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

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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 semi-confined 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

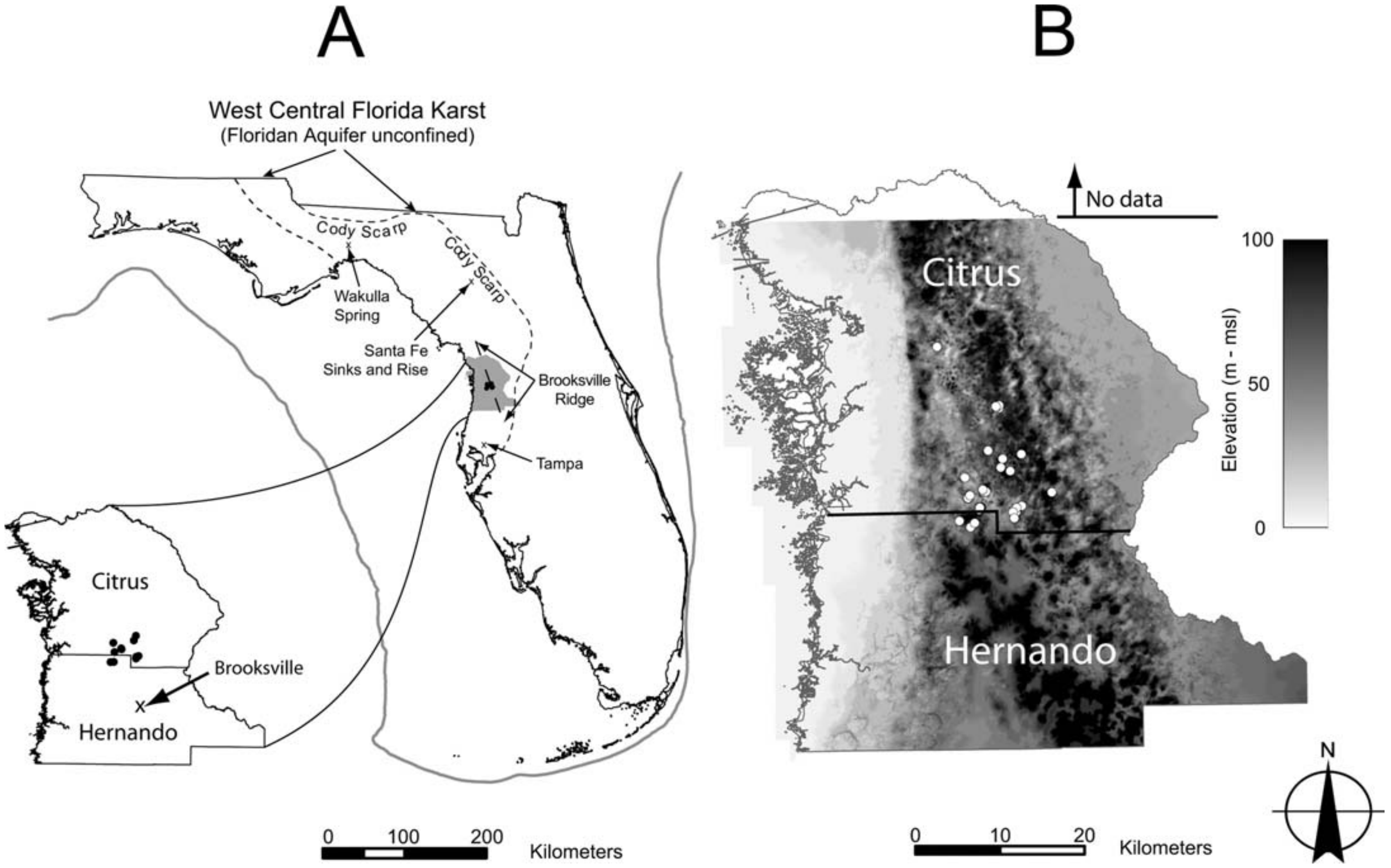

Figure 1. Data locations and topographic elevations. A) The grey line surrounding Florida is the –120 m bathymetric contour on the continental shelf. Inset is included for Citrus and Hernando Counties. Air-filled caves surveyed in this study are indicated by black dots. An "x" indicates the location 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.

