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Quaternary cave levels in peninsular Florida

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Abstract

The hypothesis that caves in the Florida Peninsula are tied to Quaternary sea levels was proposed by hydrogeologists, without data, some 40 years ago. The hypothesis is a version of glacial control of cave levels, which is the logical combination of the water-table theory of speleogenesis and the concept that base level positions the water table. At the USA type example of glacial control of cave levels—Mammoth Cave in the Paleozoic rocks of Kentucky—the intermediary is base level determined by rivers. By hypothesis, the intermediary for Florida is glacioeustatic sea level. This paper presents elevation data that supports this hypothesis.

Recent cave surveys in the air-filled caves and spot elevations from archived maps reveal prominent levels of passages centered at 5, 12, 21, and 30 m above sea level over broad areas. They do not follow the large-scale structure of the Floridan aquifer. Instead, they align with nearby, coastal marine terraces identified as modal peaks on frequency plots from various topographic data bases. Levels matching with the three highest terraces—Wicomico, Penholoway, and Talbott—are particularly clear. Lower levels, if they accord with sea-level stands, are likely composites.

Data from cavities encountered in drilled wells (e.g., bit drops) and spot elevations from archived underwater cave maps demonstrate passage levels at depths of 15, 30, 70, and 90–120 m below the modern water table. The depths below water table are similar to the depths below sea level of distant submerged terraces and paleoshoreline features identified using multibeam bathymetric data in the Gulf of Mexico.

The cave, bit-drop, and terrace data are all consistent with the concept that Quaternary sea level is the fundamental control on the cave-scale porosity within the Floridan aquifer. This conclusion does not rule out the possibility that lithologically favored positions, paleokarst features and confining units, and mixing zones are also involved in the location of caves levels in this near-coastal environment.

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1. Introduction

> Nearly every cave contains passages at a variety of elevations, and even the casual visitor tends to group them mentally into different "levels."
>
> Palmer (1987, p. 50)

The fundamental connection between cave levels and the water table has influenced geomorphic thinking for at least a century. When Alfred Grund (1903) and Cvijić (1918), for example, concluded from their studies in the *kras* region of the Dinaric Alps that the landscape denudes to the lowest seasonal water table, they noted that the flow of water at springs and the levels of caves appear to respond to and form at the level of the water table. Subsequent investigations long considered whether limestone dissolution is greatest above the water table in the vadose zone (Martel, 1921), at the water table (Swinnerton, 1932; Rhodes and Sinacori, 1941; Thrailkill, 1968), or below the water table in the phreatic zone (Davis, 1930; Bretz, 1942, Ford and Ewers, 1978; Worthington, 2004). More recent investigations consider descending, epigenic waters (Palmer, 2001), ascending, hypogenic waters (Hill, 1990; Klimchouk, 2003), or the mixing of two water masses (Mylroie and Carew, 1995; Smart et al., 2006) as the origin of cave levels.

The type example of cave levels in the USA is Mammoth Cave, Kentucky (Palmer, 1987), where near-horizontal

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cave levels cut across geologic structure and align with sediment terraces of the Green River. This famous cave system was one of the field areas of Allyn Swinnerton who argued the water-table origin of caves (Swinnerton, 1932). As noted by Swinnerton (1929),

> … the lowest levels of Mammoth (Cave) … represent the active zone of cave development approximately at the altitude of the Green River. So-called cave levels may be found at many altitudes, but the continuous system of caverns at approximately 200 feet above the river is so strongly marked that it may be regarded as indicating an intermediate stage in the physiographic history of the region.

Now it is known from ^{26}Al and ^{10}Be geochronology of sediments within the levels of Mammoth Cave (Granger et al., 2001) and the river terraces in the greater Ohio River valley (Granger and Smith, 2000) that the cave levels record base-level lowering and sediment aggradation during the past 3.5 Ma in response to the reconfiguration of the pre-Pleistocene Teays River into the present-day Ohio River. These changes were brought about by the advance and retreat of the Laurentide ice sheet.

The purpose of this paper is to examine caves that may be related to a different kind of base level—sea level. If it is true that cave passages in the Cenozoic limestone of the Florida Peninsula form at water tables graded to sea level and if it is true that coastal terraces mark the former positions of sea level brought about by advancing and retreating Quaternary ice sheets, then one would expect cave levels that line up with the coastal terraces. This paper investigates whether there are cave levels in peninsular Florida and the degree of alignment between the cave levels and the coastal terraces.

2. History

2.1. *Sea level and caves in Florida*

The concept that caves in Florida are related to the impermanent position of sea level is at least as old as Swinnerton's water-table theory of speleogenesis. Swinnerton himself noted the idea. Stringfield and LeGrand (1966) explicitly stated the hypothesis of glacial control of Florida cave levels. The period of time from Swinnerton to Stringfield and LeGrand was one of classic and momentous work in both coastal geomorphology and limestone hydrology in the southeastern USA.

Swinnerton was aware of cavernous, groundwater springs offshore Florida, and, following Davis (1930), noted that they posed a contradiction to the notion that caves form at the water table (Swinnerton, 1932, p. 689). He resolved the contradiction by referring to earlier workers in Florida who showed that "the coastal portions … have not been static in recent geologic time" (Swinnerton, 1932, p. 690). To Swinnerton in 1932, the disparity between the position of sea level and the level of caves was due to uplift and subsidence.

Swinnerton's work was during the general time period that the concept of glacioeustasy was taking hold as a geomorphic paradigm in the American geologic community. The writings of Reginald Daly (1925, 1934) were prominent. Particularly influential was the great coral reef debate (Davis, 1928), in which Darwin's subsidence theory of coral reefs Darwin (1842) was challenged by Daly's glacial control theory (1910, 1915).

At the same time, C. Wythe Cooke of the US Geological Survey was beginning his seminal study of the coastal terraces of Georgia (Cooke, 1925), Florida (Cooke and Mossom, 1929), and South Carolina (Cooke, 1936). Earlier, Matson and Sanford (1913, p. 31–35) had recognized three terraces that border the coast and extend up the large rivers in northern and central Florida and attributed them to stages in the emergence of the peninsula. Cooke (1930) noted the similarity in elevation of the terraces that had been described in the various eastern and southern states from New Jersey to Florida and used that similarity to argue that glacial control of sea level was the cause. Soon Cooke (1931) organized the data into seven discrete terraces. Taking names from a variety of locations in states along the east coast, Cooke promoted his now-classic coastal plain nomenclature (Cooke, 1931, 1935, 1939, 1945): from highest to lowest—Brandywine (Maryland), Coharie (North Carolina), Sunderland (Maryland), Wicomico (Maryland), Penholoway (Georgia), Talbott (Maryland), and Pamlico (North Carolina). The lowest (and youngest) terrace, the Silver Bluff, was added soon after, named after a low coastal ridge on the southern outskirts of Miami, Florida (Parker and Cooke, 1944).

Also in the 1930s, Victor Stringfield of the US Geological Survey mapped the potentiometric surface of what became known later as the Floridan aquifer in peninsular Florida (Parker et al., 1955). This study (Stringfield, 1935, 1936) identified the karst region of west-central Florida (Fig. 1A) as the area where the Floridan aquifer is unconfined. Stringfield's work culminated with the definitive USGS treatise on the carbonate aquifer system of the southeastern US (Stringfield, 1966).

