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Underground Florida: a fieldtrip guidebook of the west central Florida karst

Kali J. Pace-Graczyk
Aurel Perșoiu
Jason Samuel Polk

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Underground Florida: A Fieldtrip Guidebook of the West Central Florida Karst

First Semi-Annual “Best of Karst” Event
Featuring: Dr. Alexander Klimchouk
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University of South Florida
Karst Research Group
Edited by Kali Pace-Graczyk, Aurel Persoiu, Jason Polk
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I: Introduction to the karst issues in west central Florida

By Robert Brinkmann, Sarah Koenig, Kali Pace-Graczyk

The Florida peninsula is known for its unique karst landscape (Lane, 1986). Karst, which forms as a result of the solution of soluble rocks, often is expressed by landforms particular to the karstic environment such as caverns, sinkholes, disappearing streams, lakes, and solution valleys (Kinglinger et al., 1999). All of these features are present in Florida (Randazzo, 1997).

Karst landscape covers approximately 20% of the world’s land surface and significant areas of the United States (Fig. 1). The terrain is often considered marginal due to the droughty nature of the surface: most water quickly filters off of the surface into subsurface cavities. In addition, the soils are often quite poor. Unfortunately, there are currently tremendous development pressures in these areas due to expanding global populations. Thus, there are many areas in the Yucatan, Caribbean basin, China, the Philippines, and the United States that are undergoing significant environmental change. The karst landscape is especially vulnerable to this modification.

Fig. 1. Distribution of karst in the lower 48 states of the United States (http://water.usgs.gov/ogw/karst/kig2002/jbe_map.html).

It is important to recognize the influence karst has on hydrology in Florida for several reasons. Florida has an extremely high population density; as of 2003, an average of 315.2 people occupied each mile$^2$ (RAND, 2005). The principal geologic influence in Florida is karst related; 575 sinkholes have been recorded in Pinellas County (Seale, 2005). In Leon County, over 3,300 karst features have been identified including sinkholes, closed depressions, springs, large lake
basins with known sinkholes, and open basins originating from solution processes (Benoit et al., 1992). Understanding karst hydrogeology in Florida will aid in environmentally responsible development.

The Floridan Aquifer extends through several southeastern U.S. states and is one of the most productive carbonate aquifers in the country. Limestones in the Upper Floridan Aquifer (UFA) are young (Eocene to Oligocene) and have retained much of their depositional porosity (White, 1988, Budd and Vacher, 2004). The majority of storage in the UFA occurs within the matrix which has a permeability between $10^{-11}$ m$^2$ to $10^{-13.8}$ m$^2$ (Worthington, 2000; Budd and Vacher, 2004; Florea and Vacher, in press). The UFA can be defined as having triple porosity flow. Groundwater flow occurs through primary pore spaces, secondary fractures as well as through karst conduits (Budd and Vacher, 2004; Screaton, 2004; Florea and Vacher, in press). Because the UFA exhibits porosities between 30-40% and extremely high hydraulic conductivities, matrix flow has the ability to compete with fracture flow significantly affect the isotope ratios found in drip waters of Florida caves (Florea and Vacher, in press). The UFA is in stark contrast to the Paleozoic and Mesozoic limestone aquifers located within the continent’s interior. These limestones have undergone significant burial and diagenesis, and have matrix permeabilities on the order of $10^{-15}$ m$^2$ to $10^{-20}$ m$^2$ (Florea and Vacher, in press). Storage and flow in the matrix of the telogenetic karst is minimal as fractures and karst conduits offer the primary means of water transportation (Budd and Vacher, 2004).

In Florida, dominant features of the Floridan Aquifer are the springs emanating from the upper portions of the aquifer (Johnston and Bush, 1988). Twenty-seven first magnitude springs exist in the unconfined portions of the UFA (Spechler and Schiffer, 1995) five of which lie in the northern portion of the Southwest Florida Water Management District (SWFWMD). There are a number of environmental issues associated with the karst landscape (Sinclair and others, 1985). They involve water, environmental pollution, ground stability, and ecosystem management. The water issues include problems with water quantity and quality. The region receives most of its rainfall during the summer months from intense, convectional thunderstorms. Occasional hurricanes or tropical storms accentuate the rainfall totals in the summer and early fall and weak cold fronts bring moderate rainfall amounts in the winter (Fig. 2).

Even though the state has intense bursts of rainfall, there are few surface streams in the state to carry runoff. Instead, water filters through the ground to enter karst aquifers or it runs off through overland flow into lakes, ponds, or small rivers or creeks. Many communities rely on surface water of the low-flow streams, although groundwater is still the main source of drinking water in the state.

Evaluation of water quality trends for springs in the northern portion of the SWFWMD reveal increases in nitrate levels (Champion and Starks, 2001; Jones et al., 1997). Efforts to protect the quantity and quality of spring discharge have
been implemented at the state-level. Various studies on the karst features in the UFA as well as on the stable isotopes and trace elements of water infiltrating the UFA are currently being conducted by students of the Karst Research Group at the University of South Florida to help link the poorly constrained mechanisms connecting hydrogeologic contamination issues and variations in climatic processes in Florida to other locations worldwide.

A cartoon cross-section of a typical Florida aquifer system is shown in Fig. 3. The state is known to have a type of karst landscape called a ‘covered karst’. This means that the porous rocks are covered with some type of other material. In the upper Midwestern United States and in parts of Northern Europe, the rocks responsible for the development of a karst landscape are covered with glacial deposits. In contrast, the limestone rocks in Florida are covered with marine sands. There are a number of projects underway in the region to decrease the reliance on subsurface aquifers due to problems with regional decline in the aquifer system and associated land subsidence. For example, the nation’s largest desalination plant is producing water in the region and a large 15 billion gallon, 1100 acre above ground reservoir is used to store excess water skimmed from rivers during the rainy season for delivery during dry months.

![Annual Rainfall, Tampa Florida](image)

*Fig. 2. Average monthly rainfall in Tampa (National Weather Service).*

The karst aquifer systems have been badly damaged by over-pumping and associated saltwater intrusion and regional water table declines. In addition, the subsurface aquifer system is extremely porous. Some have compared the system to Swiss cheese with interconnected holes allowing pollutants to migrate very rapidly across the state. Some areas of the aquifer are known to have turbulent
flow. One of the most permeable and productive units, the Ocala Limestone, is dominated by multiple 12-35 meter thick, shallowing upward depositional sequences (Randazzo, 1997; Copeland, 1991). The lower Ocala consists of grainstones to packstones and may show localized dolomitization; the upper unit shows increased mud content and is quite friable (Copeland, 1991). The Ocala Limestone is unconfined in central Florida, along the Ocala Uplift; the majority of caves in Florida are clustered here (Palmer, 2002). To the North, increased sediments derived from the Appalachians are present (Fig. 4). Where confined, the Ocala Limestone is overlain by the Hawthorn Group, a clay rich, partially laminated limestone to dolostone (Randazzo, 1997). The Hawthorn is often considered a confining unit for the UFA.

Another challenge for Florida is sinkhole development (Beck, 1986). The state’s karst landscape is perhaps best known for these features, largely as a result of the Winter Park sinkhole that is featured in introductory physical geography texts around the world. The formation of sinkholes occurs largely as a result of slow raveling of the sediments in the surface aquifer into voids in the Floridan Aquifer. Thus, most sinkholes form very slowly in a fashion similar to the movement of sand within an hourglass. Because of this, the dramatic sinkholes like the Winter Park sinkhole event are rare. Instead, most sinkhole damage is in the form of cracked foundations and walls, broken windows, or broken pipes. Unfortunately, these seemingly small problems can cause a home to become condemned.
Florida is unique in the United States in that it requires all property owners in the state to be insured for sinkhole damage to property. This is a controversial issue because sinkholes are not distributed evenly throughout the state. Indeed, even in one of the most sinkhole-prone regions, Tampa Bay, the distribution of sinkholes is distinctly regional (Fig. 5). There are very few sinkholes that cause property damage from Lake Okeechobee south. However, all of the residents in the communities in these areas, including major metropolitan areas like Miami, Fort Myers, and Fort Lauderdale pay for sinkhole insurance.

Fig. 4. Stratigraphic sections of southern, northern and panhandle Florida. Many formations present in the panhandle are absent in northern and southern Florida. (Copeland, 1991).

Another problem associated with sinkholes insurance is how the state defines the term ‘sinkhole’. By state insurance law, sinkholes are defined as having topographic or subsurface characteristics. This means that property damage may be covered if a property owner can prove that there is some sort of void under the property and that there is a raveling zone where sand is filtering into the void. This is difficult to prove and many geologic consulting firms work with insurance companies and property owners in insurance evaluations. Also, there are other subsurface anomalies that can cause structural damage that are not covered by insurance. These anomalies include peat, buried trees, and the presence of shrink-swell clays. Many law firms in the state focus on helping homeowners or insurance companies evaluate claims.

Another issue in the region is ecosystem management of karst lands. Many of the lakes, wetlands, and ponds that occur in the region are small sinkholes. Unfortunately, these small features are very susceptible to destruction in Florida’s hyper real estate market. While there are rules that require wetland mitigation and preservation, the unfortunate outcome is that the rules are not
very effective. Wetland banking, which preserves large areas of wetlands in trade for the destruction of smaller wetlands is effective at preservation of large areas but smaller habitats, that can be important for niche species, are often lost. Some of these areas are known locally as cypress domes, cypress strands, and sloughs.

Fig. 5. Distribution of reported sinkholes in the Tampa Bay area since 1960.

Another environment of interest is the subsurface cavernous environment. As noted above, the subsurface of Florida is quite porous. There are over 300-400 known caves in the state and there are certainly many more that have not been mapped or that remain undiscovered. Some of these caves are flooded and some are aerated. Each of these environments provides unique habitats for unusual animals. Perhaps the most unusual animals in the flooded caves are the cave divers. In Florida, cave diving is considered an adventure sport. Much of what we know about subsurface caverns in the state is due to the diligence and hard work of these explorers. There are many known flooded caves in the Tampa area and some of them run underneath urbanized portions of the city.
II: A Background on Florida Phosphate

By Robert Brinkmann, Sarah Koenig

Leading the nation in phosphate production, Florida contributes approximately 75% of the nation’s supply and approximately 25% of the world’s supply of phosphate (Brown, 2005). The largest phosphate deposit in the world, the Bone Valley Deposit (Fig. 6), is located in central Florida (PCBOCC, 2006). This deposit encompasses approximately 500,000 acres in Polk, Hillsborough, Manatee, and Hardee Counties and yields most of the phosphate mined in the state (Jasinski, 2005).

