Speleogenesis and Evolution of Karst Aquifers
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Perspectives in karst hydrogeology and cavern genesis

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Abstract

Hydrogeology and speleology both began during the 19th Century. Their approaches to limestone aquifers diverged because hydrogeologists tend to measure phenomena at very local scales between drilled wells and generalize from them to basin scales, while speleologists study the large but sparse conduits and then infer conditions around them. Convergence of the two approaches with modem computing should yield important genetic models of aquifer and cave.

Genesis of common cave systems by dissolution is a three-dimensional problem, best broken down into two-dimensional pairs for purposes of analysis. Historically, the dimensions of length and depth have received most attention, especially the question of the location of principal cave genesis with respect to the water table. Between 1900 and 1950, different scientists proposed that caves develop principally (1) in the vadose zone; (2) at random depth in the phreatic zone; (3) along the water table in between. Empirical evidence suggests that these differing hypotheses can be reconciled by a four-state model in which the frequency of penetrable fissuration controls the system geometry.

For the dimensions of length and breadth (plan patterns) there is widespread agreement that dendritic (or branchwork) patterns predominate in common caves. Irregular networks or anastomose patterns may occur as subsidiary components. When hydraulic conditions in a fissure are anisotropic (the usual case), dissolutional conduit development is competitive: local hydraulic gradients are reoriented toward the first conduits to break through to outlet points, redirecting others toward them in a cascading process. Plan patterns are most complex where there have been multiple phases ("levels") of development in a cave system in response to such effects as river channel entrenchment lowering the elevation of springs.

Keywords: karst aquifers, karst hydrogeology, cave origin

Introduction

Scientific study of groundwaters (geohydrology and hydrogeology) and of dissolutional cave systems (speleology) both became established in the second half of the 19th Century. Since then, development of the two subjects has been quite divergent. Groundwater hydrologists generally make physical investigations of most kinds of aquifers by means of a few wells and cored holes, measuring the very local rock properties and applying local drawdown and slug tests. Recharge to the aquifers is normally diffuse and thus to be approximated only in a similarly generalized manner, while the discharge (springs and seepages) is often dispersed into wetlands or alluvial channels and so is also difficult to isolate. In contrast, speleologists and karst hydrologists have focused on those conduits and fissures sufficiently large and unobstructed to permit human entry, which will be a tiny proportion of the totality in most cases. They have sought to investigate inaccessible regions of the aquifer between, above and beneath conduits by means of dye traces from the largest points of recharge (stream sinks, which are not necessarily the quantitatively dominant sources of recharge) to the most apparent regional springs. At the recent 6th Conference on Limestone Hydrology and Fissured Media (Switzerland, August 1997), Bakalowicz (1997) and Bonacci (1997) also commented on the contrasts of hydrogeological and speleological approaches.

This dichotomy of approach was made plain early in our century with the publication of the two radically different groundwater models for the classical Dalmatian karst that are shown in Fig. 1. Grund (1903) proposed a Darcian solution, with fresh karstic recharge circulating in an essentially isotropic and homogeneous aquifer above deeper, stagnant waters; Katzer (1909) imagined the karst waters to be circulating independently in rather inchoate cave river networks.

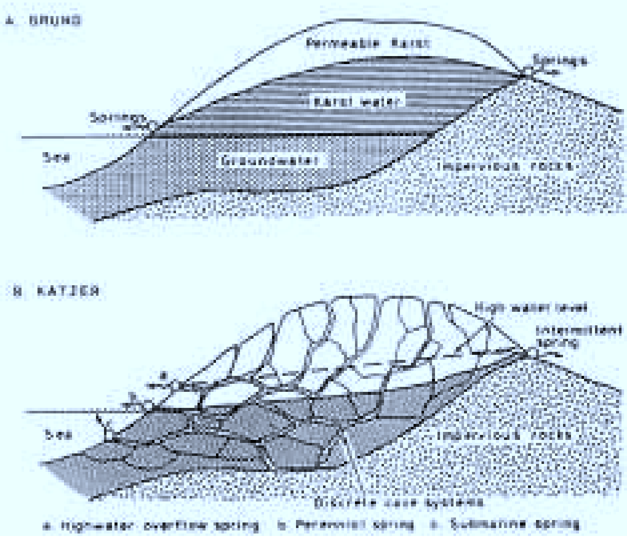

Fig. 1. Groundwater flow models for the Dalmatian karst according to (A) Grund (1903); (B) Katzer (1909).

It is now appreciated that the truth is more complex than either model. If karst aquifers are defined simply as those in which groundwater transmission and storage have been and are being significantly enhanced by bedrock dissolution, they can exhibit many different conditions. Some display strictly single porosity, either as matrix only (common in young reefal and eolian limestones) or as fissure only (e.g. incipient karst in marble or porcellaneous limestones). Large volumes of most karst aquifers will display at least dual porosity, however, exhibiting significant matrix plus fissure, matrix plus conduit, or fissure plus conduit transmission. True triple porosity (matrix-fissure-conduit) can be recognized in at least some portions of most large explored caves.

The difficulties that this natural variety and inhomogeneity can pose in the design and operation of quantitative models for groundwater flow in karst rocks will be appreciated. In addition, within saturated fissures the flow may be simply laminar (Darcian), or non-linear laminar requiring an approximation such as the Hagen-Poisseuille equation. Conduits may be permanently water filled (pipefull, Hagen-Poisseuille or Darcy-Weisbach equations), permanently open channel (free surface, Manning equation or similar; see, e. g., Hauns et al., 1997), or switching between the two as the discharge varies. Evaluation of the friction factors to be applied to these or similar turbulent flow equations in cave passages is especially difficult. For the friction factor (f) in the Darcy-Weisbach equation, for example, I have obtained a range of values from 0.1 to 340 in "back of an envelope" estimates for various situations underground.

