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GENETIC RELATIONS OF CAVES TO PENEPLAINS AND BIG SPRINGS IN THE OZARKS

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ABSTRACT. 1. Most Ozark caves were made by a phreatic circulation of meteoric water beneath the mature topography which preceded peneplanation of the Ozark dome.

2. During old age, cave-making ceased as hydrostatic head disappeared with reduction of the uplands. To a large extent the existing caves then became filled with residual red clay filtered down from the peneplain soil. Remnants of this clay fill are considered as valid a record of peneplanation as are the flattish uplands beveling structure.

3. Later uplift caused deep dissection of the peneplained dome. This lowered the water table and brought most of the caves into the vadose zone.

4. The ensuing (present) vadose circulation, by removing the clay fill, is devoted more largely to restoring the original phreatic caves than it is to enlarging them.

5. The big springs of the Ozarks are interpreted as discharges from members of the early cave system which lay so low that post-uplift dissection has just reached them. Some of these subterranean aquifers are still operating under phreatic conditions.

INTRODUCTION

THE concept of solutional cave-making largely by a circulation in the phreatic zone (below the water table) should be credited to W. M. Davis. He became interested in cave origins too late in life to undertake subterranean explorations and developed his theory (1930) entirely from a literature containing almost no suggestion of the origin he proposed. There are few comparable cases where the significance of field facts has been almost completely missed and only vague interpretations made on an assumption. In this case, the assumption was that vadose water, descending to and perhaps flowing along the water table, was responsible for solutional caves in limestone and dolomite. Critically analyzing the data he found, Davis pointed out many features of cave patterns, proportions and relations which could not be satisfactorily explained as consequent on vadose circulation alone but had a logical explanation in the theory of subwater table origin.

The clash of rival theories is a healthy state because new field criteria thus are sure to come to light. But the cave problem is complicated because every enterable cave must have had some experience with vadose water, even if its origin dates back to completely saturated conditions. Cave features resulting from the earlier experience may thus become obscured or obliterated during the later one. More critical study of caves obviously was the answer to the Davis challenge.

Such studies by Swinnerton (1932), Stone (1932), Gardner (1935), McGill (1935), Malott (1936), and Tullis and Gries (undated) have specifically considered caves in various limited regions and have reached different conclusions. Caves vary in character in terms of differing calcareous formations containing them and of differing character and history of the topography and drainage above them. An outstanding example of refusal to follow Davis was Malott's "invasion theory." The Indiana caves of his studies were interpreted as the product of lost rivers, sinking creeks and sinkhole drainage of storm water, all discharging into "primitive" phreatic routes and vastly enlarging them to the dimensions of Marengo, Wyandotte and other capacious caves. In this interpretation, Malott was right. The vadose enlargements in Indiana caves have almost destroyed the relatively small phreatic caves of earlier date, only small remnants recording his "primitive tubes."

On the other hand, Tullis and Gries found the large group of Black Hills caves to conform to the Davis phreatic theory and to carry almost no record of vadose enlargement. Stone, studying Pennsylvania caves, also found convincing evidence of phreatic origin.

From a study of more than a hundred caves in 16 states, including Indiana, South Dakota and Pennsylvania, the writer stated in a paper (1942) postdating publication by all the above-mentioned authors, that 44 of the caves he had examined were entirely phreatic in origin, 49 carried a record of vadose enlargement of phreatic cavities and 3 were wholly vadose in origin. He later undertook a detailed study of the caves of southern Missouri for the Missouri Geological Survey, on the results of which this paper is based. Because most of the 138 Missouri caves he studied were largely of phreatic origin, portions of the manuscript for the Missouri Survey were sent to Malott for comment and criticism. In the ensuing correspondence, Malott indicated surprise at the extensive cave development in the Ozarks where no lost rivers, only a few sinking creeks and but little karst topography exist. He also stated that he had never seen the red clay fills or the spongework which the writer had argued can exist only in cavities of phreatic origin. All this is understandable in the light of his experience; limited to caves whose extensive vadose chambers have been greatly enlarged from small phreatic predecessors. The Black Hills caves, with no vadose record, might have puzzled him still more.

In sum, most subterranean drainage ways in calcareous rock conform to regional habits just as do surface drainage ways, and in addition many record experience in varying degree with the two contrasted environments, the phreatic experience preceding the vadose.

ACKNOWLEDGMENTS

Several months of cavern study under the Missouri Geological Survey and Water Resources has more than doubled the writer's list of caves studied and has enlarged his understanding of the relations of Ozark caves to the overlying topography. Thanks are due to the State Geologist, Dr. E. L. Clark, for permission to publish this paper in advance of the detailed report the Missouri Survey will issue.

OZARK PENEPLANATION

"The Ozark dome" is a widely used phrase for a far from simple structure constituting the southern half of Missouri and overlapping into northern Arkansas. Its complexities include faulting and folding under different stresses at different times. The net result, under later erosion, is an asymmetrical domelike area, a topographic high of the present drainage with the subcentral Precambrian St. Francis Mountains surrounded by irregular belts of Paleozoic sediments ranging from Cambrian to Pennsylvanian in age and dipping radially outward a little more than does the surface. Varying degrees of resistance to erosion in rocks of this belted pattern have produced a series of cuestas whose scarps face the central area.

At least three partially base-leveled surfaces are recorded in the present topography. The cuestas have existed since the second cycle of erosion was initiated and their crests and upper back slopes carry some of the best preserved records of the first two base levelings.

