2009

The Biscayne Aquifer of Southeastern Florida

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The Biscayne Aquifer of Southeastern Florida

Kevin J. Cunningham and Lee J. Florea

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).

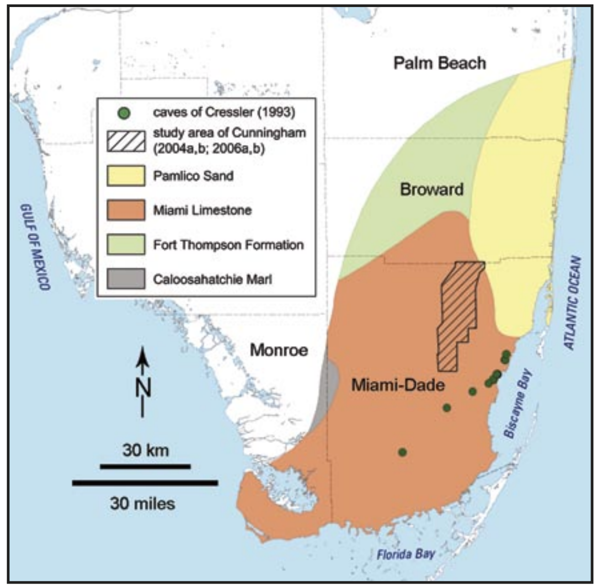

Figure 6.29: Map of southern Florida showing the location of the Biscayne aquifer. The rock or sediment that constitutes the top of the aquifer is mainly limestone (Fort Thompson Formation and Miami Limestone), but quartz sand and minor marl also. Green dots show generalized locations of poorly explored 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

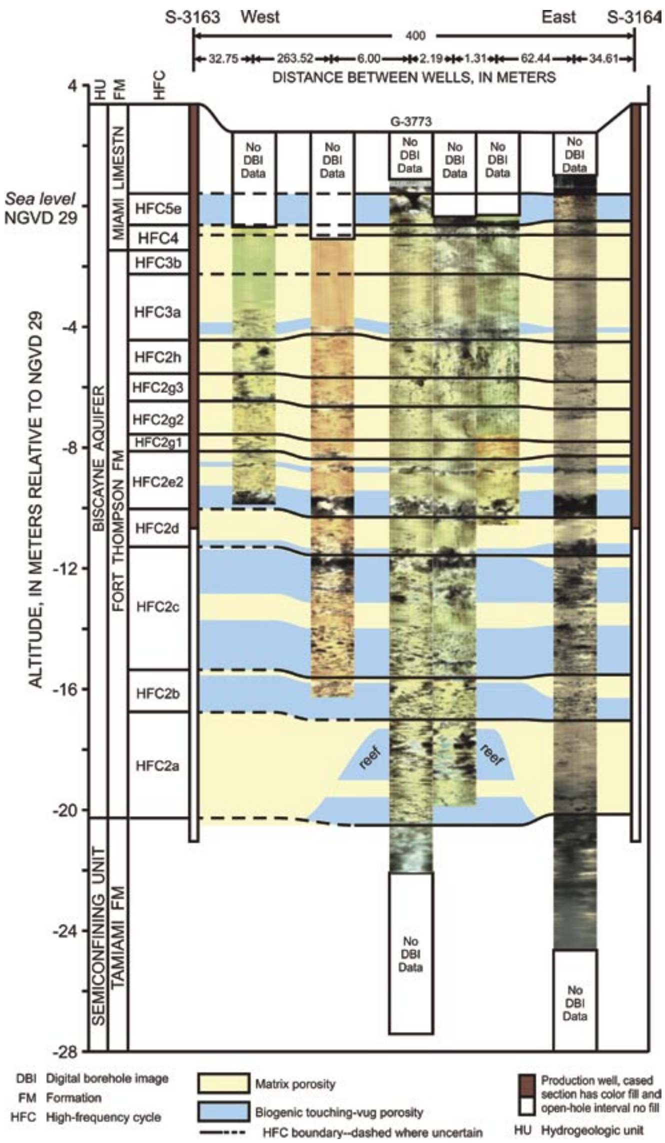

Figure 6.30: Digital borehole images of the Biscayne aquifer that show stratiform zones of biogenic touching-vug porosity (modified from Cunningham. These macropores form groundwater flow zones in the Biscayne aquifer between pumping wells S-3163 and S-3164 at a municipal well field in the study area of Cunningham et al. (2004a,b; 2006a,b; see Fig. 6.29). Well G-3773 is the tracer injection well and S-3164 the pumping well used in a forced-gradient tracer test reported by Renken et al. (2005, 2008). The shallow caves reported by Cressler (1993) that we have field checked are all within the high-frequency cycle HFC5e of the Miami Limestone.

were 8–31 g/L, outside the range of drinking water and discharge rates were low (Gonzalez, 2006).