Stringfield's regional study of the Floridan aquifer (Stringfield, 1966) was the springboard for a series of papers over the next decade by Stringfield and LeGrand (1966, p. 39) on the hydrogeology of coastal karst and, in particular, the development of secondary porosity in that setting. The first of these papers contains the following on the organization of cavernous porosity in the Floridan aquifer:

> Lateral zones of solution cavities at different depths were formed … when the water table stood at higher and lower levels in response to changes in sea levels in Pleistocene time.

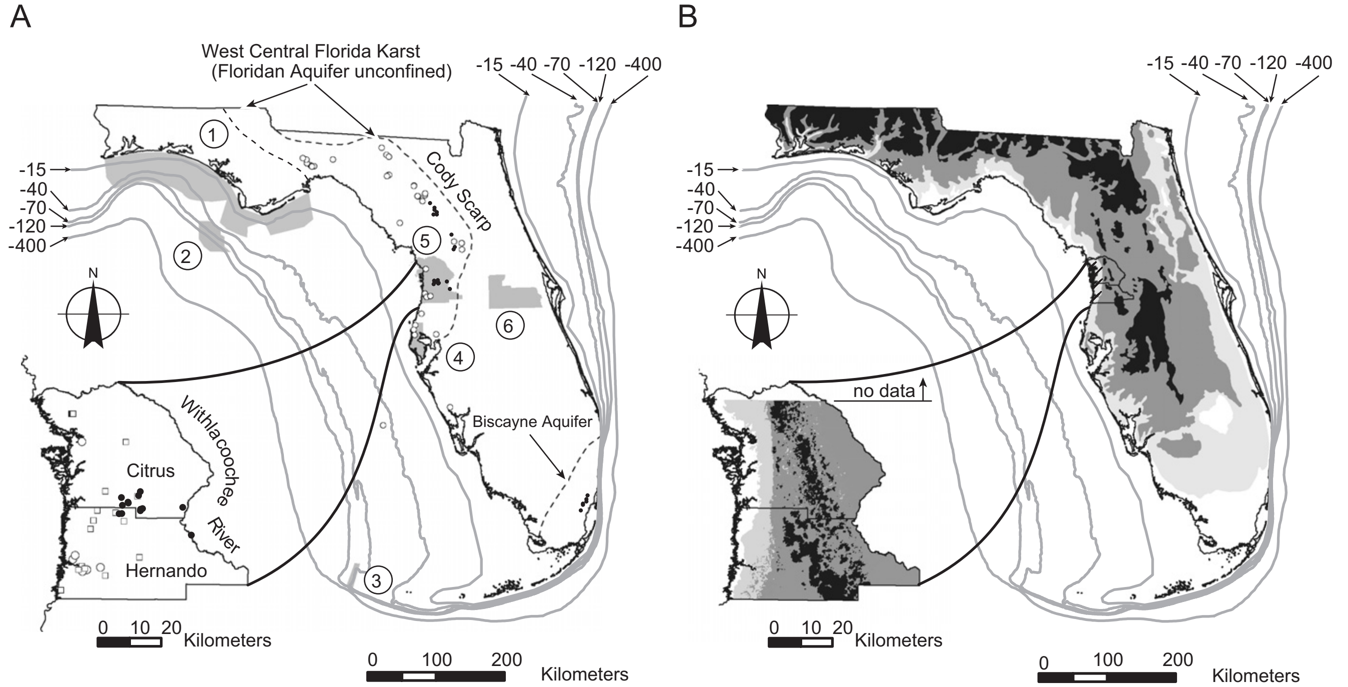


Fig. 1. Data sources, locations, and elevations. Gray lines are bathymetric contours on continental shelf in meters. Insets are included for Citrus and Hernando Counties. (A) Springs (circles), wells (squares), and caves (black dots) included in this study. Dashed lines delimit the extent of the unconfined Floridan and Biscayne aquifers. Shaded gray regions 1–6 are sites of additional data that include: (1) GRID from DLG bathymetric data from offshore the Florida Panhandle; EM 3000 multibeam bathymetric data for (2) Steamboat Lumps, and (3) Pulley Ridge; (4) ALSM elevation data for Pinellas County (Seale, 2005); (5) GRID from DLG data for Citrus and Hernando Counties; (6) Well cavity records for Orange County from (Wilson, 1988; Lichter et al, 1968). (B) Elevations and terraces for Florida. White regions are less than +2 m. Light gray regions are greater than +2 m and less than +10.5 m and include the Silver Bluff and Pamlico terraces. Dark gray regions are greater than +10.5 m and less than +30.5 m and include the Talbott, Penholoway, and Wicomico terraces. Black regions include the uplands above +30.5 m.

However, their statement of water-table control linked to sea-level stands was a hypothesis, for they also said:

> Only general information is available about the vertical distribution of cavities in the limestones of the south-eastern states.

How does the notion of a water-table locus of cave development linked to sea level stands hold up to elevation data now, some 40 years later?

2.2. More recent work

Florida sea level: Since the time of Cooke's studies, investigations of the subaerial terraces in Florida have focused mainly on pre-Wicomico terraces of the interior (MacNeil, 1950; Altschuler and Young, 1960; Alt and Brooks, 1965; Pirkle et al., 1970). Terraces higher than the Wicomico (+30.5 m), however, are higher than Florida caves and, in general, higher than the limestone. A map of all the eight terraces throughout Florida is now available (Healy, 1975).

The age and origin of the coastal plain terraces in Florida remain open questions—as is the case regionally throughout the coastal plain of the southeastern United States (Muhs et al., 2003). In general, the subaerial terraces manifest as surfaces that are relatively flat or gently inclined in a seaward direction and are ''bounded landward by marine cut scarps or other shoreline geomorphic features and often underlain by fossiliferous marine and marginal marine deposits'' (Cronin et al., 1984, p. 23). The terraces and associated scarps are not strictly constructional or erosional features, but represent a ''broad range of depositional environments'' (Cronin et al., 1984, p. 25), which combine with post-depositional erosion and denudation to produce a fragmentary record that is particularly difficult to correlate over large distances.

Numerical age estimates for the Wicomico and lower terraces throughout the coastal plain are Quaternary based upon limited biostratigraphic, paleomagnetic, palynologic, and analytical evidence (Cronin et al., 1984; Colquhoun et al., 1991; Muhs et al., 2003; Otvos, 2005). These dates also generally support the prevailing thought of Cooke (1935) that the older terraces are higher in elevation than the lower terraces, although there is a large degree of uncertainty regarding the exact age of a particular terrace (Muhs et al., 2003).

Many researchers link the formation of the subaerial terraces of the southeast coastal plain to transgressions during interglacial periods of sea-level fluctuations (e.g., Cronin et al., 1981). There is, however, a noticeable variability in the age and elevation of the individual terraces over large distances, especially outside of Florida (Winker and Howard, 1977; Cronin et al., 1984), that has not been fully resolved on this passive continental margin.

Some attribute this variability to warping of the crust following isostatic rebound (Walcott, 1972; Clark et al., 1978). At least one study (Opdyke et al., 1984) suggests that epeirogenic uplift from the dissolution of limestone in the karst of Florida could be a source of the variation in terrace elevation. Regardless of the cause of the warping, the caves and the terrace surfaces will move together during adjustments of the crust. Questions of the age and origin of the Wicomico and lower terraces, therefore, do not affect the matching of terraces and cave levels.

