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Conduit fragmentation, cave patterns, and the localization of karst ground water basins: the Appalachians as a test case

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Abstract

Because conduit systems in maturely developed karst aquifers have a low hydraulic resistance, aquifers drain easily and karst aquifers are subdivided into well-defined ground water basins. Ground water elevations are highest at basin boundaries; lowest at the spring where the ground water is discharged. Parameters that control the type of conduit development are (1) the effective hydraulic gradient, (2) the focus of the drainage basin, and (3) the karstifiability of the bedrock. Moderate to highly effective hydraulic gradients permit the runaway process that leads to single conduit caves and well ordered branchwork systems. Low hydraulic gradients allow many alternate flow paths and thus a large degree of fuzziness in the basin boundaries. Low gradient ground water basins also tend to merge due to rising water tables during periods of high discharge. Focus is provided by geological constraints that optimize discharge at specific locations that can evolve into karst springs. Karstifiability is a measure of the bulk rate at which aquifer rocks will dissolve. Fine grained, pure limestones and shaley dolomites mark the opposite ends of the range. The cave surveys of the Appalachian Highlands provide a data base that can be used to classify the lateral arrangements of conduit systems and thus determine the relative importance of the factors defined above.

Keywords: conduits, triple permeability, karst parameters, karstifiability, lithologic controls, structural controls.

Introduction

Karst aquifers have (among others) two characteristics that distinguish them from most other aquifers. One is an extreme permeability distribution generally described by the "triple porosity" model, one component of which is a system of pipes (known as "conduits"). The second is an intimate connection between ground water and surface water. Any functional model of karst aquifers must take account of the conduit system. In general, this is difficult because the complete conduit system can only rarely be directly observed and there are no really reliable techniques for mapping the conduit system from the land surface. The only data usually available are the results of tracer experiments which give overall connections and transit times, measurements of hydrographs and chemographs at the springs, and such segments as may be accessible to cave explorers. This leaves an immense amount of uncertainty in the proper placing of conduits and the internal functioning of ground water basins.

The most direct information on conduit patterns is obtained from the maps of caves that occur within the drainage basin. Caves consist of those fragments of active and abandoned portions of the conduit system large enough to permit human exploration. However, cave maps require interpretation. Cave explorers regard all accessible passages as part of the same cave. Thus, a large cave can be composed of a sampling of conduit system fragments that may be separated in both time and space. Higher (and generally dryer) parts of the cave are portions of conduits that were formed under earlier conditions sometimes extending far back into the Pleistocene and may not be related to contemporary drainage basins. A single accessible cave may also represent portions of the conduit system of more than one drainage basin. The most serious limitation is that almost all caves represent only small fractions of the complete conduit system.

A great deal of effort has gone into modeling the evolution of karst aquifers along the time axis. Recent papers, e.g. Palmer (1991), Dreybrodt (1992; 1996), Groves and Howard (1994), Howard and Groves (1995), Siemers and Dreybrodt (1998), Kaufmann and Braun (1999, 2000), have shown that it is possible to describe the evolution from an initial fracture to a fully developed conduit and place the processes on a reasonable time scale. Although a tremendous number of caves systems have been examined in many parts of the world (Klimchouk et al., 2000), the geological constraints that limit ground water basin development have not been as well systematized. In this paper we return to issues of the development of karst ground water basins that were first raised long ago (White, 1969; 1977). Using examples from the Appalachian Highlands to illustrate points, we attempt to understand the geological factors that control development of karst drainage basins and their associated conduit systems.

The Appalachian Mountains of eastern United States have extensive regions of karst development including the complexly folded and faulted Cambrian, Ordovician, and Devonian carbonate rocks of the Valley and Ridge Province and the dissected Appalachian Plateaus with low dip Mississippian limestones overlain by caprocks of shale and quartzite (Davies and Legrand, 1972; Davies et al., 1984). The varying geologic settings in the Appalachian Mountains provide examples of many combinations of geologic constraints on karst drainage basin development.

Aquifers, karst aquifers, and surface water basins

As a point of reference, we briefly describe what may be called a "textbook aquifer" ("textbook" means such standard references as Freeze and Cherry (1979), Domenico and Schwartz (1990), or Fetter (1994)). A 'textbook' aquifer consists of these parts, arranged vertically: (1) The land surface where recharge is provided by precipitation. (2) The soil with its vegetative cover where precipitation is distributed between stored soil moisture, water that is infiltrated downward into the aquifer, and water that is returned to the atmosphere through evaporation and transpiration. (3) The vadose zone, a region of bedrock and regolith with air-filled pore spaces, that serves as a pathway for water in excess of soil moisture to move downward into the aquifer. (4) The water table, the surface that delineates the boundary between saturated and unsaturated portions of the aquifer. (5) The phreatic (or saturated) zone where all void spaces are water filled.

The "textbook aquifer" is characterized by the aquifer thickness (the total thickness of the rock unit for a confined aquifer and the thickness of the saturated zone for an unconfined aquifer), and the hydraulic conductivity of the medium. There are, in addition, hydraulic boundaries set in place by impermeable beds and structural constraints such as folding, and faulting. However, the width of the aquifer is usually unspecified — the aquifer is limited only by the limits of the rock unit. Flow fields are set by highs and lows in the water table which in turn are controlled largely by surface topography. Surface streams act as zones of ground water discharge.

Karst aquifers are rather more complicated. The essential components have been discussed at length in several textbooks (White, 1988; Ford and Williams, 1989) and in recent papers (White, 1998; 1999) and are sketched in Fig. 1. As with the "textbook" aquifer, there is a diffuse component of recharge infiltrating through the soil and moving downward through fractures into the aquifer. As an additional factor, there may be some storage in the epikarst. Closed depressions on the land surface act as catchments for storm runoff which enters the aquifer through drains in the bottoms of the closed depressions. The third source is from sinking surface streams that provide what is known as allogenic recharge. The fraction of the ground water basin occupied by the catchment areas for sinking surface streams is one of the important parameters characterizing karst ground water basins.

Sinking surface streams and the drains from closed depressions feed directly into the conduits which act as master drains transmitting water at high velocities to their discharge points at karst springs. Well developed conduits have low hydraulic resistance and often create troughs in the water table. Hydraulic gradients within the surrounding bedrock thus point toward the conduits rather than toward the springs (Ewers and Quinlan, 1981). Because of the arrangements of hydraulic gradients, each conduit system with its up-gradient infeeders and its set of sinking surface streams defines a ground water basin. The better the development of the conduit system, the better defined is the ground water basin. Hydraulic heads are low along the conduit and high between adjacent conduit collection systems. Thus the shallow part of the aquifer becomes segregated into cells, each functioning as a separate ground water basin. The downstream ends of the basins are located at springs where the drainage returns to surface routes. The boundaries of the ground water

