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A Model for Cavern Development Under Artesian Ground Water Flow, With Special Reference to the Black Hills

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ABSTRACT—Three classes of ground water flow within limestone are responsible for the development of caverns: *subsurface stream, integrated water table*, and *artesian*. Subsurface streams are comparable in method of flow and properties to surface streams. Integrated water table flow occurs as lateral flow at the top of a nearly planar water table. Artesian flow of ground water is through enclosed solutional cavities in the completely saturated zone where there is no free water surface. In the Black Hills of South Dakota structural situations have promoted the development of artesian ground water circulation through limestone, and all three of the above classes of ground water flow are involved in the ground water movement through the limestone. Caverns formed through the action of the last two categories of flow within limestone are similar, but criteria are given to distinguish between the two classes of origin on the basis of cavern morphology. These criteria are applied to Wind Cave in South Dakota, and the balance of evidence indicates an artesian origin of the cavern system.

Using the present ground water conditions in the Black Hills it is possible to develop a theoretical model for artesian ground water movement and cavern development which result from certain topographic and geologic conditions where a hydraulic potential is present across a limestone unit.

Three intergrading classes of ground water flow may be contemporaneously involved in active artesian cavern systems. Using common terminology these classes may be referred to as *subsurface stream, integrated water table*, and *artesian*.

For the purpose of this paper I define the *water table* as the upper boundary of any subterranean body of water or zone of saturation. Thus many of the streams and pools of water in caves would necessarily represent perched water tables.

Cavern development of the first type is characterized by the presence of free-surface subterranean streams with a relatively steep gradient. Malott (1922) has outlined the suite of cavern characteristics generally resulting from the action of subterranean streams. These include: coarse, stream-worn cavern sediments; current produced wall flutings; simply connected cave passages which are sometimes in a trellis arrangement; and an irregular downhill cavern gradient. The theoretically distinguishing characteristics of this pattern of ground water flow are: thinness of the zone of ground water movement, that is, the subterranean stream; the steep, irregular profile of the water table along the direction of ground water movement, which is the stream longitudinal profile, and this is minutely controlled by the bed of the stream; and lastly the poor integration of ground water levels between adjacent streams.

Contrasted to the above is cavern development by lateral movement of ground water along an integrated water table.

By an *integrated*, or *coordinated*, water table I mean a ground water-atmosphere surface which describes between and along the cavern passages a fairly regular surface, for example, that of an irrigation network or canal system without dams or gates compared to that of mountain streams with rapids and waterfalls. The driving potential for ground water movement is a slight gradient of the water table. Streamlines of flow are nearly parallel to the water table and average discharge and associated solution decrease with depth (White, 1960; Davies, 1960; and Ewers, 1962). The necessary presence of a well-defined water table for this type of cavern development implies earlier stages of solutional activity by either subterranean stream or artesian ground water movement. If, because of some physiographic control, the ground water level remains stationary for an extended period, a well-defined cavern level may be expected to form, but if the water table fluctuates, cavern development will occur over a wider interval. Where a stable physiographic situation has allowed sufficient solution to occur to create a nearly flat water table, this ground water regime may be distinguished from the previous case by several criteria:

1. The upper boundary of the completely saturated zone, namely, the water table, is nearly flat and of simple contour, that is, integrated.

2. The passage floors, which are the lower limit of solution, may be uneven, and generally this lower boundary does not directly determine the configuration of the water table.

3. Solutional passages may be multiply-connected, and will, like the water table, be well integrated with each other.

Caverns formed as a result of integrated water table flow should exhibit some of the following characteristics: distinct cavern levels, nearly horizontal; a tendency for major cavern passages to be aligned along the strike in dipping beds; where passages cross the stratigraphic dip, the passages should remain essentially horizontal even though cutting across the structure (Appendix 1); absence of coarsest cavern sediments, but clays and silts deposited from suspension may be expected; and in larger cavern systems there should be an abundance of phreatic features (Bretz 1942), for example, spongework, natural bridges, network, or multiply-connected passages, ceiling pockets derived from high stands of water, and if the water level changes, a multi-level cavern.

In artesian cavern systems ground water flow has been structurally and stratigraphically constrained to flow at an altitude well below the static water level.