Previous interpretations of Ozark physiography have called for two erosion cycles preceding the present, but not in all cases the same two. Hershey (1895), the first to announce the idea of multiple cycles for the Ozarks, found his upper surface on the broad upland underlain by Mississippian rocks on the far western slope of the dome, the region variously termed the Springfield plain, plateau or platform.[1] His second erosional surface consisted of benchlands and terraces carrying old stream gravel, hence his terms "two troughs" and "duplex valleys." Hershey's work in Missouri was limited largely to this Mississippian upland region and, although correct, it fell short of a complete outline of Ozark physiographic evolution. He apparently never realized that the benches and terraces along valleys incised in the Springfield upland were products of the same cycle which almost completely removed Mississippian rocks from the central part of the dome, leaving the lower and much more extensive Salem upland largely on Ordovician rocks. He did not comment on the significant behavior of streams like James River, which flow westward from the (dissected) Salem upland toward the east-facing Burlington or Eureka Springs scarp of the Springfield upland, cross that upland and return to the lower Salem surface.

Later writers[2] who have reported two erosion surfaces on the Ozarks have studied regions where the Salem upland or its equivalent was the higher and older product, where the Springfield surface had been entirely destroyed during the second

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[1] Another interpretation of the Springfield upland is that it is a structural plain, commonly referred to as the Burlington plain. But this plain, descending westward at a gentler angle than the underlying Mississippian formations, bevels successively younger rocks until it truncates Pennsylvanian strata. Furthermore, it cuts smoothly across local structures. The Chesapeake fault (Lawrence Co.) has lost 250 stratigraphic feet on its upthrown side and the adjacent Kenoma-Golden City-Miller anticline has suffered a maximum loss of 350 stratigraphic feet from its crest, neither structure being indicated by any break in topographic accordance of hilltops at the Springfield niveau.

[2] Marbut (1907), Buckley (1909), Lee (1913), Dake (1930), Bridge (1930), and Flint (1941).

erosion cycle. Indeed, the writer is convinced that the second base-leveled surface is itself largely gone in the central part of the dome, and that the surface which observers and interpreters of topographic maps have called the Salem upland is mostly the dissected third erosional plain. The best preserved remnants of the second surface are on the cuesta summits and the White-Gasconade divide. If Flint's Ozark peneplain east of the St. Francis Mountains is correctly correlated by the writer, it is the second erosion surface of Ozark physiography, not the earliest.

The extensive erosional reduction in both the Springfield and Ozark cycles justifies use of the term peneplain. The third surface, here called the post-Ozark, consists largely of broad straths, recording very late maturity at the time renewed uplift inaugurated the present cycle. Dake alone has reported an area where the cycle (his second) developed a broad lowland across both headwater valleys and their interfluves.

An element of confusion exists over considerable areas where the resistant Roubidoux formation crops out at the approximate horizon of the post-Ozark surface and determines strongly expressed outer valley bottoms. However, the Roubidoux is known to be beveled along some of these flats and to go below others when traced down along radial stream valleys on both northern and southern slopes of the dome, the post-Ozark surface there being developed on the younger Jefferson City formation.

All students have stated or implied that the pattern of each succeeding uplift departed but little from that of the preceding one. The drainage pattern on the dome has therefore remained essentially the same throughout this history. The remarkably entrenched meanders of modern Ozark streams can have no other explanation (Tarr, 1924) and the lack of windgaps in the cuestas indicates that there have been no notable earlier piracies.

One departure of a later warping pattern from an earlier one is recorded in the valley of the Osage River. In addition to the comment of Tarr that its upper reaches are in old age while its lower portion is in early maturity, it should be noted that its bounding uplands, traced downstream, increase in altitude as much as 100 feet in little more than 50 miles of valley length as the river enters the area of the Ozark dome.

Further evidence of slight departures from earlier uplift patterns is found in varying vertical intervals between the erosion surfaces, probably the most pronounced occurring along the Eureka Springs escarpment where the Ozark peneplain lies 350 feet below the Springfield in southwestern Missouri (Ava quadrangle) but, traced northward, this vertical interval decreases to extinction in about 100 miles, the two surfaces there being indistinguishable.

The vertical intervals separating the different erosion surfaces must be considered in the cave theory herein set forth. These intervals vary because of differential uplift and erosion and perhaps also because of differential solutional lowering in two adjacent surfaces since they were uplifted. Rarely, however, is there a difference of 200 feet in altitude; more commonly the interval is of the order of 100 feet.

The Ozark dome should afford a fair test of the Walther Penck theory (1924) of geomorphic evolution, in which the influence of uplift far transcends that of rock structure. The dome should, by that theory, possess a series of "treppen" consisting of scarps facing outward and retreating parallel to themselves toward the center of the dome, each scarp overlooking an erosional plain lying in front of it. The exact opposite of this dominates Ozark physiography; the scarps being the outcrops of more resistant formations and retreating away from the area of greatest uplift. The Davis concept of physiographic evolution far better fits the topography of the Ozark dome.

Stream gravel, said Fenneman (1936), is the least expectable feature of a peneplain. Acceptance of this statement requires some special explanation for the blanket of chert stream gravel up to 12 feet in maximum thickness unconformably overlying the diaspore and burley-filled sinks well down the northern slope of the dome. The explanation seems to be that uplift of the Ozark peneplain was first felt in restricted central areas and gradually spread radially, rejuvenating the old age streams in the same sequence. Thus this thick and widespread gravel on the Bourbeuse-Gasconade divide on the northern slope and on uplands of White River drainage on the southern slope was an alluviation on yet unelevated flanks of the peneplained dome.

OZARK CAVE-MAKING

As a result of the writer's investigation, 38 Missouri cave maps are in possession of the Missouri Geological Survey, five of them elaborately done with contoured walls and ceilings as well as floors, and the remainder, surveyed by tape or pace and compass, showing ground plan only. Two types of cave patterns appear in these maps, (1) a network of narrow and generally high passageways determined by two or more intersecting sets of joints, and (2) sinuous or subangularly irregular passageways with converging branches of similar character, the whole suggesting a dendritic stream pattern. Most Missouri caves seen are confined vertically within a narrow stratigraphic range, and only a few have more than one "level."