![Bone Valley Phosphate Deposit](image)

*Fig. 6. Central Florida's Bone Valley Deposit.*

Phosphate is a limited, un-replaceable resource (FIPR, 2004). With a rising world population and the need for dependable food supplies, global phosphate demand is expected to increase (Jasinski, 2006). A majority (90%) of mined phosphate is used in the production of fertilizer. As phosphorus is one of the three primary plant nutrients essential for growth (FIPR, 2004), there are no substitutes for phosphorus in agriculture (Jasinski, 2005). Phosphate is also used in a variety of products such as plastic, food preservatives, animal feed, soft drinks, toothpaste, and vitamins (Lane, 1994; Campbell, 1985).

Large, economic deposits of phosphate, such as Florida’s Bone Valley, are rare due to the strict combination of factors (tectonic setting, climate, sea level, and oceanic circulation) necessary for formation (Compton, 1997; Riggs, 1980). The origin of the phosphate reserves of Florida lies in Miocene marine sedimentation (Compton, 1997; Riggs, 1980). The phosphorus was derived from organic matter in areas of upwelling ocean currents (Compton, 1997). The phosphates were deposited during high sea levels and subsequently reworked to form the high concentrations of phosphorites that we see today (Scott, 1990). Phosphorite-bearing sediments of Florida belong largely to the Bone Valley
Member, Peace River Formation, of the Hawthorn Group (Compton, 1997). Phosphate mining has place in Florida for over 120 years (Fig. 7). The discovery of phosphate ore near Dunnellon in 1889 triggered a phosphate boom; by 1892, there were over 215 phosphate mining companies operating in the state (FIPR, 2004). Phosphate mining played a significant role in the development of many central Florida towns, such as Fort Meade, Mulberry, and Bartow. Phosphate mining remains a vital component to the economy of west-central Florida and Hamilton County in north Florida.

![Fig. 7. Central Florida Phosphate Mining, 1910 (source: USF).](image)

Florida phosphate mining takes the form of open-pit mining, utilizing huge draglines and buckets to remove the vegetation and overburden, which is approximately 30 feet thick (Brown, 2005). To collect the phosphorite-bearing sediments, the draglines and buckets are then used to create adjacent cuts that are 200 – 300 feet wide and up to several thousand feet long (Yon, 1983). The location of mining in the state is depicted in Fig. 8. The phosphate is separated from the matrix by a process called ‘benefaction,’ and then hydraulically shipped to processing plants for the production of a super-concentrated and highly soluble form of phosphorus.

**Florida Phosphate Mining: Landscape Alteration**

Over 300,000 acres in Florida are now dominated by phosphate mining (Brown, 2005). Annually, phosphate mining disturbs approximately 4,000 – 6,000 acres; 25 – 30% of which are wetlands (FIPR, 2004). Mining for phosphate alters the topography, stratigraphy of geology and soils, ecology, and hydrologic regime of the natural landscape of Florida (Riekerk et al., 1991). There is a large public and governmental concern regarding the environmental consequences with the mining and processing operations as well as the quality of the post-mined landscape. The land disturbed by the mining process in addition to the wastes associated with benefaction and chemical processing are major issues associated with industry (Fig. 9). The post-mined landscape is generally a combination of steep-sloped piles and water-filled troughs often being described as resembling a ‘moonscape’ (FIPR, 2004).
Clay, a waste product of benefaction, typically occupies 40-60% of the post-mined landscape. The phosphate matrix is usually a combination of clay, quartz sand, and phosphate. The quartz sand can be used in various reclamation practices, but the clay presents a distinct problem. Due to the large amounts of high-pressure water utilized to separate the matrix, the phosphatic waste clay occupies a much larger area post-processing (Yon, 1983). Settling areas used for the management and storage of waste clays settle and shift over time and possess radically different physical properties, in terms of water storage and transmission, than the landscape before it. Environmental issues associated with the chemical processing of phosphate are the storage and disposal of phosphogypsum as well as air quality. The processing of phosphoric acid yields approximately 4.5 tons of slightly radioactive waste for every 1 ton of phosphoric acid that can then be used for fertilizer (Burnett and Elzerman, 2001). In addition to the radioactive substances of uranium and radium-226,
Phosphogypsum also contains 17 heavy metals and other toxic substances including lead, mercury, arsenic, chromium, and cadmium (Satchell 1995, 2). Current EPA standards do not allow any further use of phosphogypsum; the only alternative is to store the waste in massive piles known as ‘gyp stacks’. Florida is currently storing an excess of 1 billion tons of phosphogypsum, with approximately 40 million additional tons produced annually (Burnett and Elzerman, 2001). A majority (20) of the state’s gyp stacks are located in sinkhole-prone west-central Florida (Tihansky, 1999).

The influence of phosphate mining on the hydrologic system of affected areas is often substantial and remains in the forefront in public concerns and reclamation efforts. Physical effects of phosphate mining on the hydrology of Florida include the reduction or elimination of base flow, reduced surface runoff, lowering of water levels in the Upper Floridan aquifer, the replacement of natural surface drainage by modified topography and reclaimed ditches and swales (Lewelling et al., 1998), and the erasure of hydrologic features. Additionally, water quality is an area of concern. There have been numerous gyp stack and clay settling area failures, sending chemical and physical pollutants into nearby waterways. In 1994, a massive sinkhole opened up amidst a gyp stack in Polk County (Fig. 10). It is estimated that over 4 million cubic feet of phosphogypsum and an undetermined amount of the associated contaminated water was released directly into the Floridan Aquifer (Tihansky, 1999).

The Future of Phosphate-Mined Lands in Florida

Mandatory reclamation of phosphate-mined lands was enacted July 1, 1975. Prior to this date, reclamation was on a voluntary basis and relatively rare (FIPR, 2004). It is estimated that without human intervention, the post-mined landscape will take approximately 500 years to undergo natural restoration (Brown, 2005). Reclamation involves not only restructuring the land and hydrologic functions, but also re-vegetating the land and monitoring changes. Restoring the post-mining landscape involves “re-establishing functional landscapes from otherwise barren ones” (Brown, 2005). Reclamation techniques have evolved significantly over the last 30 years. Reclamation research is now considered to be a top priority (FIPR, 2004). Early reclamation research and projects focused on wetlands and was often fragmented in approach. Reclamation and restoration of mined lands has shifted towards landscape-scale planning and management (Brown, 2005).

There is heavy responsibility associated with the state and industry’s handling of phosphate mined land. Environmental issues associated with mining and processing must be carefully monitored and managed and the quality of the post-mined landscape must be of paramount concern. As much of the highest-quality phosphate reserves central Florida are ‘mined out,’ there is global pressure for the industry to move south of central Florida to continue mining.
The desire to move south has been met with much local and regional opposition (Jasinski, 2006). Central Florida is the currently the grounds for a battle between global and national demands for fertilizer and local environmental concerns.

![Sinkhole in Gyp Stack, Polk County, 1994 (Fluoride Action Network).](image)

Efficiently managed phosphate-mined lands represent a unique landscape class in the rapidly developing state of Florida (Fig. 11). With many pressures on the natural environment of the state, such as the destruction and fragmentation of habitats, the possibilities of green spaces on reclaimed lands holds extensive value.

![Integrated Habitat Network, Hardee County (source: FDEP).](image)

The Bureau of Mine Reclamation is currently coordinating efforts towards the creation and maintenance of greenways / wildlife corridors, wildlife habitat, and riparian buffers in the phosphate-mined region under a plan called the Integrated Habitat Network (FDEP, 2005).

The future of phosphate in Florida remains uncertain. Estimates of the remaining mining life in the state vary, but it is certain that the supply will be exhausted in the near future. Global and national demands will have to find another source of high-quality phosphate. Meanwhile, the state of Florida is faced with a massive responsibility and unique opportunity of the management and utilization of phosphate-mined lands.
Florida’s springs are among the State’s most valued natural and scenic resources. Springs are an important part of Florida’s history, dating back to the days of early Spanish explorers including Ponce de León, who came in 1513 seeking “the Fountain of Youth.” Archeological evidence indicates that Indian villages were located near springs; native Floridians used the springs for their water supply and fished in the streams formed by the springs. Many of Florida’s springs are tourist attractions; the best known is Silver Springs which has been a location for movie and television productions. Most of Florida’s springs are located in the northern half of the State (Fig. 12). Springs are the surface evidence of a vast underground water resource, the Floridan aquifer system, which supplies most of the State’s drinking water. The large quantities of water discharged from Florida springs indicate the large capacity of the underground aquifer system to store and transmit water.

Springs provide base flow for many of the streams and rivers that are used for boating, fishing, swimming, scuba diving, and snorkeling. The nearly constant temperature of spring water creates an ideal habitat for many plants and animals; one example is the manatee, which seeks out the warmer waters of spring “runs” during cooler winter months. The 320 known springs in the State discharge about 12,300 cubic feet per second (ft³/s) or nearly 8 billion gallons per day. This exceeds the 7.5 billion gallons per day of freshwater used in the State (from ground-water and surface-water sources) for public supply, agricultural, industrial, domestic, and thermoelectric power purposes in 1990.


How Springs are Formed

Florida has an abundance of springs because the State is underlain by a thick sequence of limestone and dolomite—rocks that are easily dissolved by the rainwater that seeps into the ground. Carbon dioxide carried by the recharging rainwater forms carbonic acid, a weak acid that dissolves the rocks, thus creating cavities and caverns. The result is a landform called karst, which is characterized by the presence of springs and sinkholes and the absence of a well-developed surface-drainage system. Instead, most of the surface drainage enters the rocks of the Floridan aquifer system (Fig. 13). A spring is formed when the ground water, which is under pressure, flows out through a natural opening in the ground.

Source of Spring Water

The source of Florida’s spring water is rain that falls on land surrounding the spring. Contrary to popular belief, underground rivers do not bring water into Florida from other states. Instead, rainwater replenishes the aquifers which in turn supply the springs with water. Water in the aquifer flows through the permeable rocks and the various-sized openings in the rocks. Although many caverns in the aquifer can be quite large and interconnected, there are no underground rivers as such.

Fig. 13. Generalized cross section showing the geohydrology and springs of Florida.

