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MORPHOLOGIC FEATURES OF CONDUITS AND AQUIFER RESPONSE IN THE UNCONFINED FLORIDAN AQUIFER SYSTEM, WEST CENTRAL FLORIDA

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ABSTRACT

Conduits within the unconfined Floridan Aquifer of west-central Florida include both horizontal and vertical components. In this paper, we investigate each and propose theories based upon cave survey data and a collection of over 300 Florida cave maps. First, we find that vertical portions of conduits visually correlate to fractures, and these fractures tend to be the dominant control of conduit directionality. Length-weighted rose diagrams of passage directions reveal a NW-SE and NE-SW pattern of conduit directions statistically similar to results found in remote sensing studies of photolinears. Secondly we note that horizontal elements of conduits occur at consistent horizons that are pervasive and laterally continuous. Their control is presently unknown but is potentially the result of some combination of lithology, fracture density, and water-table position.

In this paper we demonstrate the variability of hydrographs from springs in karst areas. Traditional observations and interpretations of springflow hydrographs from karst areas are from telogenetic karst (e.g., mid-continent Paleozoic limestones), where the karst has developed after the limestone has been deeply buried and lithified. Limestones of telogenetic karst have very low porosities (less than 5%) and matrix permeabilities on the order of 10^{-15} – 10^{-18} m^2. Hydrographs of springs in telogenetic karst show a prompt response to precipitation events and a rapid return to base flow conditions. Because the matrix permeability is so small, only a very small percentage of the full volume of the aquifer appears to participate in the precipitation event.

Springflow hydrographs from the eogenetic karst of Florida are in striking contrast to those of telogenetic karst. These springs respond very little to single storm events, but do vary according to seasonal or longer-period cycles. It appears that the huge interparticle pore volume (20-40%) and matrix permeability (10^{-12} – 10^{-14} m^2) of these Eocene and Oligocene limestones mutes, and even eliminates, the spiky responses that have come to be featured in conceptualizations of karst springs.

Likewise, traditional classification of conduit morphology is from observations in telogenetic karst. In telogenetic karst aquifers, current classification is based upon the type of recharge to the aquifer (allogenic or hypogenic) and whether conduits are controlled by fractures or bedding planes. Recent observations in eogenetic karst (e.g., Bahamas) do not fit these classifications. We suggest that a more appropriate classification scheme of karst would incorporate diagenetic maturity of the rock, as well as recharge type and fracture density. In such a scheme, conduits of the unconfined Floridan Aquifer represent a mid-point in a range between Plio-Pleistocene karst on young carbonate islands and Paleozoic karst in the Appalachian lowlands.

CONDUITS WITHIN THE FLORIDAN AQUIFER SYSTEM

Tertiary carbonate units of the Florida platform have experienced a complex depositional and diagenetic history recorded by variations in lithology and by the development of macroporosity through dissolution. Dissolution features are present throughout the platform. Paleokarst features are omnipresent at specific horizons in Florida and were formed during periods of prior exposure. Active karst processes are limited to regions of vigorous groundwater circulation within the Floridan Aquifer System. These conditions exist where the Eocene and Oligocene carbonates are semi-confined to unconfined; principally occurring in west-central Florida in a broad band bordering the Gulf Coast and stretching approximately from Tampa to Panama City (Figure 1).

Conduit Function

Conduits within the Floridan Aquifer System can be classified according to whether they recharge the aquifer, discharge from the aquifer, or conduct water through the aquifer. Conduits serving as recharge points to the Floridan Aquifer System are scattered throughout the semi-confined and unconfined aquifer, essentially one below every sinkhole. The vast majority are inaccessible. Most have small or sediment-filled openings to the surface. The potentiometric surface is not deep below the surface anywhere in Florida; therefore, most conduits are currently under phreatic conditions. Fluctuating sea-level positions clearly affect the potentiometric surface in portions of the unconfined Floridan Aquifer System. Evidence of lower water table periods comes in the form of speleothems in conduits beneath the present-day water table.

Voids currently in the vadose zone indicate higher positions of the water table in the past. The highest densities of vadose conduits occur along the boundary between the confined and unconfined Floridan Aquifer along positive geographical features capped by Miocene siliciclastics such as the Brooksville Ridge, the Ocala Rise, and the Cody Scarp (Figure 1). Most explored vadose conduits have no natural human-sized entrance. Instead, they are intersected by quarry operations, revealed during sinkhole collapses, or dug open by dedicated cavers.

Figure 1. Simplified geology of Florida. Dark gray areas indicate where the Eocene and Oligocene carbonates (Suwannee Limestone, Ocala Limestone, and Avon Park Formation) of the Floridan Aquifer System are unconfined. Black areas delimit the surface exposure of Miocene siliciclastics (Hawthorn Formation).