In contrast to the poorly constrained geochronologic data on marine terraces north of peninsular Florida, several studies in south Florida provide evidence concerning the position of Quaternary sea level. For example, Locker et al. (1996) identified four paleoshoreline elevations below modern sea level near the Florida Keys at depths of 65, 71, 80, and 80–124 m. The ^{14}C dates obtained from the surface sediments at these sites indicate episodic rapid rises and still-stands since the last glacial maximum. Elsewhere beneath the Keys, Enos and Perkins (1977) identified five Quaternary, coral-dominated limestones (Q1–Q5) separated by unconformities. U-series dates of the subaerial Q5 unit, which includes the Key Largo Limestone and Miami Oolite, indicate deposition during marine Oxygen Isotope Stage (MIS) 5 (Muhs et al., 1992). Other studies associate the Q4 unit with MIS 7 (Muhs et al., 2003), and the Q3 unit with MIS 9 (Multer et al., 2002). Mallinson et al. (2003) have recognized analogous Pleistocene reef units in the Dry Tortugas associated with adjacent underwater terraces. Similarly, Cunningham et al. (2006) identified cyclic patterns of carbonate deposition and subaerial exposure in the Biscayne aquifer of southeast Florida that are related to the Q-units of the Keys. These collected studies from the carbonates of south Florida offer a detailed picture of the timing, duration, and magnitude of high-stands of sea level in south Florida during the Quaternary. The relationship between these limestones of south Florida and the subaerial terraces elsewhere in the southeastern United States, however, is not fully understood.

Florida caves: Quarry exposures in the karst of west-central Florida reveal air-filled caves that are vertically restricted and laterally continuous (Fig. 2). Cave exploration in west-central Florida has shown that many cave passages are wider than they are tall, and that many contain pillars of rock that have not dissolved (Florea, 2006a). The walls of the cave passages are complex with cuspate, pocket-like, or taffoni-like structures. Fissure-like passages in the caves are associated with regional NW–SE and NE–SW fractures, and human-scale passages often occur where fractures and the laterally extensive cavities intersect. The result is a "plus-sign" passage cross-section that characterizes these caves (Florea, 2006a).

The cave mapping in west-central Florida (Florea, 2006a) has also shown that passages do not extend great distances. Horizontal tabular passages pinch into low crawlways and impassable slots. Fissure-type passages thin into increasingly narrowing fractures. Siliciclastic sediment fills and structural collapse features abound. Connections between the caves and the land surface are limited. Caves are discovered mainly because they are encountered during land alteration, particularly in limestone quarrying.

Mostly inaccessible caves are routinely encountered beneath the water table when drilling the Floridan aquifer. As part of a water-resources study of Orange County, Lichter et al. (1968) compiled a figure of side-by-side cores showing that cavities have "widespread vertical distribution (and) are more prevalent in some zones than in others" (Lichter et al., 1968, p. 95). Wilson (1988) reorganized the original data of 88 cavities in 63 wells into a histogram of depth as part of an exploration of cave-diving potential in the Orlando area. About 25% of the wells encountered a cavity in each 100-ft (30-m) depth interval, and 53% of the wells encountered a cavity at 300–400 ft (90–120 m) below sea level. According to Wilson (1988, p. 7) the main cavernous zone "probably formed at grade with (Pleistocene) low stands in sea level."

The idea that the water table in central Florida stood substantially below its present position during Pleistocene glaciations (e.g., Stringfield and LeGrand, 1966; Wilson, 1988) is supported by numerous paleoclimatological studies. Pollen studies in the lake district of central Florida, for example, have shown that many lakes were dry, particularly at the end of the Pleistocene and the Early Holocene (Watts, 1969; Watts and Stuiver, 1980), and that oak-dominated savannahs of the Late Pleistocene and Early Holocene gave way to pine-dominated forests in recent times (Grimm et al., 1993). Little Salt Springs, a

Fig. 2. Photo of highwall at Haile Quarry east of Gainesville in north-central Florida. The highwall is approximately 14 m tall, and the land surface is approximately +27.5 m msl. Note the laterally continuous cavernous zone 7 m below the top of the highwall at +20.5 m msl (Photo by Bruce LaFrenz).

Table 1
Summary of cave maps, surveys, and well records used in this paper

Florida cave survey maps[a]

Cave name	County	Type[b]	n[c]
Alachua Sink	Alachua	w	11
AmberJack Hole	Offshore	w	1
Arch Sink	Pasco	w	6
Big Dismal Sink	Leon	w	27
Big Rat Cave	Alachua	d	1
Blue Grotto	Levy	w	1
Blue Hole Spring	Columbia	w	3
Madison Blue Spring	Madison	w	29
Bonnet Spring	Suwannee	w	4
Briar Cave	Marion	d	14
Cathedral Cave	Suwannee	w	14
Cave 171	Alachua	d	1
Cherry Pits	Alachua	d	3
Church Sink	Leon	w	16
Coon Cave	Dade	d	2
Crystal Beach Spring	Pinellas	w	6
Danger Cave	Citrus	d	1
Dead Man's Cave	Alachua	d	1
Devils' Eye Cave	Gilchrist	w	9
Devistation Cave	Dade	d	3
Dipolder 2 Cave	Hernando	w	6
Dog Drop Cave	Citrus	d	2
Eagles Nest Cave	Hernando	w	28
Fourty Fathoms	Marion	w	4
Herzog Cave	Alachua	d	2
Hog Sink	Alachua	d	3
Hornsby Spring	Alachua	w	14
Howard Park Spring	Pinellas	w	4
Hurricane Cave	Dade	d	3
Indian Spring	Wakulla	w	16
Isabella Spring	Pasco	w	5
Gennie Spring	Gilchrist	w	21
Lineater Cave	Suwannee	w	9
Little Dismal Sink	Leon	w	17
Little Salt Spring	Sarasota	w	2
Little Salt Spring	Hernando	w	5
Manatee Springs	Levy	w	8
McBride's Slough Spring	Wakulla	w	6
Meffert's Cave	Marion	d	1
Old Bellamy Cave	Alachua	w	18
Paradise Springs	Marion	w	1
Peace Cave	Citrus	d	1
Peacock Spring	Suwannee	w	76
Razor Rock Cave	Dade	d	2
Sally Ward Spring	Wakulla	w	12
Schouten Cave	Alachua	d	4
Silver Springs	Marion	w	35
Smather's Cave	Dade	d	1
Squirrel Chimney	Alachua	d	3
Stink Vine Cave	Dade	d	2
Sulphur Springs	Hillsborough	w	23
Suwanacoochee Springs	Madison	w	7
Sweet Gum Cave	Citrus	d	3
Tarpon Springs	Pinellas	w	1
Telford Springs	Suwannee	w	12
Twin Dees Cave	Hernando	w	9
Vandal Cave	Citrus	d	1
Wakulla Spring	Wakulla	w	18
Waldo's Cave	Marion	d	2
Ward Sink	Pasco	w	1
Warm Mineral Springs	Sarasota	w	4

Table 1 (*continued*)

Florida cave survey maps[a]

Cave name	County	Type[b]	*n*[c]
Warren Cave	Alachua	d	20
Waynes World Cave	Pasco	w	9