Characteristics of Springs

Springs can be classified on the basis of several characteristics including the following: the discharge of the spring; the aquifer supplying the spring; or the water temperature of the spring. The most common classification of Florida’s
springs is by discharge. O.E. Meinzer, a pioneer ground-water scientist of the U.S. Geological Survey, devised a classification system in 1927 based on discharge; the system relates magnitudes to ranges of discharge (Table 1). Discharge from Florida’s springs can range from less than 1 pint per minute to more than 1 billion gallons per day. The amount of water that flows from springs depends on many factors, including the size of the caverns within the rocks, the water pressure in the aquifer, the size of the spring basin, and the amount of rainfall. Human activities also can influence the volume of water that discharges from a spring—ground-water withdrawals in an area can reduce the pressure in an aquifer, causing water levels in the aquifer system to drop and ultimately decreasing the flow from the spring.

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Average Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100 ft³/s or more (65 Mgal/d)</td>
</tr>
<tr>
<td>2</td>
<td>10-100 ft³/s (6.5-65 Mgal/d)</td>
</tr>
<tr>
<td>3</td>
<td>1-10 ft³/s (0.65-6.5 Mgal/d)</td>
</tr>
<tr>
<td>4-8</td>
<td>Less than 1 ft³/s (0.65 Mgal/d)</td>
</tr>
</tbody>
</table>

*Table 1. Classification system for springs according to average discharge (ft³/s, cubic feet per second; Mgal/d, million gallons per day).*

Florida has more first-magnitude springs than any other state in the Nation. The sum of the average flow from Florida’s 27 first-magnitude springs (Table 2, Fig. 12) is estimated to be 9,400 ft³/s (6,075 Mgal/d), or about 76 percent of the average flow of all the known springs in Florida. Several first-magnitude springs are nationally or even internationally known, such as Silver Springs, Rainbow Springs, Wakulla Springs, and Weeki Wachee Springs. About 70 springs are second-magnitude springs; these collectively discharge about 2,600 ft³/s (1,680 Mgal/d) or about 21 percent of the total discharge from all known Florida springs. More than 190 springs are third-magnitude or less; these collectively discharge more than 300 ft³/s (194 Mgal/d), or about 3 percent of total discharge from all Florida springs.

Spring Creek Springs and Crystal River Springs are the two largest springs in Florida. Discharge measured from Spring Creek Springs (a group of eight known spring vents) in 1974 was about 2,000 ft³/s (1,293 Mgal/d). The average discharge from Crystal River Springs is 878 ft³/s (567 Mgal/d) from 30 individual spring vents. Both of these springs are located near the coast. The discharge of springs near the coast commonly is affected by tides.

Silver Springs in Marion County is the largest inland spring in the State (based on average discharge). Measured discharge from this spring ranges from 517 to 1,290 ft³/s (334 to 834 Mgal/d), and the average discharge is 799 ft³/s (516 Mgal/d) based on records from 1933 to 1993. The highest recorded discharge from any inland Florida spring is 1,910 ft³/s (1,234 Mgal/d), measured at
Wakulla Springs. This maximum discharge is about 50 percent greater than the maximum measured discharge from Silver Springs (1,290 ft³/s, 834 Mgal/d). Wakulla Springs also has the greatest range in discharge of all Florida springs, from 25 ft³/s to 1,910 ft³/s (16 to 1,234 Mgal/d); however, the average discharge (391 ft³/s, 253 Mgal/d) is less than half that of Silver Springs (799 ft³/s, 516 Mgal/d).

Numerous springs and seeps probably occur off the coast of Florida, but most are difficult to detect. Presently (1995), the locations of 15 submarine springs are documented. Most are located off the west coast of the State, but at least one, Crescent Beach Spring, is 2.5 miles off the northeast coast. Many of these submarine springs are located near the coast, mainly in bays or estuaries; a few others are as much as 20 miles offshore. Submarine springs sometimes can be detected by the appearance of a “boil” or “slick” at the water surface.

<table>
<thead>
<tr>
<th>Map Number</th>
<th>Name</th>
<th>County</th>
<th>Average discharge ft³/s</th>
<th>Specific conductance µS/cm</th>
<th>Chloride (mg/L)</th>
<th>Sulfate (mg/L)</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>Spring Creek Springs</td>
<td>Wakulla</td>
<td>2,000</td>
<td>4,300</td>
<td>1,200</td>
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<td>Crystal River Springs</td>
<td>Citrus</td>
<td>878</td>
<td>4,300</td>
<td>1,400</td>
<td>200</td>
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<td>3</td>
<td>Silver Springs</td>
<td>Marion</td>
<td>799</td>
<td>410</td>
<td>9.5</td>
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<td>St. Marks Spring</td>
<td>Leon</td>
<td>517</td>
<td>260</td>
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<td>Wakulla Springs</td>
<td>Wakulla</td>
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<td>270</td>
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<td>Jefferson</td>
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<td>Ichetucknee Springs</td>
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<td>230</td>
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<td>25</td>
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<td>780</td>
<td>110</td>
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<td>Blue Springs</td>
<td>Jackson</td>
<td>189</td>
<td>210</td>
<td>2.6</td>
<td>.3</td>
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<td>Manatee Spring</td>
<td>Levy</td>
<td>178</td>
<td>410</td>
<td>3.9</td>
<td>24</td>
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<td>Weeki Wachee Springs</td>
<td>Hernando</td>
<td>174</td>
<td>280</td>
<td>6.3</td>
<td>7.5</td>
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<td>15</td>
<td>River Sink Spring</td>
<td>Wakulla</td>
<td>164</td>
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<td>Gainer Springs</td>
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<td>.6</td>
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<td>Volusia</td>
<td>138</td>
<td>1,700</td>
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<td>Lake</td>
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<td>1,100</td>
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Table 2. Summary of discharge and water-quality data collected at Florida’s 27 first-magnitude springs.
(Map number refers to Fig. 1. all values are averages. Ft³/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter).
**Water Quality of Springs**

The quality of water discharged by springs can vary greatly because of factors such as the quality of the water that recharges the aquifer and the type of rocks with which the groundwater is in contact. The rate of flow and the length of the flowpath through the aquifer affects the amount of time the water is in contact with the rock, and thus, the amount of minerals that the water can dissolve. The quality of the water also can be affected by the mixing of freshwater with pockets of ancient seawater in the aquifer or with modern seawater along the coast.

Water from springs usually is remarkably clear. Water from some springs, however, may be “tea-colored,” indicating the presence of tannic acid. Many surface waters in Florida contain natural tannic acids. If surface water enters the aquifer near a spring, the water can move quickly through the aquifer and discharge at the spring vent. The discharge of highly colored water from springs can indicate that water is flowing quickly through large channels within the aquifer without being filtered through the limestone.

The quality of spring water represents the general water quality of the groundwater system. Most spring water is of excellent quality. The specific conductance of spring water generally is less than 500 microsiemens per centimeter, indicating that small amounts of minerals are dissolved in the water (table 2). Chloride and sulfate concentrations generally are less than 12 and 60 milligrams per liter, respectively. Spring-water temperatures range from 66 to 97 °F. The temperature of spring water in north Florida averages about 70 °F and about 75 °F in central Florida. Higher water temperatures in some Florida springs indicate that the water originates from deeper parts of the Floridan aquifer system. For example, the temperature of water discharging from Mud Hole Spring, a submarine spring located off the southwest coast of Florida, is about 97 °F.

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**For Further Information**

Information on reports and data collected by the U.S.G.S. may be obtained from:

District Chief; U.S. Geological Survey
227 N. Bronough St., Suite 3015
Tallahassee, Florida 32301
IV: Florida Springs Field Trip,
Thursday, January 25, 2007
Field trip led by Dave DeWitt (SWFWMD) and Melissa Hill (USF/SWFWMD)

Itinerary
7:00am   Meet at USF in the SCA parking lot
8:30am   Pick up Brooksville residents at Publix parking lot on the corner of Cortez and Broad Streets.
9:00am   Arrive at Weeki Wachee Springs Complex; View the springs, visit underwater amphitheater, and hear a short lecture by Melissa Hill on managing and protecting the springs.
10:30am  Depart for Chassahowitzka Springs Group.
11:00am  Arrive at Chassahowitzka. Group will split in half; Group A canoes on Chassahowitzka Springs while group B hikes through Baird Swamp. Lecture on Chassahowitzka Springs Complex by Dave Dewitt.
12:30pm  Lunch at Chassahowitzka.
1:15pm   Group B canoes on Chassahowitzka; Group A hikes through Baird Swamp.
2:45pm   Drive to Homosassa Springs.
3:15pm   Arrive at Homosassa Springs; view manatees, hear talk from Homosassa Springs park employees.
4:45pm   Depart for Brooksville.
5:00pm   Drop Brooksville residents at Publix parking lot.
6:30pm   Return to University Mall parking lot.

Stop 1: Weeki Wachee Springs
By Melissa Hill

The Weeki Wachee Spring Group (Fig. 14) is located in southwestern Hernando County and has a cumulative discharge of over 200 ft³/s (6 m³/s; Champion and Starks, 2001). It is unique relative to the other first magnitude spring groups in the SWFWMD in that it consists of the fewest number of vents, has large explorable conduit systems, and data from the 1930's. Two of the vents, Weeki Wachee Main and Twin Dees discharge freshwater and are not tidally influenced. Salt, Mud, and Jenkins, which are located a few miles west of Weeki Wachee Main and Twin Dees, discharge brackish water and are tidally influenced (Fig. 15). Little is known about the water quality of a sixth vent identified as 831-237-A (Wetterhall, 1965) or Unnamed Spring No. 3 (Rosenau
et al, 1977). However, the presence of bacterial deposits associated with transition zones suggests that discharge is brackish. Today's tour will include stops at Twin Dees and Weeki Wachee Main.

Weeki Wachee Main and Twin Dees are paleo sinkholes that transitioned to points of discharge as sea level rised. Divers describe the main vent at Weeki Wachee as a narrow vertical fracture which opens into a large room at a depth of approximately 150-205 ft (46-62 m) bbls (Sinclair, 1978; Jones et al., 1997). Two passages exiting the large room were identified, but their trends were not indicated. Divers report that more water appears to be exiting the room through the two passages rather than through the fracture leading to the main vent (Jones et al., 1997).

Weeki Wachee Spring discharges from the bottom of a conical depression with gentle side slopes. The spring pool measures 165 ft (50.3 m) east to west and 210 ft (64 m) north to south. Spring depth is 45 ft (13.7 m) over the vent in the center of the pool. Bare limestone is located near the vent, but none is exposed around the pool edges. The water is clear and light greenish blue, and a boil is visible in the center of the pool. Thick, filamentous algae cover the majority of the spring bottom, and there are some native aquatic grasses in the spring pool. The spring is rich with fresh and salt water fishes and aquatic turtles. The Weeki Wachee River flows westward approximately 5 miles (8 km) into the Gulf of Mexico. The river flows through low-lying, densely forested swamp. The nearest high ground east of the spring is rolling sand hills terrain and gently rises to 15 ft (4.6 m) above the water level. All uplands and land adjacent to spring are developed.