Caves of the Biscayne Aquifer

The earliest known report of caves in southeastern Florida is from Small (1921), who describes using a dredge, and blasting with dynamite (circa 1917), to construct the Old Ingraham Highway in what is now Everglades National Park. The dredge uncovered a large underwater cave, for which there is anecdotal evidence for speleothems up to a meter in diameter. It was presumably buried and has never been rediscovered. Small (1921) further mentions karst features, including caves, tunnels, and a natural bridge in the Miami Limestone in Miami. More than 70 years later, Cressler (1993) described 19 air-filled caves and one water-filled cave in Miami-Dade County and provided 16 sketches. The longest was estimated at 120 m with a vertical extent of 4.5 m. Cressler (1993) noted small speleothems in at least two of the caves.

The caves found by Cressler (1993) are along the Atlantic Coastal Ridge (Fig. 6.29), a southwest-trending, low-relief, topographic feature with a maximum elevation of 7.3 m (Hoffemeister et al., 1967). The landward part of the southern Atlantic Coastal Ridge consists of fossil oolitic shoals and channels (Halley et al., 1977) interpreted to be an ancient southwest-trending tidal-bar belt. The more seaward and continuously linear part is inferred to be an ancient oolitic barrier bar that parallels the southwest axial topographic trend of the Atlantic Coastal Ridge. The oolitic shoals correspond to low-relief topographic highs and are separated by lower topographic areas, called *transverse glades*, which correspond to relict tidal channels (Halley et al., 1977). These channels are commonly oriented northwest-southeast, essentially perpendicular to the axis of the Atlantic Coastal Ridge. Most caves of southeastern Florida occur on or along the flanks of the ancient barrier bar, or along the edges of transverse glades that cut through the bar. There are three others within the patchwork of fossil ooid shoals. The caves of southeastern Florida provide an opportunity to contrast and compare speleogenetically with those in similar MIS 5e limestone within the islands of the nearby Bahamas (see Chapter 14).

From field observations and descriptions by Cressler (1993), caves in the Pleistocene limestones of southeast Florida fall into the following four categories: (1) At least one was oriented along fractures. In other caves, we have observed passages that are linear and taller than wide. Such fracture-oriented passages are common elsewhere in the eogenetic karst of Florida (Florea, 2006). (2) Some caves are concentrated along the margins of transverse glades. Cressler (1993) hypothesized that slightly acidic water from the Everglades could be a potent agent for dissolving such caves in the Miami Limestone. Most caves identified by Cressler (1993) are located in this setting. (3) Some caves are composed of stratiform lateral passages. Observations within Deering Glade indicate that variations in stratigraphy may have played an important role in the origin of many small caves along its northern wall, including the 100-m-long Fat Sleeper Cave, which was first mapped by Cressler (1993). At Deering Glade, cave passages are commonly low, wide, and sandwiched between crossbeds of oolitic limestone. These stratiform passages seem confined to a zone of rock with many centimeter-scale vugs related to complex burrow systems (*Ophiamorpha*). It is hypothesized that the burrow-related porosity provided early preferential pathways for groundwater and concentrated dissolution. In some caves, solution pipes penetrate the upper cross-bedded limestone and connect to the land surface. (4) Some caves have entrances along the margins of cave-roof collapse. The entrance of Palma Vista Cave, in Everglades National Park, probably formed by the collapse of a thin roof that spanned a stratiform cave (Fig. 6.31). Other nearby karst features have similar morphologies. These collapses collect organic matter and provide access to the water table in an otherwise pine and palmetto scrub ecotone. The resulting features have a morphology and function similar to those of the Bahamian "banana holes" of Harris et al. (1995).

Karst of the Biscayne Aquifer

Vacher and Mylroie (2002), using the scheme of (Choquette and Pray, 1970), first described the porosity of the Biscayne aquifer as eogenetic. Cunningham et al. (2009), building upon the carbonate pore-space classification scheme of Lucia (1995, 1999), divided the pore system of the Biscayne into two types: (1) matrix porosity (interparticle and separate vugs), which provides much of the groundwater storage; and (2) touching-vug porosity (biogenic macroporosity), which creates stratiform, areally extensive groundwater flow pathways and less common bedding-plane and cavernous vugs, and vertical solution pipes. Biogenic touching-vug porosity is typically within or between burrows, roots, and fossil molds. Non-biogenetic touching-vug porosity includes all other types unrelated to ichnology or fossil molds. As demonstrated by Florea and Vacher (2006), the matrix porosity provides most of the groundwater *storage* in eogenetic karst such as the Biscayne aquifer. The various types of touching-vug porosity provide for much of the groundwater *flow*.

Figure 6.31: Palma Vista Cave, located in a small hardwood hammock in Everglades National Park, is the southernmost explored cave in the continental United States. The cave contains a perennial pool of fresh water, and during the wet season the cave is filled with water. Photo by Alan Cressler.

