EROSION BY SOLUTION AND FILL.

By Willis T. Lee.

INTRODUCTION.

In a region where the rocks are honeycombed surface material may find its way into subterranean cavities on a large scale. In southeastern New Mexico the formation of caverns by the solution of certain kinds of rock and the transfer of surface material to these

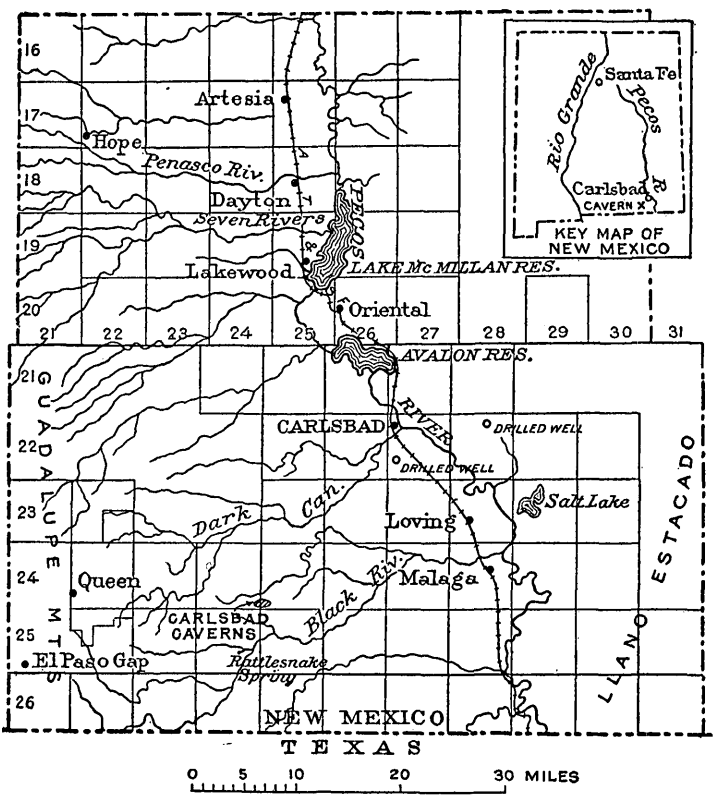


Figure 12.—Map of Eddy County, N. Mex.

caverns have been carried on so extensively that these processes may be considered the chief causes of the formation of a broad valley.

Pecos Valley lies between the Guadalupe Mountains on the west, which rise to altitudes of nearly 10,000 feet, and the Llano Estacado on the east. (See fig. 12.) It is the broad, shallow depression through which Pecos River flows, but it is not wholly a valley of erosion in the sense in which the term erosion is generally used.

Streams from the mountains to the west reach the river and erode their channels in the ordinary way. Pecos River also carries much sand and silt and functions in many ways as a normal stream. But no tributary streams were found east of the Pecos in Eddy County, and over a wide area not even the dry bed of a temporary stream was seen.

ROCKS OF PECOS VALLEY.

N. H. Darton, who has made a comprehensive study of the "Red Beds" of New Mexico, has shown that in the eastern part of the Pecos Valley the Dockum group, of Triassic age, crops out, but through most of its course in Eddy County Pecos River flows over rocks of the Permian series. These rocks consist of limestone, anhydrite or gypsum, rock salt, and red sandstone and shale. Near the surface much of the gypsum and salt have been removed by solution, but at some distance below the surface their full thickness is found undisturbed. A well drilled 2 miles south of Carlsbad, after penetrating red beds containing much rock salt and gypsum, entered a limestone that is locally called the Big lime. The record of this well gives the best available data on the thickness of the Big lime and beds above it. It is as follows:

Record of well drilled south of Carlsbad, N. Mex., in sec. 18, T. 22 S., R. 27 E.

[Data furnished by Scott Etter.]

	Feet.
Gravel cemented by calcium carbonate, limestone, and sand	80
Sandstone and clay, red	60
Limestone, white	7
Sandstone, gray	9
Limestone, white	17
Red beds	42
Limestone, white	13
Sandstone, red	6
Limestone	19
Red beds	62
Gypsum	23
Red beds	32
Gypsum	15
Rock salt	65
Limestone	35
Gypsum	49
Rock salt	34
Limestone (Big lime)	1,137
Shale, blue	5
Limestone, black	51
Limestone, black, sandy in some places	69
"Sandy beds" and salt water	46
Limestone, white	30
	1,906

SOLUTION CAVITIES.

SOLUBLE ROCKS.

It is significant that much of the material penetrated in the well whose record is given above is soluble. According to this record the drill went through 1,378 feet of limestone, 87 feet of gypsum, 99 feet of rock salt, and 342 feet of insoluble material.

The Big lime is underlain by another group of gypsiferous red beds and a still older massive limestone, and much soluble material occurs in the rocks younger than those represented in this record. As the rocks dip in a general southeasterly direction, a considerable thickness of strata east of the river is not represented here. (See fig. 13.)

Although there is much soluble material below the Big lime, attention will be confined here to this limestone and the rocks above it. Solution cavities occur in great numbers in all the limestones and in the beds of gypsum and rock salt. Some of those in the Big lime

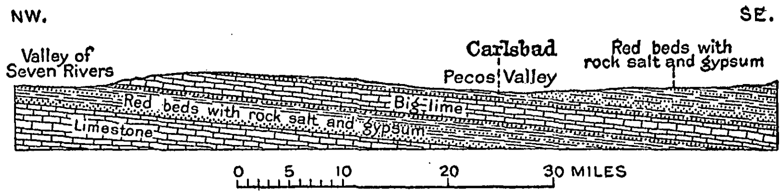


FIGURE 13.—Sketch section from the Valley of Seven Rivers southeastward through Carlsbad, N. Mex., showing the relation of the cavernous limestone, locally known as the Big lime, to red beds above and below it, which contain gypsum and rock salt.

are spacious and may be entered and examined. Those in the softer material are smaller and have never been entered to any considerable distance.

The limestone is hard and dolomitic and forms rugged hills. But although it strongly resists erosion, it yields readily to solution. Numerous large springs and many extensive deposits of travertine, some at flowing springs, others at springs now extinct, are convincing evidences of a general honeycombed condition of the rocks. One of best examples of the cavities in the limestone is Carlsbad Cavern. Those in the salt and gypsum beds are perhaps best illustrated in the sink holes described on page 115.

CARLSBAD CAVERN.

Carlsbad Cavern is about 22 miles southwest of Carlsbad, in sec. 31, T. 24 S., R. 25 E., and sec. 36, T. 24 S., R. 24 E. It is an unusually large cavity, and because of its size and the splendor of its onyx decorations it has been made a national monument. It has been known since 1901 as a bat cave and a source of guano, but only recently have the scenic parts been explored.

The outlet of this cavern has not been discovered. The only natural opening now known is at the top, where the roof collapsed and the rocks fell 246 feet to the floor. Another entrance has been constructed by sinking a shaft for the recovery of guano. The main passageway was surveyed in the spring of 1923 for about 3 miles, by Robert A. Holley, of the General Land Office, and the surface was contoured by E. E. Teeter, of the United States Bureau of Reclamation, in January, 1924. From these surveys the accompanying map (fig. 14) was constructed. The cavern has been explored by James White, of Carlsbad, for some distance beyond the area surveyed, but relatively little is yet known of its size.