Twin Dees (aka Little Spring) is approximately 3000 ft (914 m) southwest of Weeki Wachee Main (Fig. 15). Discharge varies from zero to second magnitude at Twin Dees. Discharge is significantly lower than Weeki Wachee Main, however this relatively small spring is fed by a large conduit system with rooms that exceed 100 ft (30 m) in diameter. Divers have mapped an extensive conduit system at Twin Dees (Fig. 16). Cave maps suggest that the geometry of the system has been influenced by both fracture sets and bedding. Divers describe
the main vent at Weeki Wachee as a narrow vertical fracture which opens into a large room at a depth of approximately 150-205 ft (46-62 m) b.s.l. (Sinclair, 1978; Jones et al., 1997). Two passages exiting the room were identified, but their trends were not indicated. Divers report that more water appears to be exiting the room through the two passages rather than through the fracture leading to the main vent (Jones et al., 1997). The maximum extent of the conduits have not been explored as they continue to depths beyond 300 ft (91 m) b.s.l. Two vents exist at Twin Dees, but one vent, according to cave divers, has been plugged for some time. Freshwater discharges from Twin Dees, but cave divers have identified the influx of brackish water at various locations in the conduit system (Champion and Starks, 2001).

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**Fig. 15. Location of Weeki Wachee Springs within Group.**

**Fig. 16. Conduit system at Twin Dees Spring, Weeki Wachee Spring complex; from Champion and Starks, 2001; surveyed by Karst Underwater Research.**
The region surrounding Weeki Wachee Springs can be characterized as a karst terrain with internal drainage. Additional evidence for the abundance of cavities occurs at a former irrigation well which tapped into the ceiling of a conduit at approximately 270 ft (82 m) bss (Well WW-F) Fig. 2. However, not much is known concerning the degree of connection among these karst features. Anecdotal evidence suggests that a high degree of connection may exist among south-southeast trending conduits and Weeki Wachee Main. On or around March 19, 1976, Weeki Wachee Main became cloudy allegedly due to collapse of a conduit below Crescent Lake, which is approximately 1.6 miles southeast of the vent. Additional episodes of cloudiness have not been documented, nor has a cessation of flow occurred since the 1930's. Based on diver accounts, Twin Dees has periodically ceased to flow during periods of drought. Weeki Wachee Main is topographically lower that Twin Dees.

It has long been suspected that Weeki Wachee Main and Twin Dees are hydraulically connected. Geochemically, the discharge is very similar from the two vents. Natural tracer studies are currently in progress to evaluate response times for the springs. Future quantitative tracer studies are planned. It is hoped that the quantitative tracer studies will reveal travel times and the degree of connection among the vents.

Weeki Wachee Spring is extensively developed into a tourist attraction that features underwater mermaid shows with a submerged observation area. It was recently purchased from private ownership by the Southwest Florida Water Management District (SWFWMD). The District leases the land to a private firm for the continuation of the mermaid shows. Shops and facilities are located all around the spring.

Stop 2: Chassahowitzka Springs


Chassahowitzka Springs form the headwaters of the Chassahowitzka River, which flows westerly to the Gulf of Mexico approximately 6 miles (9.7 km) though low coastal hardwood hammock and marsh. Chassahowitzka Springs are located 5.8 miles southwest of Homosassa Springs on the Chassahowitzka River. Rosenau et al. (1977) report as many as five springs flow into the upper part of the river and many more springs are known to exist in the lower portion. Average discharge from Chassahowitzka Springs is 138.5 ft³/s with a maximum recorded discharge of 197.0 ft³/s on May 18, 1966 and a minimum recorded discharge of 31.8 ft³/s on July 8, 1964. The entire river is tidally influenced.

Chassahowitzka Main Spring is 360 ft (110 m) northeast of the boat ramp and is in the middle of the run (Fig. 17). This spring is at the head of a large pool that measures 147 ft (44.8 m) north to south and 135 ft (41.1 m) east to west. The
depth measured over the vent in 13.5 ft (4.1 m). The spring has a sand bottom. No limestone was exposed. Water is clear and greenish. The spring run from Chassahowitzka Number 1 Spring flows into the Chassahowitzka Main spring pool from the east. There is a boat ramp with facilities on the southwest side of the pool. Aquatic vegetation is common including exotic aquatic vegetation and algae. A boil is visible at low tide. The spring is surrounded by lowland hardwood swamp forest with mixed hardwoods, cypress, and palm.

Fig. 17. Chassahowitzka Main Spring (photo by R. Means).

Chassahowitzka Number 1 is at the end of a spring run that flows into the Chassahowitzka River from the north approximately 250 ft upstream from the boat ramp (Fig. 18). This spring issues from a small cavern in the bedrock limestone. The spring pool measures 69 ft (21 m) north to south and 81 ft (24.7 m) east to west. There are two closely spaces openings though which the small tannic stream flows into the northeast side of the spring pool. There is a thin layer of algae covering most of the bottom of the spring pool. The surrounding land is low lying and heavily forested with hardwoods and palm. The spring flows southwest approximately 350 ft (106.7 m) into the Chassahowitzka Main Spring pool. There are several other spring vents along the spring run about half way to the Chassahowitzka Main spring pool. Chassahowitzka Springs and River are used for fishing, swimming, snorkeling, and pleasure boating. Manatees frequent the springs and river year round, but are especially common in the winter.

Fig. 18. Chassahowitzka Number 1 Spring (photo by R. Meegan).
Stop 3: Homosassa Springs

By Dave Dewitt

The Homosassa Springs Group is located in west-central Citrus County at Lat. 28° 47’ 56.65" N., Long. 82° 35’ 18.70" W (Fig. 19). The springs are at the head of the Homosassa River and contribute significantly to the discharge of the river. Most spring discharge at Homosassa is tidally influenced and water quality is slightly brackish. The largest spring is located at the Homosassa Springs State Wildlife Park, which like the Rainbow Springs State Park, was once a private tourist attraction, with the head spring area remaining developed as a botanical garden. The main spring pool, into which all three vents issue, is also developed as a manatee sanctuary and education facility, and a large viewing structure remains in the center of the spring pool, known as the Fishbowl.

![Fig. 19. Homosassa Springs Group (photo by H. Means).](image)

The main spring pool contains several spring vents, the largest being the opening to a fairly restricted cave-conduit system underneath the spring. Water quality samples are collected from three sampling tubes positioned at different depths in separate conduits to monitor discreet discharge points in the cave system. Discharge from Homosassa Main averages about 104 cfs, or about 66 mgd.

The Halls River is a major spring-fed tributary to the Homosassa River downstream of the head springs. A small head spring exists north of Homosassa, but much of the discharge appears to be dispersed across the shallow, sandy stream bottom. Spring flow is difficult to determine from discreet vents, but an
approximate composite discharge for the tributary varies between 130 and 190 cfs.

Several smaller springs also occur upstream of the main spring and state park, on the Southeast Fork of the Homosassa River. The springs are typically located on private residential lots and are generally not accessible, although property owners have cooperated in allowing data collection at the springs for many years. The head springs on the Southeast Fork are not brackish, although the combined discharge is somewhat less than Homosassa Main Spring.

The main spring pool and adjacent lands are within Homosassa Springs Wildlife State Park. The area is developed into an interpretive center for manatee and Florida wildlife education. There is a floating observation deck in the spring pool with a submerged aquatic observation room. Injured and rehabilitating manatees are captive in the spring pool for year round observation. Swimming is not allowed.
V: Tampa Springs Trip,
Saturday, January 27, 2007
Field trip led by Peter Schreuder (Schreuder, Inc.)

Itinerary
8:00am Meet at the University Mall parking lot, behind Sears
8:15am USF GeoPark
8:45am Schreuder, Inc.- Presentation regarding field trip stops
9:15am Tour Ewanoski Springs, Curiosity Creek, Blue Sink Complex, Orchid Sink, Poinsettia Sink, and Sulphur Springs.
12:00pm Arrive back at University Mall

Stop 1. The USF Geopark.

By Beth Fratesi, Len Vacher, and Lee Florea

The USF Geopark is an interpretive park that provides information about the landscape of the region. The park has interpretive signs and some interesting landscape features (Fig. 20). The faculty, students and alumni of the geology department at the University of South Florida (USF) have molded a tract of undeveloped land on the Tampa campus into a community education site focusing on karst. Tampa is built upon a mantled karst terrain, and local public interest in karst is fueled by sinkhole damage and water resource issues concerning the Floridan Aquifer.

The geology faculty at USF have long used the site for education and research into mantled karst landscapes and hydrology, as well as geophysics. The alumni use the site for annual expositions of geological field equipment and techniques. Exhibitors at these events have installed many permanent monitoring wells in the Surficial and Floridan Aquifers and run numerous geophysical surveys across the sinkholes. The GeoPark has several sinkholes, three large limestone boulders of Floridan Aquifer material, and a mulched trail with educational signs. A recent community education grant funded by SWFWMD provided the resources to develop the signs. Each sign highlights a different feature of the GeoPark and uses it to discuss the characteristics of karst landscapes and aquifers: “Hillsborough River Basin” orients visitors within the river basin using a collage of aerial photographs of the Hillsborough River Basin; “Floridan Aquifer” explains the concept of an aquifer and the formation of caves; “Sinkholes” includes descriptions of sinkhole types, distributions, and techniques used to study them; and “Sources of Contamination” emphasizes the connectivity of the aquifer to the surface and list potential sources of contamination. The park and signs are the results of a combined effort by members of the local geological community, and faculty and students of USF.
Stop 2:  Tampa Springs and Sinkholes: Ewanoski Springs, Curiosity Creek, Blue Sink complex, Orchid Sink, Poinsettia Sink

This group of small yet connected and hydrologically important springs and sinks are located near downtown Tampa. These springs, like many others in Hillsborough County, Florida, lie in a karst region that is heavily urbanized, yet no study has been undertaken measuring the degree of human disturbance. Van Beynen and Townsend (2005) created a hierarchical and standardized disturbance index specifically designed for karst environments. To address the problem of determining human disturbance in the county, the above index was successfully applied and it was found that Hillsborough County was highly disturbed (disturbance score of 0.69 of 1.0) because of its predominant urban and rural land use. Furthermore, the application of the index allowed for its refinement and the highlighting of environmental aspects in need of remediation such as soil compaction, deforestation, disturbance of archaeological sites, and the expanding urban footprint. Several minor issues arose during the application: the need for broader indicator descriptions that encompass a variety of scenarios, the need for a revised water quality indicator, inadequate data on

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sinkholes, and a lack of data for species richness and species population density. The utility of the index to resource managers arises from emphasizing certain areas of the environment that require immediate attention and determining temporal changes in environmental quality. Future application of the index requires potential retooling of the biota indicators, tightening of scoring descriptions for certain indicators, and further examination of the scale at which the index can be applied.