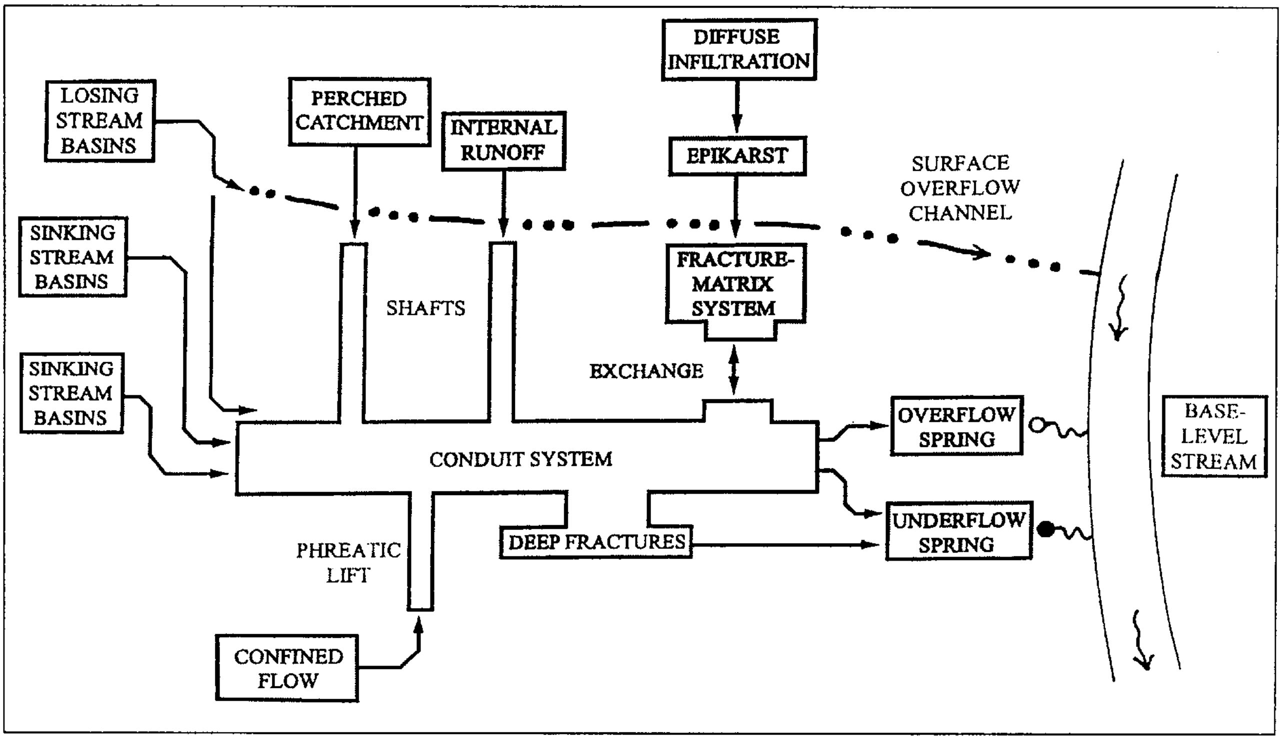

Fig. 1. Conceptual model for a karstic aquifer. From White (1999) with modification by J. A. Ray.

basins are defined by the total recharge areas including all surface stream catchments that drain into the conduit system. Ground water basins evolve with time as the base level surface streams continue to downcut their channels. The evolutionary pattern has been interpreted in the Mammoth Cave area (Quinlan and Ewers, 1989).

Some karst ground water basins are truly isolated so that all precipitation that falls within the basin ultimately appears at the spring. The boundaries of these basins often show a good degree of correlation with the boundaries of overlying surface water basins. Others, however, are linked by either piracy routes or spillover routes. Conduits may develop across surface water divides and thereby transmit water to or from other nearby surface water basins. Piracy routes are common and result in ground water basins seriously out of register with overlying surface water basins. The term "spillover route" is used for abandoned conduits that lie just above the active conduit system. These transmit water only during high flow conditions. Thus a ground water basin may have one set of flow paths active during base flow conditions and a quite different set of flow paths during flood flow conditions. The boundaries of the ground water basins also depend on ground water stages and flow conditions. The greater the internal relief of the basin - that is the head difference between the spring and the basin divides, the more localized the basin and the more stable the basin boundaries.

Karst aquifers in the Appalachian Highlands of eastern United States are restricted because of the limited thickness of the carbonate rock units. The Mississippian limestones that underlie the Cumberland and Allegheny Plateaus have thicknesses of only a few hundred meters. The Ordovician carbonate rocks of the folded Appalachians range in thickness up to several thousand meters but consist of mixed limestone and dolomite sequences. As a result, most ground water basins span the entire saturated thickness of the aquifer. The entire aquifer must be interconnected by diffuse flow through the matrix and fracture permeability but the transmission of water through the conduit system is so much more efficient that the ground water basins account for nearly all of the water budget.

The active conduit systems in the Appalachian ground water basins are generally shallow. Some can be explored under base flow conditions as open cave passages with free-surface streams. Often the conduit is an alternating sequence of open stream passage and sections that are completely flooded. Explorations by cave divers are revealing some of the characteristics of the flooded sections. Typically, these extend to depths on the order of tens of meters below base level. Much greater depths have been reached in other areas and much remains unknown concerning the extent of conduit development below local base levels. Evidence from diving exploration and from the vertical development of some dry caves shows that these depths can reach hundreds of meters.

Conduit and permeability patterns

The *triple permeability model* (or triple porosity model) contains three components: *matrix permeability, fracture permeability,* and *conduit permeability.* Matrix permeability is the permeability of the bedrock itself - the interconnected pores, vugs, and other void spaces on the scale of individual mineral grains. Unconsolidated sand or gravel is an example of a medium with only matrix permeability. Fracture permeability is the result of mechanical rupturing of the rock, either joints, joint swarms, faults, or bedding plane partings. Brittle rocks are usually fractured. In some rocks, such as fractured granites, fracture permeability is the only significant permeability. Other rocks, such as massive sandstones, may contain both fracture and matrix permeability. Conduit permeability is provided by pipe-like openings created in such rocks as limestone, dolomite, and gypsum by the solvent action of circulating ground water. Although conduit permeability is usually confined to karstic rocks, it also occurs in some volcanic rock aquifers.

There is a great diversity of karstic aquifers depending on the relative contributions of the three permeability types as illustrated schematically in Fig. 2. Many of the karst aquifers in eastern United States have formed in Paleozoic limestones with a negligible matrix permeability and are dominated by conduit systems and by allogenic recharge from surface catchments. Fracture flow plays an important role in transmitting water from diffuse recharge on the land surface to the conduits and in transmitting water to wells drilled in these aquifers. Aquifers in dolomite tend to have more poorly developed conduit systems so that the ground water movement is dominated by fracture flow. Fractured dolomites tend to be more useful for water supplies because the water can be more readily accessed by properly located wells and because the supply is less threatened by surface contaminants derived from sinkholes and sinking streams. In contrast, young limestones such as those making up the Floridan aquifer are highly permeable so that much of the ground water is transported through the matrix. Concentrated flows produce large conduits within the permeable rock mass. Fractures are relatively less important. The *Edwards Aquifer* in Texas is an intermediate case involving all three types of permeability.

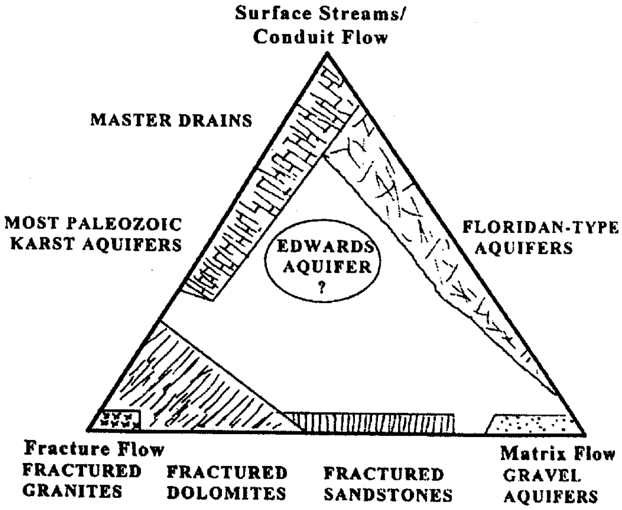

Fig. 2. Contributions of the three components of the triple permeability model to various aquifers.

