brought about in two ways. During the later stages of an erosion cycle, especially in a region several hundred miles inland from its river mouths, the slow continuance of degradation must lower the valley floors to fainter and fainter gradients, and the associated water table will then also be lowered, so that caverns which were previously below it will now be left above it, and their water-filling will thereupon be discharged. But the same result is more efficiently brought about by regional elevation, as Grund pointed out. If this takes place after peneplanation the old rivers, rejuvenated, will during and after the elevatory movement erode new valleys, and the caverns that are tributary to such valleys will be drained. It is quite possible that some caverns may then have roofs so thin that they will collapse when the water, which aided in sustaining it then, is drained away. Such caverns will soon assume the form of valleys, open or blind. They should not be expected near the peneplain divides.

As soon as ground-water caverns thus come to be occupied by ground air, their replenishment with dripstones may begin, except in the lowest galleries where the ground air is dampened by streams. At the same time the streams will attempt to convert any network in their courses into a branchwork; but as this attempt is not made until the cavern galleries are of good size, it will have little or no effect on them, especially on the higher galleries, in which the network will therefore survive.

Facts to be Accounted For

All our greater caverns are in uplifted and more or less dissected peneplains. Under the theory of excavation by vadose water, these caverns must have been excavated and their dripstones deposited within them since the upheaval of their regions. Under the theory of excavation by ground water, they should have been produced before the elevation of their region, during the previous cycle of peneplanation, and only subordinately modified, chiefly by dripstone deposition, since their elevation.

All our larger caverns have galleries of a pronouncedly network pattern. This is wholly inconsistent with the requirements of the current theory of vadose excavation, but perfectly consistent with the alternative theory of ground-water excavation. And if great network caverns have been thus excavated, smaller caverns of simpler pattern may have been similarly excavated.

Three caverns in a much degraded part of southern Indiana, with some network loops in their galleries as described by Malott,[7] appear to illustrate successive stages in the withdrawal of a former water-filling as a result of slow valley deepening, independent of regional elevation.

Some linear caverns in the same state, described by Malott[8] and by Addington,[9] exhibit angular turns, suggestive of quiet, immature solution by ground water on intersecting joint planes, rather than of stream corrasion.

The walls and roofs of certain caverns exhibit peculiar rock forms that are much more suggestive of solution than of corrasion.

A few caverns are known in which the walls are studded with calcite crystals, some of which are over a yard in length. One of these caverns in Missouri[10] and another in Arizona[11] were water-filled when first found, but they have been emptied by pumping in the course of mining operations. A third in the Black Hills had been naturally drained; its crystals are described as in part covered by dripstones.[12]

The floors of cavern galleries are by no means always graded. The broad floor of a large gallery in Carlsbad cavern, New Mexico, has a pronounced slope.[13]

As far as these varied facts go, they discredit the theory of excavation by vadose water and give good support to that of ground-water excavation. But it is still eminently possible that certain caverns of simple pattern are of vadose-water origin.

Caverns in Inclined Limestones

Several important caverns in the inclined limestones of the Appalachians have, as described by Hovey[14]

6 W. H. Emmons, "Sulphide Ores in the Mississippi Valley." *Econ. Geol.*, 24, 221–271, 1927.

7 C. A. Malott, "Three Cavern Pictures." Proc. Ind. Acad. Sci., 38, 201–206, 1929.

8 C. A. Malott, "Physiography of Indiana," in "Handbook of Indiana Geology." Ind. Dept. Conserv., p. 236, 1922.

9 A. R. Addington, "Special Topographic Features . . . Bloomington, Indiana, Quadrangle." Proc. Ind. Acad. Sci., 38, 247–261, 1929.

10 Arthur Winslow, "Lead and Zinc Deposits." *Mo. Geol. Surv.*, 7, 566, 1894; also, Bain, as above, 109, 110.

11 J. B. Tenney, personal communication.

12 E. O. Hovey, "Crystal Cave of South Dakota." *Sci. Amer. Suppl.*, 57, 23657–23658, 1904.

13 This statement is based on a detailed topographic map made for the National Geographic Society by R. H. Runyan on a scale of 50 feet to an inch, with 5-foot contours on the gallery floors.