Cunningham et al. (2006b) developed a three-dimensional conceptual hydrostratigraphic model of the Biscayne aquifer for a 246 km^2 study area (Fig. 6.29) using data from approximately 78 drilled wells, including cyclostratigraphic interpretations, tracer tests, and down-well geophysics and flowmeter measurements (Renken et al., 2005, 2008). Cunningham et al. (2006a,b) delineated five major depositional environments for the Biscayne aquifer (Fort Thompson Formation and Miami Limestone): (1) platform margin-to-outer platform, (2) open-marine platform interior, (3) restricted platform interior, (4) brackish platform interior, and (5) freshwater terrestrial environments.

High-frequency cycles form the building blocks of the rocks of the Biscayne aquifer. Lithofacies successions, with recurring stacking patterns, fit within the high-frequency cycles. Upward-shallowing subtidal cycles, upward-shallowing paralic (associated with the sea coast) cycles, and aggradational subtidal cycles define three ideal high-frequency cycle types that occur within the Biscayne. The upward-shallowing cycles occur within the Fort Thompson Formation and the aggradational cycles comprise the Miami Limestone. Predictable changes in porosity and permeability commonly exist within the three ideal cycles. Biogenic touching-vug porosity is common within the lower part of the upward shallowing cycles of the Fort Thompson Formation and throughout the vertical thickness of an upper aggradational cycle (MIS 5e high-frequency cycle) of the Miami Limestone. Matrix porosity dominates the upper part of upward-shallowing subtidal cycles and middle part of the upward-shallowing paralic cycles. Micrite dominated, leaky, low-permeability lithologies commonly cap upward-shallowing paralic cycles and occur throughout much of the lower aggradational cycle of the Miami Limestone.

The relations among lithofacies, cyclicity, and aquifer attributes (porosity, permeability) are crucial elements of the hydrostratigraphic framework in the Biscayne aquifer. Not only is the permeability of the Biscayne confined within the upper and lower stratigraphic boundaries of high-frequency cycles, but there is a trend for rocks older than MIS 9 to be more permeable than the younger MIS 5e and 7 units. We suspect that a greater number of vadose dissolution events, during periods of low-stand sea level, have enhanced the permeability of the older units.

Cunningham et al. (2004a,b; 2006a,b) suggest that much of the groundwater flow in the Biscayne is related to biogenic touching-vug porosity that forms tabular-shaped stratiform flow zones. The hydrologic importance of biogenic porosity were determined by examining outcrops, cores, and down-well geophysical data that include digital optical image logs and flowmeter, fluid conductivity, and fluid temperature measurements. Digital image logs and 72 of 85 geophysical measurements (85%) in 21 boreholes indicate that biogenic porosity is the principal pore type in groundwater flow zones. Most of the remaining down-well geophysical measurements across groundwater flow zones detected inflow or outflow from bedding plane vugs. Intraburrow pores that are likely *Ophiomorpha*, a common ichnofacies in the Pleistocene of the Caribbean and south Florida (Curran, 2007), are typically centimeter-scale and either unfilled or partly filled with younger sediments (Fig. 6.32). To emphasize the potential for biogenic touching-vug porosity in controlling groundwater flow, 75% of the vertical thickness of the Biscayne is characterized by this biogenic macro-pore type in one well on the western perimeter of the study area of Cunningham et al. (2004a,b; 2006a,b).

Recently, Renken et al. (2005, 2008), within the study area of Cunningham et al. (2004a,b; 2006a,b), performed a forced-gradient tracer test in a large municipal well field with rhodamine WT and deuterium. Geologic studies (Cunningham et al., 2006a), combined with hydraulic responses during pumping, suggest that the aquifer behaves as a dual-porosity medium (matrix and biogenic touching-vug porosity) in which principal pathways for groundwater flow and chemical transport are multiple, extensive stratiform beds of biogenic touching-vug pore space (Fig. 4). Tracer movement was characterized by rapid breakthrough, high relative mass recovery, and low dispersivity. The results identified preferential tracer migration through one of the biogenic touching-vug flow zones; however, other flow zones of the same type in the Biscayne were also found to contribute to tracer migration. More recent geologic and geophysical evidence from drilled wells not included in the local tracer test of Renken et al. suggests that, in some other areas, non-biogenic touching-vug porosity composed mainly of bedding plane vugs, solution pipes, and caves can also contribute to groundwater flow in the eogenetic karst of the Biscayne aquifer.