Ground water velocity increases in a nonlinear fashion with the effective aperture of fractures and conduits, resulting in a concentration of flow along a few preferred pathways. Flow velocities in conduits are often sufficient to drive the system into a turbulent regime. The contrast in velocity between the least permeable and most permeable parts of the same aquifer is often six to ten orders of magnitude. It is a common fallacy to assume that if one scales over a sufficient volume of the aquifer, then the fractures and conduits will average out and the aquifer as a whole can again be characterized by a single hydraulic conductivity. This does not work. The contrast in velocity and flow is too extreme. Worthington (1999) has calculated that more than 90% of the flow in a selection of karst aquifers is through what he calls the "channel" system.

The karstic characteristics of an aquifer can be evaluated in terms of the degree of development of the conduit system, the degree of coupling between the conduit permeability and the matrix and fracture permeability, and on the relative contribution of surface water. The arrangements of the conduit system are reflected in resulting cave patterns. Some of the possibilities are sketched in Fig. 3 in a manner similar to patterns proposed by Palmer (1991).

The pattern in 3(A) shows a *single, conduit cave* with the stream from a surface catchment entering one end and the discharging through the other end. The cave segment itself may either contain a free-surface stream or be located completely in the phreatic zone. There is little hydraulic coupling between the water stored in the surrounding bedrock and the surface water draining through the cave. The limit, as the length of the cave segment is made shorter and shorter, is the natural bridge. Many caves are found in many parts of the world that are essentially underground reaches of surface streams.

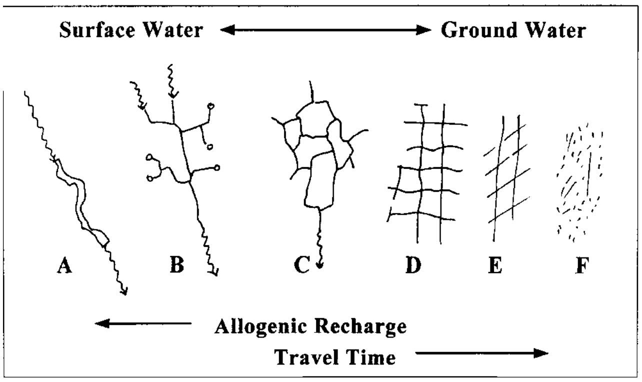

Fig. 3. Sequences along the continuum from a single conduit cave acting as an underground route for a surface stream to non-karstic fracture and porous media aquifers.

The best known such cave in the Appalachians is the Sinks of Gandy (Fig. 4). Whether or not the water in such conduit segments should be considered ground water is a matter of semantics. The main catchment is a surface water basin with a well-defined divide.

The pattern in 3(B) is that of a *branch-work cave.* There are multiple surface inputs both from sinking steams and from the drains of closed depressions. The underground pattern has many features in common with the headwaters regions of surface streams. The branchwork drains into a master trunk that ultimately leads to the spring. A cave fragment of the downstream trunk, of course, is not distinguishable from a trunk of type 3(A) except that its catchment is underground rather than on the surface. The branchwork pattern is typical of many Appalachian ground water basins. What is usually observed are inlet caves at stream sinks or at sinkhole collapses, outlet caves accessed through springs or paleosprings, and other bits of the collector system accessed in various ways through shafts, collapses, and valley intersections. In many drainage basins, various caves can be spliced together along with locations of stream sinks and rise points to construct a moderately accurate description of the conduit system. Fig. 5 shows a particularly nice reconstruction of conduit system for the Buffalo Spring Basin in Mammoth Cave National Park, Kentucky (Meiman and Ryan, 1999).

Patterns 3(C) and 3(D) are both characteristic of low gradient aquifers. Circulation of water primarily along bedding plane partings produces an anastomotic maze pattern; circulation of water primarily along joints produces a *network maze* pattern (Palmer, 1975). Flow velocities are lower both because of lower gradients and because of the larger effective cross-section since the flow is distributed over a large number of individual cave passages. The catchment boundaries for patterns (C) and (D) are less well defined. Exploration into the perimeters of such cave systems is often limited by passages simply too small for human penetration. The limit of pattern 3(D) is pattern 3(E). The solutional enlargement of joints and bedding plane partings becomes less and less until the passage becomes impenetrable by humans and at the limit becomes fracture permeability. Fewer and fewer fractures and all that remains is the matrix permeability, 3(F). With patterns 3(E) and 3(F) the basin boundaries have essentially disappeared and in the limit, the karstic ground water basins have blurred into fracture or porous media aquifers.

In the sequence of conduit permeabilities sketched in Fig. 3, those on the left are dominated by surface water; those on the right by ground water. The fraction of allogenic recharge decreases from left to right. Travel times increase from left to right. The concept of a ground water basin is well defined for conduit systems of the left. Basin boundaries and indeed the very concept of a ground water basin becomes increasingly fuzzy and finally fades away completely from left to right.

Parameters controlling the development of karst ground water basins

There have been three broad approaches to the study of karst aquifers: (1) Calculations of the flow mechanisms in the conduits. (2) Geochemical/ hydrodynamic modeling of the evolution of fracture systems to maturely developed conduits. (3) Interpretation of cave patterns and drainage basin patterns based on the geologic setting in which the cave or basins are located. Calculations of type (1) have assumed various geologic frameworks but generally take the geologic framework as a given condition. Early speleogenetic research was largely intuitive and depended strongly on the geologic framework. As analysis of karst aquifers became more mathematically and geochemically sophisticated, the emphasis shifted to approaches (1) and (2). Recent work has been returning to the geologic framework.

Our concern here is with the geologic boundary conditions that provide the limitations on how the ground water basins can develop. If we think - in a rather idealistic sense - of the process of conduit system development being guided by a differential equation, there must be parameters that provide the boundary conditions for the differential equation. Parameters that describe the boundary conditions for the development of the aquifer can be broadly classified into: (1) the effective hydraulic gradient, (2) the focus of the drainage basin, and (3) the karstifiability of the bedrock.