More than half of the caves examined have either perennial- or storm-water streams today and many others record former streams. A few cave streams can be traced to sink hole sources and a very few to engulfment of surface streams. Most of them are dripwater collections or enter the caves through minor bedding plane crevices. To a small extent, these cave streams undercut walls or erode gorges in bedrock floors and thus add locally to a cave's capacity. Far more commonly such streams bury the bedrock floor with detritus or flowstone. Sink hole breaches in cave roof rock are almost all younger than the cave, and debris contributed from them and not carried on by storm water collects in alluvial fans or cones to decrease an earlier capacity. Associated dripstone deposits contribute to the same result. Ground-water changes today are destroying Ozark caves. Surface streams, widening the valleys into which caves open, destroy the lower cave lengths. Waste from valley slopes migrates back into the mouths of streamless caves, in some cases almost obliterating such openings. Failure of cave roof rock is widespread. Most enterable caves of the Ozarks are in their decadence, emphatically are not being made under present conditions.

These destructive changes are normal consequences of the present cycle of erosion. As surface valleys are deepened, the chief underground change in cavernous zones is lowering of the upper limit of constantly saturated rock. If this brings about cave deterioration and destruction, then the caves must pre-date such lowering past their horizon.

This *a priori* argument does not stand alone in defense of the Davis thesis. The writer has published (1942) descriptions of solutional features on cave walls and ceilings and of cave patterns which are essentially impossible by the older idea that streams now flowing on cave floors are the makers of the

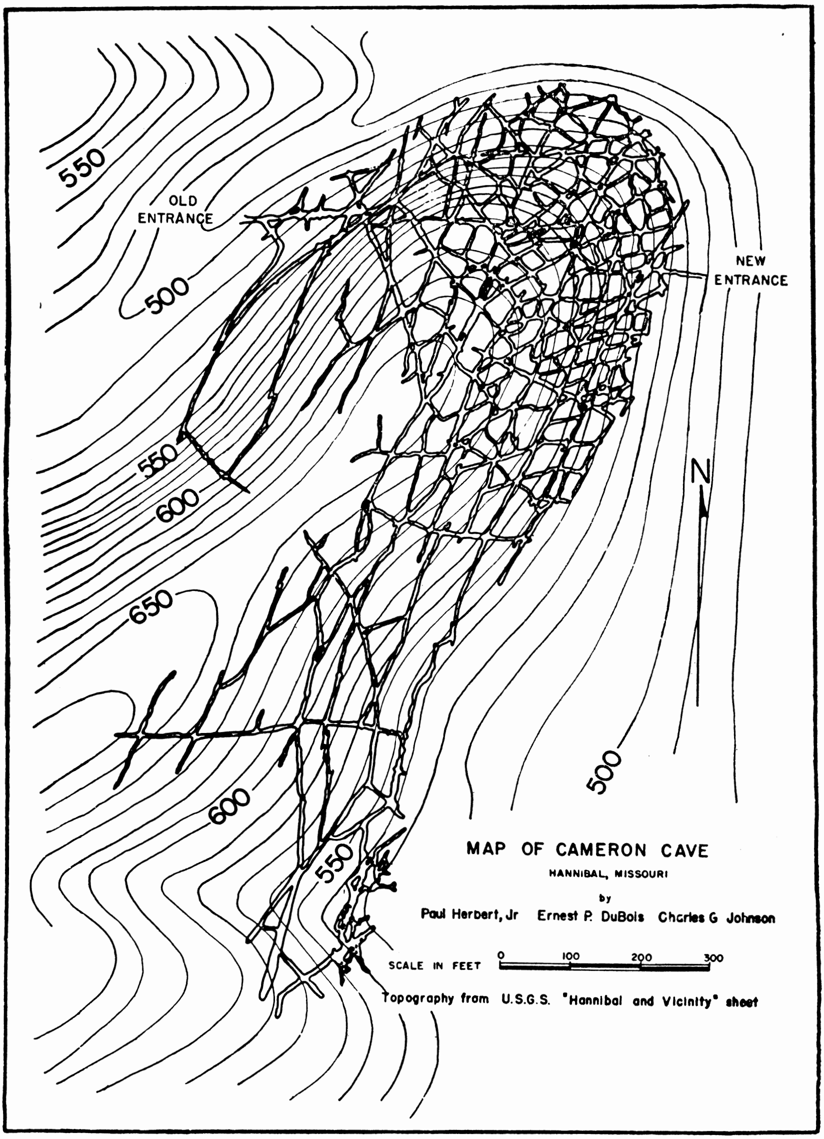

Fig. 1

caves they follow. Instead of briefing the descriptions here, a few typical Missouri caves will be described.

Cameron Cave.—Figure 1 is a carefully surveyed map of Cameron Cave and its overlying topography. Cameron is two miles south of Hannibal, Marion Co., and not far from the well-known Mark Twain Cave, a creek valley separating them. The total length of all of Cameron's passages is four and one fourth miles, the total area above the cave only about 30 acres. The network of high, narrow passages along four sets of joints completely underlies the hill whose slopes transect the cave system in more than 25 places. The system lies low in the hill, is confined to the Louisiana limestone and is roofed by the Hannibal shale. The shale roof is tight and, except at the slope waste blockades where passages and hillsides intersect, there is no seepage water and no secondary limestone in the cave.