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.

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.

Figure 2. Gentle rolling topography of the Brooksville Ridge near the city of Brooksville. An upland mesic-hardwood hammock is visible in the background. The foreground is a sinkhole lowland (photo by author).

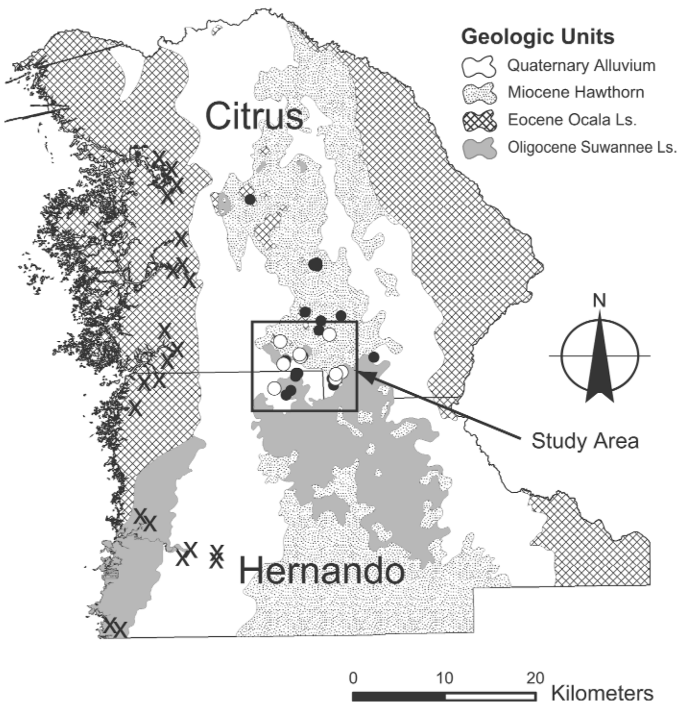

Figure 3. Geologic map of Citrus and Hernando Counties. Geologic units generally dip and thicken to the south. The Miocene Hawthorn Group is thin to non-existent in northern Hernando and southern Citrus Counties. The Oligocene Suwannee Limestone occupies only the topographic highs in the study area.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

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 $10^{-12.7}$ m^2, which compares to an estimated value of $10^{-17.7}$ m^2 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. Air-filled 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.

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

Table 1. Caves surveyed in this study.

Cave Name	County	Length (m)	$n_{(sta)}$[a]	$n_{(az)}$[b]
Big Mouth Cave	Citrus	96	13	14
Blowing Hole Cave	Citrus	257	50	54
BRC Cave	Hernando	1,033	276	281
Football Cave	Citrus	142	29	31
Legend Cave	Citrus	44	12	12
Morris cave	Citrus	92	12	13
Werner Cave	Citrus	561	105	115
Totals		2,225	497	520

[a] Number of survey stations.
[b] Number of azimuth readings.

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 Figure 4. Of the caves surveyed, BRC Cave is by far the longest with more than a kilometer of mapped passage