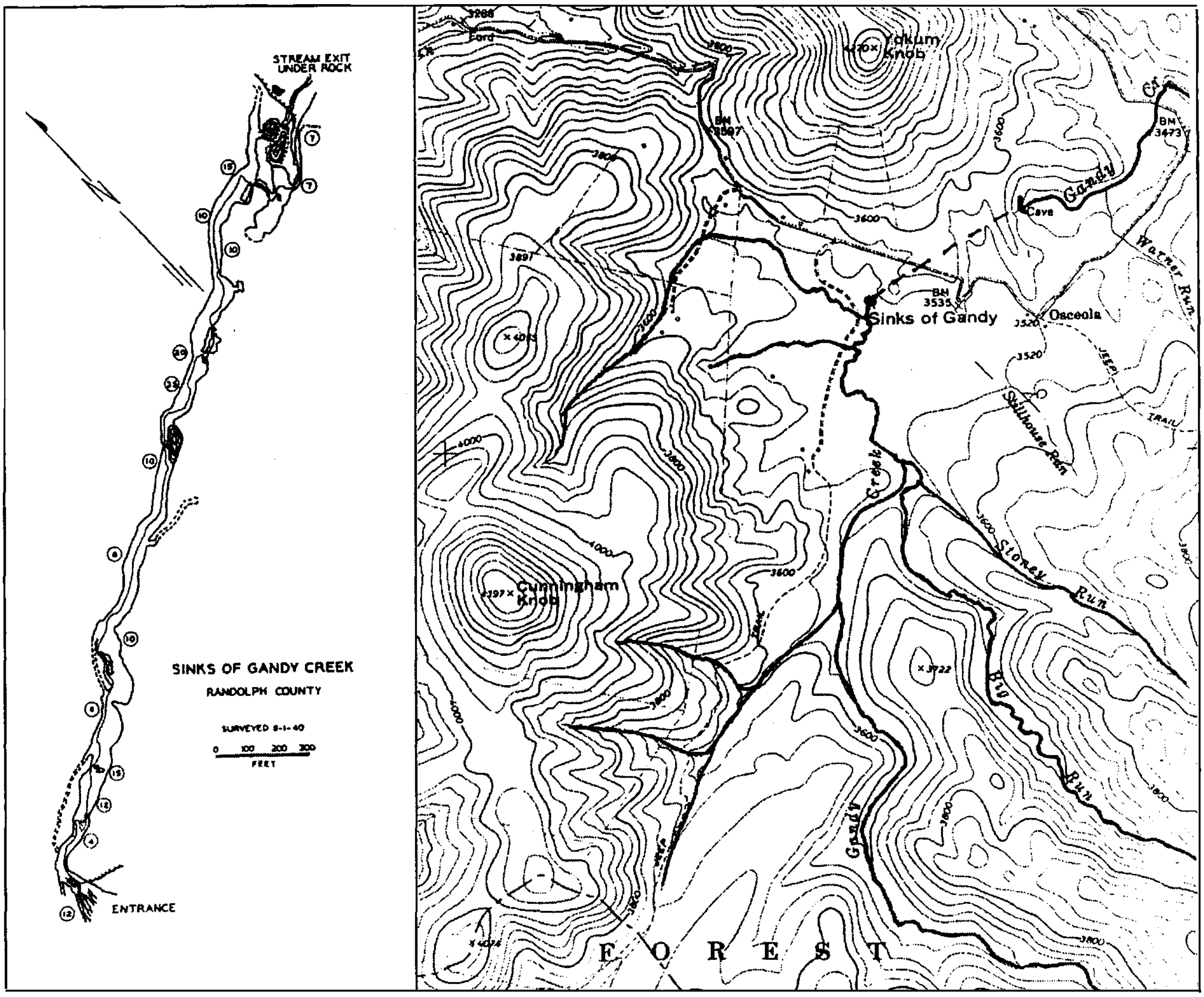

Fig. 4. Map of the Sinks of Gandy, Randolph County, West Virginia. Topography from US Geological Survey Sinks of Gandy 7.5 minute Quadrangle. Cave map from Davies (1958). A more detailed map appears in Dasher (2000).

Effective hydraulic gradient

Localization of ground water flow into a relatively small number of relatively large conduits is a runaway process driven by local hydraulic gradients. Steep gradients such as those in the tributary valleys of the dissected Cumberland Plateau which range from 0.01 to 0.03 are more than adequate. Cave profiles in these settings tend to be stair-step with vertical segments interspersed with reaches of low gradient passage. The gradients in the Mammoth Cave area of Kentucky are in the range of 0.001. Gradients in the Valley and Ridge Province and in the Great Valley Province where the carbonate rocks occur on the valley floor, are in the range of 0.01 to 0.001. All of these are entirely adequate for the development of conduits and distinct ground water basins. If other factors are favorable, conduits and thus localization of flow into ground water basins will occur with extremely low gradients. As other factors become less favorable, higher gradients are needed to overdrive the system.

The overall hydraulic gradient of a drainage basin is given by H/L where H represents the maximum internal relief between the highest input point and the discharging spring. L represents the length of the basin. Larger basins require higher relief to maintain the same gradient. The internal relief of Appalachian karst drainage basins is generally less than 300 meters. The lengths of Appalachian basins are generally in the range of a few kilometers to a few tens of kilometers so in this setting hydraulic gradients are rarely controlling factors. In low relief karst areas and in very large karst drainage basins hydraulic gradient becomes more important.

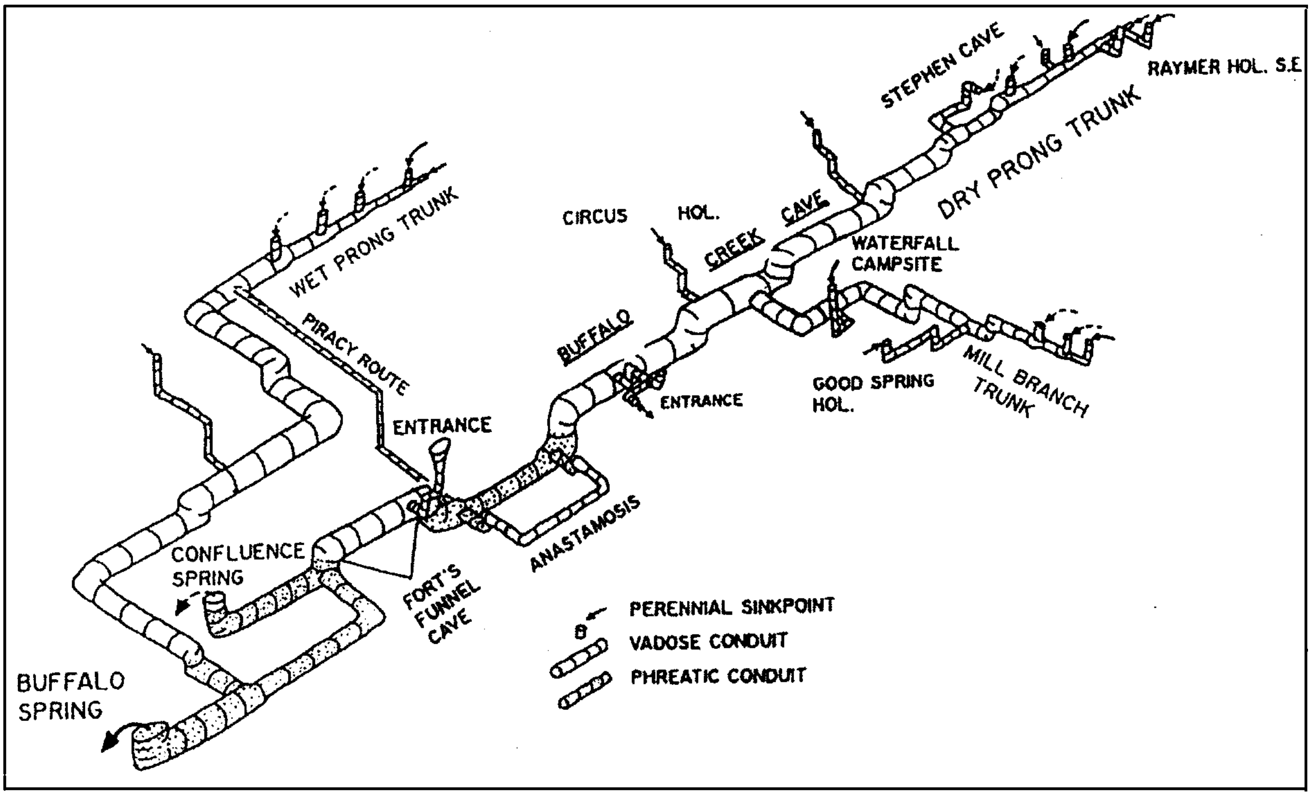

Fig. 5. Conduit system for Buffalo Spring drainage basin. Mammoth Cave National Park, Kentucky. Reconstruction from surveyed caves and known sink and spring locations by Meiman and Ryan (1999).