Where movement of water is by artesian pressure, no true water table for the artesian unit exists, because structural and stratigraphic impediments to vertical circulation prevent establishment of a water column equal to the pressure head within the unit. The static water level is the altitude of the top of the theoretical equilibrium water column. In such cases water flows under pressure in a manner analogous to water flow within pipes, as opposed to the open-channel flow of the previous cases. Water velocity through an artesian cavern system is probably very slight. Therefore a near absence of coarse sediment transported by traction or turbulence may be expected, through suspended detritus may be brought into the cave and deposited. Characteristics of artesian caves are those given by Deike (1960) and by Bretz (1942) for his "deep phreatic" zone; for example; spongework; a complex, three dimensional network of passages where the passages are formed at intersects of joints and the more soluble limestone zones; ceiling pockets and intimate interconnections between cavern levels; cavern passages following stratigraphy and structure, that is, not necessarily horizontal; and a down-dip orientation of the cavern system as a whole.

All of the three types of ground water movement discussed may be expected in some artesian situations, as in the case of ground water circulation in the southern Black Hills. A section extending from Beaver Creek within Wind Cave National Park, southeast of Beaver Creek near Buffalo Gap Pass cut the southeastern flank of the Black Hills domal uplift with local dip to the southeast. However, a small anticlinal flexure is present near Buffalo Gap (Darton and Page, 1925). Ground water flowing within the limestone seems to be prevented from vertical flowage into the overlying sandstone by shale horizons at the upper limestone boundary (Appendix 2). The combination of the resistance to erosion of the Pahasapa

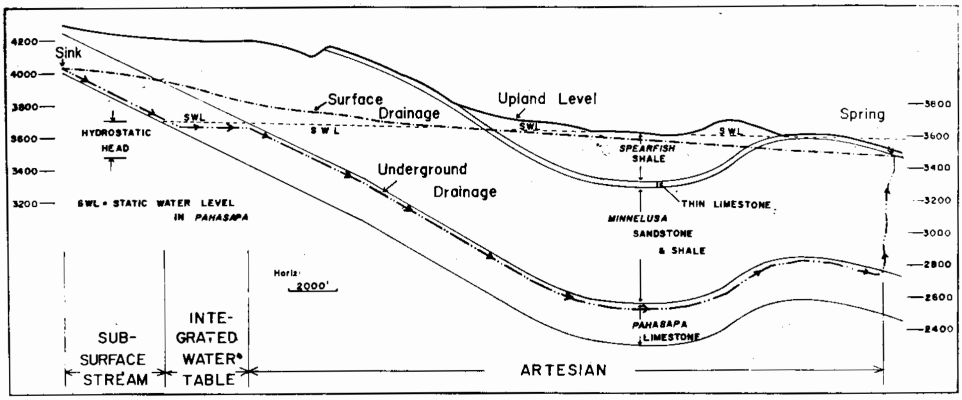

Figure 1

Geologic cross section through the southeastern flank of the Black Hills, showing ground water conditions. Vertical exaggeration 6⅔x.

limestone and the overlying Minnelusa sandstone compared with the easily eroded Spearfish shales overlying these two resistant units has created an altitude differential between the ground water collection area to the northwest in the Pahasapa limestone exposures and the discharge point at Buffalo Gap. Almost all streams originating in the central portion of the Black Hills which cross the Pahasapa exposure in the southeastern Black Hills lose their drainage to subterranean flow within the limestone and probably to a lesser extent to similar flow within the Minnelusa sandstone. This underground drainage then comes to the surface as artesian springs around the outer margins of the Black Hills, for example, the springs shown at Buffalo Gap, and springs at Hot Springs and Cascade (Fig. 1).

The assumed localization of ground water flow within the upper portion of the Pahasapa limestone is based upon the almost total absence of solutional cavities in the lower levels of this formation, where it is presently exposed. It cannot be decided at present whether this is the result of a difference in solubility of the upper and lower portions of the limestone, or to density factors in ground water flow concentrating solutional activity within the upper levels of limestone.

Theoretically this ground water flow may be divided into three zones characterized by ground water movement of the three types discussed previously. Where a surface stream flowing from the northwest first encounters soluble limestone, it will generally become subterranean, following solutional and erosional cavities at the base of the limestone. Such ground water movement would be steep, rapid flow of independent free-surface subterranean streams. The lower lateral boundary of this zone is where the free water surface becomes nearly flat and integrated. Note the difference in elevation of the water table between the areas where the rock units underlying the limestone are exposed, where permanent surface streams indicate the water table always lies above the lowest local points of the land surface, and the 200-300 feet deep water table within the limestone. This lower, well-defined water table and the completeness of underground drainage indicate that the present underground drainage system has existed for a long time, geologically.