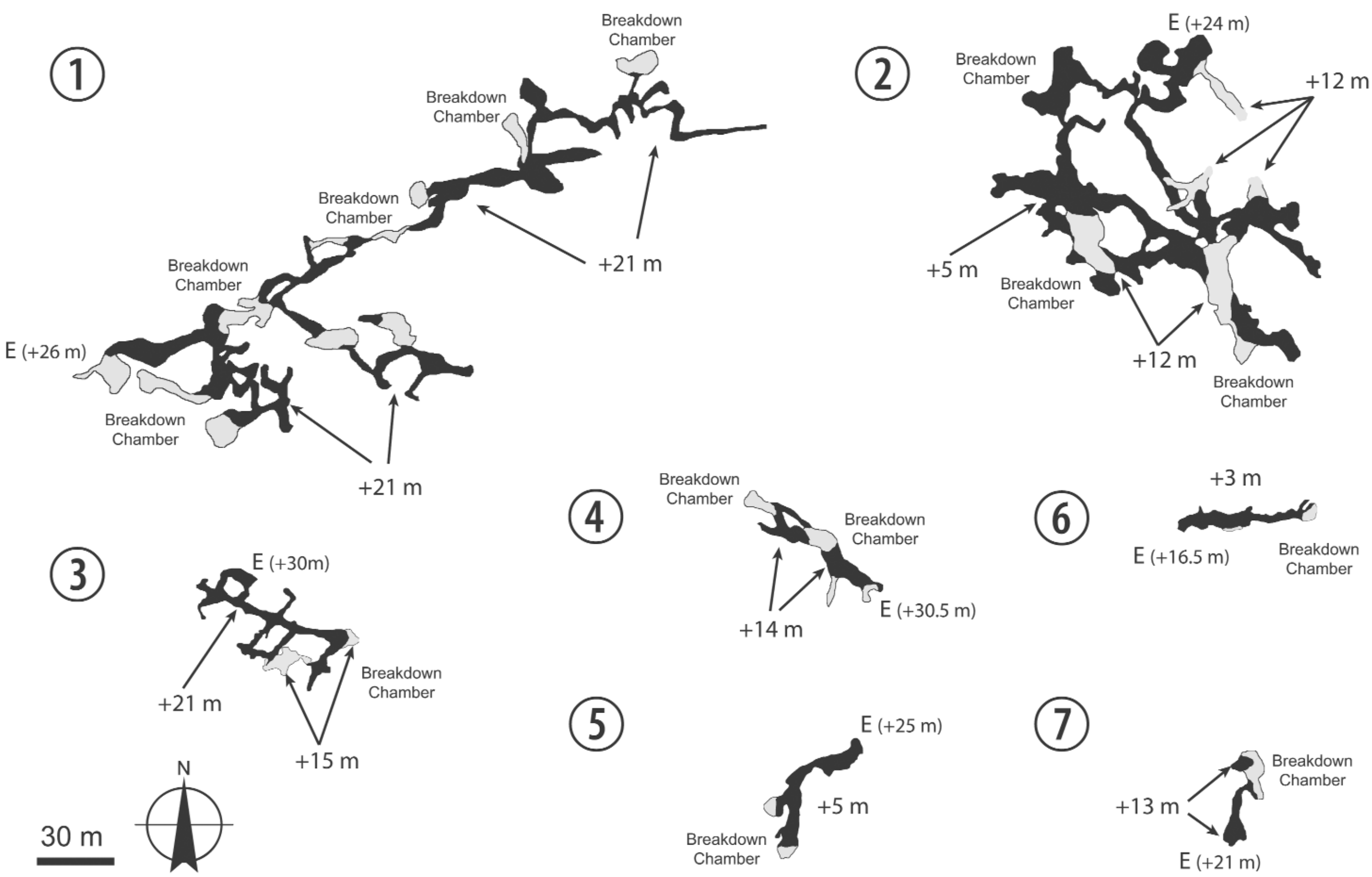

Figure 4. Index maps from air-filled caves surveyed during this study. 1 – BRC Cave, 2 – Werner Cave, 3 – Blowing Hole Cave, 4 – Football Cave, 5 – Big Mouth Cave, 6 – Morris Cave, 7 – Legend Cave. The cave passages occur on distinct levels. For instance, Werner Cave, Big Mouth Cave, and Morris Caves 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.