The chambers and passageways as originally formed by solution have been partly filled by rocks falling from the walls and ceiling. In many places loose aggregations of broken rock lie on the floor. The thickness of this débris is not known, but in some places where the blocks are large and the spaces between them open, men are said to have made their way downward 200 or 300 feet below the present floor. In other places the rock fragments are cemented by calcium carbonate into resistant masses of limestone breccia.

The walls of the cavern are very irregular, approaching within perhaps 100 feet of each other in a few places, then receding in lateral chambers many times that width. At the sides of the main passageway are many alcoves and rooms, few of which have been entered and none of which have been described. In most places the walls are rough and jagged where masses of rock now lying on the floor have fallen away after they were undermined by solution or shaken loose by some earthquake. In other places the walls are relatively smooth.

The cavern is a great solution cavity extending diagonally downward to a depth of nearly 1,000 feet. The shape of this cavity has been modified by the deposition of calcium carbonate in the several forms characteristic of limestone caverns. Stalactites and stalagmites, popularly known as "dripstone," are numerous and are remarkable for size and variety of form, as shown by Plates XXIV, *B;* XXV, *A;* XXVI, *B;* XXVII, *B.* Deposits of calcium carbonate have also accumulated against the walls in many places where water trickles from the rock. Here and there these accumulations assume forms that closely resemble masses of ice, and some of the "cascades frozen in stone" are large and impressive. To distinguish this material from that deposited by dripping water, it has been called "flowstone."

Little can be said of the size of the chambers and passageways in this cavern, as few measurements have yet been made. Some of the chambers are several hundred feet wide and have ceilings so high that torches fail to illuminate them. The largest compartment yet

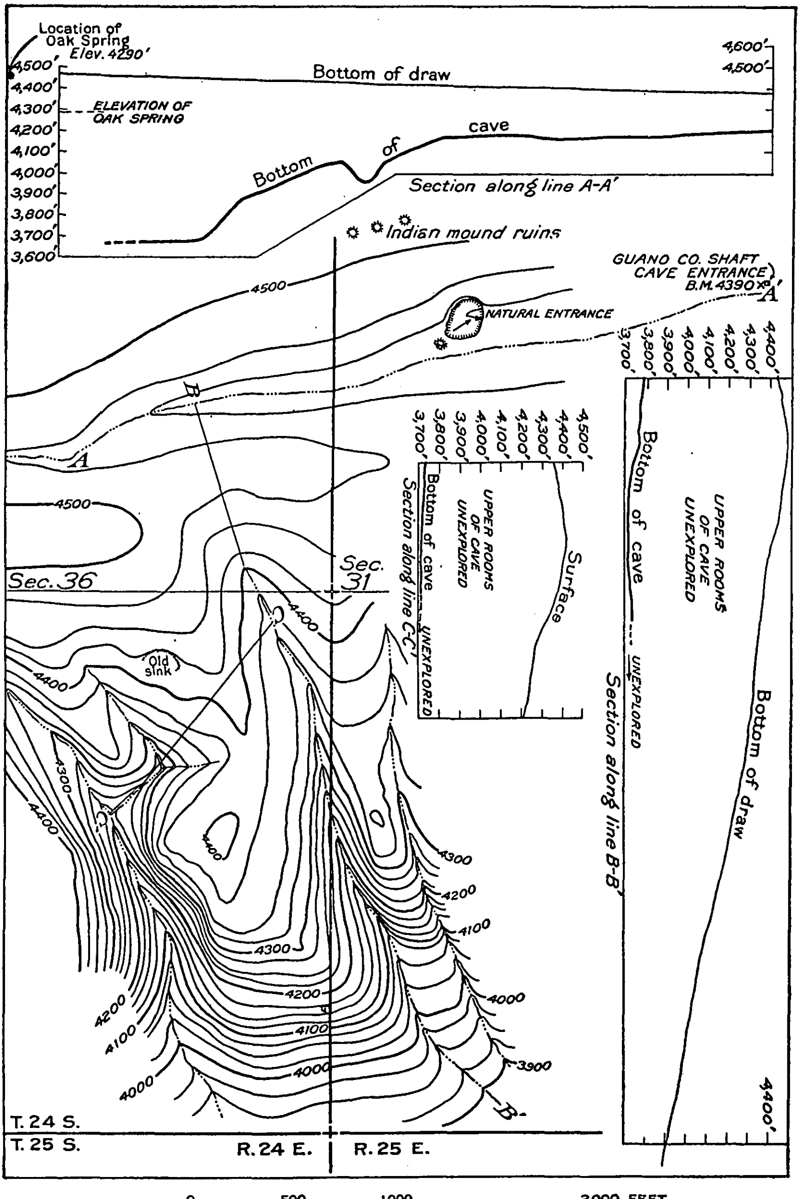


FIGURE 14.—Map and profiles of Carlsbad Cavern National Monument, N. Mex., showing the alinement of the surveyed parts of the cavern and its relation to the ground surface. From surveys made by Robert A. Holley and E. E. Teeter.

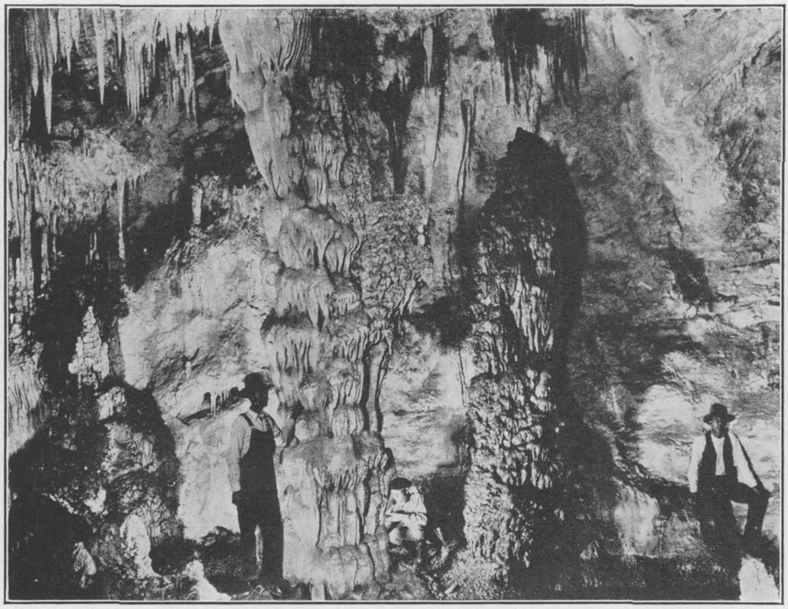
discovered is appropriately called the Big Room. Holley's survey shows that this room is more than half a mile in length, and it probably averages more than 200 feet in width. The floor lies about 700 feet below the surface of the ground, and apparently the rock cover is little more than a shell. This room is as remarkable for ornate decoration as it is for size. Dripstone decorations occur in infinite variety of size and shape. (See Pl. XXIV, *B*.) There are thousands of pendants, some so delicate and slender that they break under the slightest pressure; some so massive that the observer marvels that so enormous a weight can be sustained. (See Pl. XXIII, *B*.) The stalagmites are less varied. One group in which the forms are usually tall and graceful has been called the totem poles. Some of these only a few feet in diameter rise to a height of 40 feet.

Many of the stalagmites in this part of the cavern have blunt, rounded ends (see Pl. XXV, *A*) and are composed of material that seems to differ from that of the surrounding forms. They appear dark colored and contrast sharply with other forms in having a smooth surface in place of the chalky-white frost-work surface which is more common. Some of the stalagmites are of unusual dimensions. The twin domes (see Pl. XXVI, *B*) are said to be more than 100 feet high and to measure more than 200 feet across the base. This base is a mammoth dark-green mound having a wet, slippery surface. The color of some of these forms suggests the presence of algae or other forms of plant life. It remains to be determined if algae can live in the darkness of the cavern. Fungi might thrive in the darkness and may possibly have had something to do with the deposition of the calcium carbonate.