It has been suggested that Cameron was made when Mississippi River water, during higher Pleistocene stages, ran through the base of this hill along the joint cracks, its solvent action leaving the amazingly complex network. This idea is rejected because (1) no gradient or pressure adequate to cause such a circulation appears remotely possible, (2) jointed limestone well exposed in quarries and road cuts in the vicinity and within reach of Pleistocene flood waters has essentially no cavern development, and (3) another splendidly developed network cave (Mark Twain) lies in the same stratigraphic position but twice as far back up the tributary valley from the Mississippi as Cameron.

Instead of Cameron and Mark Twain networks taking origin under their respective hills, these hills and the separating creek valley are younger than the caves. The valley development has cut an earlier large network cave in two, Twain and Cameron being only separated remnants. A subwater table circulation, perhaps artesian, followed the joint system down the gentle dip of the formation and dissolved the limestone in places *up* to the overlying shale long before the adjacent Mississippi River trench had been deepened to the cave level. Discharge of such a phreatic flow occurred as a big spring somewhere in the lowland of that earlier topography, a discharge comparable to the pressure flow of many of the Ozark big springs of today.

Vadose water has later used both caves as valley deepening reached their level. The creek itself has found entrance through some of the many hillside intersections and has wandered through limited parts of both caves, cutting non-paired shelves and meander niches in the phreatic spongework walls of the passages it used and bringing in hackberry seeds, snail shells and pebbles from the glacial drift. The entire pattern is utterly impossible for a free-surface gravity cave stream. It required phreatic conditions for its origin.

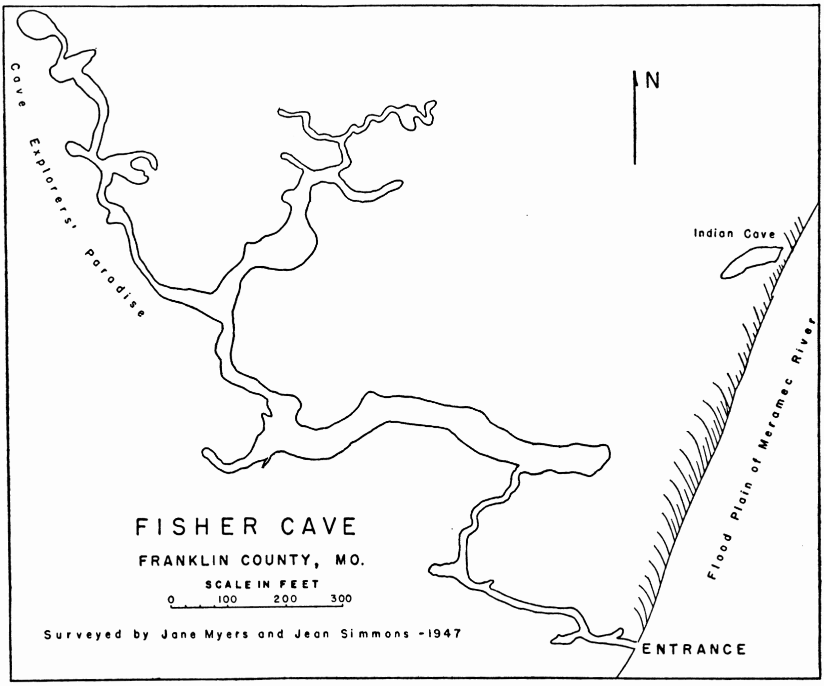

Fig. 2

Fisher Cave.—Figure 2 shows another carefully surveyed Missouri cave, one exemplifying the dendritic type of ground plan. Fisher Cave, in Meramec State Park, opens at flood plain level on the Meramec River valley, its perennial stream supplied by drip and bedding plane seepage and never having flash floods of muddy water such as sink holes feed into caves. Fisher is exceptional, although not unique, in having no wide-mouth hillside opening of the main chamber. Instead, the stream following that capacious linear room abruptly leaves it by a narrow passage 600 feet long, a stoopway for part of that distance, to reach the outside. The main chamber, headed for the Meramec's cliffed valley side, is completely blockaded by dripstone 100 feet beyond the head of the stoopway. Also exceptional but not unique is a bedrock floor for the 600 foot passage although there is no sign of such beneath the trench cut in the tan-colored clay fill that floors the high-ceilinged main chamber. The surface of the clay deposit is higher than the ceiling of the stream's escape route, the bottom is an unknown depth below. Clearly the small passage is of later development than the main chamber, is probably younger than the tan-colored clay fill. An adequately proportioned valleyward continuation of the main chamber must exist beyond the massive dripstone blockade.

The river cliff is less than 200 feet distant and its base is about 25 feet lower than the clay floor at the blockade. In this cliff, about 700 feet north of the stream's emergence, is Indian Cave, a small opening some 30 feet above the floodplain but containing a fill of unknown depth back of the cliff talus. Indian can be penetrated for 50 feet or so, its course back under the hill heading for the blockaded terminus of Fisher. In all likelihood Indian Cave is a portion of the continuation sought. A straight line connection would mark about 350 feet of occluded main chamber here.

The top of the fill in Indian contains a stream gravel close to the ceiling, the record of a free-surface or vadose stream which functioned just before or just after the fill was completed and certainly before this river cliff was made. Thirty to 40 feet of deepening of Meramec Valley since the gravel was deposited seems indicated. The detrital fill, not the dripstone, is the real blockade. Both caves are older than the fill, therefore are older than the present river valley. By no stretch of the imagination can the present cave stream of Fisher be held responsible for the main chamber with its ceiling of spongework deeply indented with upside down "wash tubs," "bath tubs," "chimneys" and "nail kegs." Its narrow escapeway is the only part of Fisher attributable to its own work.