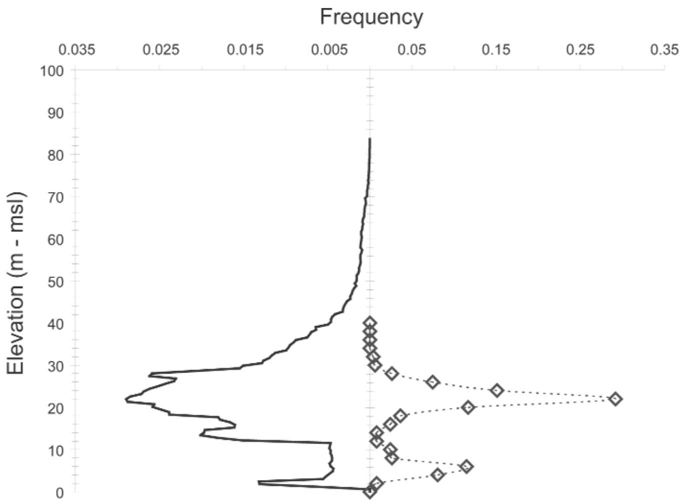

Figure 5. Frequency of data of land elevations in Citrus-Hernando Counties (left) compared to elevations of cave-survey stations in this study (right). Modes in the cave-survey data correspond with modes in the elevation data set from Citrus and Hernando Counties and with known marine terraces.

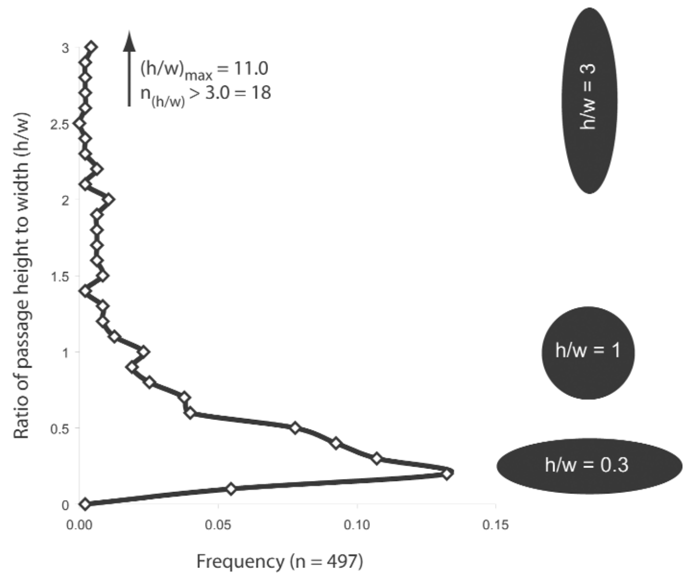

Figure 6. Frequency of passage height-width ratios at all survey stations in this study. Almost 15% of measured passages are more than four-times wider than they are tall, and 47% of measured passages are more than twice as wide as they are tall.

(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 lime-rock quarry. Werner, Big Mouth, and Morris Caves did not have natural entrances. Rather, a quarry operation intersected structural collapses within the cave.

Figure 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 Figure 1B. Figure 6 presents a frequency plot of passage dimensions. Figure 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.

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 Figure 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

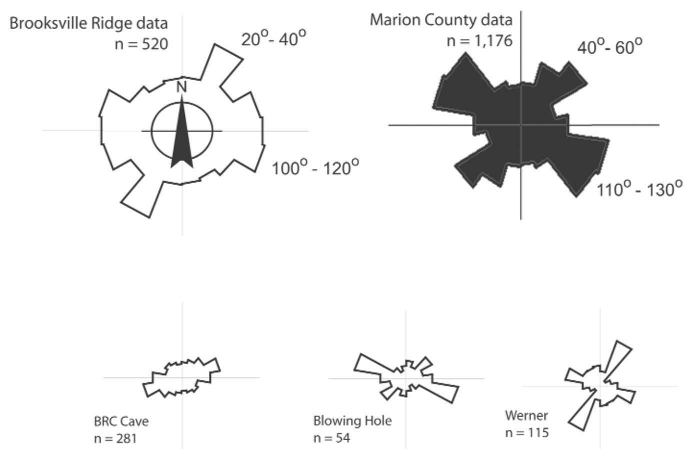

Figure 7. Length-weighted rose diagrams for the orientation of all segments of cave survey obtained during this study and from 14 caves in Marion County to the north and east of the study area. The data from this study reveal a regional WNW-ESE (100°-120°) and NNE-SSW (20°-40°) pattern of passages similar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

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).