Stop 3. Sulphur Springs

By Jason Polk and Kali Pace-Graczyk

Sulphur Springs (Fig. 22) is located near downtown Tampa and provides an interesting karst feature right in the middle of urban sprawl. It was a major tourist destination for many years; however, in 1986, the spring closed due to water quality problems, particularly *e. coli* bacteria. People used to come to the springs to bathe in its "healing" waters, but now that is prohibited. A modern swimming pool is now located next to the spring for swimming and recreation.

![Fig. 22. Sulphur Springs as it looks today, with a modern swimming pool and controlled water flow via concrete toboggan flumes (photo by Schreuder, Inc).](image)

Sulphur Spring has been highly altered from its natural condition into a circular pool enclosed by concrete walls (now closed for swimming). The diameter of the pool is 90 ft (27.4 m). The pool is uniformly about 15 ft (4.6 m) deep with a limestone and sand bottom. Rosenau et al. (1977) report a maximum depth of 30 ft (9.1 m). The water is slightly murky and greenish colored. Algae are abundant in the pool. Spring outflow is southeast, cascading over a 7 ft (2.1 m) high weir. The falls continue for approximately 50 ft (15.2 m), and the rest of the run travels approximately 600 ft (182.8 m) to the Hillsborough River. The spring run is sand-bottomed and algae-laden. A hydrogen sulfide odor is associated with the spring. There is a City of Tampa water pumping facility on the west
side of the pool where a large metal pipe discharges water forcefully into the spring. The facility pumps a portion of the spring flow for municipal use, and the other portion is rerouted out the pipe into the pool.

Sulphur Springs discharges an average of 95 million l/d into the Hillsborough River and its water quality has declined significantly over the past few decades. The Blue Sink Complex connects hydrologically to Sulphur Springs, but has been blocked by debris for some time now. Schreuder, Inc., the City of Tampa, SWFWMD, Hillsborough County Environmental Protection Commission, and the USGS have been working to understand the connection between the Blue Sink Complex and Sulphur Springs and possible sources of contamination.

The main suspects for bacterial contamination of the pool were two significant sinkholes located 1950 and 2300 m north of the spring (Wallace, 1993). After a series of dye tests and water-quality tests were performed another source of contamination was found in a Department of Transportation (DOT) stormwater retention basin in which a sinkhole had opened up and was receiving stormwater (Wallace, 1993). The two significant sinkholes received stormwater from commercial and residential areas, and this stormwater brings a large amount of bacteria into the sinkhole, which funnels into the underground system and induces a bacteria spike at Sulphur Springs pool that exceeds the bathing water standards (Wallace, 1993). The City of Tampa has constructed an experimental initial flush capture basin that will sand-filter stormwater to see if this will favorably affect bacteria levels (Wallace, 1993). This locally famous landmark illustrates both the importance of karst water and the potential problems faced in karst environments.

**Urban karst management: Sulphur Springs and the Blue Sink complex**

**Peter Schreuder and Holly Reager**

**Location**

Sulphur Springs is located in the City of Tampa and discharges water into the Hillsborough River from an apparent drainage area of approximately 50 mi². The Blue Sink complex is located within the Curiosity Creek/Sulphur Springs subbasin of the Hillsborough River. The Curiosity Creek sub-basin is a closed basin with a drainage area of approximately 4 mi² ending at the Blue Sink; the Blue Sink complex, a series of sinkholes located on the east side of the of the creek, previously accepted large volumes of water. At elevated stages in Curiosity Creek, the surface water discharges into a constructed storm water retention pond known as the F-100C pond on the southern end of the Blue Sink.

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3 SCHREUDER, INC., 110 West Country Club Drive, Tampa, FL 33612
**Background**

Rapid urbanization has occurred throughout the basin and has significantly stressed the local hydrologic environment. Prior to the 1970’s, storm water in Curiosity Creek flowed south to the Blue Sink complex where the surface water entered Blue Sink and traveled through solution channels in the Upper Floridan Aquifer to Sulphur Springs and then into the Hillsborough River. The estimated intake capacity of the Blue Sink was 60 mgd prior to urbanization. Larger storm-water flows continued southward of Blue Sink into a retention area where the surface water entered other sinkholes. Large rainfall events in 1960 and 1979 exceeded the sinkhole flow capacity and caused extensive flooding in the Forest Hills area. In the mid-1970’s, trash and debris accumulated in the sinkholes and reduced the flow capacity of Blue Sink. In 1974, a storm-water retention pond at the edge of Blue Sink collapsed during a storm and partially blocked the sinkhole, preventing water from draining out of the creek basin. By 1985, the sinkhole and underground channel were completely blocked. The City of Tampa subsequently installed a pump system to manage the storm water in the Forest Hills area. Schreuder, Inc. (SI) has been investigating options to restore the Blue Sink complex back to its natural state and restore the groundwater flow to Sulphur Springs.

**Hydrologic system**

Sulphur Springs is a second magnitude spring which is located on the north bank of the Hillsborough River. The average flow of the spring is 38 cfs (25 mgd). The spring is contained in a concrete pool about 90 feet in diameter. The outlet is equipped with two slide gates, so the spring level can be lowered for cleaning and maintenance. The hydrogeology of the area consists of a surficial cover of sand or silty sand with a thickness of 5-20 feet. The sand overlies a layer of blue-gray marine clay with a thickness between 10-15 feet. Beneath the clay is weathered limestone of the Tampa Limestone Formation and marine limestone of the Suwannee Formation. The Tampa Limestone and Suwannee Formations comprise the top of the Floridan Aquifer. The clay layer serves as a confining layer for the Upper Floridan Aquifer. Numerous sinkholes have penetrated the clay layer in the area. Three major sinkholes occur directly north of Sulphur Springs. These sinkholes are Alaska Sink, Orchid Sink, and Poinsettia Sink (also called Trinity or Jasmine Sink). Many of the sinkholes to the north of Sulphur Springs have been used as stormwater discharge basins by the City of Tampa and local businesses.

**Regional stress test**

To evaluate the hydraulic connection between Sulphur Springs and the Blue Sink complex in Forest Hills, SI installed 15 monitoring wells before conducting a regional stress test. The network was developed to delineate the groundwater flow regime through thorough analysis of the discontinuities in the
potentiometric surface. Continuous water-level data have been collected throughout the area to further understand the effects of seasonal fluctuations and storm events on the flow system. A regional stress test was performed on January 24, 2002. The Sulphur Springs pool-water elevation was lowered six feet and a drop in the potentiometric surface elevation was measured as the pressure in the system was reduced by lowering the head in the spring pool. Fifteen Upper Floridan Aquifer monitoring wells and three surface-water locations were monitored for the duration of the five day test. The maximum water level drop of 6.3 ft was measured in the Sulphur Springs pool. A 4.3-ft and a 3.0-ft water level drop were measured in the Orchid Sink and Poinsettia Sink monitoring wells, respectively. As the water-level drawdown propagated up-gradient and stabilized, a maximum change of 0.3 ft was measured at Ewanowski Spring, upstream along Curiosity Creek from Blue Sink and the most northern data collection location in the study area. The blockage of the Blue Sink complex was reflected in the water-level response to the pressure drop measured in the monitoring wells. An abrupt gradient change was measured in the Blue Sink complex and Honda Land monitoring wells south of the blockage. The blockage in the Upper Floridan Aquifer causes the surface-water and groundwater to be impounded and not flow toward Sulphur Springs as it had done prior to the rapid urbanization of the area.

**Future investigation scope**

The retention-pond failure and the increased storm-water runoff in the Blue Sink Complex, compounded by lowered flow velocities through the system due to these events, have reduced the feasibility of restoring the system to its natural state. SI concluded that removal of the blockage at the Blue Sink complex is not economically feasible currently, and so the primary focus of the investigation has shifted to the southern portion of the Curiosity Creek/Sulphur Springs subbasin. Numerous sinks in the southern portion of the area are still connected to the Sulphur Springs flow system and need to be preserved. One option currently being investigated to restore the flow to Sulphur Springs from the Blue Sink complex is through direct recharge into Orchid Sink after the water has undergone wetland treatment at the F-100C storm-water pond. This sink is down gradient and currently is connected to the groundwater flow system discharging at Sulphur Springs.

**References**

VI: Caving Trip, Sunday, January 28, 2007
Field trip led by Robert Brooks, Lee Florea (USGS), Bogdan Onac (USF), and Tom Turner

Itinerary
7:00am   Meet at the University Mall parking lot, behind Sears.
8:30am   Pick up Brooksville residents at Publix parking lot on the corner of Cortez and Broad Streets.
9:00am   Arrive at Blowing Hole and Werner Caves. Group splits in half; group A visits Blowing Hole Cave, group B visits Werner Cave.
12:00pm  Lunch at Radar Hill Quarry, lecture by Colleen Werner on cave management and protection.
1:00pm   Depart for Thorton’s Cave
1:30pm   Arrive at Thorton’s Cave, tour cave. Optional river hike for those who do not wish to enter cave. Thorton’s Cave is partially water filled; you WILL get wet. Bring an extra set of clothes.
4:00pm   Depart for Publix parking lot
5:30pm   Return to University Mall parking lot in Tampa
Required Gear: 8AA batteries, extra set of clothing.
Blowing Hole Cave, Plan View
Citrus County, Florida


Datum: Blowing Hole Entrance, Station E0. (WGS 84 / NAD 83)
Latitude: N28° 43' 49"N,
Longitude: W82° 24' 33"W
Datum Elevation: 29.0 m (msl)
Survey length: 257 m, depth: 16.3 m

Station elevations in meters (msl).
Cave is formed within the Eocene Ocala Limestone.
Cave is located in the Withlacoochee State Forest

Key To Features

- Sediment floor
- Large breakdown
- Small breakdown
- Bedrock pillar
- Direction of slope
- Speleothems
- Stalagmites
- Flowstone
- Change in ceiling height
- Change in floor height
- Drapline
- Survey station
- Ceiling height (m)

IMPORTANT NOTE -
Blowing Hole is a gated cave.
Visitaton requires a special use permit from the Withlacoochee State Forest. Blowing Hole is closed from May through October for bat maternity season.

