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Caves and Karst of West-Central Florida

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matrix. It is therefore becoming clear to hydrogeologists and water resource managers that large springs like Wakulla, rather than wells, provide the best means of sampling the water quality of an aquifer, because their discharge represents a composite of all water sources in the basin.

Cave and Spring Protection

The Woodville Karst lies just south of the growing city of Tallahasee, which not only uses the spring water but also contributes to its pollution. A 10-year decline in water quality at Wakulla Spring and in the ecological health of the spring basin (Chelette et al., 2002) has fostered efforts to protect the spring from further degradation. Part of this attention has focused on revising the zoning ordinances, regulations on development, and management practices. In this context, the most important aspects of protecting the spring should center on a determination of where and how water is recharged within the springshed and how a given development will likely impact the quality and mechanism of that recharge.

Recent strides taken by local municipalities to protect Wakulla Spring include (1) initiating the development of an advanced wastewater treatment facility for the City of Tallahassee to remove nitrate prior to discharging treated sewage to the land surface, where it recharges the Floridan aquifer; (2) halting fertilizer use by government entities in rights-of-way within the unconfined region of the aquifer; (3) delineation of the "Wakulla Springs Protection Zone" (WSPZ), in which zoning ordinances prohibit or restrict potentially harmful land use; and (4) requirements of advanced septic systems in all new development in the WSPZ. These are important steps toward protecting Wakulla Spring and north Florida's groundwater resources, and they have been possible only through recognizing the important role of caves and conduits in groundwater hydrology.

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Caves and Karst of West-Central Florida

Lee J. Florea, David Budd, and Robert Brinkmann

THE REAL west-central Florida is far from the "Sunshine State" image of white sand beaches and palm trees. Gently rolling hills, dense jungle-like forests, pine and palmetto scrublands, impenetrable cypress swamps, and alligator-laden rivers are more common. Numerous crystal-clear springs offer a glimpse of the hidden world below – a world that could challenge the most imaginative Disney artists (Fig. 6.17).

Stratigraphic Framework

In this region, Eocene and Oligocene limestones of the Floridan aquifer are at or very near the land surface (Fig. 6.18). The karst area described here borders the Gulf of Mexico and extends more than 200 km from the Suwannee and Santa Fe Rivers in the north to Tampa in the south.

The thickness of the Floridan aquifer generally increases to the south from 60 to 1070 m and averages 600 m thick in west-central Florida. In peninsular Florida and south Georgia the stratigraphic units within the aquifer are the Middle Eocene Avon Park Formation, the Late Eocene Ocala Limestone, and the Early Oligocene Suwannee Limestone (Miller, 1986; Fig. 6.18). Regionally these stratigraphic names vary along the northern outcrop. Where it is most permeable, the Tampa Limestone member of the Arcadia Formation (in the Miocene Hawthorne Group), caps the aquifer. Most of the karst features in the aquifer are in the Suwannee and Ocala Limestones, particularly where they are unconfined (Florea, 2006). The older Avon Park, in contrast, has a very limited outcrop area and it contains few known caves aside from bit drops in drilled wells.

The Ocala Limestone was deposited on a low-sloping carbonate ramp during a 3-million year period of the Late Eocene (Loizeaux, 1995). It contains three depositional sequences 12 to 35 m thick, dominated by a granular texture. Each sequence is bounded by a transgressive surface. Fossils are diverse and indicate open marine conditions. The large sea-floor foraminifera *Nummulites* and *Lepidocyclina* dominate, with other common organisms including bryozoa, mollusks, large echinods, some red algae, and rare solitary corals. The Suwannee Limestone was deposited on a carbonate platform in open-marine, relatively shallow, wave-swept settings. Grainstones are dominant, with individual units up to 30 m thick. Fossils are diverse and dominated by bryozoa, red algae, foraminifera, mollusks, and echinods.

Subaerial exposure surfaces, indicating periods of lower sea level, are common in the limestones of Florida, as are paleokarst features associated with them. Eocene paleokarst includes cave-filling breccia encountered in cores through the Avon Park (Budd, 2001). Similar records of exposure and erosion, as shown by unconformities, occur at the top of the Ocala

Figure 6.17: Diver Mark Long enters the main vent of Silver Springs, near Ocala. On this dive he collects water samples and measures flow velocity for the St. Johns Water Management District as part of the largest sampling and survey project conducted in the region. Rapid declines in water quality and native river vegetation are of concern. Photo by Jill Heinerth (*www.IntoThePlanet.com*).