The second zone of ground water flow occurs along the integrated water table toward the lowest point of this water table, presumably nearest the artesian spring. In Figure 1 this zone is greatly foreshortened, for the main component of flow is long the strike of the limestone. Caverns within this zone should be of the integrated water table type. Several cave levels associated with different previous stable stands of the water table might be expected.

The third zone of ground water movement is that of artesian flow. The hydrostatic head of about 200 feet between the

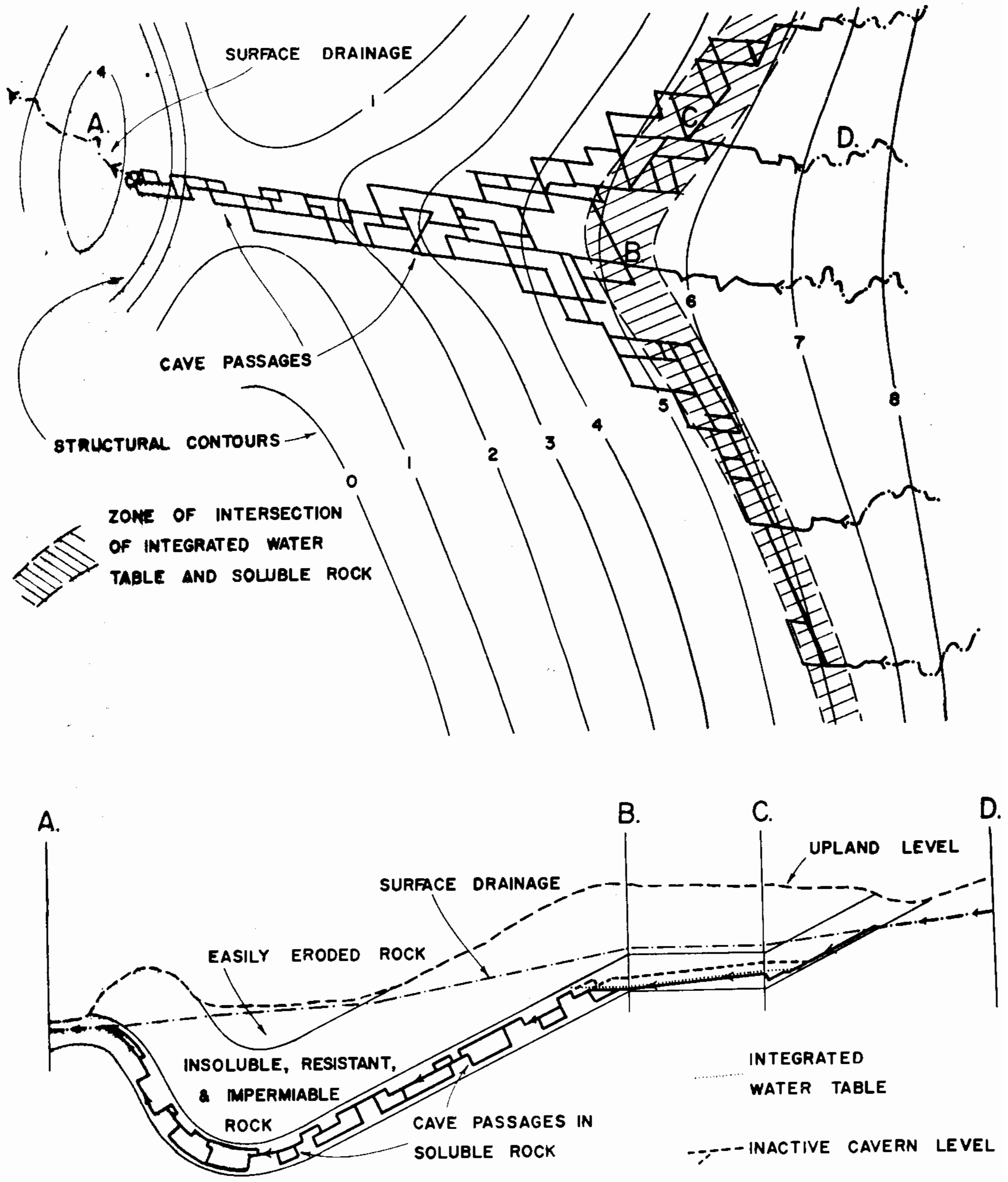

Figure 2

Theoretical properties of cavern development by artesian ground water flow.