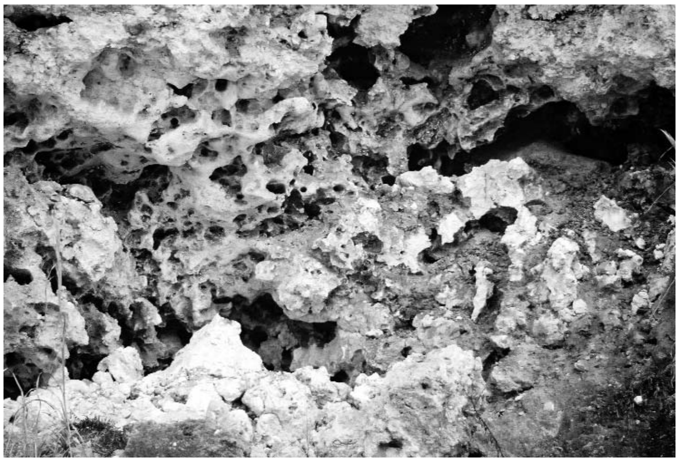

Figure 8. Spongework-like features present in the walls of an exposed cavity in the Haile Quarry near Gainesville, Florida. Height of cavity is approximately 40 cm (Figure 12 of LaFrenz *et al.*, 2003).

Observations from quarry highwalls 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 Figure 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 Figure 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.

Figure 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 (Figures 5a and 9 of LaFrenz *et al.*, 2003).

Figure 10. Breakdown chamber in Werner Cave. Such collapse features are common in the caves of the study area. Main level of passages is approximately 3 m below the top of the breakdown (photo by Tom Turner).

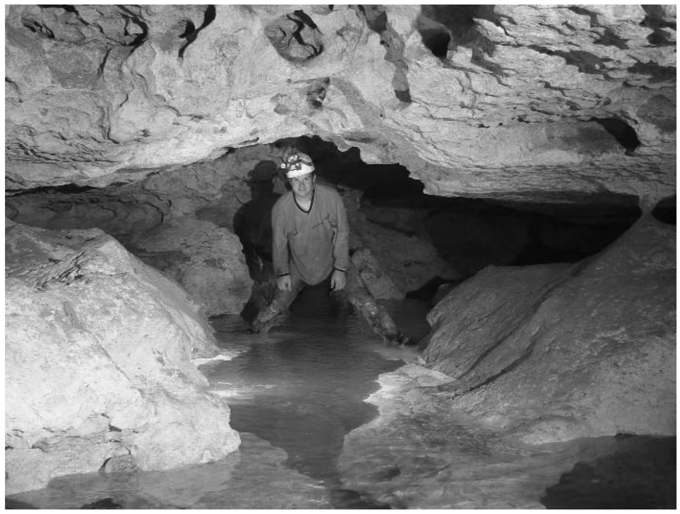

Figure 11. Plus-sign passage in Roosevelt Cave in Marion County, Florida. Note that the vertical extension of the passage visually correlates to a fracture. Also note the laterally continuous horizon of passage approximately 1 m above the water table (photo by Sean Roberts).

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).

PASSAGE DIRECTIONALITY

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.