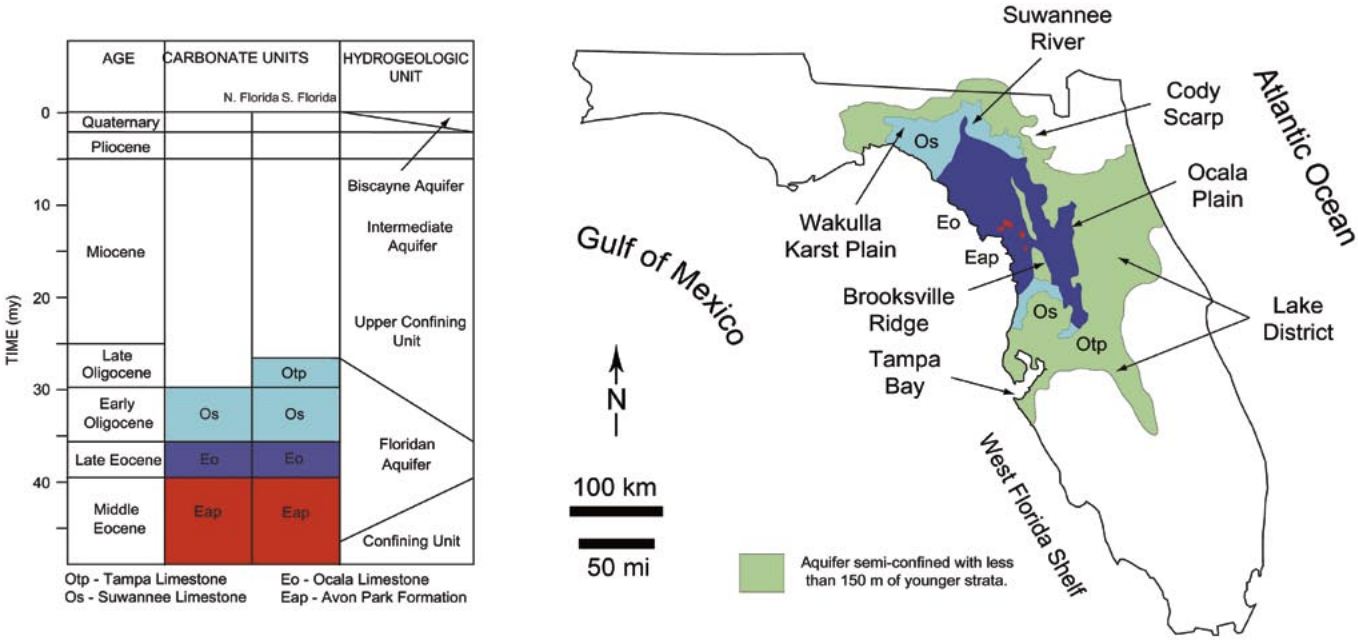

Figure 6.18: Generalized stratigraphy and outcrop map of the Floridan aquifer in west-central and north-central Florida.

and Suwannee Limestones, specifically on the depositional highs of the Peninsular Arch and Ocala Platform (Florea, 2006; Budd et al., 2002; Yon and Hendry, 1972). The mid-Oligocene unconformity at the top of the Suwannee Limestone is particularly interesting, as it marks the end of 100 million years of nearly continuous carbonate deposition on the Florida peninsula, except for the Quaternary Biscayne aquifer in southeast Florida (see next section) and reefs that compose the Florida Keys. Where the Suwannee is confined in south Florida, the exposure surface is marked by rhizoliths (fossilized roots), caliche, karst breccia, red-stained surfaces, limestones altered by soil processes, infiltrated sediment, and microkarst (Budd et al., 2002). On the depositional high of the Ocala Platform, late Oligocene and early Miocene paleokarst take the form of large sinkholes filled with Miocene sediments (Yon and Hendry, 1972) that feature extensive paleontological remains of vertebrates 24-29 Ma in age. These fossil remains include large terrestrial herbivores and smaller trogloxenes, such as bats (Morgan and Czaplewski, 2003).

In fact, several generations of Miocene and younger karst features are present in the southeastern United States. The origin of these paleokarst features is tied to the complex sea level history during the past 30 million years. Younger sediments fill many of the older features. Others remain open as caves. Deciphering the multigenerational history of Florida karst is a complex undertaking and is far from complete (Florea et al., 2007).

Figure 6.19: Sinkhole at Winter Park, Florida, near Orlando, which formed catastrophically in one day in 1981 (U.S. Geological Survey photo).

Sinkholes

The inelegant and unspecific term "sinkhole" is a vexing term used by the American public to refer to any subsidence- or collapse-related feature, regardless of origin. In Florida, the term extends beyond public perception, because it has become a legal definition: "…a landform created by subsidence of soil, sediment, or rock as underlying strata are dissolved by groundwater. A sinkhole may form by collapse into subterranean voids created by dissolution of limestone or dolostone or by subsidence as these strata are dissolved" (Florida Statute 627.706). This definition of sinkholes established by Florida law has led to mandatory sinkhole insurance coverage on all homes. Florida is the only state in the U.S. to require it.

This legislation was prompted by frequent catastrophic collapses. The most famous example is the Winter Park Sink, which swallowed an entire city block in the city of Orlando in 1981 and destroyed a car dealership and a public swimming pool (Fig. 16.19).

Such dramatic collapses in Florida include two main categories: ***cover-collapse*** and ***cover-subsidence*** sinkholes (Tihansky, 1999). Their number and types depend on the thickness of surficial sands and clays deposited during the past 25 million years that cover the limestones in many areas. Where this cover is thick, the Floridan aquifer is confined (as in parts of northern and southern Florida), and caves and karst are limited. Where the layer is only a thin veneer, as in west-central Florida, the result is a covered-karst terrane (Upchurch and Randazzo, 1997). ***Cover-subsidence sinkholes*** form when surficial sediments rich in sand trickle into cavities, like sand in an hourglass, gradually forming a depression at the surface. ***Cover-collapse sinkholes***, in contrast, form when the surficial sediments contain a large amount of clay. The clay binds the soil so that it can bridge small cavities, but not large ones. Collapse into large cavities, as at the Winter Park Sink, can be sudden and even catastrophic, consuming everything on the surface in a matter of minutes.

Although cover-collapse sinkholes can be devastating, the cumulative effects of cover-subsidence sinkholes pose a much greater economic risk to urban planners, developers, homeowners, and insurance companies (Scheidt et al., 2005). Surficial sediments often obscure the presence of cavities at depth. For instance, studies of a plot of land on the campus of the University of South Florida, in Tampa, show that the density of

possible cavities is on roughly one feature per 625 m^2 (25 x 25 m) of land surface (Parker, 1992). That translates to approximately 256 features for this plot of land the size of a city block, although only two sinkholes are visible at the surface. Many sinkholes have been obscured due to modern development. For example, in Pinellas County, it is estimated that 87% of the depressions identified on 1926 aerial photographs were covered or modified by 1995 (Brinkmann et al., 2007).

Because of the non-specific language in Florida law and the inherent difficulty of seeing the underlying cause of subsidence, the public and media assume a geological origin even though there are several anthropogenic causes. For example, it is common for depressions to result from breaks in water pipes or collapse of old sewer lines. In addition, depressions can form as the result of poor construction or site-development practices in urban areas.