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ARCHITECTURE OF AIR-FILLED CAVES
WITHIN THE KARST OF THE
BROOKSVILLE RIDGE,
WEST-CENTRAL FLORIDA

LEE J. FLOREA

Department of Geology, University of South Florida, Tampa, FL 33620,
lflorea@chuma1.cas.usf.edu

Air-filled caves surveyed in the Brooksville Ridge of west-central Florida provide insight into the organization of karstic permeability within the unconfined portions of the Upper Floridan Aquifer. The morphology of the passages that compose these caves in geologically young, high-permeability limestones is strikingly different from caves found in ancient carbonates far from the influence of the coast. Cave passages in west-central Florida are laterally extensive and tiered. Principal horizons of cave development occur between +3 m and +5 m, +12 m and +15 m, and +20 m and +22 m above modern sea level. The primary guide of cave passage orientations within these cave levels is widespread fractures oriented approximately NE-SW and NW-SE. Cave passages of human dimensions form at the intersection of the laterally extensive cavities and fractures and often acquire a characteristic plus-sign shape. The walls of cave passages in west-central Florida are porous and complex, with small-scale solution features such as pockets and tafoni structures extending into the host bedrock. Additionally, these cave passages often end in blind pockets, ever-narrowing fissures, sediment fills, and collapses. The passages do not appear to represent an integrated system of conduits between aquifer inputs and outputs.

INTRODUCTION

Cavers and karst scientists have long appreciated and recorded information concerning the morphology of passages in caves. These data about caves are important to understanding the flow of water in karst aquifers, which cover approximately 15% of the land surface and provide water to approximately one-fifth of the world’s population (Ford and Williams, 1989). For example, compilations of cave maps reveal patterns in both the organization of passages in a cave and the shape of individual passage cross-sections that are a direct consequence of hydrogeological conditions within karst aquifers (e.g., Palmer, 2000; White 1988). To date, these observations are drawn primarily from experiences in caves formed far from the influence of the coast and within ancient carbonate rocks that are remarkably different from carbonate rocks that
are geologically recent or are forming today. This paper presents a case study of the morphology of caves within the coastal karst aquifers of west-central Florida.

**GEOLOGIC FRAMEWORK OF THE BROOKSVILLE RIDGE AND THE UPPER FLORIDAN AQUIFER**

The Tertiary limestones that compose the highly productive Upper Floridan Aquifer are intensely karstified in regions that experience active groundwater circulation (e.g., Lane, 1986; Stringfield and LeGrand, 1966), particularly in the portion of west-central Florida where the Upper Floridan Aquifer is semiconfined to unconfined. This region, characterized by 33 springs with average discharge greater than 2.8 m$^3$ s$^{-1}$ (e.g., Scott *et al.*, 2004; Roseneau *et al.*, 1977; Meinzer, 1927), stretches from the panhandle near Tallahassee in the north to Tampa in peninsular Florida (Fig. 1A) and encompasses several physiographic provinces including the Brooksville Ridge (White, 1970). The Brooksville Ridge, a linear, positive-relief topographic feature extending from northern Citrus County, through Hernando County, and into southern Pasco County (White, 1970), is bounded by coastal lowlands to the west and south and wetlands of the Withlacoochee River to the east and north. The ridge system is a consequence of a localized geologic high termed the Ocala Platform by Scott (1988), who attributed this topographic feature to a westward tilt of thickened Eocene strata. Elevations in the Brooksville Ridge range from five to more than 75 m above sea level (Fig. 1B). The topography is rolling with internal drainage (Fig. 2). Upland mesic-hardwood hammocks separate sinkhole lowlands that are mostly occupied by wetlands or lakes. The Withlacoochee State Forest manages more than 525 km$^2$ (157,000 acres) in the region, including the 100-km$^2$ (30,000 acre) Citrus Tract that includes much of the study area. Pasture land and lime-rock quarries compose the remaining land uses. The city of Brooksville lies in the heart of the Brooksville Ridge (Fig. 1A). Upper-Eocene and Oligocene carbonates (42–33 Mya) compose the Upper Floridan Aquifer, which is semi-confined to unconfined in the Brooksville Ridge. The strata of the Upper Floridan Aquifer thicken to the south along a regional dip that averages less than half of one degree (Scott *et al.*, 2001; Miller *et al.*, 1986). Miocene-age sands and clays of the Hawthorn Group thicken to more than 150 m in northern and southern Florida where the Upper Floridan Aquifer is confined (Scott, 1988). The Hawthorn Group is thin to missing in the center of the Brooksville Ridge in northern Hernando and southern Citrus Counties (Fig. 3). The Suwannee Limestone, a pale-orange, partially recrystallized limestone that is extensively quarried in northern Hernando County, is more than 30 m thick to the south. In the up-dip sections of the northern Brooksville Ridge of Citrus County, the Suwannee Limestone is thin to nonexistent as a result of post-Oligocene exposure and erosion (Yon and Hendry, 1972). As a result, the Suwannee Limestone is thickest beneath the topographic highs and missing in many topographic lows (Yon *et al.*, 1989). Paleokarst filled with Miocene-age
siliciclastics pierces the Suwannee Limestone throughout the Brooksville Ridge (Yon and Hendry, 1972). These paleokarst sinkholes indicate a period of intense karstification during the end-Oligocene exposure.

Fig. 1. Data locations and topographic elevations. A) The grey line surrounding Florida is the –120 m bathymetric contour on the continental shelf. Inset is included for Citrus and Hernando Counties. Air-filled caves surveyed in this study are indicated by black dots. An “x” indicates the location of the city of Brooksville. B) Elevations for the Brooksville Ridge in Citrus and Hernando Counties are generated using GIS topographic data. Known air filled caves in the Brooksville Ridge are indicated by white circles.

An irregular exposure surface with chert lenses, clay-rich marls, and a transition to non-recrystallized limestone marks the boundary between the Oligocene carbonates and the Ocala Limestone of late Eocene age. The Ocala Limestone is cream to white, soft, friable, and very porous in the Brooksville Ridge. It ranges in thickness from 30 m north of the study area to more than 120 m south of the Brooksville Ridge (Miller, 1986). Petrographic investigations of the Ocala Limestone by Loizeaux (1995) demonstrate three 3rd-order cycles of deposition. Shallow-water, high-energy facies, such as cross-bedded, low-mud grainstones and mixed-skeletal packstones, dominate all three cycles of the Ocala Limestone in the Brooksville Ridge.

The geologically young carbonates of the Upper Floridan Aquifer retain much of their original porosity and permeability, which is highly heterogeneous and facies-dependent (Budd and Vacher, 2004). Measurements during this study from cave and core samples from the Brooksville Ridge indicate that the matrix permeability of the Ocala Limestone averages 10–12.7 m2, which compares to an estimated value of 10–17.7 m2 for the much older Paleozoic limestones of the Mammoth Cave region of Kentucky (Worthington et al., 2000).
KARST OF THE BROOKSVILLE RIDGE

Historically, exploration of air-filled caves in Florida has been concentrated in portions of the panhandle near Florida Caverns State Park (Lane, 1986) and along the Cody Scarp in north-central Florida (e.g., issues of the Florida Speleologist, published by the Florida Speleological Society). In west-central Florida, the emphasis of karst research has surrounded the first-magnitude springs concentrated near the Gulf of Mexico (Meinzer, 1927) (Fig. 3). These large springs, such as Weeki-Wachee, Crystal River, Chassahowitzka, and Homosassa, discharge several hundred million gallons of water per day (Scott et al., 2004). The known underwater caves near these springs, such as Eagle’s Nest, Twin-Dees, and Diepolder, are famous in the popular press for their large passages, great depths (in excess of 100 m), and technical diving challenges. Less is known about the caves within the watersheds of the large springs along the coast in west-central Florida. These watersheds cover hundreds of square kilometers and include portions of the coastal lowlands and the Brooksville Ridge. In the coastal lowlands, most caves are currently underwater because the depth to the water table is less than 15 m. Thick Quaternary sediments mantle karst features, subduing their surface expression (Tihansky, 1999). In contrast, the depth to the water table exceeds 45 m in the uplands of the Brooksville Ridge, and Quaternary sediments are thin to non-existent. Airfilled caves in the Brooksville Ridge have been known for decades; e.g., the Dames Cave complex of southern Citrus County (Brinkmann and Reeder, 1994). However, there has been only limited exploration or scientific documentation of these caves until this study. The restricted number of natural, human-sized cave entrances contributes to the lack of exploration. Beginning in 2001, local cave explorers...
located several previously unknown caves of significant size in the uplands of the Brooksville Ridge (e.g., Turner, 2003). These newly-found caves are the focus of this study. Many of the discoveries were fortuitous; for example, otherwise hidden passages were revealed after structural collapses of cave roofs below abandoned lime-rock quarries. Such air-filled caves provide insight into the architecture of cave-scale porosity in the Upper Floridan Aquifer and greatly expand our perception of karst features in west-central Florida.

Fig. 3. Geologic map of Citrus and Hernando Counties. Geologic units generally dip and thicken to the south. The Miocene Hawthorn Group is thin to non-existent in northern Hernando and southern Citrus Counties. The Oligocene Suwannee Limestone occupies only the topographic highs in the study area. Air-filled caves surveyed in this study are indicated by white circles. Additional airfilled caves known in the region are indicated by black dots. Springs are indicated with a black “X.”

DATA COLLECTION

The data for this study are largely from surveys of seven caves within a study area in northern Hernando and southern Citrus Counties in west-central Florida (Fig. 3, Table 1). Maps of additional air-filled caves in the Brooksville Ridge were acquired from the archives of the Florida Cave Survey. The seven surveyed cave sites are in the central portion of the Brooksville Ridge where
Miocene siliciclastics are thin and the Suwannee Limestone occupies only the upland hammocks. The Withlacoochee State Forest manages five of the seven sites; private landowners own the other two. At each of the seven caves, I established elevation control using established data where available or by using an Ashtech Z-Extreme RTK (real-time kinematic) GPS base station and rover unit operated by the Coastal Research Group at the University of South Florida. I used a NOAA-HARN benchmark for our base station. The elevation of each in-cave survey station above mean sea level is based upon these control points. Subsequent survey from the control points, using a fiberglass tape and a hand-held compass and clinometer, is accurate to one-degree per station; this error propagates through the survey. In most of the surveyed caves, the number of azimuth readings exceeds the number of survey stations (Table 1), because some stations were located at passage junctions where multiple azimuth readings were required to accommodate splay shots or loop surveys. I generated detailed maps of each cave in Adobe Illustrator and ESRI ArcGIS software using a combination of detailed sketches and the cave survey data. These maps were used to assess the overall cave morphology in plan and profile view, including height-width ratios of the passages, length-weighted rose diagrams of passage orientations, and a histogram of all the survey-station elevations.