Conduits serving as discharge points from the aquifer, i.e., springs, collectively release billions of gallons of water every day from the Floridan Aquifer System. Many of these springs are subjacent to the west-central coast (Scott, et al., 2004). The west-central coast of Florida is on a broad continental margin with low slope; therefore, it is plausible, even likely, that the locations of these springs are transient and may change in conjunction with sea-level changes. It is also possible that during sea-level lowstands, many of these springs may have served as recharge points to the aquifer. A few springs in Florida, such as Madison Blue and Fanning Springs within the Suwannee River basin, behave as estevelles, recharging the aquifer during high river stages.

Conduits conducting water from input to output in the aquifer are less common and are associated with river systems; however, springs emerging from these systems are among the largest in Florida. Clear examples of river-type systems occur where surface streams sink and re-appear some distance downstream. River-type systems are more numerous in north Florida and include the Santa Fe Sinks and Rise (Martin and Dean, 2001) in North Central Florida, the Steinhatchee River Rise, the Alapaha Rive Rise, Nutall Rise, and the St. Marks River Rise in North Central and the Panhandle of Florida. The Curiosity Creek-Sulphur Springs System (Schreuder, Inc., 2001) in Tampa is the southernmost example of a river-type system. The Woodville Karst System including Wakulla Springs, Leon Sinks, and the Spring Creek Springs Complex near Tallahassee is the best understood and likely the most extensive river-type system in Florida.

Conduit Morphology

Observations based on over 300 maps of Florida caves, both vadose and phreatic, contained with the files of the Florida Cave Survey suggest that conduits enlarge along both vertical and horizontal planes. Whereas some conduit cross-sections develop "fissure" or "tabular" morphologies; a combination or "plus-sign" morphology is more common, and may even be the signature morphology of conduit cross-sections in Florida (Figure 2a and b). Visual inspection correlates vertical extensions of the conduits to fractures. Horizontal extensions can be pervasive and laterally continuous. Their origin is unclear; however, it is likely that their existence is related to water-table positions, lithologic variability, or a feedback combination of the two.

Directional anisotropy. Development of conduits along fractures is strikingly visible from cave maps in plan-view (Figure 2c and d). These conduits produce directional anisotropy in groundwater flow. Rose diagrams of conduit lengths for 14 individual caves in the Ocala area reveal repeating fracture orientations; however, the length of conduit can be heavily weighted in one direction. No strong correlation is visible between these anisotropic rose diagrams and major lineaments, hypothesized basement faults, hillslope directions, or presence of Miocene cover, although the evidence is suggestive that all have an influence (Figure 3). Further interpretation will require orders of magnitude more data. A combined rose diagram for all caves shows that the regional signal is an

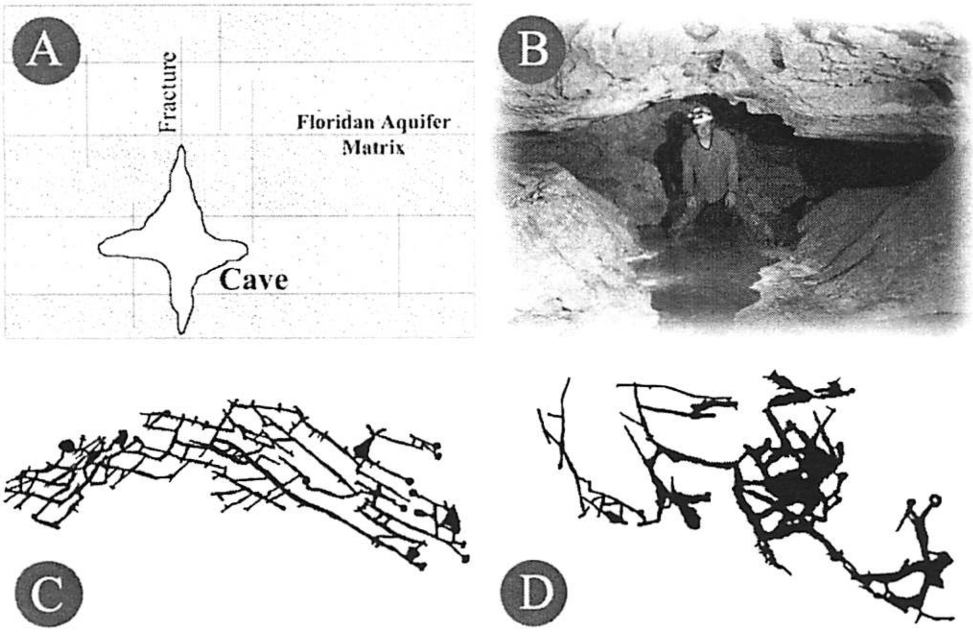

Figure 2. Fracture control within Florida caves. A) Conceptual model of Floridan Aquifer framework with typical "plus-sign" conduit cross-section. B) Photogarph of "plus-sign" passage in Rosevelt Cave in Marion County, Florida (photo by Sean Roberts). C and D) Maps of Florida caves with significant fracture control (adapted from maps within the Florida Cave Survey files).

underlying pattern of sub-orthogonal NW-SE and NE-SW fractures (Figure 3). These field measurements of fractures confirm the results of remote sensing studies of photo-linears by Vernon (1951), and Littlefield et al. (1984).