Sinkholes and related phenomena caused more than $100 million in structural damage in Florida in 1997, and damage estimates increase every year in part because of population growth and urbanization. In 2006, many homeowners saw their property insurance rates triple, with promises of more increases to come. Many insurers ceased writing homeowner policies in the state, leaving many with a state-funded, high-risk insurer of last resort, Citizen's Insurance. Sinkhole insurance claims by Citizen's Insurance rose from 9 in 2002 to 632 in 2005. In the first half of 2006 alone they received 432 claims (Florida Office of Insurance Regulation, 2006). Reflecting this trend are the growth and number of engineering and consulting companies established solely for evaluation and intervention related to sinkhole damage. Also, there is an increase in the number of law firms that specialize in sinkhole claims. The direct threat to personal property caused by sinkholes in Florida drives a high level of government and public interest in karst processes.

Insurance claims must be backed by evidence that sinkhole damage had natural causes. Geophysical investigations seem to provide the best evidence. In the case of dramatic cover-collapse sinkholes, these investigations are simple and the cause for karst activity is obvious. On the other hand, the vast majority of damage is caused by the subtler cover-subsidence sinkholes. In these cases, the ground motion is imperceptibly slow, and damage takes the subtle form of cracks in walls or foundations, doors that will not close, or even floors that are no longer level. In these situations, more detailed fieldwork and geophysical surveys are required. Most popular are shallow seismic techniques, electrical resistivity (Dobecki and Upchurch, 2006), and ground-penetrating radar (Kruse et al., 2006).

Brooksville Ridge – the Florida High Country

Most people consider Florida to be flat, and by many standards this is valid. But there is some topography. The most prominent topographic feature in west-central Florida is the Brooksville Ridge. This 100-km-long chain of hills rises to more than 70 m (Fig. 6.20). They rise in several steps – marine terraces – above the coastal lowlands. The Brooksville Ridge contains many of the highest points in Florida and is a focus for much cave exploration.

The surficial sediments, so common elsewhere, are absent from much of the Brooksville Ridge. In the uplands, the Ocala and Suwannee Limestones are exposed in a series of rocky live-oak hammocks. The ridge roughly follows the axis of the Ocala Platform, historically called the "Ocala Uplift," which is not a true structural arch, but rather a feature produced either by thickening of the Middle Eocene carbonates (Winston, 1976) or by the thinning of Late Eocene and younger carbonates during subaerial exposure and erosion (Florea, 2006).

Archaeological and paleontological research in the Brooksville Ridge has uncovered a wealth of data. Collapsed caves and vertical-walled solution tubes were perfect traps for artifacts from Native American inhabitants and for ice-age bones. For example, Sabertooth Sink and Iron Ladder Cave, excavated in the 1940s, yielded bones of fossil mammals including Smilodon, the huge Pleistocene sabertooth cat (Holman, 1958).

Caves and karst of the Brooksville Ridge have seen ecological investigations for more than a century. In 1894, noted entomologist H. G. Hubbard collected troglobitic crayfish from Sweetgum Cave. This collection now resides in the Smithsonian Institute in Washington, D.C. Sweetgum Cave is the only known location of the Withlacoochee light-fleeing crayfish (*Procambarus lucifugus lucifugus*).

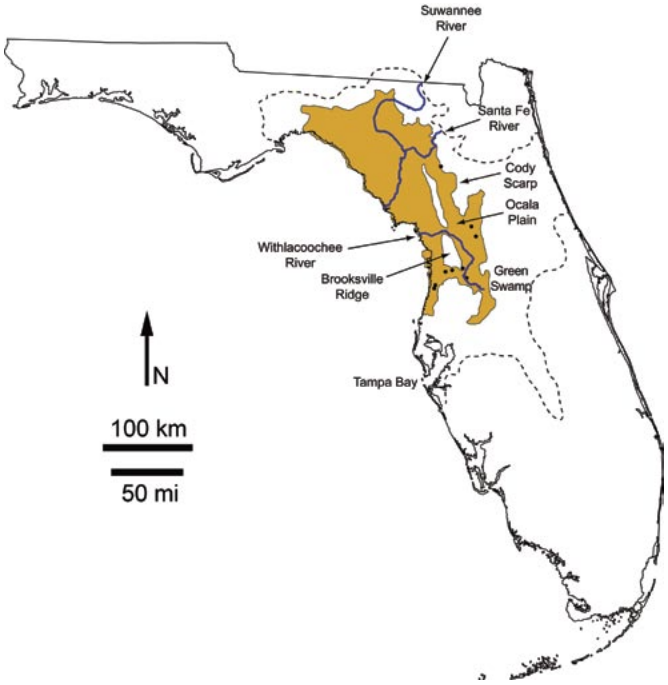

Figure 16.20: Location of features described in this section. The region within the dashed line is semiconfined by less than 150 m of Miocene and younger rocks that are mainly insoluble. The yellow region shown here indicates where the Floridan aquifer is unconfined. Black dots are caves.

In 1934, J. K. Small, the first Curator of Museums at the New York Botanical Gardens, explored the microclimates of cave entrances and sinkholes in the Brooksville Ridge for new species of ferns. Several that he identified are listed as rare or endangered. Today the ridge continues to serve as a natural time capsule for the natural history of central Florida. The Florida Division of Forestry currently owns and manages a large portion of the Brooksville Ridge as the Withlacoochee State Forest. The rest is used for pastures and limestone quarries.

Limestone Quarries – Portals into Crystal Palaces

Since the late nineteenth century, the Brooksville Ridge region has been heavily exploited for its easily mined limestone. While limestone quarries permanently scar the natural landscape, these operations have been instrumental in the discovery of many of the significant dry cave systems in west-central Florida. Of the caves that we have surveyed, as well as all others in the region whose maps are in the Florida Cave Survey archives, no cave passages have been intersected by the surface. Some entrances are natural fissures that intersect the cave below; but many other cave entrances are exposed in the walls of limestone quarries.