water table and the exit spring at Buffalo Gap provides the driving potential for the movement. Based on well logs it would appear that about half of the driving potential is consumed in the movement of ground water from the free surface water table to the point in the limestone beneath the exit spring, and about half is utilized in forcing the water upwards through the constriction of the overlying rocks. The path of ground water movement presumably follows about the shortest path from the water table to the rise; such a path would be parallel to the regional dip. In the case of the springs at Buffalo Gap, which exit from a stratigraphic horizon well above the limestone, it may be assumed that a vertical fracture zone probably associated with the local anticline allows vertical discharge of ground water from the limestone.

Several conditions must be met if an artesian cavern system is to form: a structural situation involving a sealed limestone layer which connects ground water collecting areas to lower discharge points: this would generally be an asymmetric syncline, and a geologically influenced topography which gives the altitude differential between collection

TABLE 1

CRITERIA FOR DIFFERENTIATION OF CAVE DEVELOPMENT BY ARTESIAN FLOW AND INTEGRATED WATER TABLE

Feature	Caves Formed by Artesian Flow	Caves Formed by Integrated Water Table
1. Major controls upon cavern passage location and trend.	1. Joint system, stratigraphy, and direction of ground water movement.	1. Joint system, stratigraphy, water table, and direction of ground water movement.
2. Trend of dominant passages and cave system as a whole.	2. Parallel to dip.	2. Parallel to strike.
3. Controls upon vertical profile and vertical orientation along cave passages.	3. Cavern passages follow structural configuration (i.e., may dip strongly). Passages have no vertical constraints other than stratigraphic (i.e., high, narrow passages may be found).	3. Cavern passages nearly horizontal, following water table. A stable water table limits vertical development of passages to within a few tens of feet of the water table. However, a fluctuating water table will promote more vertical development.
4. Vertical profiles of cavern passages.	4. Irregular ceilings and floors may be expected.	4. Rather regular ceilings and floors.
5. Relation of cavern levels.	5. Cavern levels intimately interconnected. Major cavernous zones may interchange between levels (reflecting shifting of ground water flow between cavern levels).	5. Cavernous levels are largely independent, with relatively few interconnections. Cavernous zone should not interchange between levels.
6. Cavern sediments.	6. Little transport of detritus by traction, varying amounts of introduced fine silts and clays, with *relatively* high proportion of chemical deposits.	6. Fine to coarse introduced detritus may be present. Generally low percentage of chemical sediments.
7. Cave temperature during solution period.	7. May be considerably higher than average annual temperature, for deeply formed caverns.	7. Close to regional average annual temperature.
8. Amount of solution per unit volume of rock within cavern.	8. Stable ground water regime allows very large cavern systems to form.	8. Relative instability of water levels means usually smaller amount of solution per unit volume.

and discharge points. Because of the well-developed artesian circulation occurring at present within the Black Hills, it is reasonable to speculate that cavern formation is now taking place on a large scale within the Black Hills. If this true, then there is significance in the fact that this is occurring without much development of karst topography in the classical sense. In addition the caverns now forming will not have a direct relationship with the immediately overlying topography, but are products of larger scale patterns of drainage and structure (Fig. 2).