Drilled well and core records

Well ID	County	Well reference[d]	*n*[e]
Central Citrus Wellfield mw-4	Citrus	(SWFWMD) GB 1025.F55 W52	9
Central Citrus Wellfield well-3	Citrus	(SWFWMD) GB 1025.F55 W52	33
Florida Power mz-2	Citrus	(SWFWMD) GB 1025.F55 G41	14
Florida Power pw-1	Citrus	(SWFWMD) GB 1025.F55 G41	11
Florida Power pw-3	Citrus	(SWFWMD) GB 1025.F55 G41	24
Florida Power pw-3	Citrus	(SWFWMD) GB 1025.F55 G41	21
Florida Power pw-4	Citrus	(SWFWMD)GB 1025.F55 G41	13
Florida Power pw-5	Citrus	(SWFWMD) GB 1025.F55 G41	15
Florida Power pw-6	Citrus	(SWFWMD) GB 1025.F55 G41	19
Florida Power pw-7	Citrus	(SWFWMD) GB 1025.F55 G41	33
Guest Sink	Hernando	Boatwright and Allman (1979)	25
ROMP TR-20-2	Hernando	(SWFWMD) TD 404.5661	51
Sugar Mill Woods smw-5	Citrus	(SWFWMD) GB 1025.F55 S41	15
Sugar Mill Woods smw-6/2	Citrus	(SWFWMD) GB 1025.F55 S41	16
W-13518	Hernando	(FGS) W-13518	3
W-15681	Hernando	(FGS) W-15681	7
W-16001	Citrus	(FGS) W-16001	0
W-17469	Hernando	(FGS) W-17469	9
W-17692	Hernando	(FGS) W-17692	6
W-18154	Hernando	(FGS) W-18154	9
W-34000	Hernando	(FGS) W-34000	29
Weeki Wachee ww-2	Hernando	Hill and DeWitt (2004)	63
Weeki Wachee ww-3	Hernando	Hill and DeWitt (2004)	31
Weeki Wachee ww-4	Hernando	Hill and DeWitt (2004)	24
World Woods l-3	Hernando	(SWFWMD) GB 1199.3.F55 A5	5
World Woods tw-1	Hernando	(SWFWMD) GB 1199.3.F55 A5	41

Caves surveyed in this study

Cave name	County	Length (m)	Type[b]	*n*[f]
Big Mouth Cave	Citrus	96	d	13
Blowing Hole/Jackpot Caves	Citrus	501	d	138
BRC Cave	Hernando	1033	d	276
Floral City Cave	Sumter	300	d	93
Football Cave	Citrus	142	d	29
Legend Cave	Citrus	44	d	12
Morris Cave	Citrus	92	d	12
Thornton's	Sumter	313	d	75
Werner Cave	Citrus	651	d	143

[a] Maps used in this study are the work of several cartographers and are contained within the archives of the Florida Cave Survey, Inc.

[b] Type of cave: (d) cave above present day water table; (w) cave underwater.

[c] Number of spot elevations used from map.

[d] Location of record. (SWFWMD) Record number in the library of the Southwest Florida Water Management District. (FGS) Record number in the core repository archive of the Florida Geological Survey.

[e] Number of foot-length increments with cavities identified.

[f] Number of survey stations. This number is equal to the number of elevation measurements from each cave.

cenote near the present shoreline in southwest Florida, has provided archeological evidence, gathered from ledges at water depths of 26 m, that humans utilized the cenote for fresh water at a time when the water level was at least that low, and the coast was distant (Calusen et al., 1979). Ostracods in the sediments at the base of the cenote indicate a transition from freshwater to brackish water as saltwater intruded with the advancing sea (Alvarez-Zarikian et al., 2005).

The sheer number of caves indicated by these recent studies (Wilson, 1988; Florea, 2006a) implies that human-sized passages are more than curiosities with significance only to cave explorers. They are essential elements of the crucially important Floridan aquifer in central Florida, and they potentially hold key information about the Quaternary history and geomorphology of the peninsula. In particular, a back-of-the envelope calculation by Wilson (1988) puts into perspective the magnitude of the cave-scale porosity. Using the well-cavity data of Lichter et al. (1968) for Orange County in central Florida, Wilson (1988) estimated that the upper part of the Floridan aquifer contains $2.9 \times 10^6\,\mathrm{m}^3/\mathrm{km}^2$ of cave, or, in terms of cylindrical passages with diameter equal to the average cavity height (3.3 m), some 550 km of passage per square kilometer.

3. Level versus datum

Palmer (1987, p. 50) comments as follows about the term *cave level*: "Serious investigators usually restrict the term to large low-gradient passages that appear to represent distinct stages of cave development. This idea assumes that the cave-forming process has concentrated at a particular elevation because of favorable geologic or geomorphic conditions, and that elsewhere in the same cave, or in nearby caves, a similar concentration of passages should exist at the same elevation."

Palmer's comments call attention to a fundamental distinction between the terms *cave level* and *sea level*. Sea level, by definition, is an equipotential surface and, therefore, is horizontal. Cave levels, on the other hand, are not level surfaces; they have low gradients relative to a sea-level datum. To the extent that caves in Florida reflect dissolution along ancient water tables, they will follow complex, low-relief surfaces that intersect the positions of ancient sea level along paleoshorelines and lie above them at locations further inland.

Air-filled caves of today's Florida Peninsula are, by definition, above the present water table. To the extent that they formed along ancient water tables, they date from times of higher-than-present sea levels, when much of the peninsula was submerged (e.g., maps in Cooke, 1939, 1945). At such times, the caves were not far from their contemporaneous shorelines, and so one can expect comparatively precise agreement between the elevation of those cave passages and paleosea levels.

Presently submerged caves on the peninsula, on the other hand, are by definition below the present water table and, to the extent that they formed along ancient water tables, they date from times of lower-than-present sea level. Given the broad shelf west of the peninsula (Fig. 1A), these presently submerged caves would be distant from their correlative paleoshorelines, and so the agreement between cave and paleosea-level elevations would not be as precise as for the air-filled caves. Moreover, one can expect that the frequency of cave elevations for these presently submerged caves on the peninsula would organize better relative to the present water table as a datum than to sea level.

The data of this paper, therefore, partition into two categories in two different ways. One way is by type of data, and the second is by relation to water level. Partitioning by type of data, the two categories are: (1) caves, both air-filled and submerged varieties vs. (2) terraces, both onshore and offshore. Partitioning by relation to water level, the two categories are: (1) above-water features, including both air-filled caves and subaerial terraces vs. (2) underwater features, including both submerged caves and offshore terraces. We will use both categorizations.