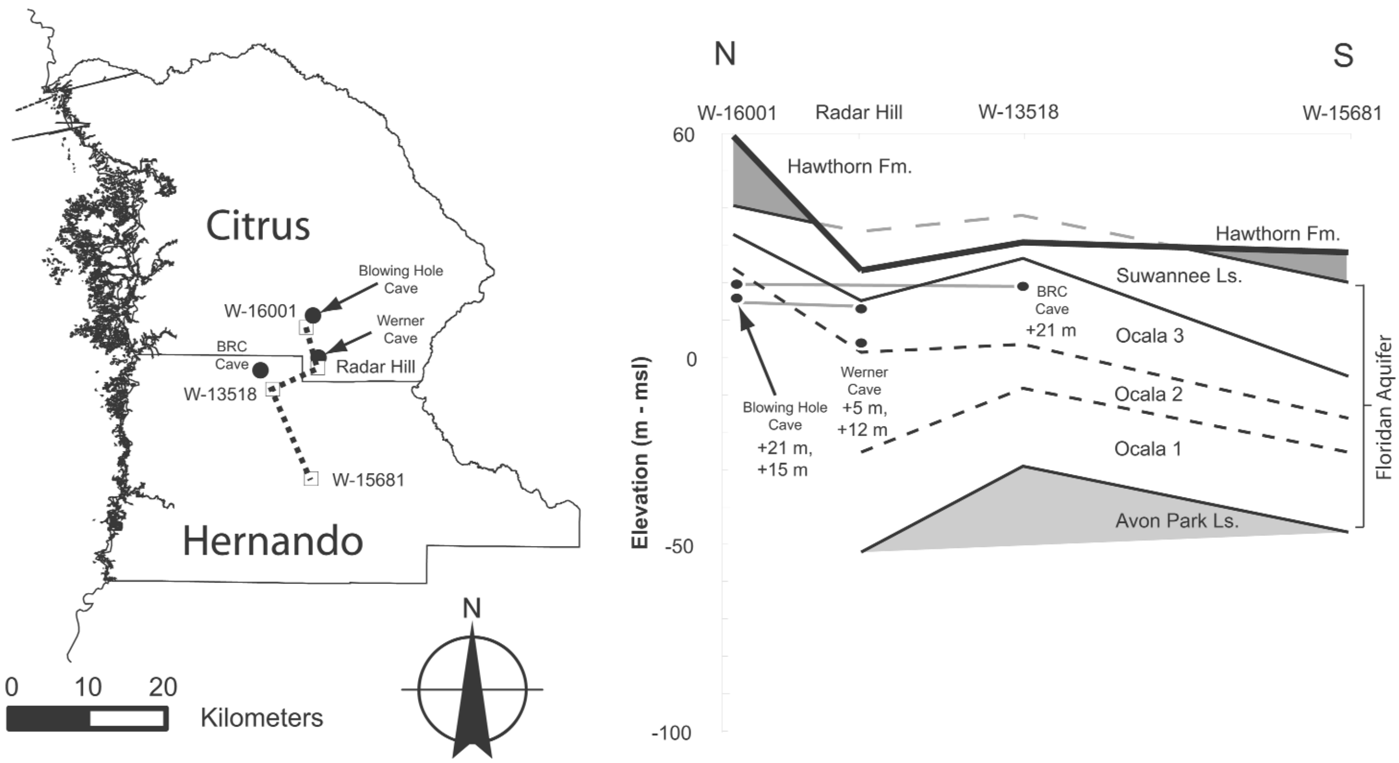

Figure 12. North-south cross-section through the study area in the Brooksville Ridge. Dashed line on the map at left indicates the location of the cross-section. White squares are the wells used for lithologic identification. Black dots are the caves from this study near the line of cross-section. Note that the levels within these caves do not occur in the same geologic units throughout the study area.

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 10^5 times more permeable than the ancient limestones of the mid-continent. 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 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 lime-rock 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 mid-continent. 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 mid-continent (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 cuspate 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, spongework 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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REFERENCES

Back, W., and Hanshaw, B.B., 1970, Comparison of chemical hydrology of the carbonate peninsulas of Florida and Yucatan: Journal of Hydrology, v. 10, pp. 330–368.

Brinkmann, R., and Reeder, P., 1994, The influence of sea-level change and geologic structure on cave development in west-central Florida: Physical Geography, v. 15, p. 52–61.