Brooksville Ridge Cave is the best and most widely known example of a cave with a man-made entrance. It was discovered in November 2002, when cavers noticed an opening at the base of a small abandoned limestone quarry, from which cool air gushed (Turner, 2003). They enlarged the opening just enough to squeeze in. Nothing could prepare them for what followed.

Once underground, a wonderland of speleothems greeted them (Fig. 6.21). Low, wide, sediment-floored passages connected breakdown chambers filled with translucent helictites, only observed at a few sites in Florida. Blade-like helictites hang precariously by the thinnest of connections and indicate the path of air currents in the cave like weather vanes. Snow-white stalactites loom above shallow pools of sparkling dogtooth spar. With more than a kilometer of mapped passages, Brooksville Ridge Cave is currently the fifth longest dry cave in Florida, and more passages remain unexplored.

Werner Cave, 9 km east of Brooksville Ridge Cave, was encountered by limestone quarry operations in 2002. The entrances are at the bottom of a pair of two 13-m-deep sinkholes in the floor of the quarry. It appears

Figure 6.21: Speleothems in Brooksville Ridge Cave (photo by Bruce Brewer).

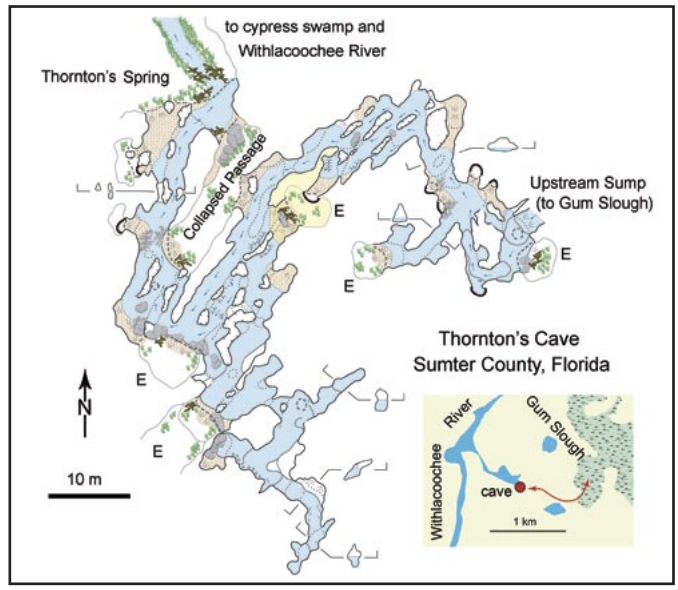

Figure 6.22: Map of Thornton's Cave. Map by Lee Florea.

that mining equipment breached the roof of a large room in the cave and must have terrified the operator of the mining equipment.

Moving loose breakdown at the bottom of the sinkholes, cavers exposed an opening that carried much air. Encouraged by the airflow and bat guano, they dug and squeezed through 75 m of low passage partially filled with rocks up to soccer-ball size to a series of large breakdown-floored rooms extending more than 500 m. These connected to an upper level. A room deep in the cave revealed the source of the guano. Several thousand Southeastern Bats (*Myotis austroriparius*) clustered on the ceiling. From the diameter of stains on the ceiling and size of the guano deposit on the floor, biologists estimate that the bat colony may have numbered 50,000 in the past. Albino crayfish discovered in the azure pools in Werner Cave are of a species as yet unidentified. The pool levels fluctuate seasonally more than 2 m in synchrony with the water in the Floridan aquifer (Florea and Vacher, 2007).

The Withlacoochee River

East of Werner Cave, the Withlacoochee River carries water north from Green Swamp through a gap in the Brooksville Ridge to the Gulf of Mexico (Fig. 6.20). On the Tsala-Apopka Plain along the eastern margin of the ridge, at an elevation of 12–14 m, the river meanders and often divides into several channels. Shallow lakes and sloughs (swamps with directional flow) drain into the river on the plain. Several springs from the Floridan aquifer contribute to the river on the Tsala-Apopka Plain, the most notable being the collection of seven springs that form Gum Slough (Scott et al., 2004). The complex channels, swamps, and islands that form the slough are a canoeist's dream. South of Gum Slough, low limestone hills bordering the river host recently explored caves.

Thornton's Cave has long been known to cavers and biologists (Fig. 6.22). Surveyed passages connect 23 entrances and form a single-level maze oriented along roughly orthogonal fractures. In at least one place, the cave connects to passages deep underwater. The Underwater Society of America *International Diver's Guide* of 1974 says "Do not go down narrow shaft to [the 45 m] level as there are loose boulders, decreasing visibility, and a maze of tunnels. Water often muddy with red clay silt."

The spring vents in Thornton's appear to act as estevelles. When the elevation of the Withlacoochee River is below the cave, water drains from the cypress slough to the west through the cave and into the river. When the river elevation exceeds the elevation of the cave, water flows east from the river, into the cave, and recharges Gum Slough. The pool elevation in the cave fluctuates by more than 1.5 m, and passages alternate between being nearly dry and entirely water filled.

Floral City Cave lies a few kilometers north of Thornton's, near Floral City. In early 2006, cavers discovered a fissure entrance in the floor of a small, abandoned quarry. At that time, the cave consisted of less than 100 m of passage along a single fracture that ended in a sump. As water-levels fell through 2006, the sump opened and cavers explored more than 300 m of additional cave, including a room 20 m in diameter

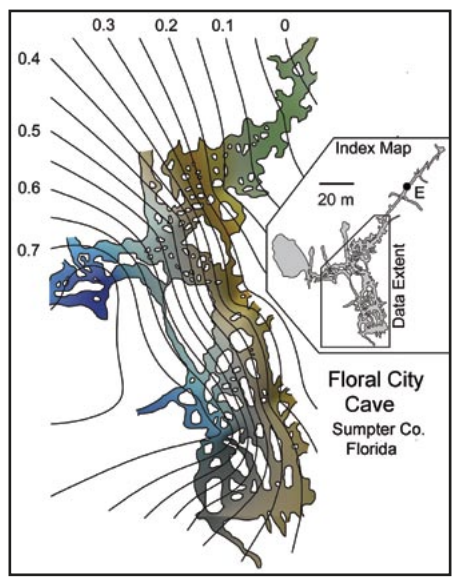

Figure 6.23: Map of a portion of Floral City Cave (see index map inset). The height of a laterally continuous stratigraphic horizon was contoured with respect to a water-table datum of 10.8 m above sea level (contour interval = 0.05 m). Passages along the horizon are low and wide. The northern and eastern sections of the cave are mainly tall, narrow fissures where the horizon plunges beneath the level of cave development.