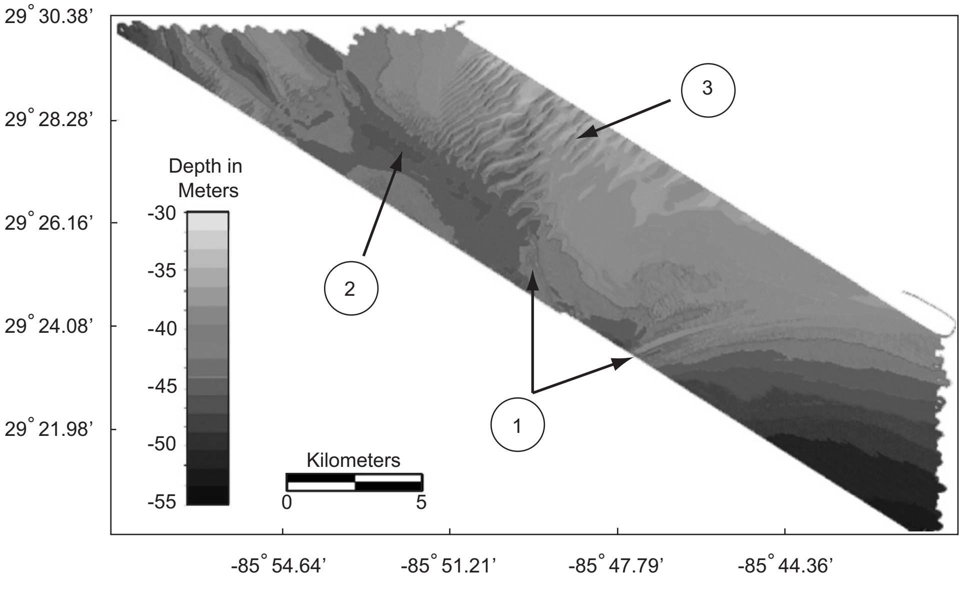


Fig. 3. Multibeam bathymetric data for the Steamboat Lumps region offshore the Florida Panhandle: (1) paleoshoreline features are visible near a break in slope at a depth of 37 m and (2) paleochannel of the Apalachicola River at a depth of 41 m. 3–4-m high sand waves on a submerged marine terrace at a depth of 37 m.

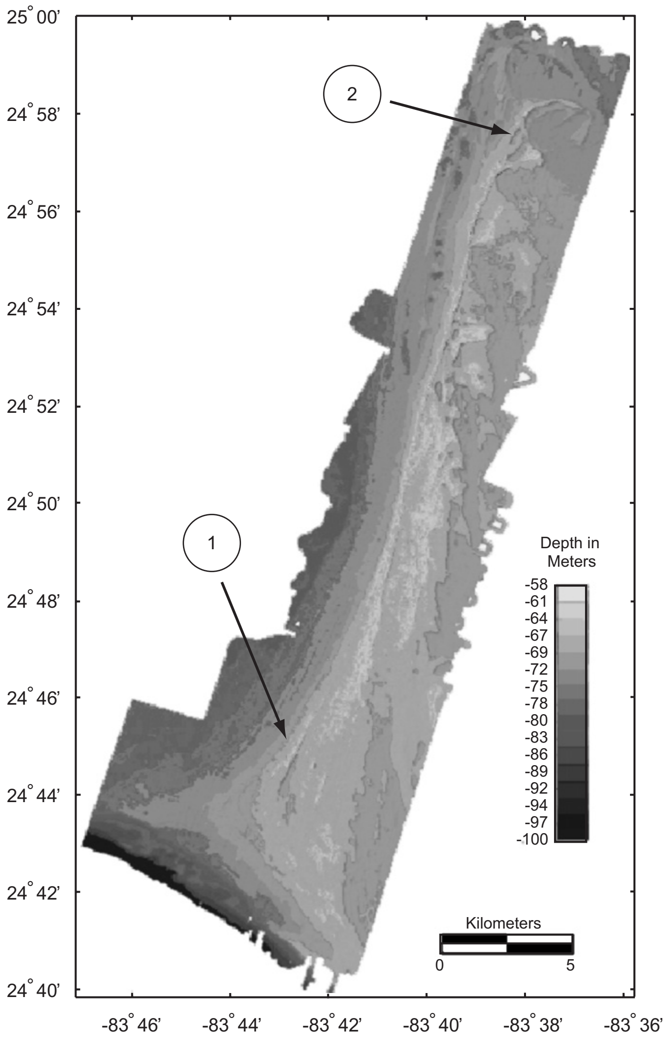


Fig. 4. Multibeam bathymetric data for the Pulley Ridge region offshore south Florida (Jarrett et al., 2005). The data reveal an ancient drumstick-shaped barrier island at a depth of 70 m: (1) accreted beach ridges and (2)—recurved spit.

4. Data

4.1. Caves

Surveys of air-filled caves: To date, the first author and colleague cavers have surveyed seven air-filled caves in the uplands of the Brooksville Ridge of Citrus and Hernando Counties (Florea, 2006a, b) and two additional caves adjacent to the Withlacoochee River (Table 1 and Fig. 1A). The data comprise 791 individual survey stations. Each station includes passage width and height to 0.1 m. Between-station data include distances measured using fiberglass tape that are accurate to ±0.5 cm, and azimuths and inclinations measured with a Suunto compass and clinometer that are accurate to ±0.5°. After processing, these surveys provide 791 cave elevations relative to modern sea level. When no entrance elevation was available, as in the case of three of the caves in a reclaimed quarry, spatial data were obtained using an Ashtech Z-Extreme RTK (real-time kinematic) GPS base station and rover unit. A NOAA-HARN benchmark was the base station.

Spot elevations on archived cave maps: Data from 23 cave maps in the archives of the Florida Cave Survey, Inc., provide an additional 76 spot elevations in air-filled caves (Table 1, Fig. 1A). Seventeen of these caves are in the karst of west-central and north-central Florida (Alachua, Citrus, and Marion Counties). The other six are within the Silver Bluff terrace of Parker and Cooke (1944) in the Biscayne aquifer south of Miami (Dade County) (Fig. 1A).

The Florida Cave Survey Inc. archives also include 40 maps of submerged caves in the unconfined portions of the Floridan aquifer which provide 498 spot elevations (Table 1, Fig. 1A). Eighteen of these caves are in the karst of west-central Florida (Hernando, Hillsborough, Marion, Pasco, Pinellas, and Sarasota Counties). Fifteen others are in north-central Florida (Alachua, Colombia, Gilchrist, Levy, Madison, and Suwannee Counties). The remaining seven are in the Florida panhandle south of Tallahassee (Leon and Wakulla Counties).

The air-filled and the underwater cave maps used for determining spot elevations are of varying quality and detail. The underwater maps are particularly imprecise because they were commonly produced from memory using dive gauge readings for depth, rough azimuth estimates, and lengths given by knots tied on the dive line. However, we used all measurements available from the maps because we could not independently identify the accurate and the inaccurate measurements.

Well logs: Following Wilson (1988), we include cavities noted in well logs. The data are from records of the Florida Geological Survey and Southwest Florida Water Management District for a total of 26 drilled wells and cores in Hernando and Citrus Counties of west-central Florida (Table 1 and Fig. 1A). In addition to the term "cavity," we included "bit drop", "recovery of sand", and "loss of circulation" as synonyms. As the well and core descriptions are recorded in units of feet, we use "foot-length" intervals in each well that intersect cavities. The data comprise 526 recorded foot-length cavities that occur both above and below the water table.

4.2. Terraces

Topographic data: Two sets of publicly available data provide land-based elevations (Fig. 1A). Data for Citrus and Hernando Counties (inset of Fig. 1B) derive from 1.5-m-contour interval DLG (digital line graph) data from the Southwest Florida Water Management District converted into a raster data set of more than 8.4×10^4 data points. Data for Pinellas County originate from a countywide ALSM (airborne laser swath mapping) data set of more than 91×10^6 data points filtered for vegetation and multipath returns (Seale, 2005).