Fig. 2 is an attempt to illustrate these difficulties with an imaginary karst. In situation 2A, there are only reconnaissance hydrogeological data. A couple of streams are observed to sink underground at an upgradient boundary to the karst, and one large and one incipient spring are detected along the downgradient edge. In between, outcrops of vuggy, reefal limestone exhibiting diffuse permeability are noted, flanked by patches of thin, densely jointed, inter-reefal beds. Elsewhere, soil obscures the bedrock but a few lineaments show up on air photos. To approximate flow patterns and velocities, we may apply a Darcian equation with a regional value for the hydraulic conductivity, K, such as that which Bocker (1969) derived for the largely obscured karstlands of Hungary:

$$K = \frac{W}{N} k_f + k_m \qquad (1)$$

(W = mean width of fissures in a set, N = mean spacing; k_f, hydraulic conductivity of fissures; k_m, hydraulic conductivity of the matrix).

Fig. 2B puts the principal karst conduits (which might be detected by exploration) onto the map, plus some smaller conduits or enlarged fissures whose location and role could be determined by subsequent detailed programs of dye tracing. There is no information at all for large areas of the map. We might choose to approximate the conditions in them by drilling and coring (Worthington and Ford, 1997); to be confident of intercepting representative principal conduits (i.e. dispensing with cave exploration altogether) it would be necessary to drill traverses on not more than one-meter centers in a majority of karsts, which is clearly infeasible: small conduits and enlarged fissures will be missed even at this exploration density.

The representative, comparatively simple, triple-porosity karst drainage system in Fig. 2B is not analytically intractable, I suggest. However, modeling its hydrologic and hydrochemical behavior offers opportunities to adopt many different theoretical approaches (see Hobbs and Smart, 1986; Clemens et al., 1977). There is scope for much imagination in the operational designs for the models, and the application of supercomputing resources is invited. The formation of computer-focused karst hydrogeological analytical groups at centers such as the Universities of Bremen, Neuchâtel, Tübingen, and Waterloo is among the most exciting developments in karst studies in recent years. There is a large, intellectually exciting and economically important field of work open to them.

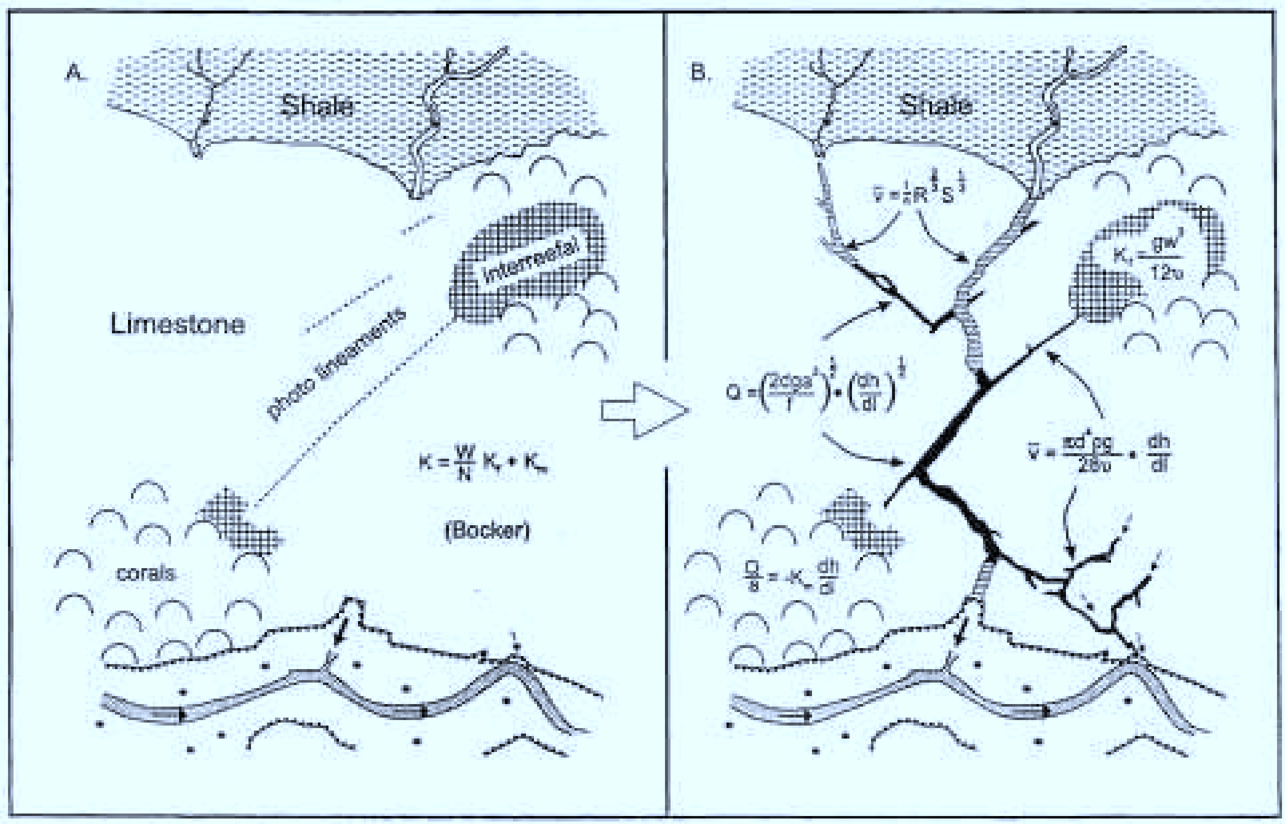

Fig. 2. The analytical structure of an imaginary karst aquifer (A) at the hydrogeological reconnaissance level; (B) following detailed cave exploration and dye tracing. See text for details.

Conceptual models of cave-system development in fissured limestone aquifers

The review that follows is brief and makes no claim to be comprehensive. It presents my own perspectives on some of the main features in the evolution of our understanding about the development of the great integrated systems of cave galleries and shafts discovered during this century. Speleologists appreciate that, in truth, the natural variation that occurs in the systems is immense and that, as a consequence, no one genetic explanation is likely to be complete. We can never be truly certain what will be found around the next bend in the passage; that is a good part of the joy of the game.

This review is limited to cave systems created by normal meteoric groundwaters circulating in limestone or other soluble rocks without any major artesian confinement. These have been termed "common caves" (Ford and Williams 1989, p. 246) because they are probably 90% or more of all known and mapped dissolutional caves longer than a few hundred meters. It does not include caves created by waters (thermal or otherwise) ascending into the cavernous rock from deeper strata, or marine mixing-zone caves.