Focus

"Focus" is a term introduced to describe the role of the physiographic and geologic setting in forcing the underground drainage into localized regimes. Development of contemporary karst drainage systems has taken place on time scales of hundreds of thousands of years although earlier stages may extend back to several million years. In general, and certainly in the Appalachians, these time scales are short compared with the age of most structural and stratigraphic features. The geologic setting can be taken as a fixed framework within which the ground water system must develop. Factors that serve to focus conduit drainage systems into particular patterns are summarized in Table 1 and discussed below.

In the Appalachian Plateaus, the most important of the focusing agents is the precursor surface drainage. Base level streams determine the down-gradient end of the drainage system. Preexisting tributary valleys on the clastic rocks overlying the carbonate units determine the pattern of surface drainage. When these tributary streams downcut into the underlying carbonate rocks, the gradient along the surface stream channel is sufficient to drive the development of a conduit system. The surface streams are eventually pirated underground and become the master conduits for a ground water basin. Underground drainage in a very large number of the tributary valleys of the dissected Cumberland Plateau of Tennessee and Alabama roughly parallel the surface drainage. The conduits are often offset from the valley thalweg and occur under the valley walls. The ground water basins with their allogenic surface catchments are well defined and are often almost coincident with the surface divides.

TABLE 1

Factors serving to focus the development of conduit systems

Precursor drainage

Structural factors

- Large scale structures
- Small scale structures
    - Fracture frequency
    - Fracture homogeneity

Stratigraphic factors

- Overall thickness of carbonate rocks above and below base level
- Hydrologic barriers
- Stratigraphic homogeneity

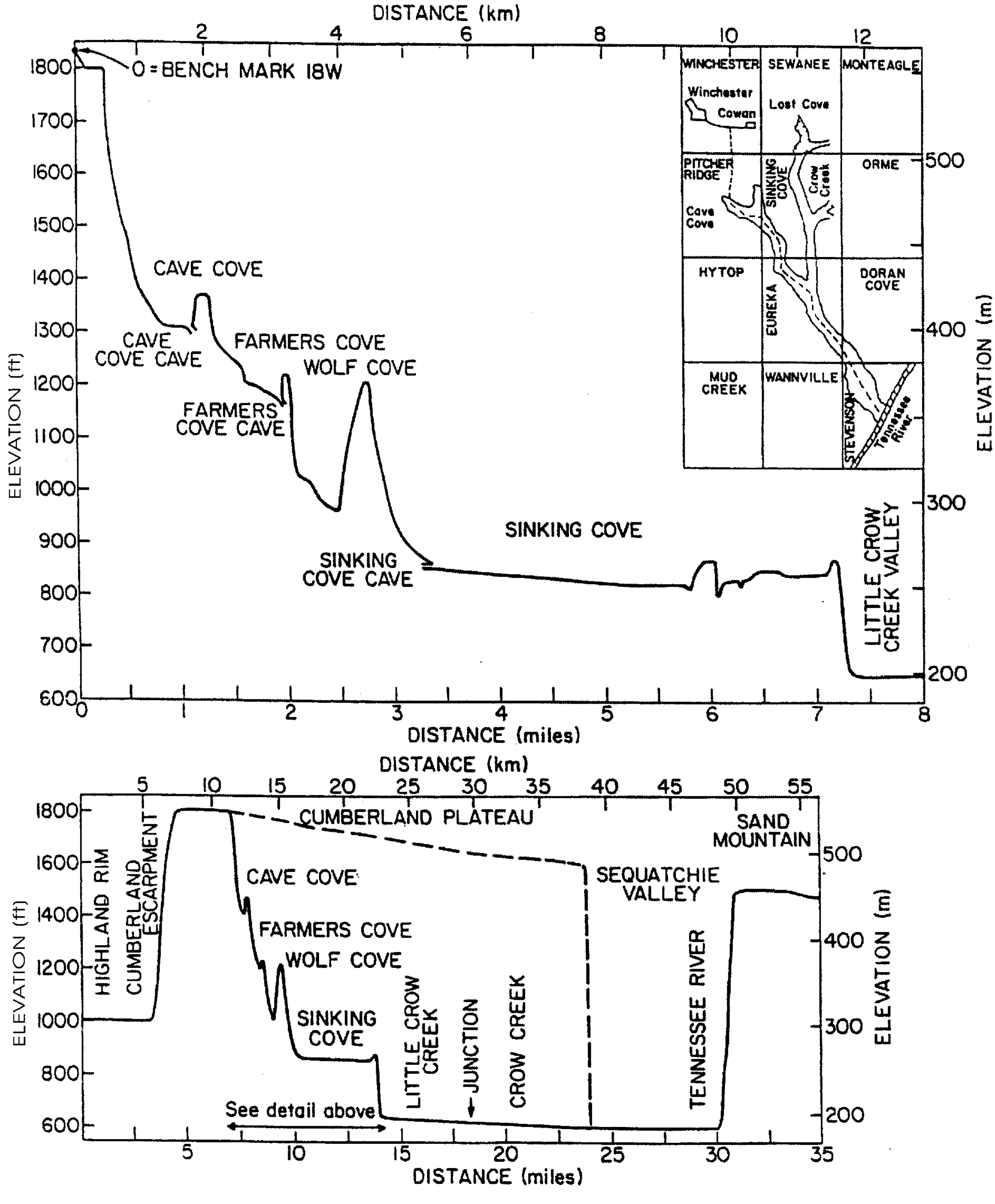

Fig. 6. Longitudinal profile of Sinking Cove, southern Tennessee. The upper figure gives the detailed profile along the valley thalweg constructed from US Geological Survey 7.5 minute topographic quadrangle maps. The maps used are given in the insert. The lower figure shows a larger scale profile across the Cumberland Plateau.

An example is Sinking Cove located in the dissected southern margin of the Cumberland Plateau in Tennessee (Fig. 6). Ancestral Little Crow Creek drained from the clastic rocks of the Cumberland Plateau to the ancestral Tennessee River. The river breached the sandstone caprock along a northeast-southwest trending anticline to form the Sequatchie Valley and rapidly downcut through the underlying carbonate rocks. Crow Creek and its tributary Little Crow Creek cut headward to the northwest gradually exposing carbonate rock along the tributary valley. Disruption of the surface drainage by underground piracies eventually produced large closed depressions along the valley floor known sequentially as Cave Cove, Farmers Cove and Wolf Cove and a 2 km-long dry valley at the bottom known as Sinking Cove. The surface stream from the Cumberland Plateau first sinks in the floor of Cave Cove, follows underground routes through Farmers Cove and Wolf Cove to appear at a spring at Sinking Cove Cave. The floor of Sinking Cove is supported by the 5 - 7 m thick Hartselle Sandstone. The sandstone is breached and the drainage goes underground again to finally reappear at the head of the Little Crow Creek Valley. The master conduit system has been fragmented but almost the entire conduit is accessible through Cave Cove Cave, Farmers Cove Cave and Sinking Cove Cave. In this example, the ground water basin is in close alignment with the surface water basin and the entire pattern of the conduit system, except for the deflecting influence of the Hartselle Sandstone, was dictated by the precursor surface drainage.