Bathymetric data: Similar to the elevation data for Citrus and Hernando Counties, near-shore bathymetric data

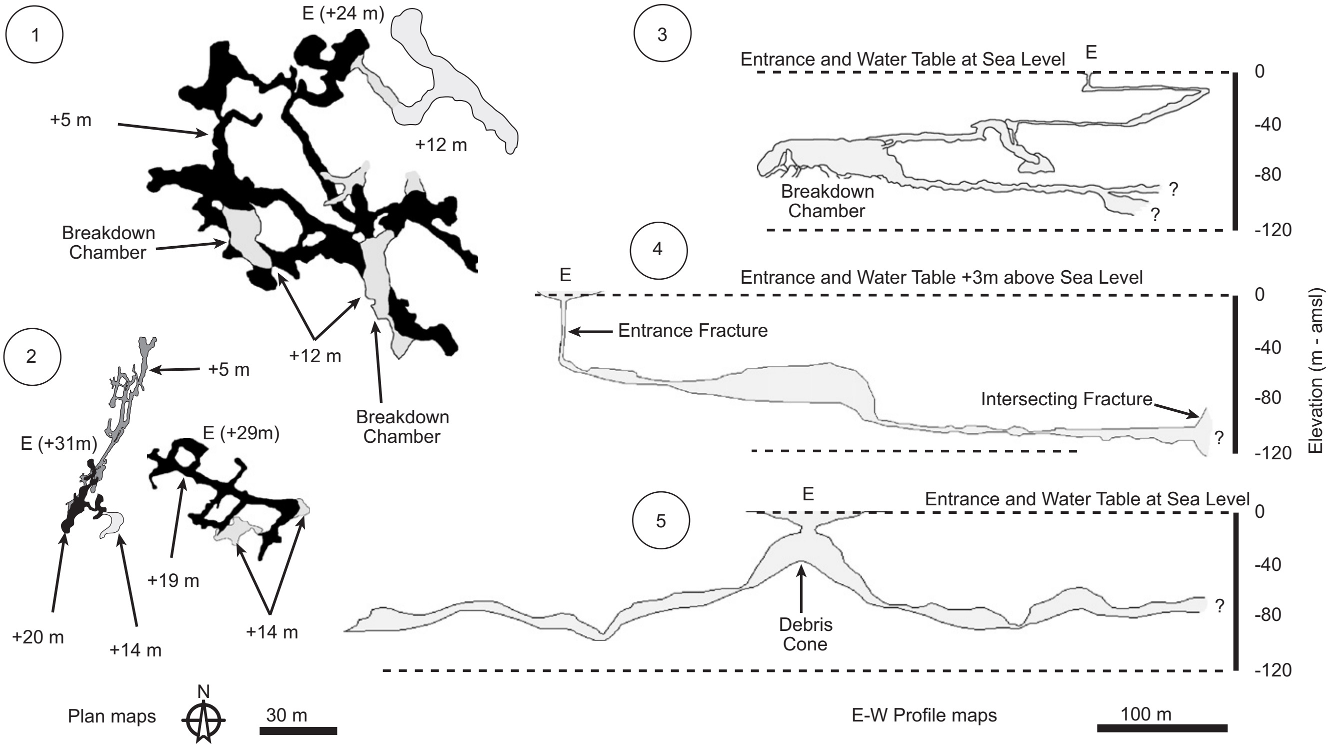


Fig. 5. Examples of cave maps that have levels of passages. 1 and 2 are plan view maps of dry caves within the Withlacoochee State Forest in Citrus County surveyed in this study, and 3–5 are profile maps of underwater caves near the shoreline of Hernando County adapted from maps within the Florida Cave Survey Inc. archives. Both dry caves have distinct levels of conduit development: (1) Werner Cave contains an extensive level near the present day water table at + 5 m, and a less widespread level at + 12 m; (2) Blowing Hole Cave contains a prominent level at + 19 to + 20 m, a less developed level at + 14 m, and an extensive level at + 5 m. The underwater caves reveal several levels of conduit development; (3) Twin-Dees has prominent levels at −15, −40, −70 m, and a deep level around −90 m; (4) Dipolder 2 includes two conduit levels at −70 m and at −100 m to −120 m; and (5) Eagles Nest contains an extensive level of conduit development that ranges between −70 and −90 m.

derive from a 1.5-m-contour interval DLG dataset for a 40-km-wide band off the shore of the Florida Panhandle. The converted raster dataset consists of approximately 1.4×10^6 data points.

For the deeper bathymetric data, we utilized multibeam mosaics along the western Florida shelf near Steamboat Lumps (Fig. 3, 12.5×10^6 data points) and Pulley Ridge (Fig. 4, 1.4×10^6 data points). The multibeam bathymetry and backscatter data were collected using a 300-kHz Kongsberg Simrad EM 3000 corrected for daily tidal variations (He and Weisberg, 2002), compensated for roll, pitch, heave, using a Applanix POS/MVT 320-V2 position and orientation system, and sound velocity profile using a Sea Bird CTD. Caris HIPS software were used to post-process and clean the data.

5. Cave levels

5.1. Sea-level datum

The two maps of air-filled caves and three sections of underwater caves in Fig. 5 illustrate the organization of passages in Florida caves and are representative of the data in our compilation. Each of the air-filled caves has two distinct levels of passage development. Together, the maps document three levels of passages above present sea level: prominent levels at 5 and 21 m, and a less-widespread level between 12 and 15 m. In addition, the underwater caves reveal levels of development at −15, −40, −70 m, and one or more deep levels between −90 and −120 m. It is noteworthy that the levels of passages in these examples are at similar elevations even though several kilometers separate the caves.

All the cave-elevation data—the stations from the seven surveyed caves, the spot elevations from cave maps, and the cavities noted in the well logs—are plotted in the frequency graphs of Fig. 6. All the datasets show prominent horizons of passages, including the passage elevations in Fig. 5. The cave-survey data range between 0 m and + 30 m with modes at + 6 and + 21 m. The spot-elevation and the well-cavity data each range from about −130 to + 35 m. The spot-elevation data have modes at −100, −70, −30, −15, + 5, and + 30 m. The well-cavity data cluster around major modes centered at −12.5 and + 2.5 m.

Not only are the caves in Florida tiered (Fig. 6), the levels extend over large geographical areas at similar elevations. Allowing for scatter, the cave levels cut across large-scale structure of the Floridan aquifer. For example, the cave levels in several of the surveyed caves do not