Common cave systems are usually large in all three spatial dimensions. For genetic analysis, it is conventional to divide such three-dimensional phenomena into singlets or two-dimensional pairings, and this happened historically in the case of caves. Most early proposals focused on their development in length and depth (i.e. in projected long sections) and were greatly concerned with the relationships between cave and water table. With the benefit of hindsight, I believe that it might have been more useful to have considered length and breadth first, i.e. the genesis of the plan patterns of cave systems. The focus on length and depth probably reflects the early European speleologists' attention to the deep shaft-and-drain types of caves that were beginning to be explored in the Alps, Pyrenees, and elsewhere. E.A. Martel, widely considered to be "the father of speleology," was certainly attracted to them (e.g. Martel, 1921).

Development in Length and Depth

The models advanced between (roughly) 1900 and 1950 A.D. are a striking example of the evolution of scientific ideas. They were concerned to determine what was the principal locus of cave genesis in relation to the water table. By the close of this period, every alternative possibility seems to have been advocated by one group of scientists or another. These conflicting models are summarized in Fig. 3.

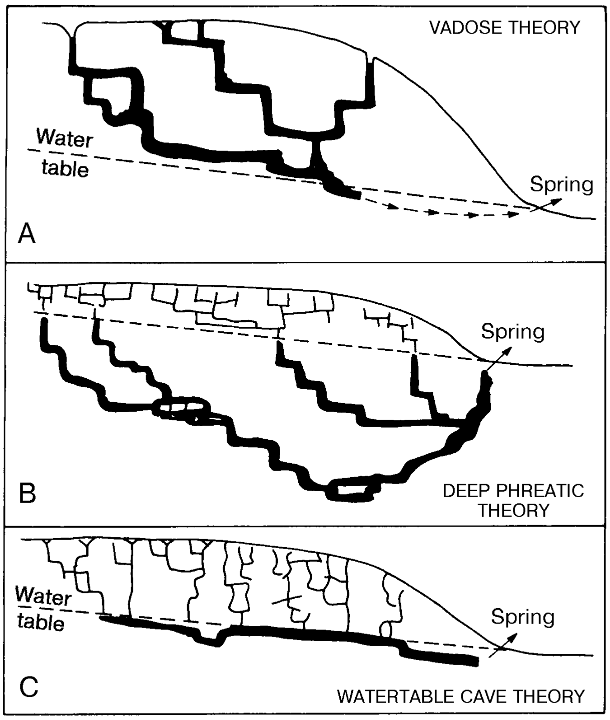

Fig. 3. Schematic diagram to depict the vadose, deep-phreatic and water-table theories of common cave genesis.

(a) Vadose hypotheses

A general vadose model is not presented explicitly in the work of any one author but is implicit in the writings of several such as Dwerryhouse (1907) and Martel (1921). A first, very important, assumption is either that a water table is already established at depth in the rock before there is significant cave genesis (its elevation being determined by some external control such as an entrenched river channel or an impermeable sill) or that it rapidly becomes established during the early cave genesis. Thereafter, it remains essentially fixed in elevation. In this early writing the role of soil CO_2 in enhancing the solubility of limestone was not appreciated. As a consequence, dissolution was believed to be restricted to the 45 - 75 mg/L $CaCO_3$ supported by atmospheric CO_2 pressure at normal temperatures. It was believed that this small solvent capacity would be largely exhausted in the zone that the groundwaters encountered first — the vadose zone. Groundwater velocities would also be greatest in the zone, exposing its cave passages to enlargement by the mechanical erosion of the stream bedload. At the water table, bedloads would be dropped and the passages would shrink to the small dimensions that could be created by the (largely expended) solvent capacity of slowly flowing waters.

Vadose caves of this form can be found. The best examples known to the author are reported in Mt. Sedom, a salt dome that is rising on the western shore of the Dead Sea (Frumkin, 1994). The climate is very arid, favoring a deep water table. Anhydrite caprocks concentrate the occasional rains into streams that reach the salt at a few specific points; dissolutional shafts are drilled beneath these (following fractures or intergranular pores) and fizzle out at an approximate regional water (brine) table where the waters become saturated with the salt. Similar, though less distinctive, shaft-and-drain caves can be found in very young limestones on oceanic islands, where the rock has high matrix porosity and the water table oscillates 70 m or more during each Quaternary sea-level cycle, exposing the mixing zone porosity at each low sea stage. Some high mountain caves in ancient limestones may also be ideally vadose as consequences of rapid uplift accompanied by the opening of the fractures by pressure release, but this is not established. The majority of simple shaft-and-drain vadose caves in mountainous regions are probably of "invasion origin," i.e. they have developed where new streams are able to invade a vadose zone that was drained by cave enlargement during earlier speleogenetic phases. This is frequently a consequence of glaciers deranging earlier surface channel patterns.

(b) Deep-phreatic hypotheses

In flat contradiction to the vadose proposals, W. M. Davis (1930, 1931) and J H. Bretz (1942, 1953) developed a general model proposing that predominant cave development takes place at depth in the phreatic zone. The model was empirical in origin, based on a wealth of field evidence of cave forms that could only have developed under pipefull flow conditions. Certain prime categories of these evidences are now seen to be invalid; for example, the great maze caves of the Black Hills, South Dakota, (prominent in Davis' 1930 discussion) are undoubtedly phreatic in origin but they are not common caves, having been created by thermal waters invading paleokarst under an artesian cover (Ford et al., 1993). Other important pipefull morphologic forms are widespread to predominant in common cave systems around the world, however, and the sum of their evidence is incontrovertible. In Davis' formulation the dissolutional caves essentially follow the stream tubes in a Darcy flow net. Bretz (1942) elegantly linked this pattern, and the cave clastic fillings, to Davis' "Geographical Cycle of Erosion" (1898), suggesting that most cave enlargement occurs during the mature stage of the landscape cycle when local relief and, thus, hydraulic gradients will be greatest and that in the old-age stage of diminishing gradients the caves will slowly fill with insoluble residuum (mostly clays) from the overlying soils.