Large scale structural features such as folds and faults have a major controlling influence on both surface and ground water basins. This is most evident in the Valley and Ridge and Great Valley Provinces of the Folded Appalachians. Here major northeast-southwest trending folds bring up Ordovician and Cambrian carbonate rocks along anticlinal valleys. Faulting is common and is mostly parallel to the regional northeast-southwest structural trend. Here structural components completely dominate the development of ground water basins. The carbonate rocks are mixed sequences of limestones and dolomites. Because the carbonate rocks are in the lower part of the Stratigraphic sequence, they tend to be exposed in the valley floors of breached anticlines. Allogenic recharge is collected from small basins on the synclinal ridges composed mainly of clastic rocks. The surface streams draining these catchments sink at the contact with the carbonate rocks. The underground drainage, however, tends to be parallel to the strike so the flow paths make a right angle turn and discharge at springs located where secondary valleys have cut across the regional structure. The surface catchments are defined by precursor drainage but the underground component is controlled largely by structure. Caves in steeply dipping rocks tend to extend primarily along strike as documented in central Pennsylvania by Deike (1969) and in many other examples in Virginia, West Virginia, and east Tennessee. Maze caves can form where dips are low on the crests of anticlines (White, 1960; Palmer, 1975). Caves as conduit fragments are particularly helpful in identifying dominant structural controls on ground water flow systems.

Small structures are mainly fractures: joints, joint swarms, and bedding plane partings. The important parameters are the density of fracturing, the initial apertures of the fractures, and the homogeneity of fracture apertures. The importance of fracture density was recognized by Ford and Ewers (1978) and used as the basis for their "four states" hypothesis for cave development. The higher the fracture density, the more readily the ground water flow can follow paths dictated by hydraulic gradients alone and thus reflect the overlying surface water basin. Because flow through fractures increases with the cube of the fracture aperture, the heterogeneity of the fracture sets is very important. Master fractures dominate the flow system. The eventual development of a conduit system will trend along the path provided by the widest fractures even if such pathway is not along the maximum hydraulic gradient. Tension fractures parallel to anticlines may assist in controlling the strike-oriented drainage in folded rocks. Stress release fractures are young geological features with wide apertures and so are important in guiding conduit systems along tributary valley walls rather than down the thalweg as is observed in many Appalachian basins (Sasowsky and White, 1994). If fracture apertures are strongly heterogeneous, the large aperture master fractures can completely dominate the pattern of the conduit system.

The ability of master fractures to override the inherited surface drainage can be seen in the Swago-Carpenters Cave System in the Swago Creek Basin, Pocahontas County, West Virginia (Fig. 7). There are two active drainage lines in this dendritic valley each fed by surface catchments on overlying clastic rocks. Multiple small surface streams sink into the nearly flat-lying Mississippian Greenbrier Limestone. The Dry Creek sub-basin is underdrained by Overholt Blowing Cave which is parallel to the surface channel although offset from it under the valley wall. The Swago-Carpenters Cave System is one of the tributaries of the second sub-basin, with a more complicated drainage that ultimately discharges in Cave Creek Spring. The Swago-Carpenters System is developed along a N60°E master fracture set which is oblique to the surface drainage. The master fracture has allowed drainage to be diverted from the Dry Creek sub-basin to the Cave Creek sub-basin.

Lineaments are lines of structural weakness on a scale somewhat larger than that of master fractures. Lineaments often cross-cut local structures. The best West Virginia example of the influence of lineaments on drainage basin development is the Simmons-Mingo Cave System in Randolph County. The cave is developed along a major lineament and diverts drainage beneath a major topographic divide along a path oblique to the surface drainage lines

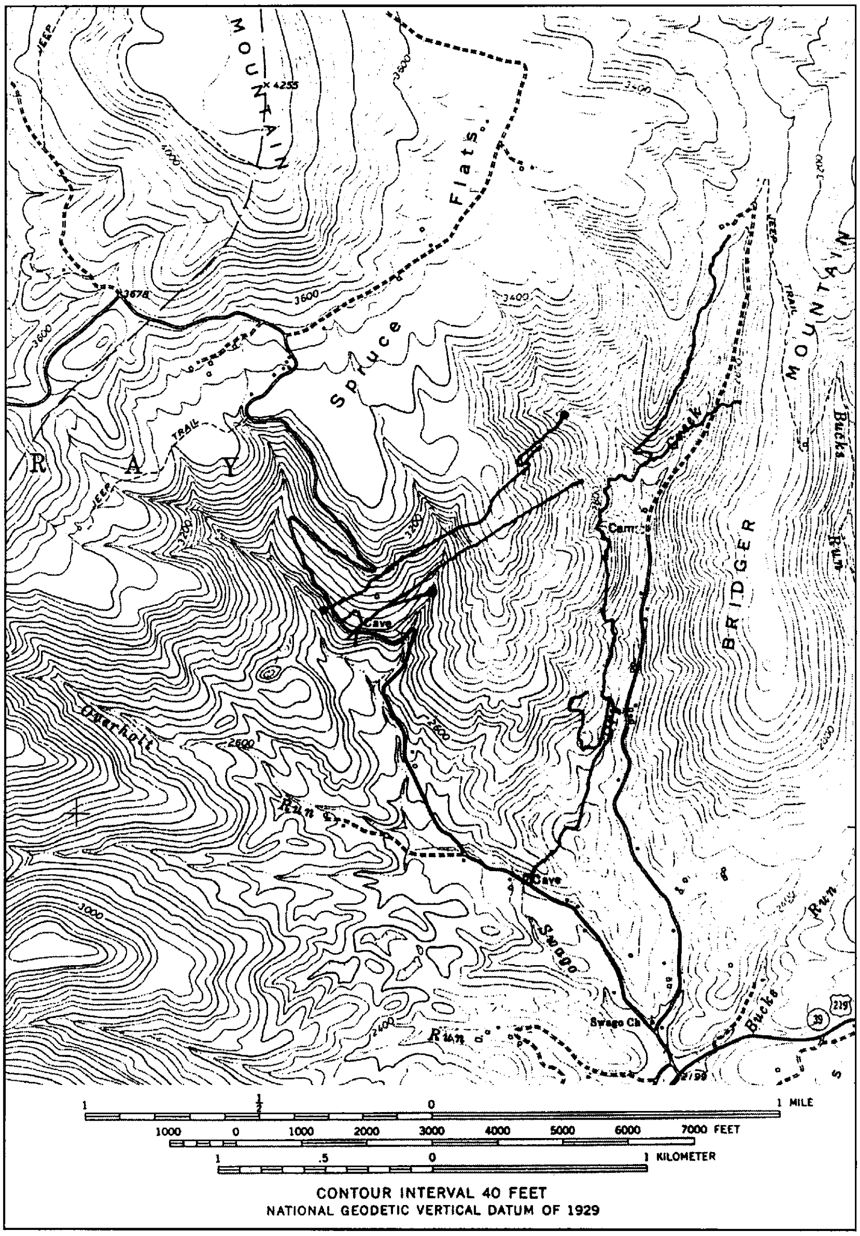

Fig. 7. The Swago Creek Basin, Pocahontas County.West Virginia. Base map from US Geological Survey Hillsboro 7.5 minute quadrangle. Superimposed cave maps adapted from Storrick (1992). Overholt Blowing Cave follows the surface route of Dry Creek. The Swago-Carpenters Cave System is guided by N60°E master fractures.

(Medville, 1977). The presence of a lineament is apparently responsible for the exceptional depth development in Fern Cave, Alabama (Wilson, 1977) and for other cavern development is the southern Cumberland Plateau.

Stratigraphic factors that guide the evolution of karst ground water include the overall thickness of carbonate rocks, interbedded shales, sandstones and other rocks that can act as hydrologic barriers, and the homogeneity of the carbonate rock units.