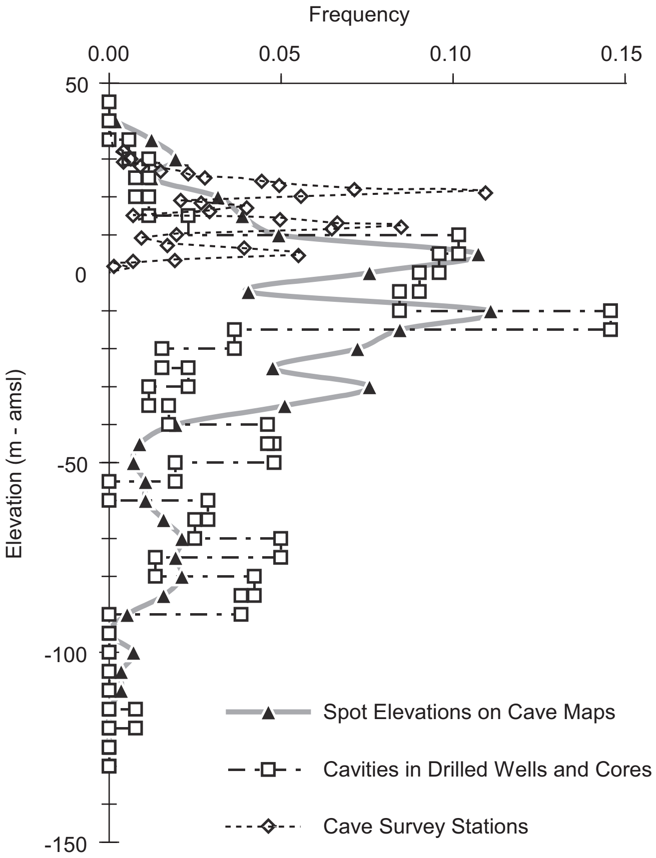


Fig. 6. Histogram of elevations relative to sea level from cave surveys, previous cave maps and well-cavity data (data from sources listed in Table 1). Several peaks are present in each of the data sets.

follow the stratigraphy of the Floridan aquifer; the stratigraphic units are inclined relative to the level of cave development (Fig. 7).

5.2. *Water-table datum*

Although cave survey and spot elevations from air-filled caves occur at the same elevation relative to sea level over wide areas (Fig. 6), the elevations of passages in underwater caves organize better according to depth below the modern water table. Fig. 8 shows the effect on the frequency graph of changing the datum for the elevations of passages that lie below water. In contrast to Fig. 6, which shows all the spot elevations relative to sea-level datum, Fig. 8 separates out the above-water elevations from the below-water elevations and plots the latter relative to the water table. Changing the datum of the underwater elevations brings out a strong mode at −15 m relative to datum. It also reveals previously obfuscated modes at +5 m and +20 m for the air-filled caves relative to sea level, and shifts the relatively small −100 m mode to −105 m.

The significant effect of changing from sea-level datum to water-table datum is well illustrated by a specific example: the case of Twin-Dees Cave vs. Peacock Springs. Twin Dees Cave (map 3 in Fig. 5) contains a prominent level of passage at a water depth of 15 m. The underwater cave system at Peacock Springs, which contains 13% of all the spot-elevation data (Table 1), also has a prominent level of passages at a water depth of 15 m. However, the water table at Twin-Dees Cave, which is near the modern shoreline of Hernando County, is near sea level, and the water table at Peacock Springs, 150 km north and approximately 75 km inland, is at +15 m. Therefore, the two clusters of elevations appear at different positions on the histogram using sea-level datum (Fig. 6) and at the same position when the data are cast relative to the water table (Fig. 8).

Changing the datum for the well-cavity data resulted in few changes. Most of the wells are near the coast, where the water table lies close to sea level.

6. Cave levels compared to terraces

6.1. *Above sea level*

Fig. 9 is a compilation of frequency plots for the topographic and bathymetric data (right), cave data (left), and well-cavity data (left). The cave data include both the cave-survey and spot-elevation data. For all topographic, bathymetric, and cave-survey datasets, the datum is sea level. For the spot-elevation and well-cavity data, the datum for the air-filled caves is sea level and the datum for the submerged caves is the water table.

The Wicomico and lower terraces identified by Cooke in Florida are visible in the combined, Citrus-Hernando and Pinellas topographic data sets at or near the elevations he described (Table 2). Approximately 68% of the land in Citrus and Hernando County lies between +10 and +30 m, and there are prominent modes at +2.5, +14, +22, and +28 m (Table 2). In low-lying Pinellas County, more than 75% of the land is below +10 m; there are prominent modes at +2 and +4.5 m, and two additional modes at +14.5 and +20.5 m (Table 2).

These modes in the topographic data match up with the cave data as follows (Fig. 9, Table 2):

Wicomico terrace: Although caves at the level of the Wicomico terrace (+30.5 m) are not included in the cave surveys, the spot-elevation data contain a prominent, albeit small, mode at this elevation.

Penholoway terrace: Most cave-survey stations occur at the elevation of the Penholoway terrace (+21 m). One of the three principal modes in the air-filled caves of the spot-elevation data is at this elevation.

Talbott terrace: A second strong mode occurs in the cave-survey data at the elevation of the Talbott terrace (+12.8 m). This level is clearly visible in the two air-filled caves included in Fig. 5.

Pamlico and Silver Bluff terraces: The cave-survey data, spot-elevation, and the well-cavity data also reveal a low-elevation mode near the elevations of the Pamlico (+7.6 m) and Silver Bluff (+2.4 m) terraces (Fig. 9, Table 2). Poor