The accessible cavern systems within the Black Hills are not directly related in origin to the present topography and patterns of ground water flow, for these inactive caverns are 100 to 400 feet above the present permanent water levels, and are being dissected by the present topography. However, the presence of well developed artesian ground water complexes at the present time within the Black Hills allows the possibility that some of the inactive caverns within the area may have been formed by similar processes. Indeed, the possibility of an artesian origin of some of these caves has been cited before (Tullis and Greis, 1938, and Neighbor, 1954). Two caverns, Wind Cave and Jewel Cave, within the Black Hills are immediately suspect of artesian origin because of their large size, phreatic features, relative lack of cavern sediments, and three dimensional maze pattern (Fig. 3 C). However, the above features might also be found in caves formed at an integrated water table. It is therefore important to be able to distinguish between these two modes of origin by the characteristics of the cavern (Table 1). The first five criteria cited in Table 1 are based on geometrical considerations and should largely follow from the definition of the two contrasted regimes. The sixth criteria, the theoretically small transporting power of the low velocity water flowing through active artesian caverns indicates that significant detrital material would not be carried into artesian cavern systems. However, Deal (1962), although adhering to the idea of an artesian origin of Jewel Cave, argues for the previous existence of large quantities of clay fills within Jewel Cave which were subsequently removed by swiftly moving ground water. However, I find no evidence in Wind Cave for the existence of more than the present small amount of introduced sediments. However, in both these caverns the addition and removal of clay fills may have been due to ground water flow patterns subsequent to and not directly related to the flow patterns responsible for the major solution within the caverns. The 7th criterion is based upon the possibility of ground water flow in artesian circulation to a significant depth. In the Black Hills at present there are artesian springs which issue tepid water. This higher temperature, however, should not be expected to have been true for all artesian caves, but only for those formed at great depth or those in areas of high goethermal gradient. Criterion 8 is based upon the difference of stability of artesian and integrated water table flow. Artesian flow should retain a stable pattern as long as the exposed structural and drainage features remain essentially the same, even though tens or hundreds of feet of erosion or aggradation occur. On the other hand, water table levels are affected by even minor physiographic or climatic changes. To utilize these criteria a large portion of a cavern must be explored to furnish detailed data on the patterns of the cavern system and related rock structures. Also these data must be tied to accurate mapping of the passages based on rigid horizontal and vertical control.

The effect of any water level control on cavern development can be shown by a histogram relating cavern volume to altitude. In constructing such a histogram it is assumed that: (1) there has been no appreciable tilting of the rocks containing the cave since the period of formation of the cave, (2) the water table which formed the cave had no appreciable slope over the area of the cave being considered. A simple approximation is the construction of a histogram relating altitude versus occurrence of surveyed stations. This was done for Wind Cave (Fig. 4). For caverns with extensive areas of breakdown that occurred after draining of the cave, only stations from portions of cavern passages free of collapse should be utilized.