(Fig. 6.23). Passages have two distinct morphologies: solution-enlarged fractures up to 4 m tall and less than 1 m wide, and a laterally continuous zone that averages 0.5 m tall and is supported by rock pillars. This zone is inclined to the water table but lies within the seasonal range of the water table everywhere in the cave. In the northern and eastern sections of the cave, the laterally continuous zone disappears as it plunges beneath the level of cave development, and fracture passages dominate beyond.

Ocala – Florida Horse Country

East and north of the Withlacoochee River, there stretches an expansive sinkhole plain with a gradual slope. At its eastern margin of the sinkhole plain, the Ocala Limestone plunges below the Miocene Hawthorne Formation along the low (10–30 m) Cody Escarpment. Grasses growing on the plain take up phosphates from the eroding Hawthorn Formation. Strong bones are promoted in horses that eat the grass, and breeders often winter their horses on farms near Ocala. During the summer, these same horses spend time in places with soils with similar levels of phosphates, such as those near Lexington, Kentucky (Chapter 3). In fact, Ocala and Lexington have both claimed to be the "horse capital of the world."

The margin of the Cody Scarp hosts the longest known air-filled cave in Florida, ***Warrens Cave***, with more than 6 km of surveyed passage, and there are many other air-filled caves in the area with more than a kilometer of passage. The two caves described here are typical of the caves along the scarp edge.

Briar Cave is located on the southern outskirts of Ocala, in a low hill between two sinkholes. The cave trends NW-SE along visible fractures and consists of a dry upper level of stratiform passage and a wet lower level, 19-21 m and 12-14 m above sea level respectively (Fig. 6.24). Miocene paleokarst, in the form of chert pillars and pendants, is intersected by the upper level. The surveyed length is about 2 km, making it one of the longest air-filled caves in Florida. Portions of the cave are inaccessible during periods of high water table. In May 1966, the cave was surveyed and a partial map was published in *The Florida Speleologist.* The owners closed the cave in 1971 using construction debris, limestone boulders, and concrete dumped into the entrance (Johnson, 1990). For 18 years, the cave was unvisited until access was once again granted. The Florida Speleological Society installed a gate in the entrance so that research and conservation could continue in the cave. More recent discoveries, including 300 m of nearly water-filled passage in the southern part of the cave, have been made as the result of falling water levels in the Ocala region.

Finch's Cave is a recently discovered cave south of Ocala, near the town of Belleview. It consists of 175 m of fracture-oriented passages mapped in 2006. Most of the cave is about 14 m above sea level. As at Briar Cave, parts lie below the water table; but the remnants of a calcite crust on the cave walls in Finch's indicate deposition when the water table was much lower (Fig. 6.25). It appears that with the Holocene water-table rise, the crust is now dissolving.

Figure 6.25: Finch's Cave, near the city of Belleview. Note the remnants of a calcite crust, particularly on the ceiling. A rising the water table has reflooded the cave and is dissolving the crust, which was deposited at a time when the water table was much lower. Photo by Alan Cressler.

Springs

The karst features in west-central Florida conduct a great deal of water into the Floridan aquifer from the more than 1200 mm of annual precipitation. The aquifer yields an estimated 1.1×10^{10} liters of fresh water per day from pumping and is the largest limestone aquifer in the United States (Miller, 1986).

Along the lowlands near the Gulf of Mexico, as well as along the Withlacoochee and Suwannee Rivers, groundwater from the Floridan aquifer feeds hundreds of springs (Scott et al., 2004). Some of them form navigable rivers of crystal-clear water (Fig. 6.26). The large springs along the coast, with names such as Weeki-Wachee, Crystal River, Chassahowitzka, and Homosassa, discharge several hundred million cubic meters of water per day from the Floridan Aquifer into the Gulf of Mexico. During the winter, when water temperatures of the Gulf of Mexico drop below 12°C, fish of many species and the endangered West Indian Manatee (*Trichechus senegalensis*) seek refuge in the comparatively warm 22°C waters of Florida springs. Springs and sinkholes near the coast of the Gulf of Mexico serve as gateways into the Floridan aquifer and to a honeycomb of underwater cave systems. Two internationally recognized examples of underwater caves are described below.

Eagles Nest is in a sinkhole that looks like many other water-filled sinkholes scattered throughout the coastal lowlands. But cave divers compare the geologic marvel below to Mt. Everest. The descent is through a solution tube in the bottom of the 13-m-deep basin and into

Figure 6.24: The Lake Room in the lower level of Briar Cave, near the city of Ocala. The water level of the Floridan aquifer in the photo is approximately 13 m above sea level. Photo by Sean Roberts.

Figure 6.26: Rainbow Springs from the air. Located west of Ocala, this is the fourth-largest spring in Florida. Photo by Harley Means, Florida Geological Survey.

the ceiling of what cave divers call the Ball Room – 70m deep and 100 m in diameter, filled with an estimated 25,000 cubic meters of crystal-clear water. From the depths of this room, sunlight streams through the tubes in the ceiling and create a magical display of light and shadow. High gas consumption in deep water limits the underwater time, so to explore the large passages in Eagles Nest at a depth of around 100 m, stage bottles, scooters, and a great deal of training are necessary. Nearly 2 km of water-filled passages have been surveyed.