The deep-phreatic common cave systems that are well known and explored are relatively few. This is because, where they remain water-filled, they are often too deep for exploration by divers. Where they are now drained and relict, their lower sections are prone to local blockage or complete infilling with detritus, while upper sections are modified or destroyed by vadose invasion processes.

Davis and Bretz explained the paucity of examples of ideal vadose caves (Fig. 3A) in the literature of their time by supposing that all limestone cave genesis was very slow; they, too, did not appreciate the potential significance of soil CO_2. As a consequence, in their model most terrain above regional water tables (i.e. the vadose zone) would have been destroyed by surface erosion processes before the caves had attained large dimensions.

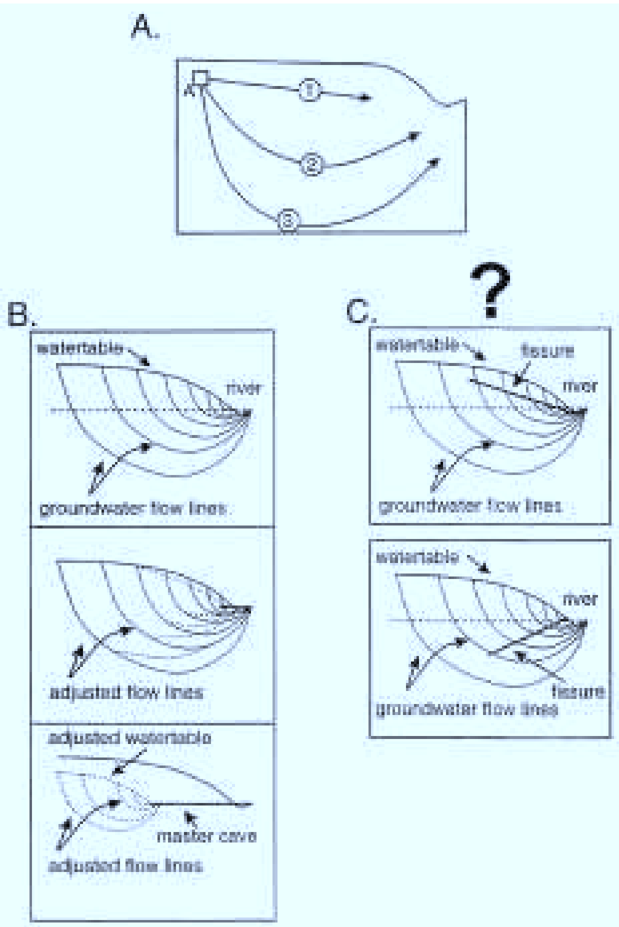

Fig. 4. (A) Detail of the water-table cave model proposed by A. C. Swinnerton (1932). (B) The water-table cave model of Rhoades and Sinacori (1941). (C) How will the Rhoades and Sinacori model evolve if inappropriately oriented fissures are superimposed on it?

(c) Water-table hypotheses

In the English-speaking world, American hydrologists are considered the first to recognize the importance of soil CO_2 as a significant booster of limestone solubility (Adams and Swinnerton, 1937). This finding weakened the strength of one of the principal points in the arguments supporting both the vadose and deep-phreatic models, that limestone dissolution is a weak process. In 1932 Swinnerton introduced a water-table speleogenetic model (Fig. 3C, Fig. 4A). The principal new contention was that, from the outset, groundwater flow in karst aquifers is not constrained by Darcian rules because the physical conditions are always anisotropic and heterogeneous. At the water table a given parcel of groundwater, "A", may split up and flow along several different fissures (Al, A2, A3 - Fig. 4A). As he drew the two-dimensional geometry, it is evident that Route 1 would win in a race to enlarge to conduit dimensions and so capture most or all of the flow. It is the shortest route and thus will experience the most rapid renewal of fresh, acidic groundwaters. Note that, if we insert a wider initial fissure along, e.g., most of Route 2, than occurs along Routes 1 or 3, this argument breaks down. Similarly, by adding the third dimension, Route 2 can be drawn as direct and Route 1 as very sinuous, also destroying its advantage.

In the Swinnerton model the water table is again believed to be established at depth before the cave-system building begins. He allowed that it might be lowered as much as several tens of meters as a consequence of greater hydraulic conductivity due to conduit enlargement along Route 1, and stressed the importance of speleogenesis in an epi-phreatic zone that is inundated by seasonal or shorter-period floods. Preferential cave development in the epiphreatic zone was first advocated by Cvijic (1918) and is repeatedly emphasized in later studies (e.g. Warwick, 1953; Glennie, 1954; Audra, 1997). In the Swinnerton model the cave is propagated along the water table from the head of the system toward the spring. Significant cave development is not prohibited in the vadose zone, but this essentially serves as a collector to deliver flow to the big caves along the water table.

Ten years after Swinnerton, Rhoades and Sinacori (1942) presented the significantly different water-table model depicted in Fig. 4B. The great advance in conceptualizing here is that the water table is no longer a fixed entity preceding the cave. Instead, it is progressively lowered as the cave (underground plumbing and reservoir) is enlarged. In this formulation the cave propagates headward (upgradient) into the rock from the spring, creating a water-table master drain to which any lateral waters (i.e. from the third dimension) will flow.

This type of cave can develop in the ideally simple form that Rhoades and Sinacori imagined. It is found in young limestones where matrix porosity is predominant and the dissolution is enhanced by freshwater/saltwater mixing along a halocline, i.e. it is the basic model for marine mixing-zone caves such as those analyzed by Mylroie and Carew (1990). These are not "common caves," however. If fissure porosity is predominant (the initial conditions in most limestone aquifers), then the locus of the master cave depends upon the distribution and orientation of whichever fissures happen to be the most penetrable by groundwaters and also efficiently directed towards potential spring discharge points, as indicated in Fig. 4C.

(d) An amplified four-state model

My Ph. D. thesis was a study of cave systems in the central Mendip Hills, England, that drain to two major regional springs, Cheddar and Wookey Hole (Waltham et al., 1997). The limestone lithology and geologic structure are complex and the cave systems are ancient, multi-phase and incompletely known. As yet, none of them have been explored all the way through from sink to spring. The morphology and geologic locational controls of the accessible passages were mapped in great detail as a data base. From this information, attempts were made to reconstruct the sequence of passage development and integration in order to establish what factors had controlled the pattern building. The process can be likened to constructing one of the new three-dimensional jigsaw puzzles of famous buildings (St. Peter's, Chartres, Taj Mahal, etc.) that are now on the market, except that in the case of the caves the puzzle pieces are progressively broken or missing above the ground floor until entire wings are gone in the upper storeys, and one rarely finds any remaining piece of the roof!