Some of the most interesting features on the floor of the cavern are grouped about the basins of extinct springs. Some of the basins are 10 feet or more in depth and perhaps 50 feet across. They are lined with an unknown thickness of onyx and in their profuse decoration closely resemble some of the hot springs in Yellowstone National Park. If the Biscuit Spring of the Yellowstone were drained, leaving the surrounding crust of mineral matter undisturbed, it would resemble one of the basins in Carlsbad Cavern. (See Pl. XXV, *B*.)

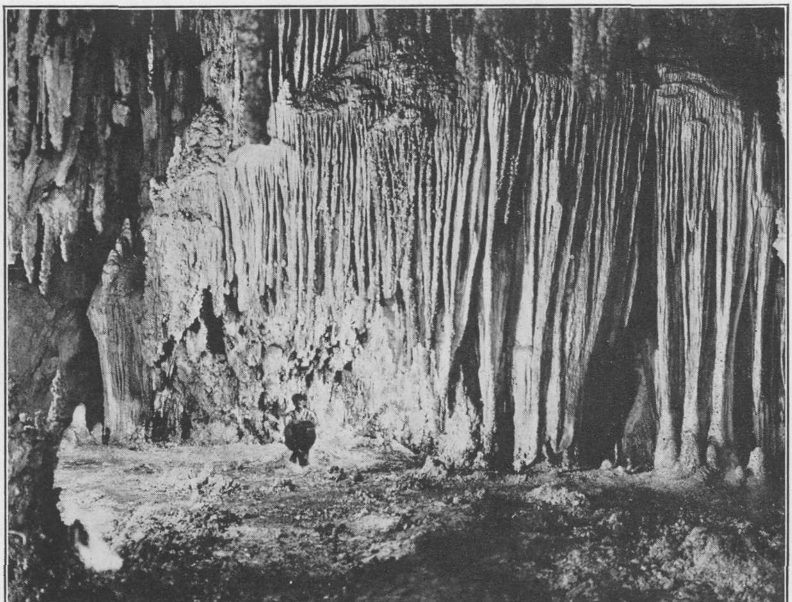
In many places stalactites and stalagmites have joined to form columns of impressive dimensions. (See Pls. XXIV, *B*, and XXVI, *A*.) No measurements of these columns have been made, but they are very high, very large, and very astonishing.

Near the end of the Big Room is a small opening in the floor, which leads to lower chambers that lie below the floor. The bottoms of these chambers are below the level of the plain, nearly 1,000 feet below the entrance to the cavern, and they probably drain through



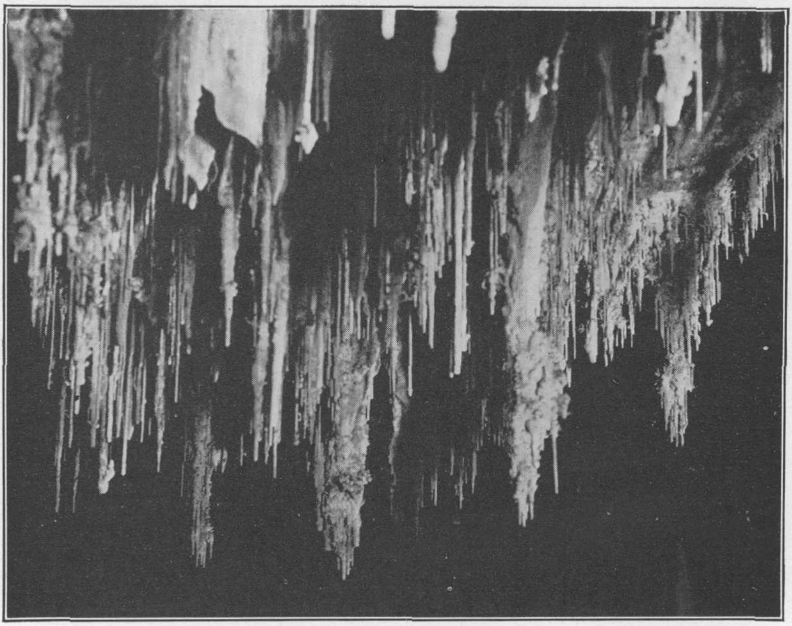
A. YEITSO'S PILLAR, CARLSBAD CAVERN, N. MEX.

Showing the side of the great chamber formed by solution and later decorated by the deposition of calcium carbonate. Copyrighted photograph by Ray V. Davis.



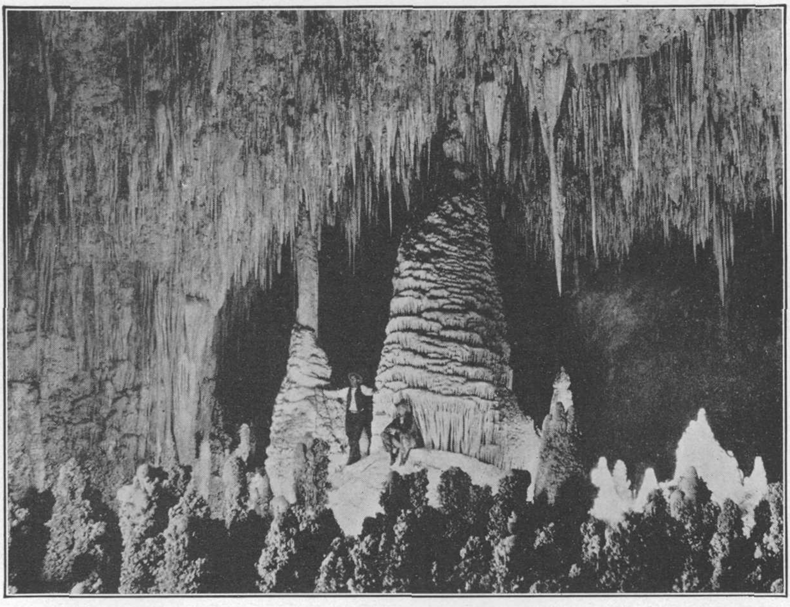
B. A PARTITION OF ONYX, CARLSBAD CAVERN.

A wall in one of the chambers known as Shinav's Wigwam (from Shinav, a mythical deity of the Navajo Indians). The stalactites have grown together laterally into a solid curtain-like mass. Photograph by W. T. Lee.



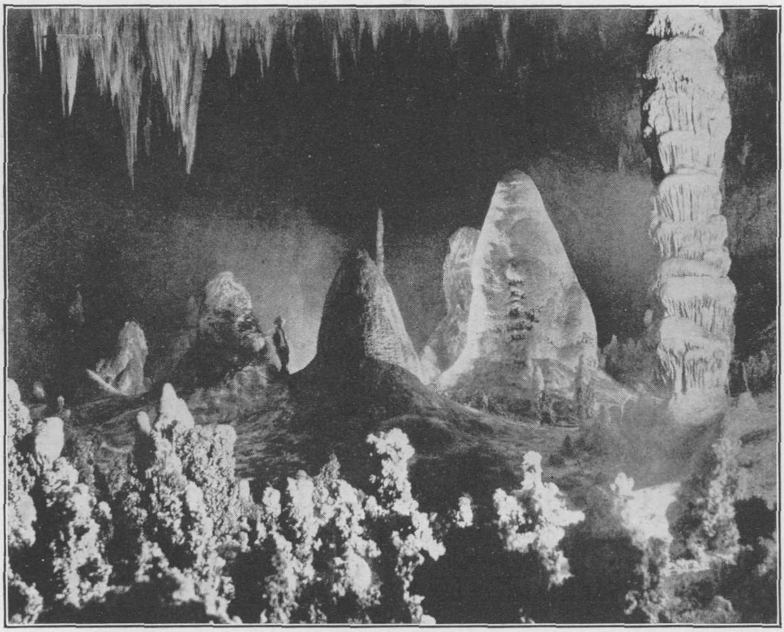
A. STALACTITES, CARLSBAD CAVERN.