Layered heterogeneity. Survey data of vadose and phreatic conduits in west-central Florida suggest that conduit development is restricted to specific horizons. In some quarry highwalls, it appears as though specific horizons have been virtually removed, creating a laterally continuous network of voids (Figure 4a) (LaFrenz et al., 2003). Lateral dissolution is evident on a map of Blue Springs in Volusia County near Orlando (Figure 4b). Conduits formed along horizontal planes (Figure 4c) provide flow at many springs. Many of these spring systems are fed from depth from multiple horizons of conduit development (Figure 4d). Core records mention bit drops and recovery of silica sand from depths greater than 100 meters in the unconfined aquifer in Hernando and Citrus Counties in west-central Florida north of Tampa (Hill and DeWitt, 2004) and from the Orlando area of central Florida (Wilson, 1988).

Conduit Integration

Data from cave maps imply that the caves do not represent an integrated conduit network in the Floridan Aquifer System. Exceptions include river-type systems such as the Woodville Karst Plain. Caves, such as those presented in Figure 2c and, consist of a network of passages that end in ever-narrowing fissures or sediment fills and collapses.

The disjunct nature of conduits within the Floridan Aquifer System is supported by one of several conclusions from a numerical study of the Silver Springs and nearby spring-sheds. The

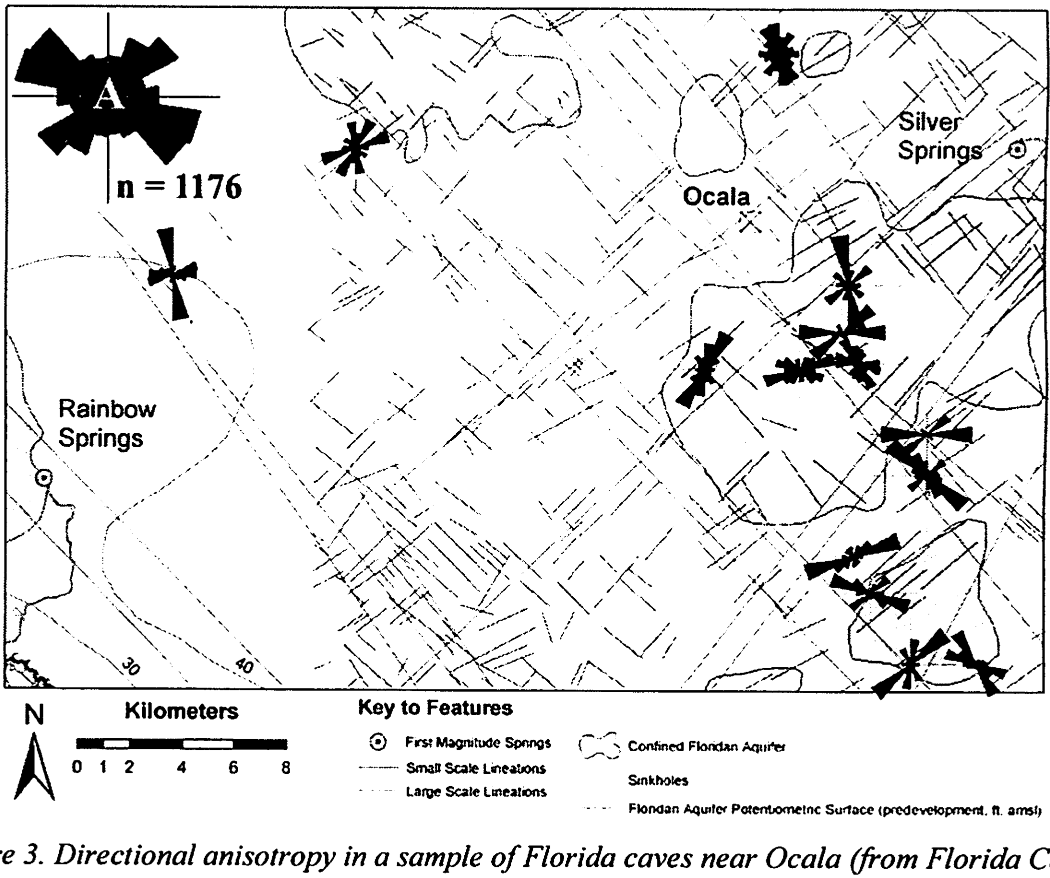

Figure 3. Directional anisotropy in a sample of Florida caves near Ocala (from Florida Cave Survey maps and personal data). Rose diagrams of length-weighted conduit segements shown for each cave in relation to local and regional fracture trends, and for all conduit segments in study (rose diagram labeled "A" in upper left).