From these reconstructions and later cave studies in North America and continental Europe, however, the model shown in frames 1-4, Fig. 5, was constructed. It is the product of several iterations (Ford 1971, Ford and Ewers 1978, Ford and Williams 1989, p. 261 *et seq.)* and is intended to apply to those aquifers in limestone, dolostone, gypsum, and anhydrite in which fissure porosity and transmission is predominant before the integrated dissolutional conduit systems develop. The water table does not precede the cave at depth in the rock; at the outlet boundary its elevation

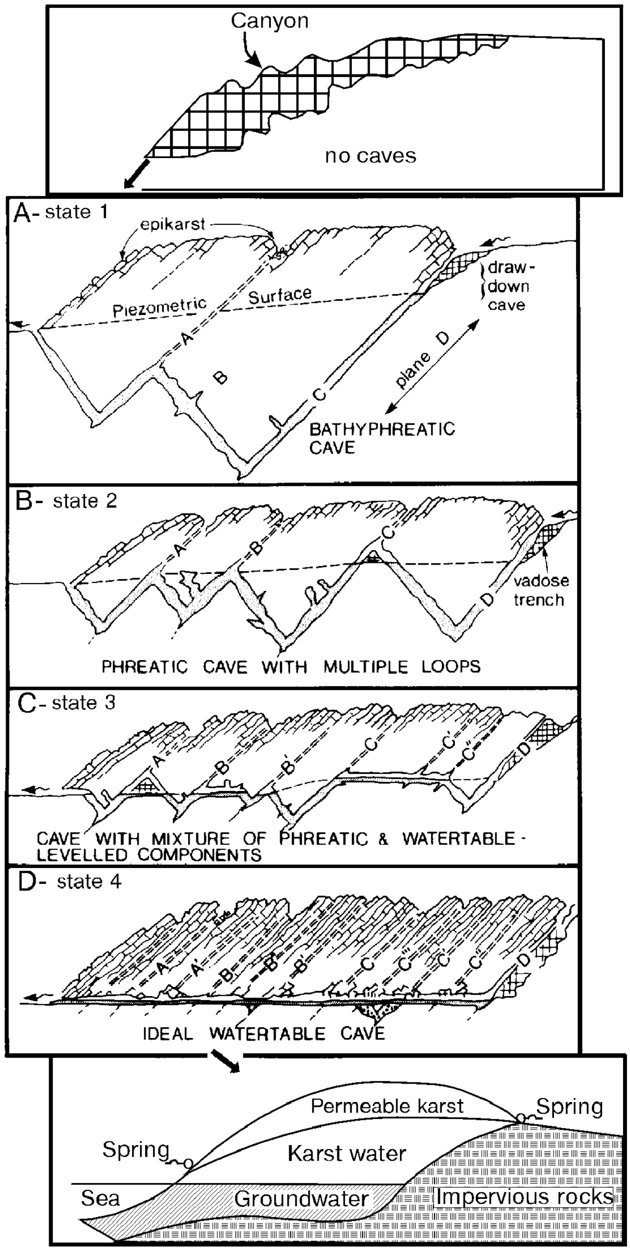

Fig. 5. The four-state model of cave system geometries (Ford 1971 *et seq.)* amplified to include: above right State 0, where fissure frequency and/or aperture is too low to permit cavern genesis; below right, State 5, where fissure frequency and/or matrix porosity are too high to permit caves to develop to an enterable scale.

may be determined by some allogenic control (river channel, impermeable barrier, etc.) but behind this position it is lowered by the evolving three-dimensional geometry of the cave system (the master plumbing), as in the Rhoades and Sinacori (1942) formulation. Where penetrable fissures are sparse but large, cave systems may thus be compelled to follow deep loops below the spring elevations. Where the fissure density is greater, loop amplitude tends to diminish and may be further reduced by subsequent gradational processes such as entrenchment of loop crests (see

Ford and Williams, 1989, p. 271-4). Rossi et al. (1997) describe excellent new examples from the Cantabrian Mountains, Spain). Bedding-parting planes, joints, and faults all serve as important links in most large cave systems. Bedding planes may be more significant because their greatest apertures tend to be more continuous than those of fractures, except at shallow depths (e.g. Knez, 1997); quite often certain of them will have been a little enlarged over wide areas by dissolution in sluggish regional flow preceding the phases of linear conduit development ("nothephreatic conditions" of Jennings, 1983; "inception horizons" of Lowe, 1992). Deep loops are favored where strata dip steeply and shallower caves where dip is gentle. Many cave systems may display mixtures of State 2 and 3 or 3 and 4 along their length. Major cave development is not inhibited in the vadose zone, (as it is in the Davis/Bretz, Swinnerton, Rhoades and Sinacori formulations), but a majority of enterable vadose passages are guided by initial phreatic tubes of lesser dimension. Further details may be found in Ford and Williams (1989, p. 261 -278).

The four-state model seeks to encompass the range of conditions encountered in common caves that are of explorable dimensions. It is an incomplete description of the meteoric groundwater conditions found in carbonate and sulfate rocks, however, as indicated in the two extra illustrations in Fig. 5. There is also a State 0 in which the penetrable fissuration is so sparse (at least, beneath the epikarst) that integrated cave systems have not been able to develop in the available hydrogeologic time. This is true of many marble outcrops because metamorphism sealed their fissures, and of dolostones because of their lesser solubility. At the other extreme, in State 5, matrix porosity is so great and/or fissure frequency is so high that groundwater flow and dissolution are too diffuse to create significant caves; piezometric surfaces and groundwater circulation can be approximated by a simple Darcian formulation such as Grund's model, repeated to round out the Figure. This is the condition that prevails in most chalks, much gypsum and many thin-bedded or very young limestones. Note, however, that allogenic streams may be able to establish and maintain caves through such rocks because their waters are focused into channels before arriving at the karst.