Hanging from the ceiling in the great chamber called Shinav's Wigwam. Photograph by W. T. Lee.



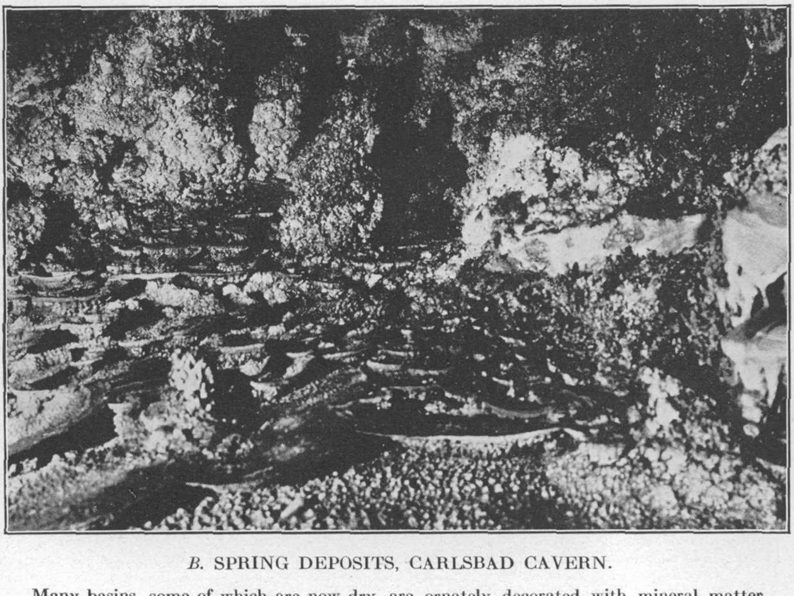
B. HATTIN'S DOME AND THE TEMPLE OF THE SUN, CARLSBAD CAVERN.

One of the spectacular scenes combining many of the characteristic features of the cavern, such as stalactites, stalagmites, columns, and monuments. Photograph by Ray V. Davis.



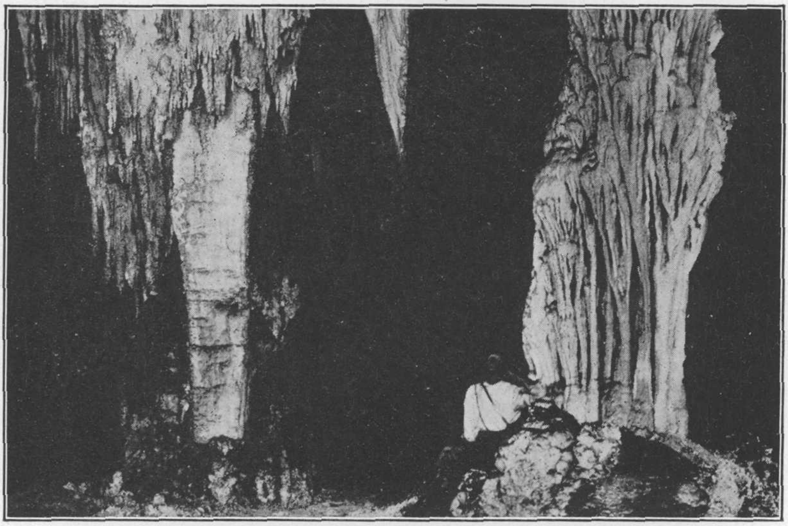
A. STALAGMITES AND COLUMN, CARLSBAD CAVERN.

The column shows the decoration characteristic of the columns in this cavern. The large stalactites are relatively smooth. Because of the resemblance of this material to ice, it is popularly known as flowstone. The stalagmites in the foreground are composed partly of coralline material and partly of smooth dripstone. Photograph by Ray V. Davis.



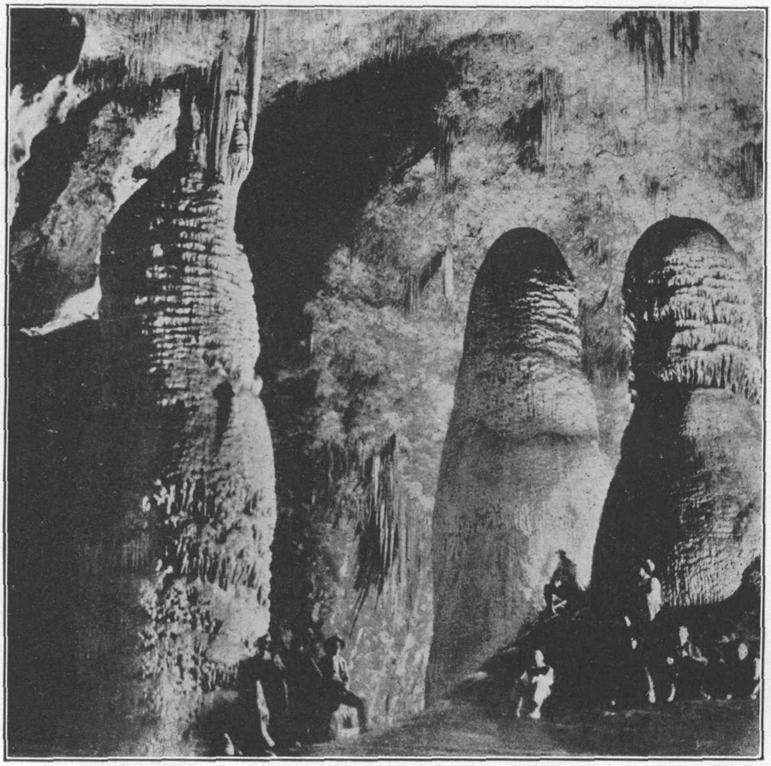
B. SPRING DEPOSITS, CARLSBAD CAVERN.

Many basins, some of which are now dry, are ornately decorated with mineral matter deposited in a variety of forms. Photograph by W. T. Lee.



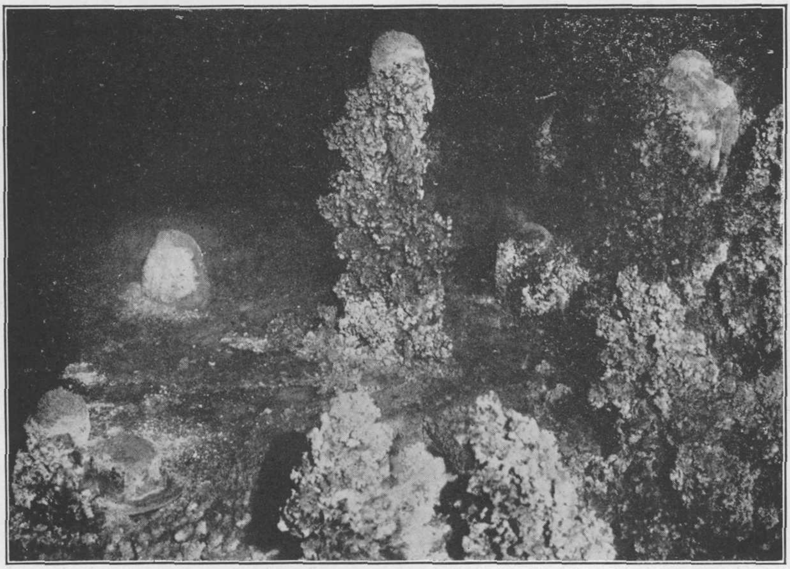
A. PILLARS OF ONYX, CARLSBAD CAVERN.