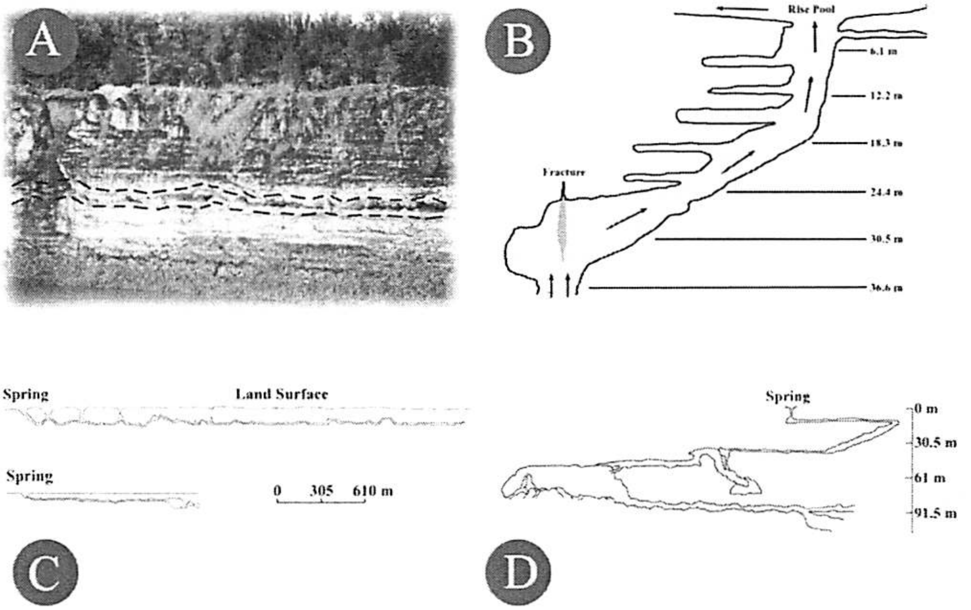

Figure 4. Layered heterogeneity in Florida Caves. A) Dissolution horizon in highwall at Haile Quarry, Alachua County (LaFrenz et al., 2003). B) Lateral development in Blue Springs, Orange County. C) Horizontal cave development in Manatee Springs, Levy County (upper) and Crystal Beach Springs, Pinellas County (lower). D) Multiple horizons of conduit development in Twin-Dees Spring, Hernando County (cave maps adapted from Florida Cave Survey files).

GeoTrans (1988) report states that regionally extensive and hydraulically connected fractures or solution features cannot be present within the aquifer. Inclusion of these features prevents calibration of the model to known potentiometric values. Rather, the model supports fractures and conduits that are discontinuous and heterogeneous. One possible source of this heterogeneity is presented by Back and Hanshaw (1970) who hypothesized that flow retardation in the Floridan Aquifer may be a result of siliciclastic residuum, eroded from the overlying Miocene Hawthorn, filling solution cavities. Indeed this is observed in some caves and core records.

Available evidence suggests that input and output points within the Floridan Aquifer System are not directly connected. For instance, unconnected input and output point would cause flow retardation in the aquifer. Flow retardation is consistent with seasonal fluctuations in water levels within the aquifer near Silver Springs found by Phelps (1992) and higher than expected potentiometric gradients observed by Back and Hanshaw (1970). As a counter example, the Yucatan karst aquifer has a well-integrated conduit system and exhibits very little hydraulic gradient (Back and Hanshaw, 1970).

TELOGENETIC AND EOGENETIC KARST

Much of our present knowledge regarding karst morphology and behavior is a result of studies within Paleozoic karst aquifers (e.g., examples in Lowe, 2004). Observations of morphology from Florida caves, both vadose and phreatic, are in distinct contrast to caves of Paleozoic limestones in the lowland plateau of the central United States. Aside from climatic and topographic factors, the primary and most clear difference between Tertiary and Paleozoic karst aquifers is the age, and therefore petrographic and hydrologic properties of the aquifer matrix.

Definitions

Carbonate rocks undergo significant alteration through their diagenetic history. Choquette and Pray (1970) subdivided the evolution of carbonate rocks into three time-porosity stages. They defined the time of deposition and early burial as eogenetic, the time of deep burial as mesogenetic, and the time of exposure and erosion as telogenetic. Karstification is primarily the result of near-surface processes and thus only concerns the eogenetic and telogenetic stages. Therefore karst development at or near the site and conditions of deposition is regarded as eogenetic karst, and karst development following burial diagenesis and uplift is labeled telogenetic karst (Vacher and Mylroie, 2002) (Figure 5).

Permeabilities

Eogenetic and telogenetic carbonate rocks differ with respect to porosity and permeability. Eogenetic carbonate rocks retain significant primary porosity and permeability. Enos and Sawatsky (1981) calculated mean permeabilities of Holocene grainstones to be $10^{-10.5}$ m^2 with a mean porosity of 44.5%. This is in contrast to $10^{-17.7}$ m^2 and 2.4% for the permeability and porosity of the Paleozoic limestones at Mammoth Cave (Worthington et al., 2000).