Nearby ***Diepolder*** holds the record for deepest cave dive in the continental United States – 130 m in Diepolder 2. Neighboring Diepolder 3 contains one of the largest explored underwater rooms in the region, with a diameter of 130 m and depths to 100 m (exceeded in size only by one in Weeki-Wachee). Unexplored passages in both Eagles Nest and Diepolder await advances in diving technology.

Synthesis – Architecture of Caves in the Floridan Aquifer

Caves in the Cenozoic, high-permeability, coastal karst aquifers of west-central Florida differ substantially from those of the traditional textbook perspective (e.g., Ford and Williams, 1989) of caves in ancient inland limestones of low primary permeability, such as those of Mammoth Cave (Chapter 3). Three aspects of those differences are discussed here, and a conceptual model is presented for how caves are organized within the unconfined Floridan aquifer.

Cave Morphology

Many cave passages in west-central Florida are stratiform (wider than they are tall), with rock pillars that have not dissolved (Florea, 2006). Walls are complex, with cuspate, pocket-like, or honeycomb-like structures. Fissure passages are associated with regional NW-SE and NE-SW fractures, and human-scale passages are common where they intersect stratiform cavities. The caves are thus characterized by passages with "plus-sign" cross sections. Cave mapping also shows that passages do not extend great distances. Stratiform passages pinch into low crawlways and impassable slots. Fissure passages thin into increasingly narrow fractures. Insoluble sediment fill and structural collapse features abound. Connections between caves and the land surface are limited. Caves are discovered mainly where they have been encountered by land alteration, such as quarrying.

Cave Levels

Variations in sea level have a great influence in this coastal environment. Past sea levels more than 20 m higher than today flooded much of west-central Florida. At those times Brooksville Ridge possibly became an island chain, like the Bahamas (Chapter 14). In contrast, when sea level was lower than it is today (e.g., during the last ice age when global sea levels were about 120 m lower), the Florida Peninsula was twice as wide and the coast was about 220 km further west. During those times, the present springs and many of the submerged caves were dry and in the center of the exposed platform. Fresh water was limited, and pollen data suggest that the widespread forests of Florida converted to savannahs (Watts and Stuiver, 1980; Grimm et al., 1993).

The changing positions of sea level appear to be archived in the caves. Throughout air-filled caves, for example, surveys reveal stratiform cavities at 3–5 m, 12–15 m, 20–22 m, and approximately 30 m above modern sea level (Florea et al., 2007; Fig. 2.10). These cavities align with nearby surface terraces (Cooke, 1931; Healy, 1975). They can be identified with the aid of GIS and LIDAR data, which suggest cavity formation during higher stands of sea level and water table. Similarly, spot elevations from underwater caves and cavities in drilled wells occur at depths of 15 m, 40 m, 70 m, and 90–120 m below the present water table (Florea et al., 2007; Fig. 6.27). These depths generally correlate with marine terraces in the Gulf of Mexico, identified with multibeam bathymetry, which formed at previously lower sea-level altitudes of sea level and water table (Jarrett et al., 2005; Mallinson et al., 2003; Rodriguez et al., 2000; Locker et al., 1996).

Passage Connectivity

The common perception of caves in epigenic karst of the mid-continent is that water enters at swallets, travels through discrete conduits, and discharges at springs. 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). 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; see section above on the Woodville Karst Plain).

Yet the available data from west-central Florida contradict the notion of an integrated network of conduits (Florea and Vacher, 2007). For example, none of the caves described here have continuous conduits that connect sites of recharge to points of discharge. Nor do passages in the surveyed caves form a dendritic pattern of conduits with tributaries. Only one cave, Brookville Ridge Cave, receives occasional water from a sinking stream and contains indicators of local directional flow, such as sediment ripples and pebble imbrication. A second, Werner Cave, receives recharge from an artificial sinking stream formed during quarry reclamation.

Thus it appears that caves in the high-permeability eogenetic limestone of west-central Florida do not follow the sinking stream - spring model of the low-permeability telogenetic limestones of the mid-continent. Rather, karst water in west-central Florida may travel through a maze of passages, fractures, sediment fills, and rock matrix at several horizons.

A Conceptual Model

Figure 6.28 shows our present conceptual model of where cavernous porosity occurs in the unconfined Floridan aquifer of west-central Florida. It contains five components (Florea et al., 2007):

A: At the largest scale, caves organize along paleo-water tables that cut across the geologic structure. However, at the scale of individual caves, as at Floral City Cave where the stratiform passage horizon is inclined to the water table (Fig. 6.23), variations in depositional permeability in the eogenetic limestones (Budd and Vacher, 2004) appear to influence passage morphology.

B: Levels in air-filled caves occur at consistent elevations above present sea level over widespread areas and align with nearby surface terraces. For example,