Some of the pillars are relatively smooth, such as that shown at the left, but many of them are composed of tiny overflow fountains beneath which streamers trail away like hanging drapery Photograph by W. T. Lee.



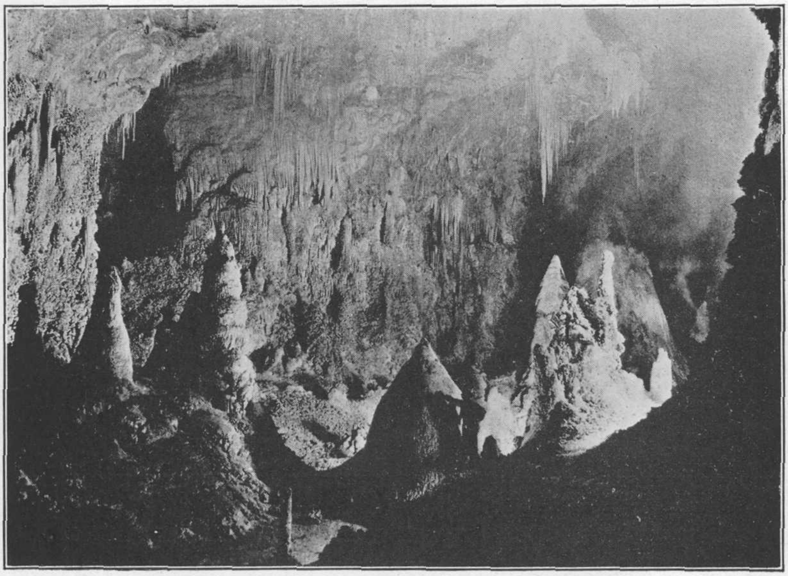
B. TWIN DOMES, CARLSBAD CAVERN.

Shows also one of the large pillars having relatively slight connection with the ceiling, where stalactites and stalagmites have joined to form a column. Photograph by W. T. Lee.



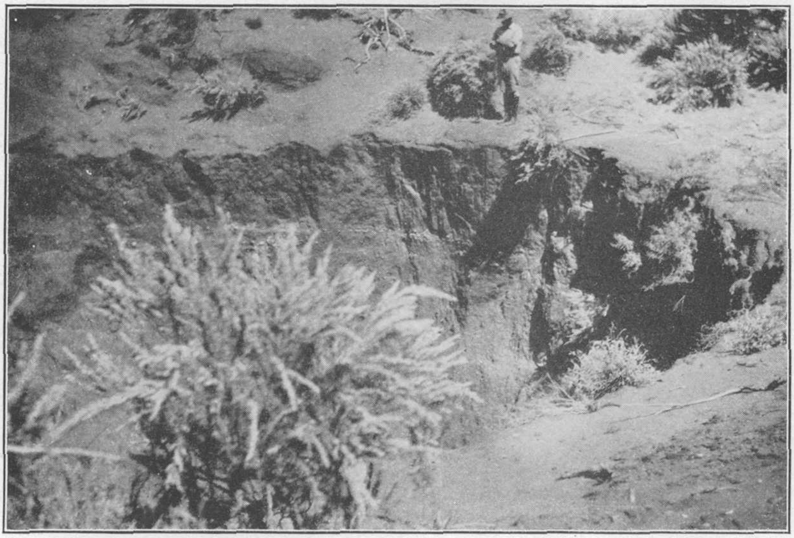
A. CORALLINE STALAGMITES, CARLSBAD CAVERN.

In some places the deposit is irregular, resembling coral growth. In other places, as at the tops of these stalagmites, the material is relatively smooth and clear. Photograph by W. T. Lee.

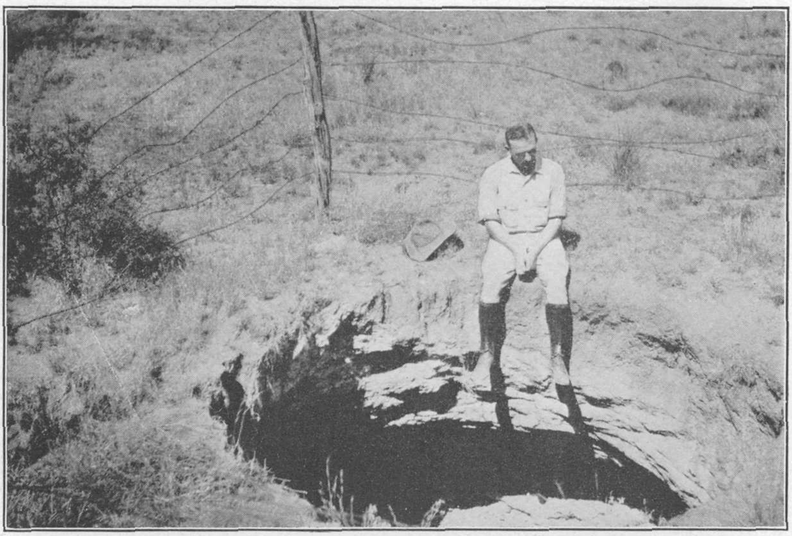


B. A CHARACTERISTIC SCENE IN CARLSBAD CAVERN.

Shows a variety and wealth of columns, stalactites, and stalagmites. Photograph by Ray V. Davis.



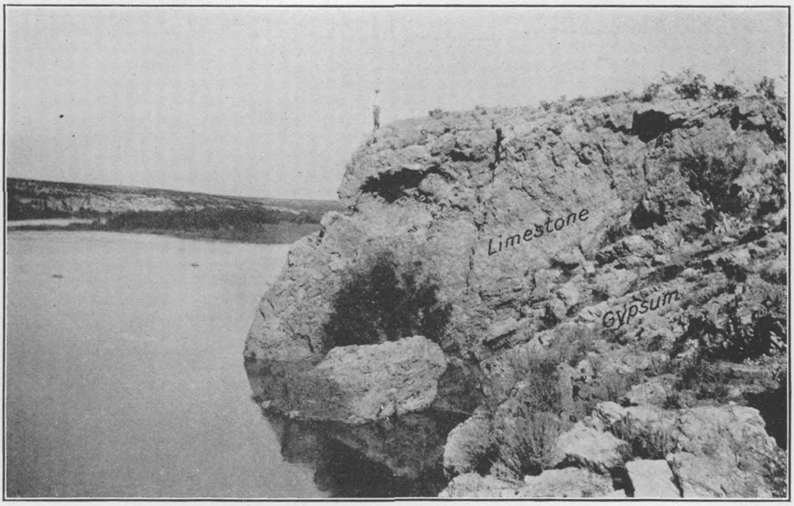
A



B

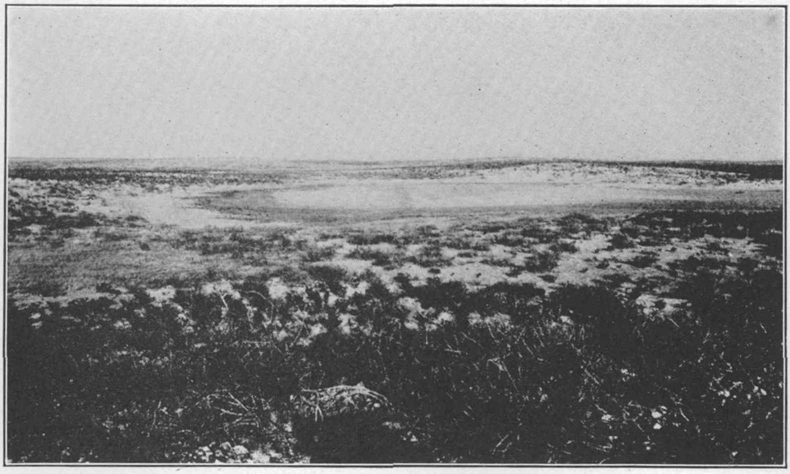
SINK HOLES ON LIVINGSTON RANCH, ABOUT 20 MILES SOUTHEAST OF CARLSBAD, N. MEX.