Porosity is retained but redistributed during eogenetic diagenesis through selective dissolution and cementation (Budd, 1988; Halley and Beach, 1979). This porosity is lost during burial as shown in the Tertiary limestones of Florida by Halley and Schmoker (1983). Vacher

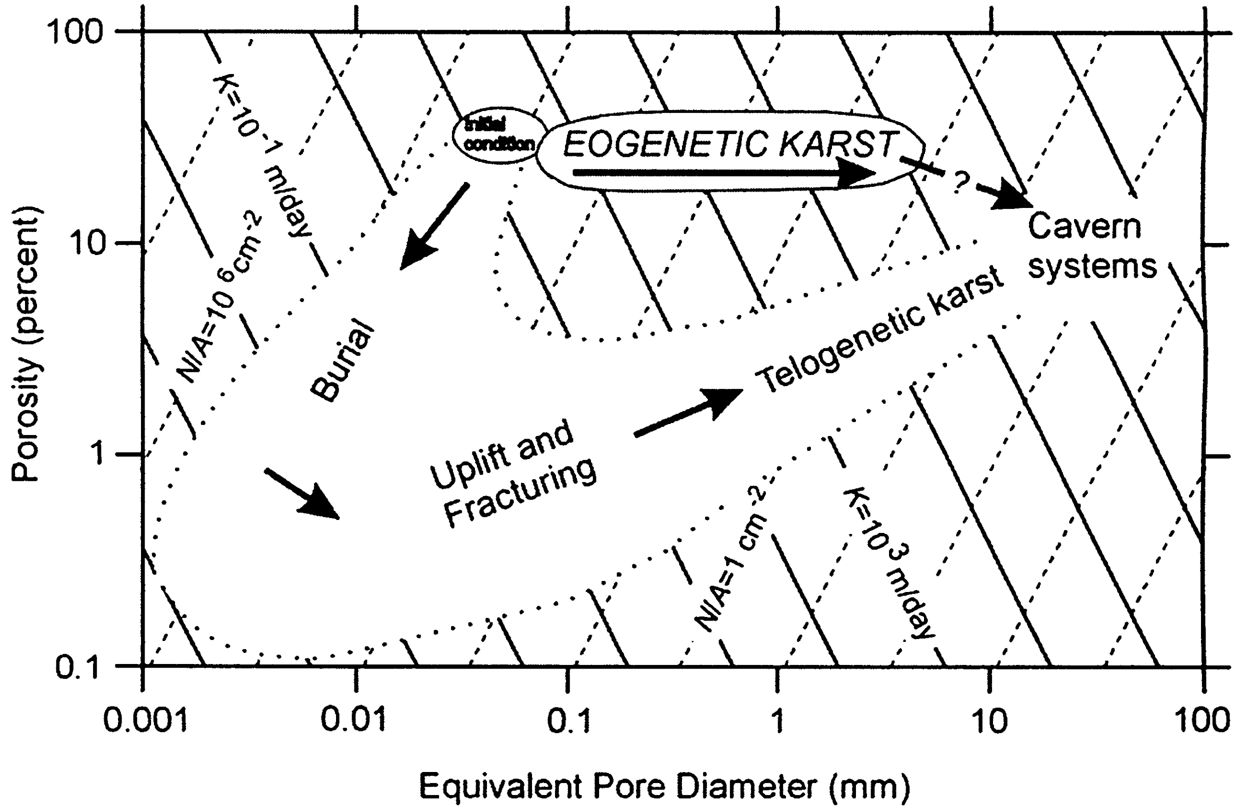

Figure 5. Eogenetic and telogenetic karst in terms of the evolution of limestone hydraulic conductivity, K (figure from Vacher and Mylroie, 2002).

and Mylroie (2002) discuss the effect of eogenetic diagenesis on the permeability of carbonate rocks. They note that the redistribution of porosity acts to enhance the rock permeability through the production of touching-vug systems. Extensive dissolution during eogenetic diagenesis, such as in mixing zones, can result in the production of eogenetic caves (Vacher and Mylroie, 2002). Halo-phreatic flank margin caves are one such example of caves formed in this way (Mylroie et al., 1995).

The matrix permeability, however, will be reduced through this process. Values for matrix permeability for the confined portions of the Floridan Aquifer have been measured by Budd and Vacher (2004) to be $10^{-12.4}$ m^2 for grainstones and 10^{-13} m^2 for all limestones. The matrix permeability of Tertiary grainstones of Florida is two orders of magnitude less than their Holocene equivalents; however, Florida limestones are 50,000 times more permeable than the Paleozoic limestones of Mammoth Cave. This contrast demonstrates the importance of matrix permeability to flow within the Floridan Aquifer System.

These values of matrix permeability stress the lack of a role the matrix plays in the development of telogenetic karst. Values presented by Budd and Vacher (2004) illustrate that matrix permeability shows a decreasing trend with increasing aquifer age. Whereas Budd and Vacher (2004) argue that the matrix permeability in Floridan Aquifer grainstones can compete with fractures if they are widely spaced or discontinuous, this would be impossible in the Mammoth Cave example. The fractures in telogenetic karst must dominate the control of initial flowpaths in the aquifer and therefore the location and direction of conduits (Ford and Ewers, 1978).