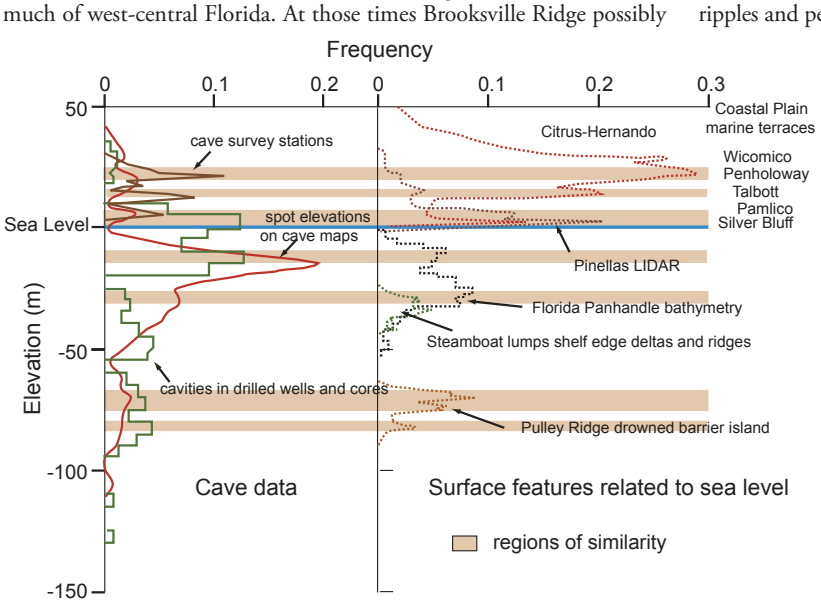

Figure 6.27: Histogram of elevations relative to sea level of surveyed passages in 9 caves in the Brooksville Ridge, spot elevations in underwater caves, and cavities in drilled wells (Florea et al., 2007) compared to histograms of topographic and bathymetric elevations and the geomorphic terraces of Cooke (1931).

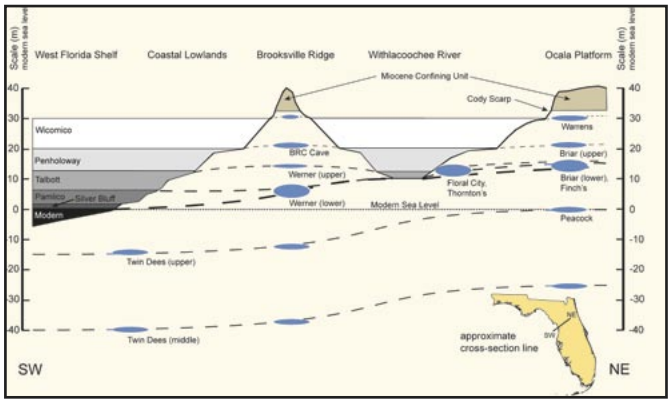

Figure 6.28: Conceptual sketch of how cavernous porosity in the upper part of the Floridan aquifer of west-central Florida connects to paleo-water tables and paleo-shorelines. The cross section is vertically exaggerated and not to scale. Note that the Withlacoochee River runs generally north-south through the cross-section and divides the uplands of the Brooksville Ridge from the Cody Scarp and the Ocala Platform. Paleo-sea levels related to the terraces of Cooke (1931) are identified. Black ovals portray cavernous horizons. Some ovals are labeled with representative cave names from the text or figures; however, these caves do not necessarily align along the cross section. Dashed lines indicate paleo-water tables that intersect the caves. Note that multiple paleo-water tables may occupy some cavernous horizons, as in the lower level of Briar Cave. Also note that the paleo-water tables are not horizontal, but instead are graded to their contemporary paleo-shorelines. The inflection in the paleo-water tables beneath the Withlacoochee River reflects recharge to the Floridan aquifer by the river, as well as reduced permeability in the aquifer caused by sediments that infiltrate through karst features in the river bed.

Brookville Ridge Cave and Briar Cave, more than 60 km apart, both have stratiform passages at +20-22 m. These air-filled caves reflect former higher sea levels. The coast was close, sea level and the water table were nearly coincident, and they are organized according to a sea-level datum. They represent a single generation of cave development.

C: Submerged caves reflect lower sea levels and are organized according to depth below the modern water table. The paleo-shoreline was much further away at the time the passage level formed along a sloping paleo-water table.

D: Because paleo-water tables are not horizontal surfaces and grade to their contemporary shorelines, some cave levels at or below the modern water table may represent multiple generations of development. This may be the case at Floral City, Thornton's, and the lower level of Briar Cave, which all occur at a similar elevation, 12-14 m above sea level, yet remain partially flooded in the modern water-table configuration.

E: Finally, a single paleo-water table can pass through cave levels associated with different sea-level stands. Such stair-stepping occurs because later water tables reoccupy zones dissolved along earlier water tables, as at Finch's Cave. As a result, the present water table can pass through caves at a higher elevation further inland near the Cody Scarp than beneath the Brooksville Ridge, while at the same time connecting to modern sea level at the present shoreline.

Toward a Conservation Strategy

West-central Florida contains an incredible ecological diversity that depends upon the connection between the surface and the underground. Even slight changes in soil moisture, elevation, and temperature have a profound effect on the surrounding habitat. In the U.S., only Hawaii, with its volcanoes, rainforests, and coral reefs, exceeds Florida in biodiversity. Native tribes in the past understood the great range of resources available in Florida. Rapid urbanization in recent decades shows that modern civilization finds the natural resources of Florida equally attractive.

More than 1000 new residents move to Florida each day, increasing the already considerable burden on natural resources. Besides the loss of critical habitats owing to the construction of homes and highways, and the chemical changes in springs, subterranean resources have also suffered. Ironically, the same construction and quarrying operations that reveal many cave entrances also prevent cave exploration because of liability concerns. The result is often elimination of the cave resource.

However, not all the news is bad. Passionate efforts by Florida cavers, scientists, and citizens have led to major strides toward the protection of surface and subsurface karst resources. Springs are protected in 17 state parks and two National Wildlife Management Refuges, and a state-level Springs Task Force channels money into water monitoring and land acquisition. Also, the Withlacoochee State Forest, in cooperation with cavers and scientists, has initiated a cave management plan that includes proper cave gates, scientific study, and monitoring. And finally, the Florida Geological Survey and the Florida Cave Survey have begun to document and archive cave data.

There are few groups of individuals more dedicated to exploration and preservation than those who cave in Florida. Their passion is addictive, their influence on public policy is profound, and their hospitality is warm.

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The Biscayne Aquifer of Southeastern Florida

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IN SOUTHEASTERN FLORIDA, locally delineated, small, poorly explored caves (Fig. 6.29) and subtle karst are characteristic of the limestone that composes the unconfined Biscayne aquifer – one of the most permeable aquifers in the world (Parker et al., 1955). The main units of the Biscayne aquifer are the Fort Thompson Formation and Miami Limestone (Fig. 6.29), both characterized by eogenetic karst (Vacher and Mylroie, 2002; Cunningham, 2004a,b; 2006a,b; and 2009).