Thickness of carbonate rocks is a self-evident factor, long recognized. Conduit drainage systems require a certain volume of rock in which to develop. The great karst regions of the world such as the Adriatic karst and the south China karst are developed on thousands of meters of carbonate rock. Fluvial drainage systems have been lost long ago to predominantly karstic drainage systems. In moderate relief terrains such as the Appalachians, a few hundred meters of good limestone is sufficient for the development of large and complex karst ground water basins. Fifteen to 20 meters of Alderson Limestone in West Virginia allows the development of significant caves. The 6-7 meter thickness of the Vanport Limestone in western Pennsylvania hosts large and complex maze caves such as Porters Cave, Brady's Bend Cave, and Harlensburg Cave (White, 1976).

An interesting question is whether there is a minimum thickness for carbonate rock. It appears from observations on thin, but good quality limestones in western Pennsylvania that there is a minimum thickness and it is on the order of one to two meters. In the thin limestone units that occur in the Pennsylvanian and Mississippian sequences of mainly clastic rocks, there are solutionally modified fractures, some of which would qualify as conduits in the sense that they exceed the 10 mm aperture required for the onset of karstic flow dynamics but they have not evolved into caves. There are, of course, other factors. Thin limestones sandwiched between impermeable shales may have no source of recharge. Hydraulic gradients are important and may be too low along the flat-lying thin limestone to initiate cave development.

Hydrologic barriers are beds of shales, sandstones, and cherts that impede ground water flow. Such barriers are particularly important in the early stages of conduit development when the choice of flow path is very sensitive to the characteristics of the bedrock. (Palmer, 1991; Siemers and Dreybrodt, 1998). The role of hydrologic barriers has been examined in considerable detail by Lowe and Gunn (1997), Lowe (2000) and Osborne (1999) as part of the concept of "inception horizons". Thin layers of shale or shaly limestone can guide the initiation phase of cave development but these barriers are usually breached as the conduit enlarges. Thicker beds can function as hydrologic barriers guiding the overall development of the drainage basin.

In the Mississippian Greenbrier-Limestone of West Virginia are two such units: the Greenville Shale, 15-20 meters thick which separates the Alderson Limestone from the remainder of the carbonate units, and the Taggard Shale, a 7 m thick limey shale that occurs in about the middle of the carbonate section (Fig. 8A) (White and White, 1983). The Greenville Shale is sufficiently thick that the Alderson Limestone is hydrologically isolated from the other carbonates. Caves developed in the Alderson are not connected with caves in the remainder of the carbonate section. The Taggard sometimes limits vertical circulation in the limestones and sometimes is breached so that cave development crosses the Taggard. Underground crossings of the Taggard Shale occur mainly along major fractures. Passages take a canyon form indicating that erosive underground streams may have been necessary to cut through the shale. In the southern Appalachians, the Hartselle sandstone, a 5-7 meter-thick unit separates the Mississippian Monteagle and Bangor Limestones (Fig. 8B). Again, this unit serves to block vertical flow so that caves tend to develop either immediately above or immediately below the Hartselle Sandstone. Both Taggard shale and Hartselle sandstone act as inception horizons. In some cases caves are formed directly above these units because they perch the ground water flow. In other cases, the caves form directly below the shaley units which can also act as confining beds. Interbedded chert horizons can also interrupt ground water flow and can act as perching or confining horizons.

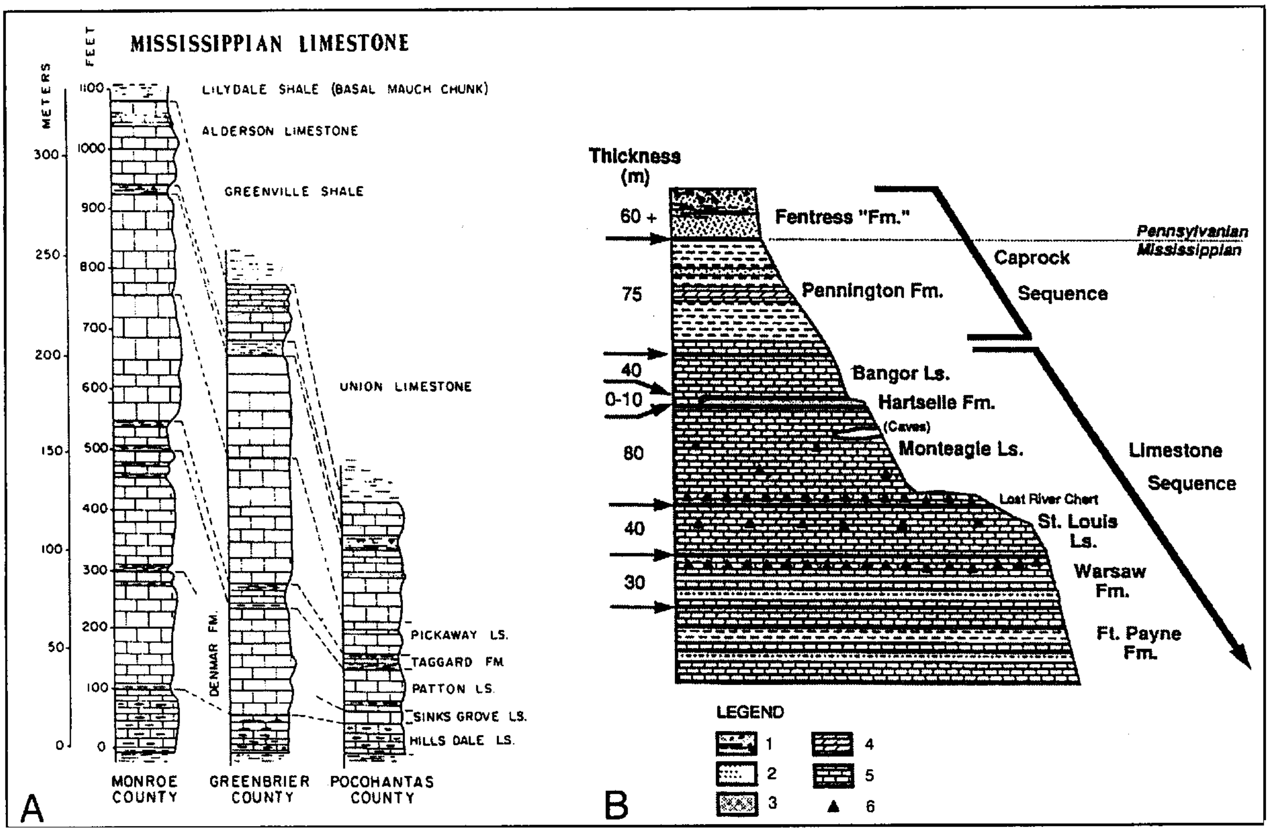

Fig. 8. Stratigraphic sections for (A) the Mississippian Greenbrier limestone of eastern West Virginia and (B) the Mississippian limestone sequence of the southern Cumberland Plateau showing the location of hydrologic barriers.

Stratigraphic homogeneity is the variability in lithologic character along the Stratigraphic sequence from one bed to another. In a perfectly homogeneous carbonate sequence all beds would have the same chemical composition and all would consist of the same carbonate lithology. Such sequences are rare. Highly cavernous rock units often vary in lithologic character, e.g. micrites, sparites, oolitic limestones and others, without disrupting cave-forming processes. Alternating beds of pure limestone and shaley limestone or alternating beds of pure limestone and dolomite inhibit the cave-forming process. Much depends on the scale of the interbedding. Alternating sequences of thin beds are most effective at inhibiting cave forming processes.