Spring Responses

To further underscore the differences between eogenetic and telogenetic karst, we will inspect the spring response from an example of each. Spring flow hydrographs are used extensively to interpret the inner workings of karst aquifers. Discharge data combined with information on precipitation and recharge serve as output and input functions of a lumped-parameter or "black box" model (Dreiss, 1982). In this approach, the aquifer acts as a transformation function between input and output

Lost River, Kentucky. Traditional interpretation of spring-flow hydrographs from karst aquifers separates the output response into components that are indicative of storage units within aquifer. These functional units of a triple-porosity flow system as defined by White (2002) are the rock matrix, fractures, and conduits. The role that each storage unit plays in spring discharge is related to its transmissivity, which is a function of permeability. In Paleozoic karst aquifers such as at Mammoth Cave, Worthington (1999) has shown that, although over 95% of storage is within the aquifer matrix, more than 99% of the total flow is through conduits. The difference is because matrix permeability in these aquifers is very low, on the order of $10^{-17.7}$ m^2, and the effective permeability of conduits within the system is $10^{-9.5}$ m^2. The permeability difference implies that the conduit system within the aquifer is essentially 100-million times more transmissive than the aquifer matrix!

A significant outcome of low matrix permeability is that these karst aquifers respond in a "flashy" manner to storm events. An inspection of a year-long record of daily precipitation data and discharge data from the Lost River Rise in Bowling Green, Kentucky, shows this relationship well (Figure 6a). Discharge at the spring reaches peak values soon after the storm event as is shown by a near zero lag time peak in a cross-correlation between precipitation and discharge (Figure 6b). This spike in discharge is related to rapid flow through conduits. Discharge values decrease exponentially following the peak. This tail is attributed to flow out of bedding planes and fractures, which according to Worthington (2000) have permeabilities on the order of 10^{-12} m^2. The aquifer response returns to base flow conditions between 7 and 9 days after each storm event.

The short time lag between precipitation and response at the spring highlights the connectedness of the conduit systems within karst aquifers of the Appalachian lowlands. Recharge enters the aquifer at discrete points (sinkholes and sinking streams) and joins with other conduits from other input points. Collectively these conduits increase in size and decrease in number in the direction of groundwater flow.

Individual storm events can be distinguished from each other within the Lost River data set. White (1988) states that this will occur when the residence time within the aquifer is less than the spacing between storm events. Beginning in February, 1986, there is a distinct increase in base flow discharge. These seasonal changes in base flow are common in Appalachian karst aquifer springs.

There are two potential phenomena that may account for this increased discharge during the spring of 1986. First is an increase in precipitation frequency. Essentially this means that before the spring returns to base flow conditions, another precipitation event occurs. Thus, seasonal changes in discharge at the spring result from overlapping tails of individual storm events. The second is an increase in epikarst storage. The epikarst acts as a leaky, perched aquifer system with high storage capacity (Williams, 1983). Using carbon isotopes, Lee and Krothe (2001) calculated the contribution to spring discharge from the epikarst to be in excess of 50%. The rate at which water stored in the epikarst is released into the underlying karst aquifer is a function of the head. This is in turn a function of rate and frequency of recharge.

Silver Springs, Florida. From a yearly data set Silver Springs, near Ocala, Florida, discharge shows no response to individual storm events (Figure 6c). Instead, the variation in spring discharge is similar to, but out of phase with, a 30-day moving average of precipitation (Figure 6c). A cross-correlation analysis of the data indicates the lag time to be on the order of 90 days (3 months) (Figure 6d).