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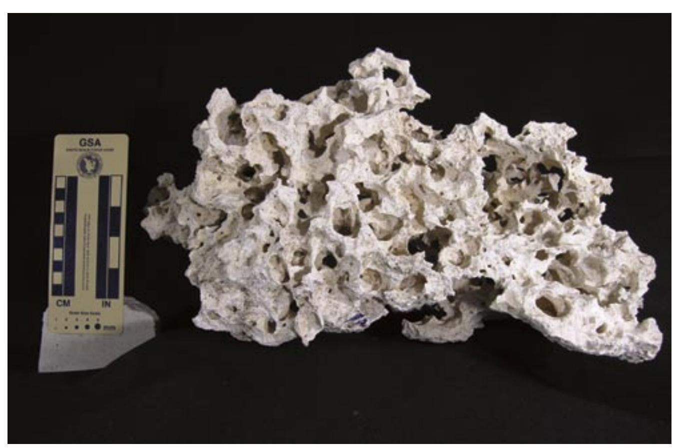

Figure 6.32: Biogenic touching-vug porosity from a stratiform flow zone in the Biscayne aquifer. The centimeter-scale vugs are associated with the trace fossil *Ophiomorpha*.

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Caves of Mississippi

John E. Mylroie

THE MISSISSIPPI KARST is an extension of the low-relief karst of northern Florida. Although not known as a "cave state," Mississippi does have a few caves (Knight et al., 1974; see Fig. 6.3). Although the caves are small, there are several active stream conduits with several hundred meters of passage. Most are less than 200 m long. Given the scarcity of limestone in Mississippi, this is not unexpected. Limestone units are thin and are exposed in rather low-relief settings (Moore, 2006). Paleozoic limestone of Mississippian (Early Carboniferous) age is exposed in the extreme northeast portion of the state, and three caves have been mapped in this unit (Moore, 2006). The second karst area is in the Ripley Formation (Cretaceous), which extends in an arc across the state from north to southeast. Five caves have been mapped in this unit (Moore, 2006). A third karst area is located in Cenozoic limestones that trend east-west through the center of the state. These units are the Glendon and Marianna Formations of the Oligocene Vicksburg Group, and 12 solution caves have been mapped there (Moore, 2006).

The Mesozoic and Cenozoic limestones still retain significant primary depositional porosity. The softer, weakly resistant nature of the carbonate rock means that they break up easily, and entrances are unstable. With insoluble sediments carried in from nearby rocks, the caves have a high sediment load that clogs many of the underground systems.

There are several well-known pseudokarst caves in Mississippi. Rock House Cave, Rankin County, has been formed, or enlarged, by animals who lick salt from the sandstone of the Miocene Catahoula Formation (e.g. Lundquist and Varnedoe, 2006). Naniah Waiya Cave, Winston County, is known as the birthplace of the Choctaw Nation, from which the tribe is said to have first emerged.

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Caves and Karst of South Carolina

From the work of Cato Holler

MANY SINKING STREAMS, sinkholes, caves and springs are located in the Coastal Plain of South Carolina (Fig. 6.2) in the Eocene Santee Formation (Holler, 2000). This is equivalent to the Avon Park Limestone in Florida. Caves are short, and many extend to sumps or are blocked by sediment, but Parler Cave, in Santee State Park, has been explored for more than 330 m (Fig. 6.33). The well-known Carolina Bays, which are shallow, oval-shaped depressions scattered throughout most of the Atlantic Coastal Plain, especially in North Carolina, South Carolina, and Georgia, are thought by some to have a karst origin. But with diameters up to several kilometers, depths of only a few meters, and outlines that cross various rock types, a karst origin is unlikely. They may instead be the results of meteorite impact. There is no consensus on the topic (Ross, 2000).

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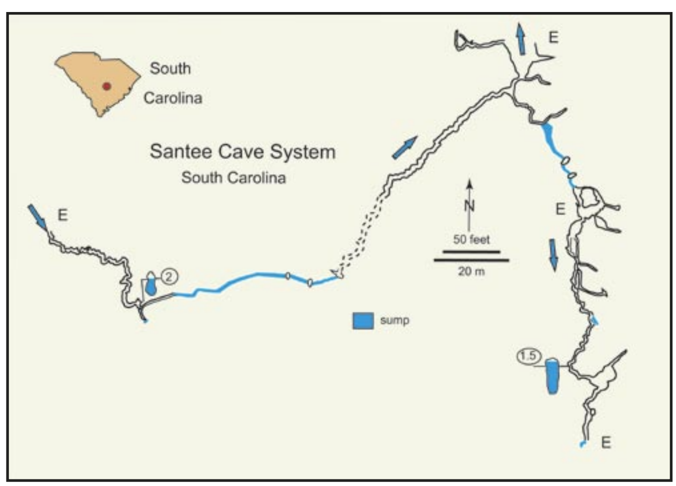

Figure 6.33: Parler (or Santee) Cave, in Santee State Park, South Carolina, is located in the Eocene Santee Formation. Note that although this cave is in a young, soft limestone similar to those of Florida, Santee Cave consists of a discrete stream passage. From map by Chris Elmore.