Karstifiability

"Karstifiability" is introduced as a term that describes the ease with which a particular rock unit yields to karst-forming processes. Karstifiability is related to the kinetics of carbonate rock dissolution but is more inclusive in that it also includes the pacifying effects of other components and the role of insoluble residues in blocking further dissolution of the primary bedrock. The main components of sedimentary rocks are sketched in Fig. 9. Within the Appalachians, the best developed conduit systems occur within the Mississippian Greenbrier, Bangor, Monteagle, and St. Louis Limestones all of which are relatively pure limestones. Conduits do occur in the dolomites of the Valley are Ridge but are generally less well developed. Fracture aquifers are common in the dolomites. High concentrations of quartz sand do not seem to inhibit conduit development. The cavernous Loyalhanna Limestone in western Pennsylvania contains about 50 percent quartz sand. In contrast, shaley limestones are rarely cavernous. These rocks, in fact often act as aquicludes. Their presence disrupts the normal development of ground water basins.

Although the role of lithology in determining the karstifiability is well understood in qualitative terms, quantitative analysis is much more difficult. A detailed comparison of cave volume with chemical, petrologic and mineralogic characteristics of the carbonate rocks (Rauch and White, 1970) revealed subtle distinctions such as an inverse relationship between cave development and the aluminum content of the bedrock. A more important question is whether there is a threshold in the impurity content that would distinguish between karstifiable and non-karstifiable rock units. The existence of such a threshold would be important in assessing land use hazards in carbonate terrains.

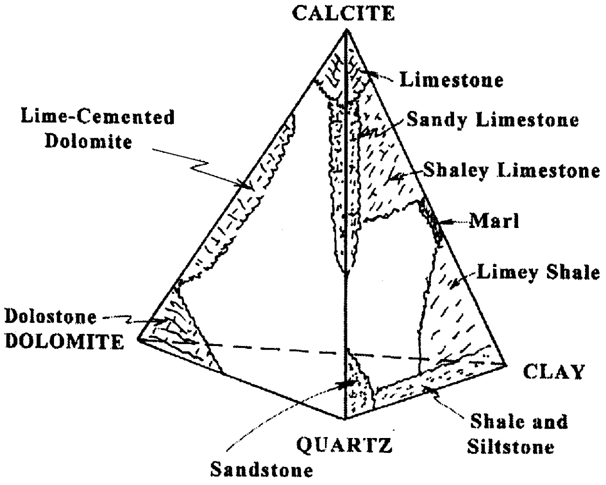

Fig. 9. Composition tetrahedron for sedimentary rocks.

As a proposal for quantitative assessment of karstifiability we can consider the bulk chemical composition of the rocks. The petrologic complexity of karstic rocks can be reduced to a set of chemical components [CaO], [MgO], [SiO_2], and [$A1_20_3$], leaving aside the carbonate, [CO_2] component and also any other minor elements that may be present. The quantities in square brackets are in units of moles, derived from chemical analyses of the rock. These can be normalized as mole fractions. The mole fraction of CaO, for example is defined as:

$$N(\mathrm{CaO}) = \frac{[\mathrm{CaO}]}{[\mathrm{CaO}]+[\mathrm{MgO}]+[\mathrm{SiO}_2]+[\mathrm{Al}_2\mathrm{O}_3]}$$

The mole fractions of MgO, Al_2O_3, and SiO_2 are defined in the same manner as *N*(CaO).

The sum of *N* (CaO) + *N* (MgO) can be used as a measure of total carbonate minerals. The dolomitic character of the rock can be represented by:

$$N(\mathrm{dol}) = \frac{[\mathrm{MgO}]}{[\mathrm{CaO}]+[\mathrm{MgO}]}$$

The composition of the rock can be represented as total carbonates, clay minerals and free silica. Clay and related layer silicate minerals can be represented by kaolinite, $Al_4Si_4O_{10}(OH)_8$. Because Al and Si occur in a 1:1 ratio in kaolinite (or in a 1:2 ratio as the oxides, Al_2O_3, and SiO_2), we can deduct the silica needed to produce clay minerals and then use the remaining silica as a plotting variable. The three plotting variables, which must be re-normalized to 100 percent, are {*N*(CaO) + *N*(MgO) representing carbonates, {$N(Al_2O_3)$} representing total clay minerals, and {$N(SiO_2)$ - $2N(Al_2O_3)$} representing free silica (quartz grains, silicified fossil fragments, or chert). These quantities can be used to plot the chemical compositions of the rock on a triangular diagram in a way that relates composition to mineralogy.

Attempts to use published rock analyses to map karstifiability are suggestive but inconclusive (Fig. 10). Three relatively pure limestones, the Pennsylvanian Vanport of western Pennsylvania, the Mississippian Monteagle of central Tennessee, and the Ordovician Stones River of eastern West Virginia are all highly cavernous. The Devonian Tonoloway of Pennsylvania and West Virginia is marginally cavernous. The Mississippian Warsaw of Tennessee is a shaley limestone that usually acts as an aquiclude. The problem is that published analyses are often from samples of unknown stratigraphic positions within a given formation. Further, most published analyses are for samples taken from rock quarries and thus represent the better quality limestone. Analyses on impure limestones with limited cave development are sparse. Although carbonate formations with limited cave development are known in the Appalachians, there are, at present, insufficient data on their chemical compositions to actually contour karstifiability on a diagram such as Fig. 10.

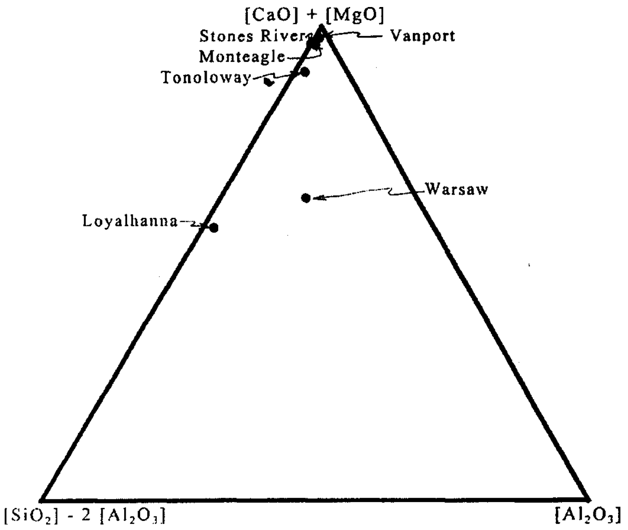

Fig. 10. Triangular plot of carbonate rock composition in terms of the three components that represent carbonates, clays, and silica. Compositions are calculated from published rock analyses. Pennsylvania data (Vanport and Loyalhanna Limestones) from o'Nell (1964). West Virginia data (Stones River and Tonoloway Limestones) from McCue el al. (1939). Tennessee data (Monteagle and Warsaw Formations) from Hershey and Maner (1985).

Conclusions

Conduit systems provide high efficiency pathways for the movement of ground water through carbonate aquifers. Because conduits act as drains of low hydraulic resistance, ground water flow becomes localized in ground water basins with well-defined drainage divides. Although entire conduit systems are only rarely accessible to human inspection, many conduits can be reconstructed from survey and mapping of existing caves within the drainage basin. Factors that determine the pattern of the conduit system and the localization of the associated ground water basin are the hydraulic gradient, geologic factors that provide focus for the basin, and the karstifiability of the carbonate bedrock.

Caves provide useful fragments of the conduit system. Inspection of cave patterns provides a useful assessment of the geologic parameters that have guided the development of the ground water basin. In particular, the competition between superimposed drainage and local hydraulic gradients and structural controls is often well displayed in the cave systems.

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