Back under the adjacent upland, Fisher possesses three converging branches whose gradients rise upstream until at the head of one the cave roof is only 50 feet thick. Here the surface slope descends 60 feet northward in a distance in which the cave floor descends 40 feet southward. The cave stream thus drains toward and crosses beneath a hill spur and in this distance it flows parallel to the Meramec Valley but in the opposite direction of the river's flow. Fisher Cave is older than the present topography.

The tan-colored clay deposit constituting the essentially horizontal floor extends upstream for 600 feet, to the junction of the first tributary. Farther than this place, the cave bottom rises above the clay floor level. But a clay has filled these upper portions. It is an older deposit, unctuously smooth, strongly red in color, completely devoid of any included chert gravel, sand, dripstone or flowstone. Remnants linger even in ceiling spongework pockets. The "Cave Explorer's Paradise" branch is a most intricately tortuous crawlway, or coalescence of crawlways, where no fat man will ever verify the statement that only partial clearing of a former complete red clay fill has occurred. This is the peneplain clay referred to in the abstract, once filling the highest and most intricately irregular cave openings of phreatic origin and now being removed by vadose water in the present erosion cycle. The tan-colored clay was deposited only after most of the red clay had disappeared and after considerable stalagmitic growth had occurred. The flat floor is its upper limit.

The cave was completely filled with ground water during its growth and it remained completely filled when solution was succeeded by deposition of the red clay. No Meramec Valley like the present one could have existed during either of these episodes. The solutional episode is assigned to the maturity of the Ozark cycle of erosion when hydrostatic head under uplands could provide for the subwater table circulation that made the cave. The episode of red clay filling marks the attainment of the Ozark peneplain, upland reduction having destroyed the hydrostatic head by which that deep movement of ground water toward the ancestral Meramec made most of Fisher Cave.

The Meramec State Park quadrangle map shows that the hill spurs close to the river valley have flattish tops between 800 and 840 feet A.T. Farther back from the river is a dissected plain, the summit country, approximately a hundred feet higher. If these surfaces are remnants of the Ozark peneplain and the post-Ozark strath and if Fisher is of phreatic origin, it follows that the cave, ranging in altitude between 600 and 690 ft. A.T., was made as much as 200 feet below the post-Ozark strath, or 300 feet below the Ozark peneplain. The ancestral Meramec theoretically received the cave's phreatic discharge by way of a big spring operating under hydrostatic pressure.

Tunnel Cave.—Appropriately named, this cave perforates Bear Ridge, a part of a hill spur occupying one of the great incised meanders of Gasconade River in Pulaski County. It receives storm water from a minor ravine, once tributary to the Gasconade and, although one of the few Ozark caves exemplifying Malott's invasion theory, it retains a perfectly adequate record of its phreatic origin.

Subterranean piracy of the ravine drainage occurred at the east (intake) end of the tunnel when the cave roof directly beneath the ravine failed and formed a ponor (collapse sinkhole) 75 feet deep. The stream, plunging into this and following the cave, reached Gasconade River floodplain on the other side of Bear Ridge, 1000 feet or so distant. In so doing, it abandoned more than a mile of its lower course and developed a sharply intrenched little rockwalled gorge in the ravine upstream from the ponor.

Ceilings and upper walls of Tunnel Cave carry excellent spongework and some can still be recognized on lower walls although greatly abraded by gravel carried through in flood time. Few caves of the writer's experience show so well a young, canyon-like, vadose, lower part of the cross section cut into the bottom of a wider, older cave retaining phreatic traits.

Tunnel antedates the valley-making and ravine-making of the present cycle, therefore is older than the ridge it perforates. Only after the river had deepened to the cave level could vadose conditions obtain. Only after the ponor collapse occurred could a surface stream enter.

Remnants of the Ozark peneplain on the summit of the cuesta a few miles north of Tunnel Cave lie close to 1200 feet A.T. Intermediate flattish summits closer to the river and presumed to be post-Ozark strath remnants are approximately 1000 ft. A.T. The cave mouth is about 800 ft. If the phreatic history of Tunnel dates back to the Ozark cycle, cave-making occurred here 400 feet below the surface of the finally attained peneplain.

Railroad Cave.—Hardly more than two miles from Tunnel is a now streamless cave with a quite different record of surface stream invasion of an original phreatic route. This is Railroad

Cave, difficult to find in the ravined and wooded country nearer the river in the same hill spur but the most outstanding cave in the writer's experience for showing superimposition of vadose stream meanders on magnificent spongework walls of phreatic origin.

Railroad Cave is not far from horizontal and has only a gopher hole entrance at each end, dug through hillside waste. A short distance inside, beyond the in-sloping talus of surface debris, Railroad is a capacious single corridor more than 1600 feet long. Although without branch chambers, it possesses alcoves along its sides, each alcove an upright half-cone cut into the spongework walls, each possessing an "island" of rock also rudely half-cone in shape and conforming to the alcove ceiling slope.

These islands are slip-off slopes and the alcoves are half-cone meander niches (see Bretz, 1942, pp. 679-682) left by a free-surface stream flowing on, and gradually lowering, a clay fill. In Railroad such niches or alcoves incise the older chamber wall in no less than 29 places, generally alternating with each other on the two bounding walls. Many of these meanders began their incision and downward enlargement close to the ceiling, others took origin at lower levels as the vadose stream lowered the clay floor. Stream pebbles still lie on some of these meander floors. The fill on which the vadose stream flowed is the red peneplain clay, much of which still remains, even in ceiling spongework cavities.

Railroad's termini are well up on the hill slopes. The cave perforates a ridge on which there is a minor ravine groove. This fails to reach the cave but its water leaks down into the cave and has made the only noteworthy dripstone deposits Railroad possesses. Solution also has occurred at this leakage and produced another vadose superimposition on the phreatic cave, an incipient dome-pit (see Bretz, 1942, pp. 682-685).