A, Formed in August, 1918, when a cavern collapsed, leaving an opening about 75 feet across and 60 feet deep; *B*, formed by the collapse of a cavern in gypsum lying near the surface. Photographs by W. T. Lee.



A. PECOS RIVER AT RED BLUFF DAM SITE, N. MEX.

Showing dolomitic limestone resting on gypsum. The limestone dips steeply to the east (left) because of slumping due to the removal by solution of some of the gypsum. Photograph by W. T. Lee.



B. A PLAYA.

Small temporary lake formed by the choking of a sink hole and the silting of a depression formed by the settling of material near the surface. Photograph by United States Bureau of Reclamation.

A. ENTRANCE TO CARLSBAD CAVERN.

The limestone of the cavern roof here fell to the floor, a vertical distance of 246 feet. Photograph by W. T. Lee.

B. TRAVERTINE IN LAST CHANCE CANYON, NEAR QUEEN, N. MEX.

The bed of limestone at the right was thickly covered with calcium carbonate deposited from spring water. The water no longer flows over the travertine, and the part showing above the century plant has begun to break down. Photograph by W. T. Lee.

one of the springs about 3 miles from the foot of the mountains—perhaps Rattlesnake Spring, described on page 120.

The myriads of cylindrical sharp-pointed stalactites give place here and there in the cavern to broad thin sheets. But the great variety of curiosities is found on the floor, where they can be examined in detail. There are vast numbers of stalagmites 1 to 5 feet high. (See Pls. XXIV, *B*, and XXV, *A*.) In some places these stand so close together that it is difficult to walk among them. Most of these low stalagmites have a rough granular surface of a general warty appearance, somewhat resembling coral. (See Pl. XXVII, *A*.) Some of the excrescences have grown into short stumpy branches, giving each stalagmite a bristling appearance. In places the excrescent forms are surmounted by masses of smooth clear onyx, which give them a startling resemblance to bald-headed men in ragged clothing. Many of these smooth-topped stalagmites have at the top a splash cup or small receptacle containing water; others may be called frozen fountains, for the splash cup is filled with clear onyx.

DEPTH OF CAVERNOUS CONDITION.

It is debatable how far below the water table a cavernous condition may develop. The entire flow of Pecos River goes underground near McMillan and reappears farther downstream. This can scarcely be a near-surface phenomenon. Furthermore, the depth to which a cavernous condition of the limestone sufficient for artesian flow extends is indicated by the wells in the Roswell artesian basin, which lies just north of the Carlsbad area. Fisher[1] shows that artesian water is derived from a porous limestone, the depth of which in 20 wells ranges from 535 to 976 feet below the surface. This limestone is older than the Big lime of the present paper—that is, it lies below the lower group of red beds shown in Figure 13—but it has similar characteristics. It seems clear, therefore, that a porous condition or the presence of incipient caverns may be expected in the Big lime to a depth of several hundred feet below the surface.

LIMESTONE BRECCIA.

Limestone composed of angular fragments cemented together with calcium carbonate occurs in many places in Pecos Valley. Some of this breccia was formed at the surface, but probably much of it was formed in caverns and resembles the very coarse masses now forming in Carlsbad Cavern. These cavern breccias are free from foreign matter and may be distinguished by careful examination from those formed at the surface, which contain fragments of rock brought from a distance.

[1] Fisher, C. A., Preliminary report on the geology and underground waters of the Roswell artesian area, N. Mex.: U. S. Geol. Survey Water-Supply Paper 158, 1906.

The fragments in the limestone breccias are held together by material resembling cement. In some places the cementing is so perfect that the rock will break through the fragments rather than through the cement. The origin of this material is illustrated in Carlsbad Cavern. Water percolating through the limestone takes calcium carbonate into solution, as shown by the analyses of water on page 120. Under favorable conditions this mineral matter is released and deposited. The great quantities of onyx in the cavern afford an impressive illustration of the magnitude of this action. Moreover, the quantity of material that has accumulated among the fallen blocks and has cemented them into solid masses must be many times greater than that now visible. Probably similar action is going on in a great number of caverns and in the numerous smaller cavities of the honeycombed rocks.

The quantity of material dissolved and redeposited is illustrated also by the beds of travertine found near the foothills west of Pecos River. In many places the plain is covered to some unknown depth with calcium carbonate deposited from spring water. Some of the springs are still active; others are extinct. In several of the canyons great deposits of travertine are found, as that in Last Chance Canyon, shown in Plate XXX, *B*. This deposit is now disintegrating, as the spring from which it issued is extinct, but other deposits near by are still growing.

As the quantity of calcium carbonate taken into solution and either carried away or redeposited is large, and as the direction of transfer of material by solution is always downward, erosion by solution in this region must, in time, accomplish large results, even though much of the material may be redeposited rather than carried completely away.

CAVITIES IN SALT AND GYPSUM.

In many places in Pecos Valley there are holes in the ground—some open, others choked or partly closed with fragmental material. Some of the most conspicuous of the sink holes were found on the Livingston ranch, about 20 miles southeast of Carlsbad, where the underlying rocks contain gypsum and rock salt. One hole observed on this ranch (see Pl. XXVIII, *A*) is circular in outline, about 75 feet across, and 60 feet deep. This hole was formed during a storm in August, 1918. Some of the material that dropped into the cavern below still rests in a conical mound on the cavern floor. At another sink hole on this ranch the rocks of the cavern roof are only a few feet thick. (See Pl. XXVIII, *B*.) The sinks are so numerous that the ranchmen fence them to prevent the cowboys from riding into them while running stock.

The cavernous condition of the rocks near the surface on the Livingston ranch is emphasized by the difficulty in finding water there. More than 50 holes have been put down on this ranch, but water has been found on the average in only 1 in 10. The ground water seems to be confined to streams in underground passageways. One well may yield water, while another within a few feet of it is dry.

Near the ranch house, in secs. 9 and 10, T. 22 S., R. 30 E., 12 wells were drilled, but water was found in only one. The following record of these wells was obtained, but their exact location can not be indicated. No. 1 supplies 2,000 cattle; No. 2 is a seep; the others are dry.

Record of wells on Livingston ranch.

	Distance from No. 1 (feet).	Depth (feet).		Distance from No. 1 (feet).	Depth (feet).
No. 1 (productive well)		66	No. 6	±100	(?)
No. 2	60	66	No. 7	±300	(?)
No. 3	120	80	No. 8	600	95
No. 4	125	237	Nos. 9-12	([a])	±100
No. 5	175	90			

[a] Less than a quarter of a mile.