Budd, D.A., and Vacher, H.L., 2004, Matrix permeability of the confined Floridan Aquifer: Hydrogeology Journal, v. 12, no. 5, 531–549.

Cooke, C.W., 1945, Geology of Florida: Florida Geological Survey Bulletin 29, 339 p.

Florea, L.J., and Vacher, H.L., in review, Quaternary cave levels in peninsular Florida: Quaternary Science Reviews.

Ford, D.C., and Williams, P.W., 1989, Karst geomorphology and hydrology, Unwin Hyman, London, 601 p.

GeoTrans, 1988, Hydrologic investigation of the northern portion of the Southwest Florida Water Management District, northern district model project, phase II final report: 151 p.

Granger, D.E., Fabel, D., and Palmer, A.N., 2001, Plio-Pleistocene incision of the Green River, Kentucky determined from the radioactive decay of cosmogenic ^{26}Al and ^{10}Be in Mammoth Cave sediments: GSA bulletin, v. 113, no. 7, p. 825–836.

Healy, H.G., 1975, Terraces and Shorelines of Florida: Florida Bureau of Geology Map Series 71.

Hill, M.E., and DeWitt, D.J., 2004, Drilling and Testing Report for the ROMP WW-2 and WW-3 Monitoring Well Sites, Hernando County, Florida: Southwest Florida Water Management District, 12 p.

Hill, C.A., 1987, Geology of Carlsbad Caverns and other caves in the Guadalupe Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 117, 150 p.

LaFrenz, W.B., Bulmer, W.H., Jamilla, S.V., and O'Neal-Caldwell, M., 2003, Characteristics and development of shallow solution features in thinly mantled karst, Alachua and Levy Counties, Florida: *In* Florea, L., Vacher, H.L., and Oches, E.A., *eds*. Karst Studies in West Central Florida: USF Seminar in Karst Environments, Southwest Florida Water Management District, p. 21–37.

Lane, E., 1986, Karst in Florida: Florida Geological Survey Special Publication no. 29, 100 p.

Littlefield, J.R., Culbreth, M.A., Upchurch, S.B., and Stewart, M.T., 1984, Relationship of Modern Sinkhole Development to Large-Scale Photolinear Features: *In* 1st Multidisciplinary Conference on Sinkholes, Beck, B.F., *ed*., p. 189–195.

Loizeaux, N.T., 1995, Lithologic and hydrogeologic framework for a carbonate aquifer: evidence for facies-controlled hydraulic conductivity in the Ocala Formation, West-Central Florida: [MS Thesis] University of Colorado, Boulder, Colorado, 125 p.

Loper, D.E., Werner, C.L., Chicken, E., Davies, G., and Kincaid, T., 2005, Coastal carbonate aquifer sensitivity to tides: EOS Transactions, American Geophysical Union, v. 86, no. 39, p. 353, 357.

Martin, J.B., and Dean, R.W., 2001, Exchange of water between conduits and matrix in the Floridan aquifer: Chemical Geology, vol. 179, p. 145–165.

Meinzer, O.E., 1927, Large springs in the United States: United States Geological Survey Water Supply Paper 557, United States Geological Survey.

Miller, J.A., 1986, Hydrogeologic Framework of the Floridan Aquifer System in Florida and in Parts of Georgia, Alabama, and South Carolina: United States Geological Survey Professional Paper 1403-B, 91p.

Mylroie, J.E., Carew, J.L., and Vacher, H.L., 1995, Karst development in the Bahamas and Bermuda: *In* Curran, H.A. and White, B., *eds*. Terrestrial and shallow marine geology of the Bahamas and Bermuda, Geological Society of America Special Paper, Boulder, Colorado, v. 300, p. 251–267.

Palmer A.N., 2003, Patterns of dissolution and porosity in carbonate rocks: Speleogenesis and Evolution of Karst Aquifers, v. 1, p. 1–9.