The vadose stream which added the half-cone meander niche alcoves came from one of the ravines outlining the ridge and came early in the ravine-making. The record is of a relatively short-lived subterranean piracy, the stream later returning to its outside course. All this vadose alteration belongs to the present cycle but the spongework cave had to exist previously. The red clay fill, although later than the phreatic cave, also had to be made before the bounding ravines were incised and the vadose stream entered the cave.

If Railroad Cave's phreatic history is to be correlated with the Ozark cycle, the cave was originally developed 300 feet below the peneplain but, by the argument of this paper, it was made before the peneplain stage had been attained, therefore at a greater depth.

OZARK BIG SPRINGS

By Meinzer's definition (1927), a first magnitude spring has an average discharge of 100 second feet (64 million gallons a day). Beckman and Hinchey (1944) found that Missouri possesses 12 such springs, and half a dozen more almost as large, all in the region of the Ozark dome. There can be no question of the existence of an integrated and capacious underground drainage system to supply these springs. The steady flow and lack of turbidity except after heavy rains indicate discharge from considerable subwater table reservoirs. Emphatically, they are not resurgences of lost rivers and sinking creeks such as Malott found in Indiana.

These large springs emerge at the bottoms of deep Ozark valleys, some of them even in the bottom of the river channel, and their present mouthings cannot date very far back in the present erosion cycle. Either their underground drainage systems have developed *de novo* since the river valleys reached their present depths, or they are supplied by phreatic cave systems older than present topography and only recently incised by valley deepening.

The writer knows of four large Missouri springs discharging from enterable caves. The mouth of one of the Greer springs, Oregon County, can be entered by boat or by wading and Roaring River spring, Barry County, only by boat but in a short distance in each the ceiling descends to the water surface of even the lowest discharge. Welch and Fishing Cave springs, Shannon County, rise in the middle of cave floors and soundings in them are surprisingly deep and very instructive as to cave theory.

Some of the big springs emerge under pressure. Big Spring, Carter County, the largest of all Ozark springs, is the outstanding example.

Big Spring.—The up-rushing discharge of this great spring throws spray above the top of the markedly turbulent water dome where an average of 252,000,000 gallons per day escape to nearby Current River. The spring has never been sounded, perhaps never can be because of the spectacular vigor of upwelling. Such a discharge is judged to be from below a water table level in adjoining higher country of adequate area, and to be using a cave system akin to that of Fisher Cave but not yet drained by sufficient deepening of Current River valley as has been done for Fisher by Meramec River. The Big Spring "Cave" is still full of water to the very ceiling, at least in its lower stretches. Its phreatic history has not yet entirely ended; it has not yet become vadose throughout.

Wastes from an iron furnace some miles distant have contaminated the spring in the past (Bridge, 1930). To do this, subterranean drainage had to *cross under* Pike Creek valley.

Roaring River Spring.—The discharge of 6½ to nearly 70 million gallons per day marks Roaring River Spring, Barry County, as a large spring, if not of the first magnitude. Situated near the convergence of two canyon-like valleys nearly 500 feet deep, the spring is the head of Roaring River during dry weather. It is on the east side of the smaller of these valleys and has no surface valley of its own. Conditioned by other nearby deep, steep-sided valleys, the spring cannot receive more than a small share of local ground water, from about two square miles on that side. The total surface drainage area that might supply local ground water from the *opposite* side of the valley is 33 square miles, and here equally deep and steep-sided valleys must take the lion's share of the precipitation. Roaring River Spring must secure its supply from outside the surface drainage area.

The region is a part of the deeply dissected country constituting the southeast-facing Eureka Springs escarpment. Most of the surface drainage on the back slope of the cuesta flows northward, away from Roaring River. Large areas on this back slope are little altered remnants of the Springfield peneplain. Depths locally of 150 feet of cherty waste are known on it. A large shallow doline on this plateau, five miles distant from the spring, 350 feet higher and containing a lake of several acres, abruptly lost its standing water in 1939 or 1940 (Beckman and Hinchey, 1944), and Roaring River Spring equally abruptly became "very muddy for several hours, causing a near-disaster in the rearing pools for baby trout" at the spring mouth.

Thus we know that the spring's supply comes from the cuesta's back slope, moves in nearly the opposite direction of the surface drainage and goes *under* Roaring River Hollow in order to discharge on the east side of the valley. Only the existence of a pre-canyoning phreatic route can fit all these facts. That route is still largely phreatic. And it lies nearly 500 feet below the peneplain remnants on the cuesta brink.

Welch Cave and Spring.—This, the fifth largest spring in the Missouri Ozarks, discharges into Current River Valley in Shannon County, on the south slope of the Ozark dome. Facts regarding it must be taken largely from other sources. The cave can be entered only by boat and no boat or raft was obtainable at the time of the writer's visit. The spring, according to Beckman and Hinchey (1944), discharges a minimum of 50 million gallons per day, a maximum of more than 200 million. They agree with Doll's idea (1939) that it is supplied by ground water from the Meramec drainage on the north slope of the dome. This drainage must cross under the Meramec-Current divide, a situation even more pronounced than that of Roaring River Spring.

Welch Spring is a great upwelling in the middle of the cave floor. Farrar (unpublished notes, about 1940) said that the "lake" made by the spring, a short distance inside the cave mouth, is 200 feet across and 75 feet deep. Beyond the lake is an "auditorium" 120 by 120 and 75 feet high, and "many side tunnels and crevices," but no stream. With the high, slot-like passage carrying the spring water to the Current River bluff, this all strongly suggests a phreatic cave system.

Although Current River's muddy flood water backs up in the cave, the 75-foot hole remains unfilled, and it seems probable that the spring is fed from a level 65 feet below river bottom. The existence of this hole is the most significant fact about Welch Cave and Spring.