Similar conditions were encountered in several parts of this ranch. Mr. Livingston states that in some places where one well had been obtained water was found in another well near by, though not invariably in the second one drilled, but that in other places search was abandoned after 10 or 12 holes had been drilled.

Sink holes are numerous wherever beds of salt and gypsum lie near the surface. Many of these were observed north of Carlsbad, near the McMillan reservoir. Here the gypsum is exposed in many places and appears to occur in detached masses, terminating abruptly where parts of the bed have been dissolved out and replaced by insoluble material. This solution of the gypsum has resulted in an unusual number of sink holes near the river. Those in the bed of the McMillan reservoir are so large and numerous that the reservoir has seldom been filled, the entire flow of the river, even at times of moderate flood, going into the sink holes. Farther south, in the basin of the proposed reservoir No. 3, similar holes were found.

Sink holes were noted in several stages of development ranging from open, newly formed holes, through holes showing varying degrees of fill, to sinks completely choked and silted over, like the one shown in Plate XXIX, *B*. In some places the collapse of the caverns is progressive. When a hole becomes choked a new one opens near by. This progressive collapse of the surface has resulted in many large basins. The road between Carlsbad and Lovington passes through a large sink called Red Lake. Except for small pools of water held in thickly silted depressions, Red Lake contains water for only short periods after storms. It is said that this depression is the natural receptacle for the drainage from several townships, but relatively little of the storm water reaches it, and that little soon disappears underground.

A similar depression about 5 miles east of Loving is known as Alkali Flat. The lowest part of this depression contains a body of salt water. Another of similar nature lies west of the river near Malaga. These sunken areas, which do not have surface drainage to the river and which are clearly due to the collapse of caverns formed by the removal of soluble rocks, suggest that the several basins through which the river flows were formed in the same way. In one such basin on Hondo River near Roswell a futile attempt was made to construct a storage reservoir. Several basins of similar nature have been investigated as reservoir sites, but construction has been delayed because of the unfavorable conditions, although one small reservoir at Avalon has proved successful.

DRAINAGE.

In southeastern New Mexico the Pecos receives little surface drainage from the east. The storm water forms sheet floods and short temporary streams, but these soon disappear underground and find their way through the cavernous rocks, naturally seeking the lowest outlet. Some of the water finds its way into the undrained lakes, such as that in Alkali Flat and the one near Malaga, but the chief outlet is to the channel of the Pecos.

Although Pecos River flows through a semiarid country and receives little surface drainage during dry seasons, it is a stream of considerable size at all times. One spring at Carlsbad discharges into the river 5½ second-feet of water. Blue Spring, 30 miles southwest of this town, discharges 18 second-feet. Records of two gaging stations near Carlsbad, 2½ miles apart, show that 80 second-feet of water enters the river in this distance. South of the McMillan reservoir underground water, some of which is derived from this reservoir, returns to the stream in large quantities.

This entrance of water into cavernous rocks in Pecos Valley and its return to the surface at some distant place has been known for many years. G. H. Russell[2] has described the disappearance

[2] Freeman, W. B., and Mathers, J. G., Surface water supply of the United States, 1910, pt. 8: U. S. Geol. Survey Water-Supply Paper 288, pp. 109–112, 1911.

of the entire river into cavernous rocks near Santa Rosa and its return to the surface a few miles farther downstream. He further states that

A chain of sinks, or so-called dry lakes, extends from a point near the place of sinking to the flowing lakes of Santa Rosa. Some of these sinks are smooth depressions covering several acres; others are holes 50 feet in diameter. The latest formed depressions have vertical sides and range in depth from a few feet to a hundred feet or more. Erosion gradually rounds off the edges and fills the middle until there remains only a pot-shaped depression. Some of these depressions have been formed since the settlement of the country. It is said that a man living upon the mesa found one morning in front of his house a hole 60 feet in diameter and about 150 feet deep. A story is also told of a suddenly formed depression that filled with water and was claimed by two men. The controversy was taken to court, but before a decision was rendered the water disappeared, leaving only a dry hole.

The lakes near Santa Rosa are 200 to 300 feet in diameter, and some of them are reported to have been sounded to a depth of about 250 feet. They receive no surface drainage, but each yields a constant overflow of several second-feet. The surface of these lakes is only a few feet above the river and is 300 to 400 feet below the level of the sink holes on the mesa. The water is heavily charged with gypsum and gives off a "gyppy" odor.

These sinks afford conclusive evidence of solution in the gypsiferous beds, and the course of their succession, leading from the place where the river sinks to a point where the water reappears in the lakes, forms strong presumptive evidence that underground passages are followed by the water between those points. The incident mentioned above, in which a depression formed by a cave-in filled with water, also affords evidence of underground passage. In this case it is reasonable to conclude that the cave-in choked some subterranean watercourse, thus forcing the water up into the depression until it acquired sufficient head to reopen its channel, when the pent-up water in the depression sunk away.

REMOVAL OF DÉBRIS FROM SURFACE.

Great quantities of surface material disappear into the caverns. In the one shown in Plate XXVIII, *A*, nearly 30,000 cubic yards disappeared in a single night. Large quantities of sand and silt are washed into the caverns by storm waters. Wind is continually drifting dust and sand into them. In brief, the surface material, which in most other regions is removed by surface drainage, here finds its way into subterranean caverns, where it lodges in spaces vacated by soluble material.

Some of the material that enters a cavern lodges near the opening. At the bottom of the hole pictured in Plate XXVIII, *A*, a cone may be seen resting on the floor, as illustrated at *b* in Figure 15. In other holes no open space is seen between the sides of the opening and the débris that chokes it. In still others the hole is filled and the surface above it is silted over, as illustrated in Plate XXIX, *A*.

The process of the transfer of surface material to subterranean caverns is not difficult to visualize, given a honeycombed condition of the rocks, as illustrated in Figure 15. In some places the overhanging material will fall, as illustrated at *b* and *c*, or slump, as at *d* and *e*. If such a slumping extends to the surface, the condition illustrated in Plate XXIX, *A*, may result. At the locality shown a limestone block has slumped because of the removal of gypsum from beneath it. The winds and floods bear surface material into the openings. The coarser matter lodges near the entrance; the finer is distributed more widely by the underground streams. A fall from the roof of a cavern may choke a passageway, as illustrated at *d*, Figure 15, or the cavern may gradually fill until it is completely sealed up, as at *g*, and made water-tight so that new openings are sought, as at *f* and *a*, which in turn become filled in time, producing

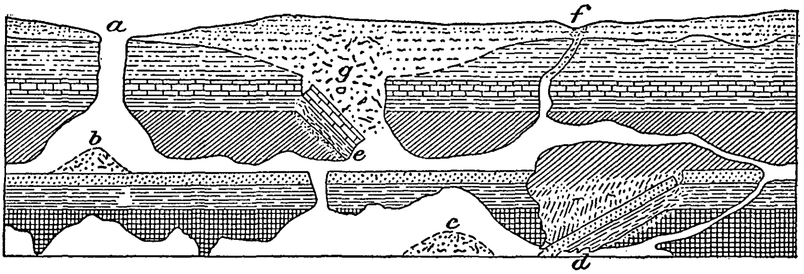


FIGURE 15.—Sketch section illustrating the formation of solution caverns in strata containing gypsum and rock salt. The caverns are formed in the gypsum and rock salt, and connecting channels are cut through the limestone and other strata. At the bottom of opening *a* is some of the material *b* which fell from the roof; at *c* material which fell within the cavern; at *d* and *e* masses of hard rock which slumped when support was removed from one side; at *f* a small choked opening; at *g* an old sealed opening.

the condition illustrated in Figure 16, where undisturbed strata end abruptly against detrital matter, as at *a*, or disturbed strata lie in an unnatural position (*b*) surrounded by fragmental material (*c*) with caverns (*d*) filled and sealed.