RESULTS AND ANALYSIS

The data include more than 2.2 km of new cave survey (Table 1). Small-scale maps of the caves are presented in plan view in Fig. 4. Of the caves surveyed, BRC Cave is by far the longest with more than a kilometer of mapped passage (Table 1); Werner Cave, (561 m, Table 1), together with Blowing Hole Cave (257 m, Table 1), round out the longest three caves in the study.

The entrances to all seven caves surveyed in this study, as well the entrances to other air-filled caves in the Brooksville Ridge, are at a higher elevation than the level of passages in the cave (Fig. 4). Football Cave and Blowing Hole Cave have natural entrances that are fractures enlarged by dissolution that are several meters deep. The entrance to Legend Cave is a small hole in a rock choke at the edge of a small limestone quarry. Werner, Big Mouth, and Morris Caves did not have natural entrances. Rather, a quarry operation intersected structural collapses within the cave.

Fig. 5 collects elevation data for all caves surveyed in this study and compares the data to a frequency plot of elevations for Citrus and Hernando Counties from Fig. 1B. Fig. 6 presents a frequency plot of passage dimensions. Fig. 7 presents the length-weighted rose diagrams of passage orientations and compares this data to a similar dataset from 14 caves in Marion County 40-50 km to the north and east of the study area.
Table 1. Caves surveyed in this study.

<table>
<thead>
<tr>
<th>Cave Name</th>
<th>County</th>
<th>Length (m)</th>
<th>n(az) a</th>
<th>n(az) b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big Mouth Cave</td>
<td>Citrus</td>
<td>96</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>Blowing Hole Cave</td>
<td>Citrus</td>
<td>257</td>
<td>50</td>
<td>54</td>
</tr>
<tr>
<td>BRC Cave</td>
<td>Hernando</td>
<td>1,033</td>
<td>276</td>
<td>281</td>
</tr>
<tr>
<td>Football Cave</td>
<td>Citrus</td>
<td>142</td>
<td>29</td>
<td>31</td>
</tr>
<tr>
<td>Legend Cave</td>
<td>Citrus</td>
<td>44</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Morris Cave</td>
<td>Citrus</td>
<td>92</td>
<td>12</td>
<td>13</td>
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<tr>
<td>Werner Cave</td>
<td>Citrus</td>
<td>561</td>
<td>105</td>
<td>115</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td></td>
<td><strong>2,225</strong></td>
<td><strong>497</strong></td>
<td><strong>520</strong></td>
</tr>
</tbody>
</table>

* a Number of survey stations.
* b Number of azimuth readings.

Fig. 4. Index maps from air-filled caves surveyed during this study. 1 – BRC Cave, 2 – Werner Cave, 3 – Blowing Hole Cave, 4 – Football Cave, 5 – Big Mouth Cave, 6 – Morris Cave, 7 – Legend Cave. The cave passages occur on distinct levels. For instance, Werner Cave, Big Mouth Cave, and Morris Caves contain passages near the present-day water table between +3 m and +5 m. Werner Cave, Blowing Hole Cave, Football Cave, and Legend Cave all have passages between +12 m and +15 m. BRC Cave and Blowing Hole Cave both have extensive passages at +21 m. The entrances to every cave surveyed are above the level of passage development. Only Blowing Hole Cave and Football Cave have natural entrances that are fractures enlarged by dissolution that are several meters deep. All of the caves surveyed contain collapse features.
Fig. 5. Frequency of data of land elevations in Citrus- Hernando Counties (left) compared to elevations of cave survey stations in this study (right). Modes in the cave-survey data correspond with modes in the elevation data set from Citrus and Hernando Counties and with known marine terraces.

Fig. 6. Frequency of passage height-width ratios at all survey stations in this study. Almost 15% of measured passages are more than four-times wider than they are tall, and 47% of measured passages are more than twice as wide as they are tall.
Upon first inspection, all of the caves within the study area are strikingly similar in their appearance. For instance, natural solution walls, ceilings, and floors of all caves of the study area, as well as many caves throughout west-central Florida, contain cuspate, pocket-like, or even tafoni features (Fig. 8). The passages in the caves of Fig. 4 terminate in blind pockets, ever-narrowing fissures, sediment fills, and collapses. Development of cave passages along fractures is visible from cave maps in plan view (Fig. 4), and individual caves demonstrate a preferred orientation of passages (BRC, Werner, and Blowing Hole Caves, Fig. 7). The cumulative length-weighted rose diagram of passage directions reveals a WNW-ESE (100°-120°) and NNE-SSW (20°-40°) pattern of passages (Fig. 7).

![Fig. 7. Length-weighted rose diagrams for the orientation of all segments of cave survey obtained during this study and from 14 caves in Marion County to the north and east of the study area. The data from this study reveal a regional WNW-ESE (100°-120°) and NNE-SSW (20°-40°) pattern of passages similar to the data from Marion County. Both are related to regional fracture sets. Individual caves have a preferred orientation to cave passages.](image)

Observations from quarry high walls in the study area and throughout west-central Florida reveal laterally extensive cavities (Fig. 9). These laterally extensive cavities occur at particular elevations throughout the study area (Figs. 4 and 5). The elevations of cave survey stations cluster between +3 m and +5 m and between +20 m and +22 m (Fig. 5) above mean sea level. The individual cave maps reveal a third, less-pervasive level of passages between +12 m and +15 m (Fig. 4) which is not visible in Fig. 5 because it is masked by the scatter in the survey data for the higher-elevation peak.

Human-scale passages within these cavities often occur where they intersect fractures enlarged by solution. Each cave presented in Fig. 4 is a group of these human-scale cavities. Passages formed along fractures in the caves of the Brooksville Ridge often develop “fissure” morphologies. In contrast, passages
not associated with fractures acquire a “tabular” morphology. The cave-survey data demonstrate the latter to be more common; 47% of the surveyed stations are more than twice as wide as they are tall (Fig. 6). Commonly, passages combine fissure and tabular morphologies into a signature “plus-sign” cross-section.

DISCUSSION

Caves in the young, high-permeability, coastal karst aquifers of west-central Florida differ substantially from those of the traditional, textbook perspective (e.g., White, 1988; Ford and Williams, 1989) of caves in ancient, low-permeability limestones of inland karst regions. The differences in cave morphology were anticipated by Palmer (2000) and briefly examined using examples of caves from the panhandle and north-central Florida by Palmer (2002).

The common conception of caves within the ancient limestones of the mid-continent is that water generally enters at discrete sites, travels through conduits, and discharges at springs. Caves in these settings have predictable geometries. According to Palmer (2003, p. 2):

Within karst aquifers, most of the dissolution porosity consists of conduits, usually arranged in dendritic patterns in which tributaries join each other to produce fewer but larger conduits in the downstream direction. In such caves, the porosity tends to form “continuous conduits rather than isolated voids” Palmer (2003, p. 2). The current perception of karst aquifers in the young carbonates of Florida is similar to this sinking-stream, spring model. For example, when speaking about the evolution of karst landscapes in Florida, Lane (1986, p. 14) states:

Continuing dissolution…will divert more of the surface water into the underground drainage. Eventually, all of the surface drainage may be diverted underground, leaving dry stream channels that flow only during floods, or disappearing streams that flow down swallow holes…and reappear at distant points to flow as springs or resurgent streams.

Fig. 9. Photo of highwall at Haile Quarry near Gainesville in north-central Florida. The highwall is approximately 14 m tall, and the land surface is approximately 27.5 m above mean sea level. Note the laterally continuous cavernous zone 7 m below the top of the highwall at +20.5 m (Fig.s 5a and 9 of LaFrenz et al., 2003).
Certainly there are many examples of underground river caves in Florida that follow this model. In fact, most major surface streams that cross the Cody Scarp in the Florida panhandle and north-central Florida sink into the Upper Floridan Aquifer (Upchurch, 2002). The water from several of these sinking streams
travels through conduits and returns to the surface as major springs (Scott, et al., 2004). Well-studied examples include the Santa Fe River Sinks and Rise (Martin and Dean, 2001) and the Wakulla-Leon Sinks Cave System (Loper et al., 2005; Lane, 1986).

On the other hand, the Cody Scarp is just one physiographic feature in an otherwise large karst region, and the underground river caves associated with the Cody Scarp account for only a small fraction of the nearly 1,500 known caves in the current Florida Cave Survey database. The Brooksville Ridge is not related to the Cody Scarp and it contains many caves that are not of the underground river type. What do the caves in the Brooksville Ridge look like? How do they differ from the caves of the mid-continent, and what do these caves reveal about the hydrogeology of the Upper Floridan Aquifer in west-central Florida?

To answer these questions, I will inspect the cave architecture documented from my cave-survey data from four viewpoints: passage cross-section, directionality, horizontality, and connectivity.

**PASSAGE CROSS-SECTION**

Many passages in the caves of the Brooksville Ridge and throughout west-central Florida are wider than they are tall (Fig. 6). These low, wide cavities can be laterally extensive (Fig. 9). Interspersed in the tabular voids created by the laterally extensive cavities are pillars of rock that have not dissolved (Fig. 4). As in an underground coal mine, these pillars hold the ceiling intact. Structural collapse of the ceiling is common between these rock pillars, predominantly where rock pillars are widely spaced or where ceiling blocks are bounded by fractures. These collapses are a mixed blessing to exploration, because, while they often create large rooms in the otherwise low, wide cave (Fig. 10), they also impede progress by blocking access (Fig. 4) to cave beyond the breakdown.

Tall, narrow passages in the caves of the Brooksville Ridge and throughout west-central Florida are always associated with fractures. Human-scale passages commonly occur where fractures and the laterally extensive cavities intersect, producing a characteristic plus-sign passage morphology (Fig. 11).