For the practice of hydrogeology in cavernous limestones the most important feature of this model, perhaps, is the emphasis that it places upon the heterogeneity of conditions such as fissure frequency, continuity, and aperture that may be encountered. There are no precise and global values for the spatial frequency of penetrable fissures that can be cited as probable boundaries between, e.g., predominantly State 2 and predominantly State 3 caves, because of the significance of varying aperture within fissure sets. However, it is often possible to calibrate the model at the regional scale within a given geologic formation with a uniform tectonic history.

Plan patterns of common caves and development in length and breadth

During the first 70 years of this century, there was much less effort to develop general models for evolution of the plan patterns of common cave systems than for their long sections. There is general recognition by authors in many nations that the patterns are broadly dendritic or branchwork in their form, focusing flow toward a single spring point. Worthington (1991) analyzed 96 published cases where river cave passages have been explored and mapped along their full length from input points to output points. He found that sinuosity (measured length along the passages/straight line distance from input to output) falls between 1.4 and 1.7 in most instances, indicating that the conduit systems tend to evolve with fairly direct connections.

Palmer (1991) has proposed the general model for the plan patterns of all genetic cave types that is shown in Fig. 6. Common caves display chiefly the branchwork forms that I have highlighted in his figure. Angular connections dominate these where joints and faults are the principal structural guides of the conduits, and curvilinear forms where they develop primarily along bedding planes. Many cave systems will display mixtures of the two patterns. The "irregular networks" and "anastomotic mazes" shown in the figure tend to occur as subsidiary components of the branchwork patterns, usually at their upstream ends where flash floods from surface channels can create extreme but short-lived hydraulic gradients. Groves and Howard (1994), Clemens et al. (1997) have published computer model studies of such maze generation.

In a fully developed branchwork cave the dissolutional conduits will occupy only a tiny proportion of the total length or area of penetrable fissures that is available to the groundwaters. The rules that govern the selection of the successful linkages that will be enlarged into the branchwork pattern were investigated by Ewers (1982) by means of comprehensive series of electrical and sand model flow-field analogs and direct solutional simulations with plaster of Paris; Lauritzen (1986) and Dreybrodt (1997) have supported many of the results with finite-element and lattice analyses. Figs. 7 and 8 summarize the principal features of Ewers' findings.

The models explore conduit propagation across a single fissure that is anisotropic. They will also apply to systems of many interconnected fissures where aperture is anisotropic within and between the individual fractures. The most important feature of the dynamic behavior is the "breakthrough," when a dissolutional proto-conduit approximately one centimeter in diameter reaches an output boundary such as a spring or an earlier cave passage. This abruptly drops the resistance to flow along its line by one or more orders of magnitude because non-linear laminar or turbulent flow can commence (Ewers, 1982; White, 1988), thereby accelerating dissolutional conduit development.

The most simple case of propagation is that of a single groundwater input to the fissure, as shown in Fig. 7A. Competing proto-conduits form distributary patterns by exploiting the wider pores and throats in the fissure until the breakthrough creates one winner or principal tube, "P". When there are competing inputs in one rank, one of them will get ahead (Fig. 7B); upon breakthrough the piezometric surface is drawn down above it, reorienting the local hydraulic gradient toward it. Nearest neighbor inputs then connect to it (breakthrough - dashed lines) in steps A2, A3, A4, etc. In General Systems terminology, common caves evolve as "cascading systems" (von Bertalanffy, 1962), one breakthrough (or energy cascade) re-orienting the local water table and so tripping off the next cascade. The main system of Hölloch, Switzerland (Bögli, 1970) is the finest example that I know of cascade linkage across a fissure (i.e. strike-oriented) in what has been essentially a one-rank-of-inputs situation: there have been four or more successive cascades as the system adjusted to allogenic lowering of the outlet springs. In Switzerland also, the pattern of Siebenhengste (Bitterli and Jeannin, 1997) appears to exhibit similar features.