The enterable part of Welch Cave is in the vadose zone but its stream rises from below the water table, is phreatic water from deeper, still submerged portions of the system. As with Big and Roaring River springs, the underground drainage system supplying Welch Spring cannot have been developed since Current River valley reached its present depth. The Ozark peneplain remnants on the Meramec-Current divide, a few miles to the north, are 500 feet or so above that valley bottom. If the cave system is of phreatic origin, it should date back to maturity of the Ozark cycle or at least to that of the post-Ozark partial cycle, and vigorous ground water circulation 400 to 500 or more feet below the surface must be envisaged.

Fishing Spring Cave.—Similar to Welch and in the same county and river valley, all of Fishing Spring Cave's air-filled portion can be seen (but not reached) without use of a boat. The cave opens at the foot of a sheer cliff at ordinary river levels. During low water a strong current three or four feet deep flows out of the cave over a rock floor. In high river stages, the cave is entirely submerged.

It is a surprisingly short cave above water level, ending rather abruptly less than 150 feet back of the cliff face. Except for two rock shelves, the entire cave floor is under water. The discharge is from 16 to 47 million gallons daily.

This water rises at the back end of the cave, making a low mound off which the boat constantly tended to slide while soundings were being made. Two lateral soundings were 73 and 74 feet and a central one was 77 feet below low water stage of the spring. A 32 candle power spotlight showed vertical walls far down on all but one side where there was a submerged overhang, the extent of which was indeterminable.

Mud from Current River floods covers the two rock shelves but the deep hole remains unfilled, due presumably to rise of spring water from the very bottom, more than 60 feet below Current River floodplain.

The river apparently has never had a deep stage, now alluvium-filled to the floodplain level, and this vertical rise records a joint-controlled passage demanded by phreatic water under the Salem (Ozark and post-Ozark) upland to the north. The cave passages submerged in Fishing and Welch are now, and always have been, in the phreatic zone. If this is true, then clearly a phreatic circulation may demand upward components near its debouchure. Certainly the underground conduits leading to Fishing Cave Spring antedate the attainment of present depths of Current River valley.

The big springs above briefly described are interpreted as still functioning portions of the deep phreatic drainage system developed during a former erosion cycle that eventually peneplained a structural dome largely of calcareous rock. The enterable caves of the dome are portions of that system lying high enough in the rock to have become drained during the later stream rejuvenation. Most of these air-filled caves possess remnants of a red clay fill deposited subsequent to the phreatic cave-making but now being removed by vadose water using the cave route. The clay fill is interpreted as a record of the peneplain stage of the earlier erosion cycle. All members of the phreatic system should once have received such a fill. In the present cycle's rejuvenation of surface streams, many properly situated subterranean conduits have also undergone "rejuvenation." The big springs of today are members of that group. From the thorough flushing they now receive, all red clay they once contained must be gone. Such subterranean rejuvenation has probably been responsible for complete or nearly complete removal of the red clay fill in some Ozark caves now air-filled and possessing only a trifling vadose stream on their floors.

MECHANICS AND DATING OF THE DEEP PHREATIC CIRCULATION

Widely accepted interpretations, especially if entrenched in textbooks, often become authoritative dogma, against which printed descriptions supporting challenges of the established view may make little impression. Davis was aware of this inertia when he wrote on "the value of outrageous geological hypotheses" (1926), and when he asked that caves be re-examined to check on the validity of the theory of vadose origin. Proponents of that theory may grant all the criteria he and later students have argued to be the results of a complete water-filling, but ask that they be explained as flood-time products under present conditions. The existence of the unctuous red clay fill may be granted but held to be due to local vadose pondings. Granted the absence of a karst topography; cannot a karst have existed earlier, cannot the caves be vadose from an earlier cycle, losing their karst during a later peneplanation? Don't all dendritic caves lead to present valleys as vadose caves must do?

There are other challenges of the Davis concept possible for defenders of the orthodox view. One that Davis rightly considered fundamental but could not answer with definite facts was demand for an adequate mechanics for the deep circulation he envisaged. Joint and stratification partings exist in the saturated zone but a circulation along them, eventually producing an integrated subwater table cave system, would require that the water escape *upward* to enter surface stream valleys.

Davis had recourse to a theoretical picture drawn by King (1899) for ground water movement in homogeneous permeable rock under a topography of adequate relief. Because the water table stands higher under hilltops than under valley bottoms and, as Davis added, because most sedimentary formations are cut by intersecting joints and bedding planes, the weight of the skeletonized water column under a hill should produce a deep lateral movement toward an adjacent valley. Curved courses of such flow, (see fig. 3) zigzagged to fit the pattern of the partings, would go deeper than the valley bottoms, then rise as the escape route was approached. With well-developed integration of the solutionally enlarged, favored courses, large springs would exist in those valley floors, their water rising along joints. This idea of deep flow under hydrostatic pressure, without using the added idea of solutional enlargement, has found favor with Slichter (1902), Tolman (1937) and Hubbert (1940) in their ground water studies. The writer had adopted it long before he learned of Welch and Fishing Cave springs, rising vertically from depths of some 70 feet below valley bottom.

There are numerous recorded instances of drillers' bits abruptly dropping into cavities below the region's water table, this despite Gardner's skepticism (1935). Moneymaker (1941) has recorded such solution cavities in bedrock at dam sites along Tennessee River, encountered below rock bottom level of the river. Well drillers have found similar cavities in several places in the Ozarks, some of them water-bearing (Beckman and Hinchey, 1944, p. 25), some yielding a red muddy water (E. L. Clark, personal communication).