Palmer, A.N., 2002, Karst in Paleozoic rocks: How does it differ from Florida? *In* Hydrogeology and Biology of Post Paleozoic Karst Aquifers, Martin, J.B., Wicks, C.M., and Sasowsky, I.D., *eds*., Karst Frontiers, Proceedings of the Karst Waters Institute Symposium, p. 185–191.

Palmer A.N., 2000, Hydrogeologic control of cave patterns: *In* Klimchouk, A., Ford, D., Palmer, A., and Dreybrodt, W., *eds*. Speleogenesis: evolution of karst aquifers, National Speleological Society, p. 77–90.

Palmer, A.N., 1991, Origin and morphology of limestone caves: Geological Society of America Bulletin, v. 103, p. 1–21.

Palmer, A.N., 1987, Cave levels and their interpretation: National Speleological Society Bulletin, v. 49, p. 50–66.

Rosenau, J.C., Faulkner, G.L., Hendry Jr., C.W., and Hull, R.W., 1977, Springs of Florida, Florida Geological Survey Bulletin 31 (Revised).

Scott, T.M., Campbell, K.M., Rupert, F.R., Arthur, J.A., Missimer, T.M., Lloyd, J.M., Yon, J.W., and Duncan, J.G., 2001, Geologic map of the State of Florida: Florida Geological Survey Map Series 146.

Scott, T.M., 1988, The Lithostratigraphy of the Hawthorn Group (Miocene) of Florida: Florida Geological Survey Bulletin 59, 148 p.

Scott, T.M., Means, G.H., Meegan, R.P., Means R.C., Upchurch, S.B., Copeland, R.E., Jones, J., Roberts, and T., Willet, A., 2004, Springs of Florida, Florida Geological Survey Bulletin 66, 377 p.

Stringfield V.T., and LeGrand, H.E., 1966, Hydrology of Limestone Terranes in the Coastal Plain of the Southeastern United States: Geological Society of America Special Paper 93, 41 p.

Tihansky, A.B., 1999, Sinkholes, West-Central Florida: *In* Land Subsidence in the United States, Galloway D., Jones, D.R., and Ingebritsen S.E, *eds*., United States Geological Survey Circular 1182, 177 p.

Turner, T., 2003, Brooksville Ridge Cave: Florida's Hidden Treasure: NSS News, May 2003, p. 125–131, 143.

Upchurch S.B., 2002, Hydrogeochemistry of a karst escarpment: *In* Hydrogeology and Biology of Post Paleozoic Karst Aquifers, Martin, J.B., Wicks, C.M., and Sasowsky, I.D., *eds*., Karst Frontiers, Proceedings of the Karst Waters Institute Symposium, p. 73–75.

Vacher, H.L., Hutchings, W.C., and Budd, D.A., 2006, Metaphors and Models: The ASR Bubble in the Floridan Aquifer: Ground Water, v. 44, n. 2, p. 144–152.

Vernon, R.O., 1951, Geology of Citrus and Levy Counties, Florida: Florida Geological Survey Bulletin 33.

White, W.A., 1970, The Geomorphology of the Floridan Peninsula: Florida Bureau of Geology Bulletin 51.

White, W.B., 1988, Geomorphology and Hydrology of Karst Terrains, Oxford University Press, New York, 464 p.

Worthington, S.R.H., Ford, D.C., and Beddows, P.A., 2000, Porosity and permeability enhancement in unconfined carbonate aquifers as a result of solution. *In* Klimchouk, A., Ford, D., Palmer, A., and Dreybrodt, W., *eds*. Speleogenesis: Evolution of karst aquifers, National Speleological Society, p. 463–472.

Yon, J.W., and Hendry, C.W., 1972, Suwannee Limestone in Hernando and Pasco counties, Florida; part I: Florida Bureau of Geology Bulletin 54, p.1–42.

Yon, J.W., Waite, W.R., and Williams, C.T., 1989, Part II – Geology, Mining, and Reclamation at the Radar Hill Quarry, Citrus County, Florida: Florida Geological Survey Information Circular 105, p. 36–51.