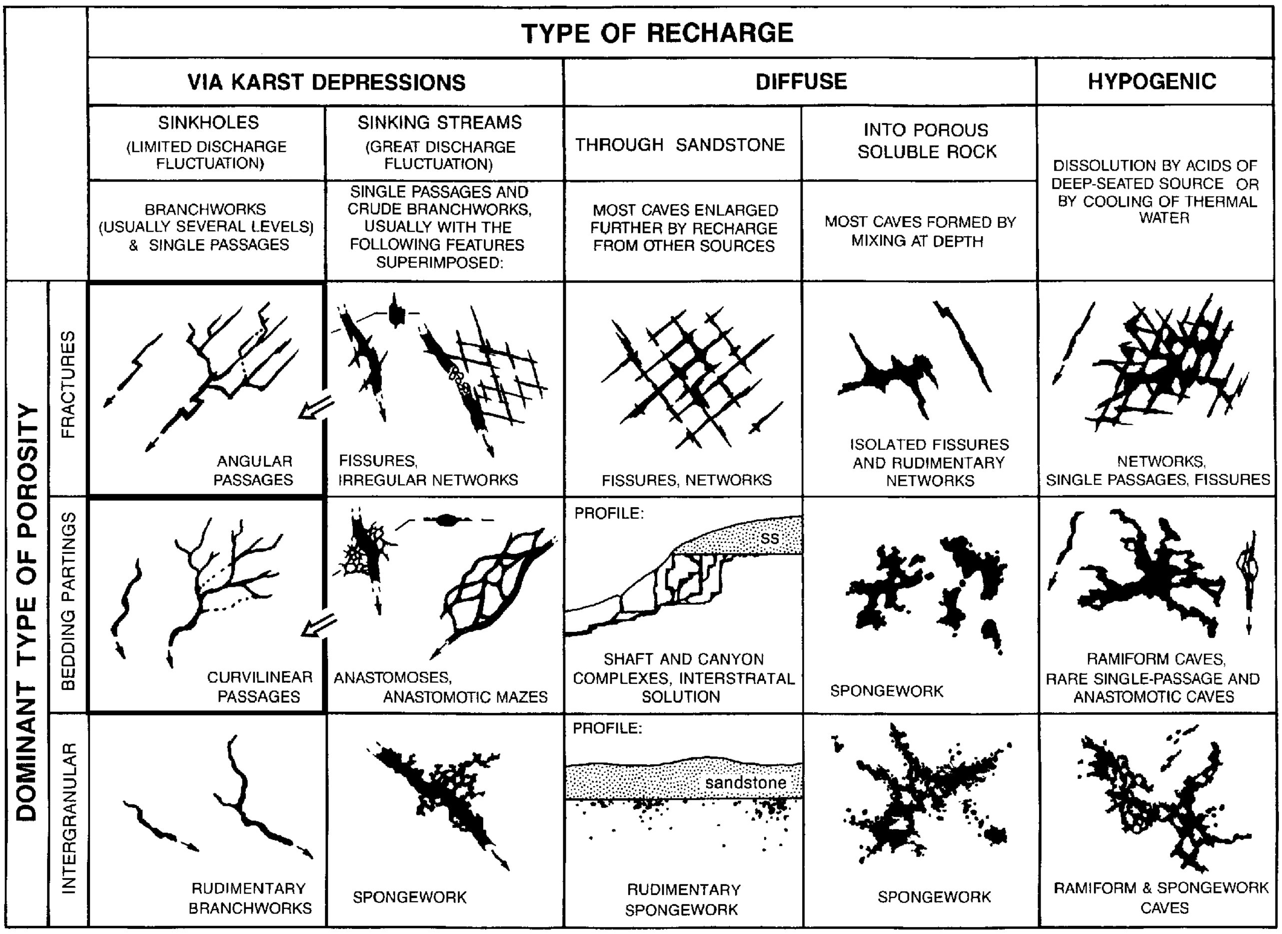

Fig. 6. The general model for plan patterns of caves proposed by Palmer (1991), modified to emphasize the branchwork patterns that are predominant in common cave systems. Irregular networks and anastomotic mazes tend to be subsidiary components of the branchworks, as indicated.

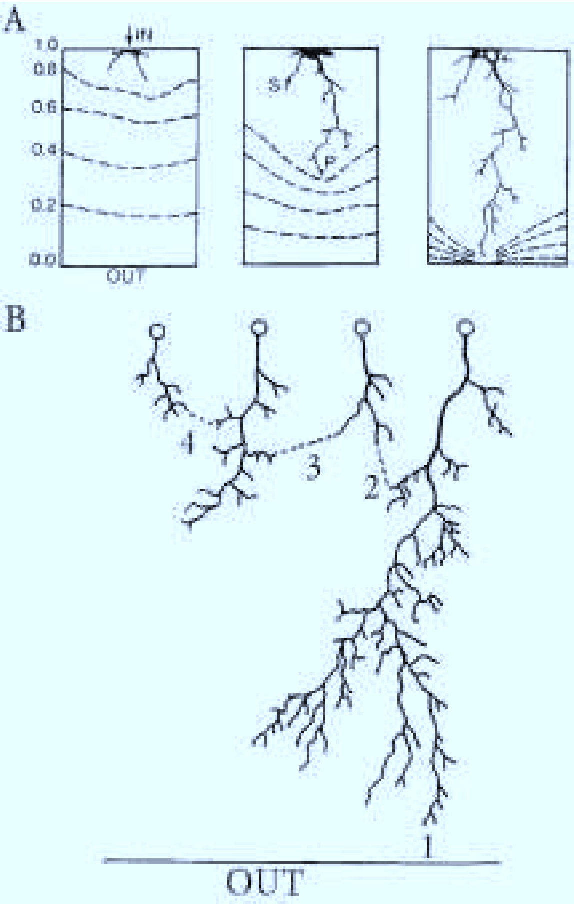

Fig. 7. (A) The competitive extension of dissolutional proto-conduits across a fissure with anisotropic porosity. "P" = principal tube; "S" = secondary tubes. Dashed lines are equipotentials. (B) Competitive extension where there are multiple inputs in a rank. Numbers and dashed lines indicate the predicted sequence of breakthrough connections that will occur and their location. (Both figures based on hardware simulations by R.O. Ewers, 1982.)

The most complex patterns arise where there are many successive ranks of inputs. This is the case in most areas of holokarst, ranging in scale from local limestone pavements (clints-and-grikes) to extensive sinkhole plains such as those of Indiana, Kentucky and Tennessee. Fig. 8A shows that there is the same sequence of competition as above, first among the distributaries of the individual inputs, next by lateral connection of nearest neighbors to the first breakthrough principal tubes. Ranks of inputs that are further from the output boundary then link to winners in the nearer ranks in successive cascades. This pattern may be broadly discerned in the organization of conduits in Mammoth Cave and nearby systems that drain to springs along the Green River, Kentucky (Fig. 8B). This is the lengthiest regional aggregation of known and mapped conduits and shafts (>600 km). Note, nevertheless, that the many gaps in the map indicate that information about the conduit system remains very incomplete, especially if we compare it to channel patterns in surface river basins of the same scale. The Mammoth map is also complicated by the fact that it mingles many successive phases of cave development targeted at different spring locations and elevations; the older passages are now hydrological relicts.