Caves and karst of the Biscayne aquifer have received little attention compared to those of the Floridan aquifer (see previous sections). To our knowledge, descriptions of only 20 small, shallow caves in the area have been published (Cressler, 1993; Florea and Yuellig, 2007). They are mostly air-filled, although at least one is water-filled in the wet season and many contain pools of groundwater. Parker et al. (1955) produced the earliest detailed report of the low-relief karst geomorphology and shallow depositional environment that characterizes the limestone of the Biscayne aquifer. Having developed in a humid semi-tropical climate with 125–150 cm of rain per year, Biscayne aquifer karst features include sinkholes, vertical solution pipes, jagged rock pinnacles, deep solution passages, a natural limestone bridge, and large solution holes open to the surface (probably similar to banana holes; see Harris et al., 1995). On a map of Florida sinkholes by Rupert and Spencer (2004), only two are identified in peninsular southeastern Florida; but we have knowledge of many others not identified in that publication, and at least one in the northern Florida Keys (Shinn et al., 1996).

Recently, Cunningham et al. (2004a,b; 2006a,b; 2009) used data from numerous drilled wells within a large study area in Miami-Dade County (Fig. 6.29) to demonstrate that much of the subsurface karst porosity and groundwater flow in the Biscayne aquifer is closely related to stratigraphic cycles (Fig. 6.30). Stratiform zones of groundwater flow in the aquifer contrast markedly with the fractures and conduits that host groundwater flow in telogenetic limestones, such as at Mammoth Cave (Chapter 3). In the study area of Cunningham et al., the greatest flow of groundwater appears to be through stratiform zones containing mazes of centimeter-scale vuggy porosity (Cunningham et al., 2009). A common strong connection between these stratiform macro-pores and burrow-related trace fossils appears to make the karst of the Biscayne aquifer unique, although similar examples are likely in other carbonate aquifers. The following discussion focuses on the caves of the Biscayne aquifer first described by Cressler (1993), and on the subsurface karst of the Biscayne aquifer in the study area of Cunningham et al. (2004a,b; 2006a,b; 2009).

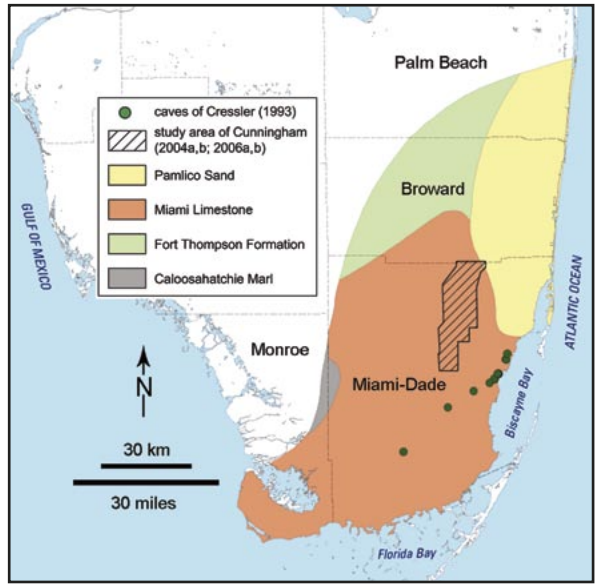

Figure 6.29: Map of southern Florida showing the location of the Biscayne aquifer. The rock or sediment that constitutes the top of the aquifer is mainly limestone (Fort Thompson Formation and Miami Limestone), but quartz sand and minor marl also. Green dots show generalized locations of poorly explored shallow caves in the Biscayne aquifer (Cressler, 1993). The shaded box shows the Biscayne aquifer study area of Cunningham et al. (2004a,b; 2006a,b; 2009).

Stratigraphy

For the purposes of this chapter, the lithostratigraphy of the Biscayne aquifer is almost entirely limestone of the Fort Thompson Formation and Miami Limestone (Fig. 6.29). Multer et al. (2002) suggest that the middle and lower part of the Key Largo Formation of the Florida Keys, which is equivalent to the Fort Thompson Formation, was deposited during Marine Isotope Stages (MIS) 11 and 9, both middle Pleistocene interglacial periods. However, chronostratigraphic data presented in Cunningham et al. (2006b) and Guertin (1998) are consistent with the lower part of the Fort Thompson Formation being as old as early Pleistocene or late Pliocene, respectively. Data from Multer et al. (2002) and Perkins (1977) both suggest that the Miami Limestone is composed of at least two high-frequency cycles bounded by unconformities that were deposited during MIS 7 and 5e. Seven of the 20 caves of Cressler (1993) that we have field checked are within the uppermost MIS 5e (last interglacial period ~125 kya) limestone unit of the Miami Limestone, and presumably so are the remaining 13 we have not visited.

Recharge and discharge patterns

The highest water levels of the Biscayne aquifer are maintained by precipitation and direct recharge in Everglades wetlands along the western margin where surface water seeps into the aquifer. In a regional sense, groundwater moves eastward and southward to the ocean (Fish and Stewart, 1991). Canals, control structures, or large well fields cause local variations in the flow pattern. Flow from the Everglades through urban and agricultural areas to the east is rapid because of the high permeability of the aquifer. Discharge principally occurs in the coastal areas of the Atlantic Ocean, Biscayne Bay, and Florida Bay (Fig. 6.29).

Many freshwater springs existed along the shore of Biscayne Bay prior to substantial lowering of surface-water and groundwater levels in southeastern Florida (Parker et al., 1955). At one such spring, marked as "fresh water" on Coast and Geodetic Survey Navigation Chart No. 166 (1896), early mariners collected fresh drinking water in kegs lowered into the spring orifice. Today there are still many near-shore springs in Biscayne Bay; however, the salinities of water measured at a few sites