Because the stratigraphic dip is about 7

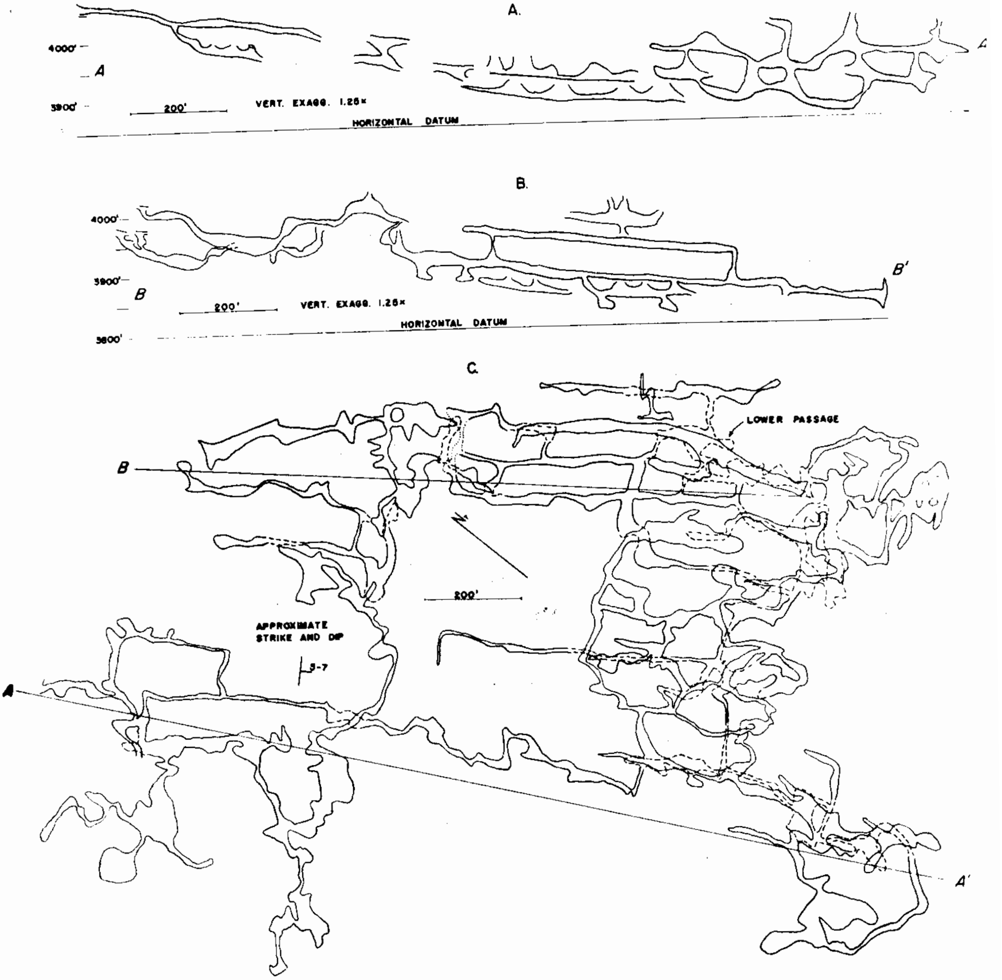

Figure 3

A generalized map of Wind Cave, and two generalized cross sections along the dip. Based on a map by Herb Conn and used by permission of the National Park Service.

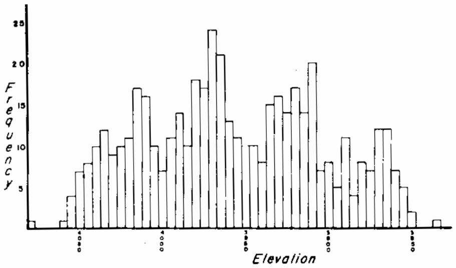

Figure 4

Frequency of survey stations within Wind Cave versus altitude within the cavern.

degrees in the vicinity of Wind Cave and the mapped passages are found within a band about 1500 feet wide along the strike, stratigraphic controls on solution should cancel out if surveyed stations are randomly distributed over the area of the cave within each cavern level. Such a random distribution should be expected to be a first approximation if there are no water level or structural controls on passage location. However, from Figure 3 C it may be seen that surveyed passages tend to be found in clusters. Such a condition probably accounts for the peaks and dips of Figure 4. Three factors could account for the unrandom distribution of stations in Figures 3 and 4:

1. There are water level controls on solution within Wind Cave. The presence of a few prominent, strike-oriented passage complexes within the cave also tends to support a water table origin for Wind Cave.

2. Exploration and mapping of passages has been concentrated within a few zones in the cave. This is probably not the major factor.

3. Structural controls, such as fracture zones and minor flexures, have caused uneven distribution of passages.

The high degree of fracture development associated with the formation of boxwork within Wind Cave and the zonal occurrence of boxwork within the cave tend to support the third factor as the cause of the uneven passage distribution.

Additional evidence supports a conclusion in favor of an artesian origin for Wind Cave (see cavern cross sections, Figure 3, A and B):

1. Zones of solution along major joints when followed laterally migrate as much as 80 feet between levels.

2. Most major passages, at least in the lower levels, follow the stratigraphic dip.

3. Cavern levels are intimately interrelated and interconnected.

4. The almost complete absence of cavern sediments and survival of very fragile boxwork suggests extremely quiescent through-flowing ground water.

5. There are mineralogic indications of a temperature of about 100 degrees centigrade at the time of deposition of calcite within the cave (White and Deike, 1962). The earlier period of solutional activity may also have taken place at an elevated temperature.

6. Numerous ceiling pits of phreatic origin extend upward from the upper levels of the cave as much as 100 feet above the main cavern levels.

The possibility is strong that successive epochs or artesian and water table movement were active in the presently known parts of Wind Cave.

This ends the main portion of the paper, but three appendices will now be presented which develop ideas supplemental to the main thesis.

APPENDIX 1

In nearly homogeneous limestones, connecting cross passages between the major cavern passages parallel to the strike in water table caverns are reasonably expected to be, like the main passages, developed near the top of the water table, and thus nearly horizontal (case 1 of Figure 5). However, an-

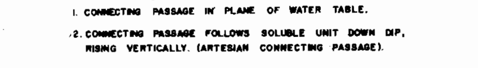

Figure 5

Two possible types of connecting passages between major cavern passages along the strike in a cavern formed at an integrated water table.