In places where the soluble material has been removed more rapidly than at neighboring localities, or where the filling has not kept pace with the removal of soluble matter, the collapse of the rocks near the surface has formed basins, such as Alkali Flat and the lake basin near Malaga. It is probable also that the basins along the streams in some of which attempts have been made to store water for irrigation were formed in this way. These attempts are generally regarded as failures. The Hondo reservoir,[3] situated in such a basin, was abandoned after leaks amounting to 200 cubic feet a second developed. The skill of the engineers has succeeded in making the McMillan reservoir useful as a regulator of flood waters, compelling

[3] Davis, A. P., and Wilson, H. M., Irrigation engineering, p. 350, New York, John Wiley & Sons, 1919.

the leaks, which they have not been able to stop, to serve as retarders of flow.

Some idea of the rate at which this lowering of the surface goes on may be gained from measurements of the volume of flow in Pecos River and the quantity of mineral matter which it carries. Near Carlsbad the water contains 2,680 parts of mineral matter per million parts of water, and it has been computed [4] that on the average this river removes each year 103 tons of mineral matter for each square mile of its drainage basin. Farther south, near the Texas line, where the river carries the water that has returned from the caverns near Carlsbad, the flow averages more than 500 second-feet and the water contains more than 4,000 parts of mineral matter per million parts

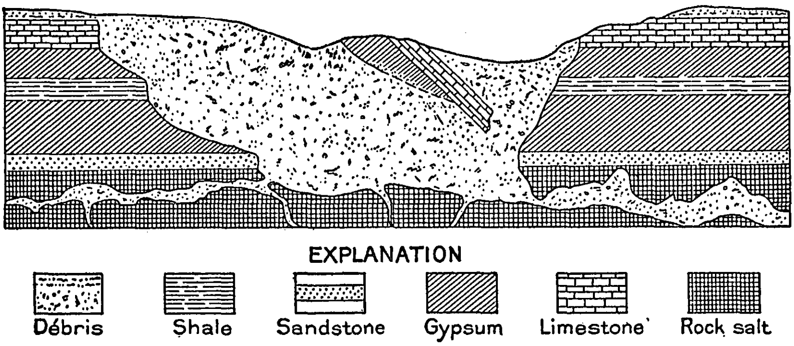


FIGURE 16.—Sketch section illustrating the filling of solution channels and the formation of surface depressions by the enlargement and collapse of caverns. Solution has proceeded until the material near the surface is a jumbled mass, giving place laterally to undisturbed strata.

of water. As the river receives little water from surface tributaries in this part of its course, the mineral matter carried across the Texas-New Mexico line, amounting annually to more than 150 tons to the square mile, comes chiefly from underground sources. Furthermore, much of the area included in this computation is little affected by solution, while from other parts of the area the soluble matter is removed rapidly.

KINDS OF WATER.

The waters of Pecos Valley are so diverse and the amount of salinity they contain varies so widely that even the average represented by the river water may be misleading. The water from some of the wells and springs is so saline as to be a brine, which can not be used for stock. Some of the water is supposed to be poisonous, but this may be due only to the abundance of gypsum it contains in solution. Five samples of water from this valley were sent to the

[4] Dole, R. B., and Stabler, Herman, Conservation of water resources: U. S. Geol. Survey Water-Supply Paper 234, p. 86, 1909.

United States Geological Survey and analyzed. The results are given in the following table:

Analyses of water from Pecos Valley, N. Mex.

[Analyzed by C. S. Howard. Parts per million.]

	1	2	3	4	5
Silica (SiO_2)	14	14	19		
Iron (Fe)	Trace.	Trace.	.08		0.6
Calcium (Ca)	96	246	460	757	762
Magnesium (Mg)	29	37	50	209	2,354
Sodium and potassium (Na+K)	24	41	38	[a] 1,160	[b] 19,580
Carbonate radicle (CO_3)	0	0	0	0	44
Bicarbonate radicle (HCO_3)	277	226	215	134	18
Sulphate radicle (SO_4)	108	551	1,104	2,295	10,890
Chloride radicle (Cl)	4.0	7.0	6.0	1,965	29,580
Nitrate radicle (NO_3)	.89	2.0	1.6		[c] Trace.
Total dissolved solids at 180° C	408	1,046	1,897	6,944	64,400
Date of collection (1923)	Nov. 12	Nov. 12	Nov. 12	Nov. 15	Nov. 4

[a] Calculated. [b] Na, 18,600; K, 980 parts per million. [c] Not more than 25 parts per million.

1. Rattlesnake Spring, on Harrison ranch, half a mile above Washington ranch, 1 mile north of Black River, and 12 miles above Blue Springs. Flows through Rattlesnake Creek and empties into Black River about 1 mile below source.
2. Main spring of Blue Springs, sec. 28, T. 24 S., R. 26 E.
3. Black River Springs, at diversion dam on upper Washington ranch, about 12 miles above Blue Springs and 1 mile south of Rattlesnake Spring.
4. Clark well, near salt lake in Alkali Flat, sec. 24, T. 22 S., R. 29 E.
5. West end of salt lake in sec. 17 (?), T. 23 S., R. 29 E., on east side of Pecos River east of Loving.

The water from Rattlesnake Spring is a normal limestone water, which may come wholly from a limestone cavern without contamination from neighboring beds of rock salt and gypsum. As this spring is only a little way from Carlsbad Cavern, it may be the outlet of the water from that cavern. The water of Blue Springs is a limestone water to which has been added much calcium sulphate. Apparently the underground drainage from some bed of gypsum joins the stream from one of the limestone caverns. Black River Springs are only a mile from Rattlesnake Spring, yet the waters are very different. That from Rattlesnake Spring is a limestone water, whereas that from Black River Springs is a strong gypsum water. The differences shown by these three analyses provoke speculation as to the cause. As thick beds both of limestone and of gypsum occur near by, it seems clear that the Rattlesnake Spring derives its supply chiefly from limestone, the Black River Springs chiefly from gypsum, and the Blue Springs from both.

The water of the Clark well contains much salt and gypsum, as is to be expected from the location of the well, in red shale that contains much rock salt and anhydrite. There is little limestone near this well.

The lake water is derived from drainage of the rocks from which the well water comes. Springs of salty water from these rocks discharge into the lake. Reports as to this lake are conflicting. It is said that salt crystals are forming on the bottom, yet this analysis shows that the water is far from being saturated. The country about Alkali Flat drains into this lake, and some of the springs are locally believed to be poisonous, but the analysis shows no poisonous properties.

SUMMARY.

Pecos Valley, in southeastern New Mexico, is a succession of broad, shallow depressions which can be attributed only in part to surface erosion. The chief cause of these basins is believed to be local subsidence due to the removal by solution of soluble rock near the surface.

Through sink holes the surface débris which in most other regions is removed by run-off is here carried into subterranean caverns. The water that washes the débris into the caverns dissolves the soluble rocks and forms other caverns, which are similarly filled later. The transfer of soluble material from below ground to the surface at some lower altitude and of surface waste to underground caverns is not unknown but has not been sufficiently emphasized to make it a familiar process of erosion. In Pecos Valley it is a dominant process.