14 H. C. Hovey, "Celebrated American Caverns." Cincinnati, 1882. 2nd. ed, 1896.

and by Reeds,[15] well-developed gallery networks, highly suggestive of excavation by ground-water solution; but they possess also one or more well-defined levels, independent of their bedding planes, and suggestive of control by water-table streams during pauses in regional elevation. How these levels are to be explained, and whether they have been determined by thrust planes I can not say.

OBSERVATIONAL STUDY OF CAVERNS

It is desirable that caverns should be studied with especial attention to the detailed form of their rock walls and to the general pattern of their galleries. During such study the attempt should be made to explain every element of their form by each one of the afore-discussed theories. Care should be taken not to be distracted from the primary study of cavern excavation by the secondary fascinations of dripstone replenishment. Each of the two theories should be impartially considered in its relation to the physiographic evolution of the cavern district, and a provisional place should be found under each theory for every cavern feature, large and small. Thus in time a good theory of limestone caverns may be established.

EDGAR FAHS SMITH: PROVOST, CHEMIST, FRIEND

By CHARLES FRANKLIN THWING
PRESIDENT EMERITUS OF WESTERN RESERVE UNIVERSITY

OFTEN have I wished I might make a book seeking to interpret the most loved teachers of our colleges. What a rich treasury it would indeed be of dear souls loving and loved. In it I would tell of "Old Peabo" of Harvard, who embodied the great phrases of Paul's eulogy on charity. Included, too, would be Shaler, also of Harvard, of whom it was said, "Late in life he was fond of telling the story of his once having overheard two students talking together. 'Where's the old man?' asked one. 'Hush!' said the other, 'if he hears you call him old man, he'll walk your d—d legs off.'"[1] Chief among the worthies would be North of Hamilton, whose other and more affectionate name was "Old Greek." Of him a graduate wrote, "Professor North, I love you because you inspired in me a desire to do my best and to realize in my life what God has made possible."[2] Of course, too, a place would be had for Garman of Amherst. Of Garman Principal Stearns of Andover has written:

> To him hundreds of Amherst men owe the best inspiration of their lives. Those who have enjoyed the privilege of sitting as disciples at his feet realize as none others can what a rare privilege has been theirs. He taught us the beauty of truth. Through him the spiritual world was brought near and its glory revealed. He made us feel the presence of the Divine within us, and he stirred as few men have been able to do within the hearts of his pupils the desire to serve. The wonderful influence he exerted over the minds and lives of his students was unique in the educational world. Sluggish minds were stimulated to activity; careless minds were taught the value of accuracy; indifference was changed to eager desire. To many an Amherst man the most sacred and cherished memory of college days will always be that morning hour in Walker Hall where intellect was quickened and ambition aroused.[3]

The interpreter also would not leave out Wright of Middlebury, who held higher hope for his students than they had for themselves. One of these students wrote to him saying, "I am trying to catch up with your ideals for me." In the list I should want to include from a wholly different zone Osler, the teacher of medical students in three universities, Jowett of Baliol, and Tholuck of Halle, a theologian gifted with wit and humor, and with paternal love for his students.

Yet as noble, as inspiring, as formative, as loved, and as loving as any other of the noble group is Edgar Fahs Smith. Of the fourteen provosts in the university I have known four: Pepper, the refounder, the inspiring teacher; Harrison, the watchful and insistent financier; Penniman, the present head, the faithful conservator and the broad-minded administrator; and Smith, whom Penniman succeeded, and of whom I now write in a way most personal.

On the campus of the University of Pennsylvania, within sight of a laboratory which he planned and in which he worked, stands a statue bearing this inscription:

[15] C. A. Reeds, "The Endless Caverns of the Shenandoah Valley" [Virginia]. New York, 1925.

[1] "The Autobiography of Nathaniel Southgate Shaler," p. 369.

[2] S. N. D. North, "Old Greek. A Memoir of Edward North with Selections from his Lectures," p. 138.

[3] Eliza Miner Garman, "Letters, Lectures and Addresses of Charles Edward Garman," p. 581.