1. Connecting passage in plane of water table.
2. Connecting passage follows soluble unit down dip, rising vertically (artesian connecting passage).

other possibility exists for cavern passage morphology if development of cavern passages is limited to certain more soluble zones within a dipping limestone formation. Because cavern passages will tend to form along paths of least resistance to ground water flow, and hence along paths of greatest ability of solutional attack, a situation such as that of case 2 of Figure 5 might prevail. Because of the lesser solubility of limestone between the major passages, a minimization of distance of flow required through this less soluble unit is realized in a path of ground water flow in the connecting passage. Such flow follows the more soluble unit downdip or the reverse to the closest approach to the other main water table passage and then rises or descends nearly vertically between the more soluble horizons. In effect then, an artesian condition is present through the connecting passage, such that ground water is forced through a deep, indirect path by a structural situation. A slight difference of elevation of the water level between the two passages would be the motivating hydrostatic potential.

Similar artesian passages in water table caves might be found if the water table rises above a cavern that had been formed by a lower water table, or if earlier formed artesian cavern passages are found at a moderate depth below the water table. In such cases some divergences of flow from the water table to artesian flow at depth utilizing previously formed solutional channels might be expected. However, given sufficient time formation of water level passages should relatively decrease the importance of the deeper connections.

APPENDIX 2

The Minnelusa sandstone rather than the Pahasapa limestone has been cited as the major aquifer within the Black Hills (Darton and Page, 1925). Deal (1962) argues that the circulation of ground water was continuous between the Pahasapa and Minnelusa, and that the Opeche shale overlying the Minnelusa is the sealing unit. If this is the case then a loss of ground water from the limestone to the sandstone in the artesian zone is indicated, because almost all of the streams flowing across the limestone from the central part of the Black Hills lose all their drainage to the limestone before crossing the sandstone. This is probably accomplished by an upward seepage from the limestone to the overlying sandstone. As a consequence of this the importance of the limestone as an aquifer, and the attendant solution, would decrease toward the artesian water outlet. There is some indication within Wind Cave that there has been communication between the ground water in the limestone and that within the sandstone at the time of formation of the cave. In many places within the cave there are upward-leading pit complexes which end in sandstone blockages, and many passages are walled by or end in sandstone fills of ancient solution channels within the limestone, and these probably communicate with the overlying sandstone. On the other hand, little water seeps into the caves from the surface where the limestone is presently overlain by sandstone. There are other lines of evidence which suggest that the Pahasapa is at present the major aquifer *within* the Black Hills (Gries, 1956). First of these is that the water levels within the Pahasapa and Minnelusa are not coincident, that in the Minnelusa being the lower. Secondly, in the zone of active artesian circulation within the Black Hills within the ring of natural artesian springs, wells drilled into the Pahasapa almost always give high yield. These criteria suggest that the shaly layers directly overlying the limestone offer significant resistance to the interchange of ground water between the two units. Probably the importance of the Pahasapa as an aquifer increases with time as continuing solution reduces resistance to ground water movement.

APPENDIX 3

A nearly horizontal, structure-crossing cavern passage has in recent literature been assumed to necessarily mean the influence of water table control. However, where the ground water entering a cavern system contains a heavy load of detritus, especially in the sand and smaller sizes, a horizontal control may be exerted even though solution occurs well below the water table. When such turbid water enters a large cavern system a drop in water velocity and increase in dissolved load should cause a deposition of all tractive and most suspended load. This accumulation will tend to fill in the low spots in the cavern floor, and by forcing greater velocity and turbulence at points where the ceiling of the cavern is lower, the lower and constricted passage zones will tend to dissolve more rapidly. The net result of the accumulation of sediment will be to create an upward dissolving action and the attainment of a "graded" passage of small slope. Theoretically, however, several criteria should distinguish caverns with nearly horizontal passages resulting from water level control from the present case:

1. The "sediment graded" passages should have greater and more irregular slope than integrated water level passages.

2. Remnants of former cavern sediments might be found in the latter case whose stratification provides distinguishing criteria.

3. Each major passage in sediment graded caves would have unique grades depending upon sediment input, and would tend to form at separate levels not necessarily correlating between passages, that is, the passage complexes would be practically independent.

Another similarly-acting factor leading to a nearly horizontal development of completely artesian passages might be density stratification of ground water flowing through the cavern system, either because of temperature differences or differences of concentration of dissolved or suspended load. If this density stratification tended to concentrate the more acidic ground water near the cavern ceilings, and if ground water turbulence was low, nearly horizontal cavern passages might eventually tend to form.

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