At Silver Springs, White (1988) calculated a maximum to median discharge ratio

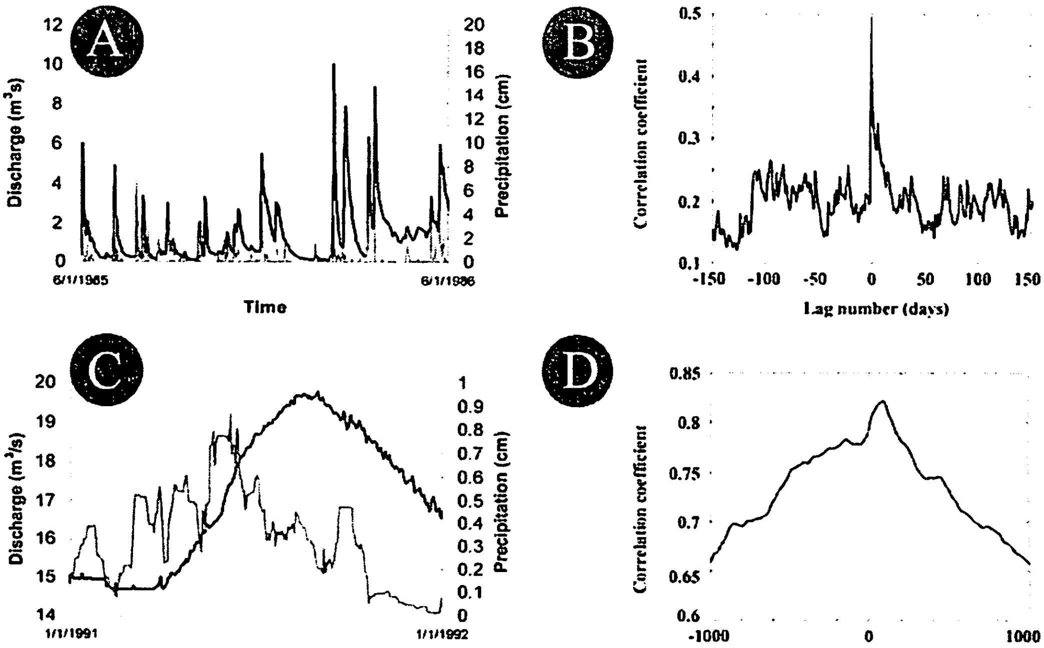

Figure 6. A) Spring discharge hydrograph for Lost River, Kentucky (dark line) and precipitation (grey line) for a one-year record.B) Cross-correlation specturum for discharge and precipitation at Lost River, Kentucky. C) Spring discharge hydrograph for Silver Springs, Florida (dark line) and precipitation (grey line) for a one-year record.B) Cross-correlation specturum for discharge and precipitation at Silver Springs, Florida. Data available from the USGS and NOAA websites.

of 1.5; a value lower than calculated for Paleozoic karst aquifers. A lower ratio indicates that the residence time of water in the Silver Springs karst aquifer is much larger than the mean spacing of precipitation events. Indeed, Katz et al. (2001) discovered using geochemical tracers that the residence time for water in karst aquifers in Suwanee County was on the order of a few decades. A decadal-scale residence time can only be consistent with a three-month phase shift between peak rainfall and peak discharge if the discharge at the spring is the result of a pressure wave within the aquifer

If we accept that conduits and fracture are discontinuous and heterogeneous as presented in section 2.3, then recharge to the system does not travel immediately to the spring. Rather, recharge results in changes to the potentiometric surface, steepening the hydrologic gradient and thereby increasing discharge from the spring. Seasonal variations in the potentiometric surface are shown by Phelps (1992) to be on the order of 1.5 to 2 meters in the Silver Springs area.

These conjectures of conduit discontinuity and heterogeneity, and residence times on the order of decades point to the importance of the matrix in groundwater flow in karst aquifers such as Silver Springs and other Florida springs. In a recent geochemical study at the Santa Fe Rise system, Martin and Dean (2001) have shown that, during low-flow conditions, ~75% of the flow originates from the matrix. Budd and Vacher (2004) have compiled matrix permeability data for 1210 m of core in the confined potions of the aquifer. Their data reveal variations in matrix permeability spanning three orders of magnitude and that grainstones and sucrosic dolomites have the highest matrix permeabilities followed by packstones and wackestones. It is important to note that, even though grainstones and sucrosic dolomites comprise only ~24% of the compiled aquifer thickness, they account for ~73% of the matrix transmissivity (Budd and Vacher, 2004). Thus, unlike Paleozoic karst aquifers such as Lost River, we must consider the role of matrix permeability in Florida as an active and perhaps dominant component in a triple-porosity karst aquifer.

CLASSIFICATION

As mentioned previously, most of the available literature and present body of knowledge of karst results from studies of telogenetic karst. As a consequence our present means of classifying karst based on conduit morphology is heavily biased toward examples from telogenetic karst. In his classic scheme, Palmer (2000) summarizes how conduit morphology and integration is a direct result of the interaction between recharge type and fracture density. The result is a matrix with diffuse and discrete recharge as rows and low, medium, and high fracture density as columns. Palmer treats the recent volumes of information concerning eogenetic karst on carbonate islands (Mylroie et al., 1995) as a special case (Palmer, 2000).

We propose that a more accurate classification of karst must include the diagenetic maturity of the aquifer matrix as a third axis to Palmer's scheme of recharge and fracture density. Following this new scheme, we propose the following eight end-members and examples (Figure 7).

A) Telogenetic, diffuse-flow, matrix dominated – Spongework systems such as Carlsbad and Lechuguilla Caves.
B) Telogenetic, diffuse-flow, fracture dominated – Massive maze cave systems such as Wind and Jewel Caves, South Dakota.
C) Telogenetic, discrete-flow, matrix dominated – Pressurized recharge systems, such as Big Brush Creek Cave, Utah.
D)Telogenetic, discrete-flow, fracture dominated – Classic river-type systems such as Lost River Cave, Kentucky.
E) Eogenetic, diffuse-flow, matrix dominated – Globular dissolution voids such as halo-phreatic caves in the Bahamas.
F) Eogenetic, diffuse-flow, fracture dominated – Directional dissolution voids such as those found

on tectonically active carbonate islands in the Pacific.

G) Eogenetic, discrete-flow, matrix dominated – Solution pit complexes on carbonate islands such as on Hog Cay on San Salvador, Bahamas.

H) Eogenetic, discrete-flow, fracture dominated – Flow-through systems on young carbonate islands such as the limestone-volcanic contact caves found on Guam.