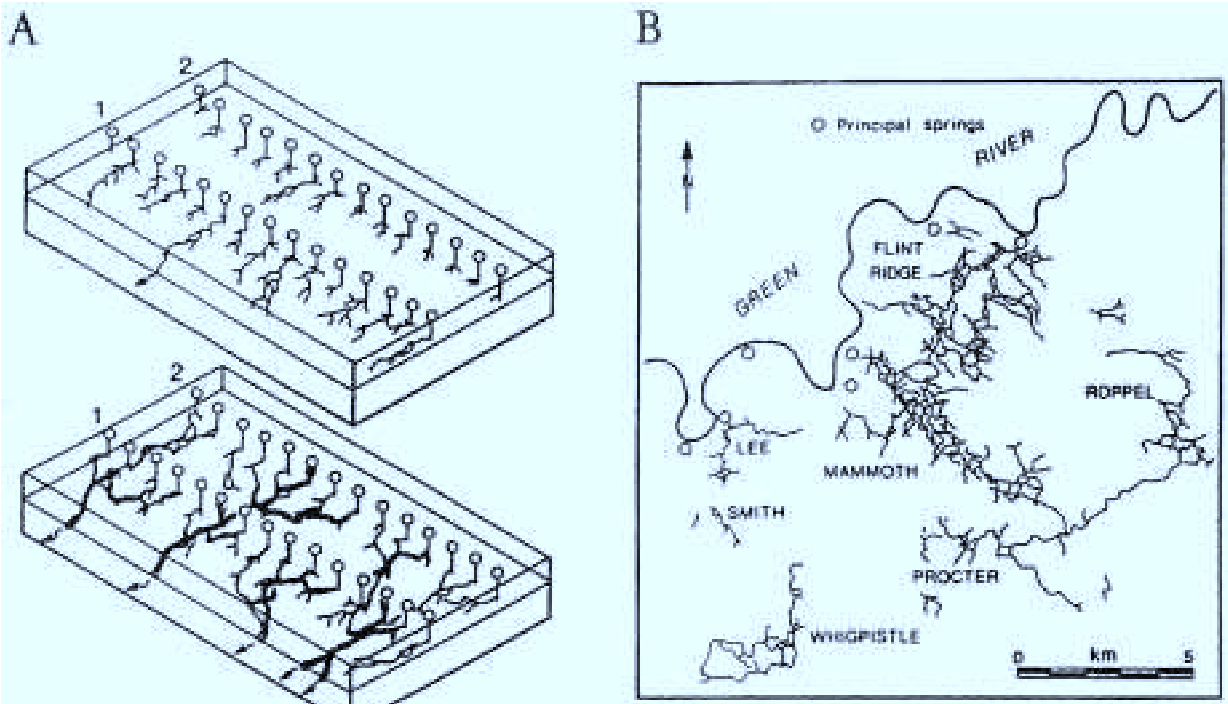

Fig. 8. (A) Patterns of proto-conduit breakthrough and connection where there are multiple ranks of inputs. (B) Map of the major galleries in Mammoth Cave and neighboring cave systems, Kentucky, to illustrate multi-rank cave genesis.

A final initial genetic pattern is found where the limestone is exposed only along a narrow valley floor and groundwater drains to springs at the valley mouth. In this "restricted input" case the sinkpoints tend to line up behind one another in a single file, with breakthrough commencing at that which is closest to the spring (see Ford and Williams, 1989, p. 259-260).

It is emphasized that the construction of these comparatively simple patterns of conduits is liable to major distortions (1) by local lithologic and structural factors such as perching on a chert bed or direction down the axis of a syncline; (2) by great differences in the quantities of water supplied to different inputs in a group, for example when allogenic flow to a stream sink is compared to seepage into nearby holokarst dolines. The pattern-building is analogous to that of the development of dendritic channel networks on the earth's surface, but with one very significant difference: the ideal river pattern is wholly stochastic, the individual channel being initiated at some random point on a surface, from which it can extend upslope and downslope until it chances to encounter another channel segment and so amalgamates. In a certain sense the location of initial input points in a karst branchwork can also be considered to be stochastic, but the successive link-ups of the principal tubes are deterministic because they are directed by local reorientation of the water table following breakthrough. Despite the strong deterministic factors in cave-pattern building (lithological and structural as well as hydraulic), however, it is rarely feasible to predict the exact locations where principal conduits will be found underground, for the reasons made evident in Fig. 7B.

Multiphase (multi-level or multi-stage) cave systems

The great majority of the large common caves that are known appear to be multi-phase systems. These display different "levels" of major conduits that have been created in response to changes in the elevation of the springs. Normally, these changes are lowerings of elevation as consequences of erosional base level lowering around the margins of the karst. Upper galleries are progressively abandoned by the streams that generated them until they become completely relict. Of course, there are also instances of the converse, i.e. cave systems reconstructed progressively above one another where base level is rising because land is sinking or the sea is rising. There are probably many such around the limestone shores of the Mediterranean and Black Sea that are responses to the Messinian Crisis (the dry-up of these seas), for example. However, they are difficult to explore and will play a less important hydrogeologic role in most regions.

In many multiphase systems the lower, younger main galleries are located close to or directly beneath the older passages that they replace hydrogeologically. But in others the new galleries may follow new directions into previously non-cavernous rock. This usually occurs where there is a major shift in the geographic location of the springs accompanying their opening at lower elevation. Re-orientation of the trend of the main drainage conduits can be 90° or more. The effect is especially important in regions of low topographic relief and stratal dip such as central Kentucky, where lowering of 2-3 meters in spring elevation can be associated with a lateral displacement of more than 1000 meters.

In addition to the younger main conduits, the multiphase patterns will be complicated by the presence of many shorter, smaller passages and shafts that interconnect the different levels. Some are hydrogeologically active, conveying tributary streams, while others functioned genetically only for brief periods during the system readjustment to a new level (Ford and Williams, 1989, p. 274-276). Where there have been small readjustments to many successive levels that were separated by only a few meters in elevation, as at Mammoth Cave, Kentucky, the final pattern can be likened to that of a tangled spaghetti.

These relict systems will be contained within the modem vadose zone. Considering the total volume of that zone within a drainage basin, the aggregate volume of all relict passages and shafts will be small, amounting to a few percent at most. However, much of the drainage of the epikarst is organized to connect to them. They intercept this drainage and may convey it laterally as underfit streams on the floors of relict galleries for many hundreds of meters before the flow can find an escape route on downward. This is to suggest that the standard assumption when modeling, that recharge descends vertically through the vadose zone, may not be strictly correct. Factors for local concentration and lateral diversion must be introduced for areas proximate to known or suspected cave systems. Very little work has been done on the problem, but see the pioneering studies of Friederich and Smart (1981, 1982).

Conclusions

Large common cave systems are very heterogeneous in space and time. Working alone and with their differing techniques, neither speleologists nor hydrogeologists can obtain a comprehensive picture of their functioning within complex karst aquifers. The processes that create them and the factors influencing those processes now appear to be sufficiently understood that quite realistic multifactorial process-oriented computer modeling of system genesis is feasible. In the future there is great potential for computer scientists, hydrogeologists and speleologists to work together at this task. It is essential and exciting.

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