Ozark springs and caves fit this concept of flow under hydrostatic pressure. Scarcely more than half a dozen of the 138 Missouri caves studied lack all evidence of phreatic origin and development. Recording a marked integration of ground water flow in the saturated zone, and in many cases oriented at marked variance to control by existing hills and valleys, they must date back to an earlier, higher water table which has been destroyed in making the present rugged Ozark topography.

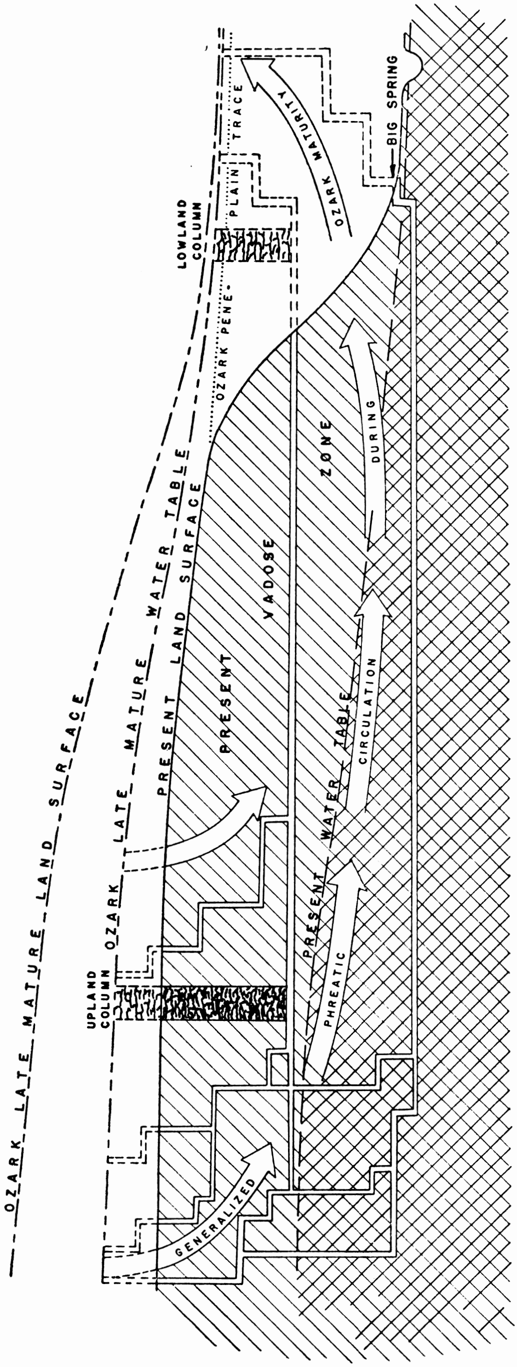

Fig. 3. Diagrammatic depiction of sequential changes in ground water circulation during evolution of Ozark topography.

These caves have suffered complete destruction of their lower stretches because of this later valley deepening. The missing parts must perforce be the theoretical rising water routes, leading to the theoretical large springs of an earlier cycle. The last cave examined during the field study happened to be Fishing Cave with its upwelling big spring. The writer's reaction to the soundings obtained can be readily imagined. At Fishing, the downcutting of Current River in the present cycle has been slightly offside a part of the rising route for that early hydrostatic flow, and in addition has thus far failed to deepen to the main horizontal component of that flow. The cave of the earlier cycle therefore is still full of water flowing vigorously under completely saturated conditions. Welch appears to be a similar case. Elsewhere, so far as now known, the present cycle of erosion has destroyed the upward components of the zigzag curved courses the theory requires. Some of the mounded or "boiling" big spring discharges, when sounded, may add to this list.

Only a region of marked relief can provide the hydrostatic head for phreatic cave-making. Today's Ozark topography has the necessary relief and possesses phreatic springs. Why should not all the abandoned caves of subwater table origin be ascribed to earlier stages of the *present* cycle? There are two answers to this challenge. One is that some caves are so high in the interfluves that peneplained flats are just above them. No adequate relief existed during early youth of the present cycle for providing the phreatic circulation they record. Nor can they be considered as products of ground water circulation under the base-leveled conditions which left the peneplain. That circulation was almost nil.

It is the red clay which records the peneplain ground water. It is this clay which provides the second answer to the challenge. There is no other time in Ozark geomorphic history for this almost universally recorded experience of the phreatic caves. Certainly the present cycle provides no suggestion of such a time.

The last item to be considered in this study is the chronological relation of the Ozark phreatic caves to the three earlier erosion cycles. Which caves belong to which cycle? It seems probable that, with each succeeding uplift and consequent reduction of the land surface, caves would be made at successively deeper levels in the calcareous rocks. But no criterion for identification of three possible generations of caves appears to exist. Depth below identifiable erosion surfaces might seem a possibility until it is realized that the vertical range between the Springfield and the Ozark, or between the Ozark and the post-Ozark base-leveled surfaces everywhere is less than the depths at which some phreatic caves were made. Furthermore, the depth at which circulation was adequate depended in part on where ground water found easiest lateral movement toward valleyways. Hydrostatic head also varied, from place to place, in terms of the overlying topography. Thus, if there were successive generations of caves, they undoubtedly overlapped. Only those caves shallowly located under remnants of the Springfield peneplain can be definitely dated.

Caves developed but little below the water table of the earliest cycle would presumably receive a red clay fill during the peneplain stage and then pass into the vadose zone by maturity of the second cycle and so remain, if they have survived, high in the Springfield uplands. If they were made far below that water table, they could have remained phreatic during the next cycle, though perhaps losing their clay fill and undergoing further phreatic solution if they became, like today's large springs, routes of vigorous subwater table flow. Conceivably they could have received another red clay filling during old age of the second cycle, and have passed into the vadose zone during the post-Ozark or even the present cycle.

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