Using this classification system, conduits in the Floridan Aquifer System occupy an interior region between diffuse and discrete recharge, matrix and fracture control, and eogenetic and telogenetic rocks (Figure 7)

SUMMARY

Conduits within the unconfined Floridan Aquifer System of west central Florida are strikingly different than described in the existing karst literature from telogenetic karst. Conduits display vertical and horizontal extensions. Vertical extensions correlate to fractures. Horizontal extensions occur as laterally continuous horizons. Individual conduits terminate in ever narrowing fractures, collapse features, or sediment fills.

We propose that these differences in conduit morphology and integration are a direct result of the hydrologic properties of the aquifer

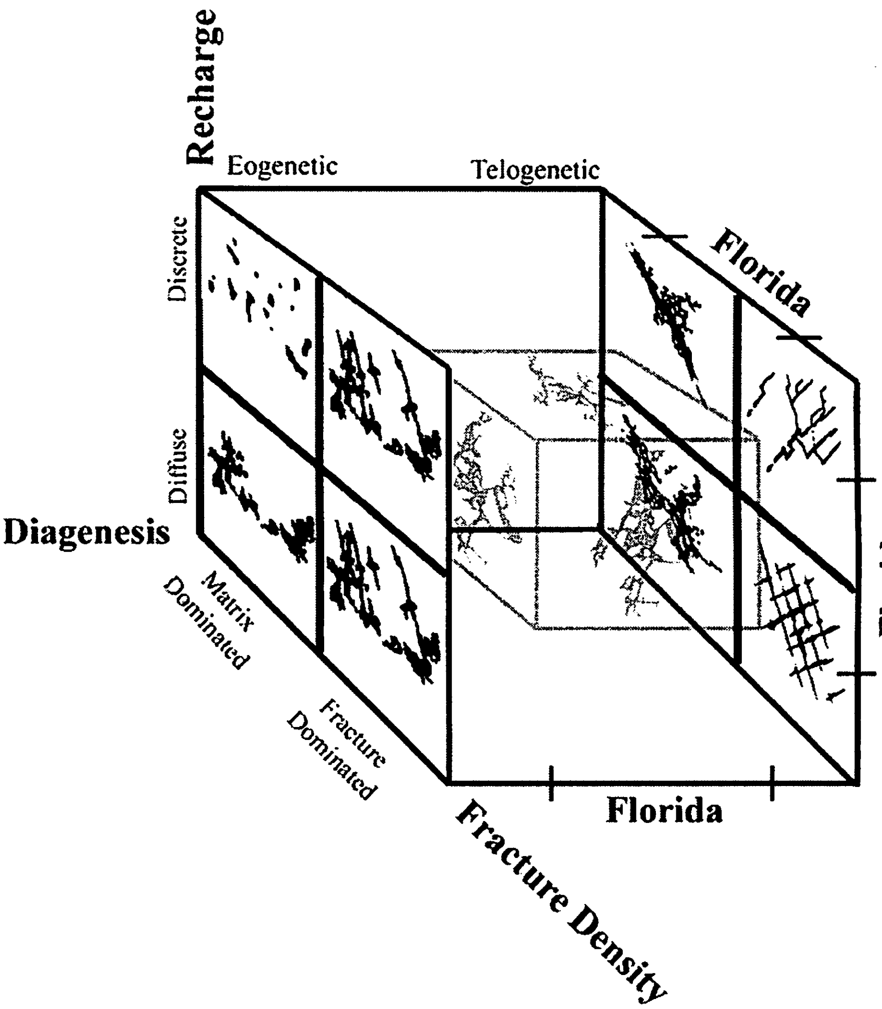

Figure 7. Proposed classification system with the eight end-member morphologies as described in text. Florida conduits occupy the interior shaded region (example morphologies modified from Palmer, 2000).

matrix. Matrix permeability within eogenetic karst ranges between $10^{-11}m^2$ and $10^{-13}m^2$ and can be in excess of 50,000 times larger than thematrix permeability in telogenetic karst. Using the Lost River Spring, Kentucky, as an example, we note that telogenetic karst aquifers respond in a "flashy" manner to storm events with short lag times between input and output. Return to base flow is rapid, indicating a low storage within the aquifer. In contrast, Silver Springs, our eogenetic example from Florida, responds very little to individual storm events. Seasonal trends in discharge are clear and lag behind peak recharge by three months in this example. Observations of conduit morphology and conduit integration, measurements of seasonal changes in the potentiometric surface, results of regional modeling studies and geochemical analyses, together are leading us to the notion that most conduits within the unconfined Floridan Aquifer System are disjunct and that, in cases other than river-type systems, recharge points to the aquifer are not linked by conduits to the discharge points.

We suggest that a more appropriate classification scheme of karst would incorporate the diagenetic maturity of the rock, as well as the traditional recharge type and fracture density. In such a scheme, conduits of the unconfined Floridan Aquifer would represent a mid-point in a range between Plio-Pleistocene karst on young carbonate islands and Paleozoic karst in the Appalachian lowlands.

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