Walls of the cave passages in this study have complex, small-scale solution features (Fig. 8). These cuspate, pocket-like, or tafoni structures are an indication of water-filled conditions during at least part of the cave-forming period. However, these features are not flow indicators as are scallops in caves within ancient carbonates of the mid-continent. Rather, they closely resemble spongework features found in the caves of young carbonate islands such as in the Bahamas (Mylroie et al., 1995) and caves of hypogenic settings such as in the Guadalupe Mountains of New Mexico (Hill, 1987).
Caves in west-central Florida, regardless of cross-section, exhibit a preferred orientation of passages along fractures in the aquifer (Figs. 4 and 7). The datasets from the Brooksville Ridge and from Marion County are similar; both generally reveal a regional NW-SE and NE-SW pattern of passages.

Vernon (1951), who looked at topographic and physiographic features (such as linear segments of the Withlacoochee River), and Littlefield et al. (1984), in a detailed study of sinkhole alignments in west-central Florida, identified a large number of photo-linear features attributed to fractures that follow this NW-SE and NE-SW pattern. The widespread nature of this pattern is a manifestation of a pervasive cause of the fractures that is not yet identified.

Individually, the rose diagrams of passage orientations vary amongst the caves in the study area and in the caves in Marion County (Fig. 7). However, these data do not provide credible evidence that explains the reason for the variation. For instance, it is unclear whether the passages surveyed in a particular cave are a representative subset of all passages in the vicinity of that cave. What is clear is that the passages are some measure of the anisotropy of the aquifer at the time the cave formed.

PASSAGE HORIZONTALITY
Cave passages in west-central Florida are not only laterally expansive, they occur at particular elevations much like the levels of cave passages within ancient limestones, such as at Mammoth Cave (Palmer, 1987). At Mammoth
Cave, cave levels formed near the water table as the elevation of the Green River experienced staged base-level lowering during glacial-interglacial cycles (Granger et al., 2001). In Florida, the origin of cave levels may also result from changing positions of the water table, but one must also consider the role of lithology and, more specifically, variations in matrix permeability.

This second option, variations in matrix permeability, is often ignored in the study of caves in ancient limestones. However, the matrix permeability of the young carbonates that comprise the Upper Floridan Aquifer may be more than 105 times more permeable than the ancient limestones of the midcontinent. Additionally, matrix permeability in the Upper Floridan Aquifer is facies-dependent and spans three orders of magnitude (Budd and Vacher, 2004). Such variations would provide preferred horizons of ground-water flow (Vacher et al., 2006).

If the cave levels in Florida are related to lithologic units with high matrix permeability, the elevations of these cave levels would change in accordance with the geologic structure. However, the widespread levels of cavities do not follow the geologic structure; the cave levels are all at the same elevation even though the lithologic units dip to the south (Fig. 12). Therefore, lithologic variability does not exert the first-order influence on the locus of cave development.

There is, however, some correspondence between the cave levels in the study area and modes in the histogram of topographic data for Citrus and Hernando Counties (Fig. 5). The modes in the topographic data manifest the classic marine terraces identified in Florida by Cooke (1945) and later Healy (1975) including the Silver Bluff (+2.4 m), Talbot (+12.8 m), Penholoway (+21.3 m), and Wicomico (+30.5 m) terraces. These marine terraces are directly related to previous elevations of sea level.

In this near-coastal setting, the position of sea level has a direct influence on the position of the water table. Since the elevations of cave levels in the survey data generally correspond to the elevation of marine terraces, it appears that the development of air-filled caves in west-central Florida may be related to positions of the water table, and thus sea level, when they were higher than present.

**PASSAGE CONNECTIVITY**

Of the seven caves in the Brooksville Ridge surveyed during this study, none contain continuous conduits that connect sites of recharge to points of discharge within the Upper Floridan Aquifer. Neither do passages in the surveyed caves comprise a dendritic network of conduits with tributary passages.

Only one cave, BRC Cave, receives occasional water from a sinking stream and contains natural indicators of localized directional flow such as sediment ripples and pebble imbrication. Three other caves, Big Mouth, Morris, and Werner,
receive recharge from artificial sinking streams created during quarry reclamation. Discharge for the water that enters all seven caves rises some 15–20 km to the west at the large springs along the coast.

Connections between the caves and the surface are limited in the karst of west-central Florida. Many caves in the Brooksville Ridge, including four of the caves in this study (BRC, Big Mouth, Morris, and Werner), had no known human scale entrance prior to lime-rock mining. In fact, most air-filled caves that are known in the karst of west-central Florida were discovered by human alteration of the land, in particular limestone quarries that excavate to the level of the cave passages. The subdued topography of Florida contributes to the lack of entrances by restricting the natural intersection of the land surface with the horizontal cave passages. The implication is that there are many more caves in west-central Florida than are currently known. The burgeoning sinkhole insurance industry in Florida is a manifestation of this fact.

Surveyed passages within the air-filled caves of west-central Florida do not extend long distances. Tabular passages pinch into low cavities. Fissure-type passages thin into increasingly-narrowing fractures. Quaternary-age siliciclastic sediments and structural collapse features are pervasive, and further segment the caves. The connections between human scale passages at the same level, therefore, are small, and additional exploration requires excavation by dedicated cavers (Turner, 2003). Vertical exploration in the caves is achieved where structural collapse features or solution-enlarged fractures connect multiple levels (Fig. 4).

**POSSIBLE HYDROLOGIC IMPLICATIONS**

Data from the air-filled caves in the Brooksville Ridge of west-central Florida contradict the notion of an integrated network of conduits above the modern water table. If the observations from this study are representative of conditions below the present water table, then connectivity between input and output points within the Upper Floridan Aquifer may be limited.

It also appears that caves in west-central Florida do not follow the sinking stream-spring model so widely accepted by karst scientists who study the ancient limestones of the midcontinent. Rather, water in the karst aquifers of west-central Florida may travel through a maze of passages, fractures, sediment fills, and rock matrix at several horizons.

Available data support this conjecture of multi-level discontinuous mazes. For instance, maps of underwater caves reveal passages throughout west-central Florida that occur at specific depths up to 120 m below the water table (Florea and Vacher, in review). Furthermore, Quaternary-age siliciclastic sediments infiltrate these underwater caves, and these sediments are commonly recovered from cavities encountered during well construction (e.g., Hill and DeWitt, 2004).
Disjunct or occluded underwater passages in the Upper Floridan Aquifer would impede ground-water flow, resulting in higher elevations of the water table and steep hydrologic gradients. These are both observed within the karst of west-central Florida. As one example, a regional, finite-difference ground-water model that includes the northern portions of the Brooksville Ridge, developed for the Southwest Florida Water Management District by GeoTrans (1988), concluded that model calibration to known elevations of the water table is possible only if fractures or solution features are not regionally extensive or hydraulically connected. If the opposite case were true (i.e., if solution features were regionally extensive or hydraulically connected), the gradient of the water table would reduce to near-zero and the elevation of the water table would equilibrate near sea level. The coastal, carbonate aquifers in the Yucatań Riviera of Mexico, with more than 400 km of mapped underwater cave and water-table gradients of less than 0.00001 (Worthington et al., 2000), illustrates this possibility. This hydrogeologic contrast between the great peninsulas of Florida and Yucatań, and its relation in part to the presence of infiltrating clastics in the case of Florida, was pointed out more than 30 years ago by Back and Hanshaw (1970).

CONCLUDING REMARKS

This study of air-filled caves in the Brooksville Ridge of west-central Florida offers an improved understanding of cave-scale porosity in the Upper Floridan Aquifer. How does the architecture of these caves compare with that of other cave systems? It is instructive to review summaries from two contrasting geologic settings, the caves of ancient low-permeability limestones of the midcontinent (Palmer, 2003) and the caves of small islands composed of Pleistocene limestone (Mylroie et al., 1995).

The first example, the caves of the mid-continent, is important because it is the paradigm view of near-surface caves. Palmer (2003, p. 2) uses the following description for such caves:

Most accessible caves are surrounded by rock in which the vast majority of openings have hardly enlarged at all. The conduits are not surrounded by porous zones, with walls like a sponge, where progressively smaller openings extend indefinitely into the cave wall. The conduits are quite discrete.

Cave passages in the young carbonates of west-central Florida do not fit this description. Tabular passages are laterally extensive, and fissure-type passages thin into increasingly narrowing fractures; both extend beyond the limits of human exploration. The walls of the passages are porous and complex, with small-scale solution features such as pockets and tafoni structures extending into the host bedrock, which itself has high permeability. Cave passages in the Brooksville Ridge are not discrete conduits, and they do not connect together into a dendritic-style drainage system as described by Palmer (1991). Ground
water in the Upper Floridan Aquifer may readily exchange between the cave and the rock matrix (Martin and Dean, 2001).

The second example, from the young carbonate islands, is important because it is the paradigm for caves in young limestone. These flank margin caves, which form by mixing at the water table and at the freshwater-saltwater interface, are summarized as follows by Mylroie and Carew (1995, p. 252-253):

Typically these caves are dominated by large globular chambers that are broad in the horizontal plane but vertically restricted...At the rear of the chamber there is usually a series of smaller chambers that change into tubular passages...Commonly there are many cross-connections between adjacent chambers and passages that give the caves a maze-like character. The passages...end abruptly. The chamber and passage walls are often etched into a variety of dissolution pockets and tubes...Flow markings, such as ablation scallops, are absent.

Many of the features found in the caves of the Brooksville Ridge are remarkably similar to this description. Laterally extensive cavities contain bedrock pillars and cuspat e dissolution features, and the passages often terminate in blind pockets. Flow indicators are generally not present. However, there are distinct differences between caves of west-central Florida and caves on young, carbonate islands. Whereas flank margin caves, for example, are composed of amorphous voids and rudimentary, sponge work mazes (Palmer, 1991), the caves in west-central Florida contain passages with a sense of directionality imposed by fractures in the rock matrix. The result is maps that resemble network maze caves in plan view, such as those in the Black Hills of South Dakota (Palmer, 1991).

In conclusion, caves in west-central Florida do not fit existing models of cave architecture. They represent a style of cavern development important within coastal karst aquifers composed of young carbonates.

These west-central-Florida caves that lie above the water table demonstrate the extreme heterogeneity of permeability within the unconfined Upper Floridan Aquifer that lies below. This study offers the following insights to the architecture of cave-scale porosity in this critical-use aquifer: 1) cave-scale porosity is widespread but often composed of isolated or partially connected passages; 2) cave passages are generally restricted to specific elevations within the aquifer framework, and 3) the direction of cave passages in these levels occurs along a NE-SW and NW-SE system of fractures.

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