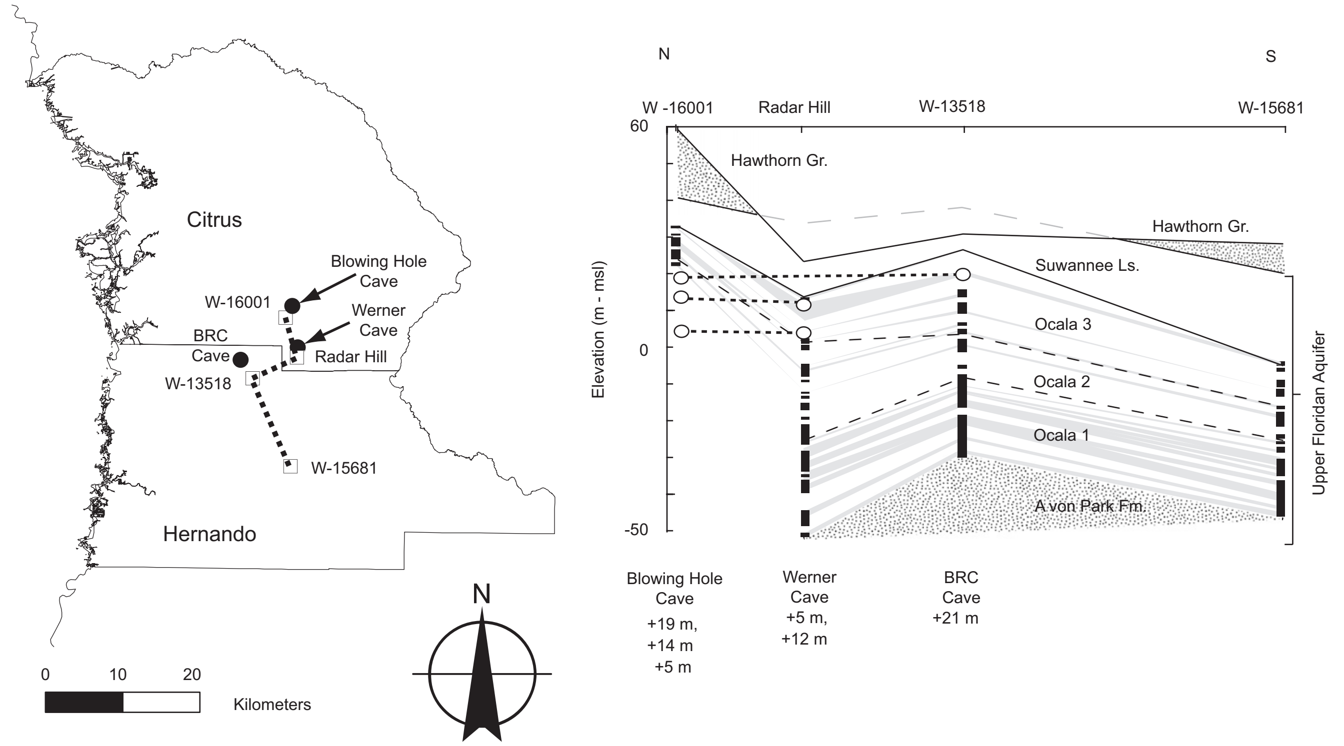


Fig. 7. North-south cross section through a portion of Citrus and Hernando Counties in west-central Florida. Dashed line on the map at left indicates the location of the cross-section. White squares are the wells used for lithologic identification. Black dots are the caves from this study near the cross-section line. On the cross section at right the open circles indicate levels in caves. Principal geologic units are labeled on the cross section. The black rectangles identify grainstones in each core, and the gray-shaded regions are portions of the Ocala Limestone that have matrix permeability greater than $10^{-13}\,\mathrm{m}^2$ (Florea, 2006b). Note that the levels within these caves do not occur in the same geologic units throughout the study area.

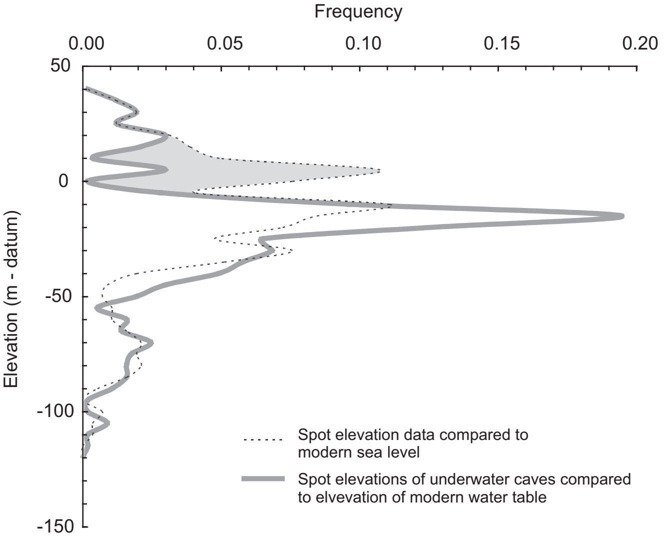


Fig. 8. Spot elevations from cave maps. Data are shown relative to both sea-level and water-table datum. The shaded region represents the spot elevations from underwater caves in the interior that shifted following the correction.

resolution makes it impossible to associate the mode with individual terraces or even to modern water-table conditions.

6.2. Below sea level

The offshore bathymetric data also define modes on a frequency plot (Fig. 9, right panel). These modes, which by definition are relative to sea level, match with modes in the onshore cave data (spot elevations and well cavities) relative to water table, particularly at water depths of approximately 15, 30, and 70 m (Fig. 9).

The matching is less clear below sea level than above sea level. Both the onshore and offshore data have more uncertainty below water. Onshore, the data can be expected to be less accurate because underwater cave surveyors face increased technical challenges and time constraints. Additionally, divers commonly opt for the shallowest path through a cave to increase dive time and reduce decompression, resulting in depth readings in large passages biased toward the ceiling. Offshore, recent sedimentation helps to smear the modes in the bathymetric data. For example (Fig. 3), 4-m-high, kilometer-scale sand waves on a 37-m-deep terrace in the Steamboat Lumps dataset produce a false terrace at −33 m. Nearby, a paleochannel of the Apalachicola River creates another false terrace at −41 m. The terrace in these data at −37 m lies below the mode in the underwater spot-elevation data at −30 m and between the modes in well-cavity data centered at −32.5 and −47.5 m (Fig. 9).

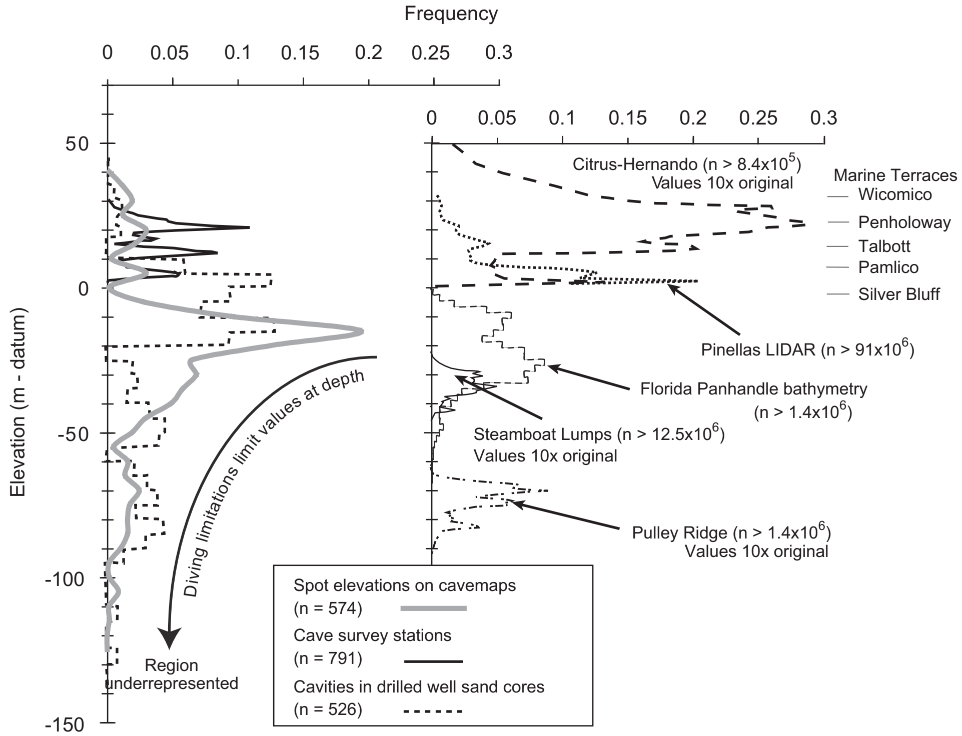


Fig. 9. Frequency of data as a function of elevation for all data sets included in this study. Modes are evident in the data sets. The modes in the cave survey, spot elevations and well-cavity data above present sea level correspond with modes in the elevation spectrums from Citrus-Hernando and Pinellas Counties and also with known terraces, and therefore are an indication of previous sea-level high stands. Likewise the modes in the spot elevation and well-cavity data correspond to modes in the elevation spectrums from multibeam bathymetry data from Steamboat Lumps and Pulley Ridge. By analogy, these modes in the data correspond to sea-level lowstands.

Table 2
Correlation of modes in data from Fig. 9, including subaerial caves and underwater caves, as well as topographic and bathymetric data sets, with marine terraces of Cooke (all data are in meters)

Cooke's terraces	Spot elevations	Cave survey data	Topographic data	
			Cit-Her	Pinellas
Wicomico (30.5)	30	—	28	—
Penholoway (21.3)	20	21	22	20.5
Talbott (12.8)	—	12	14	14.5
Pamlico (7.6)	5	6	—	4.5
Silver Bluff (2.4)			2.5	2.5

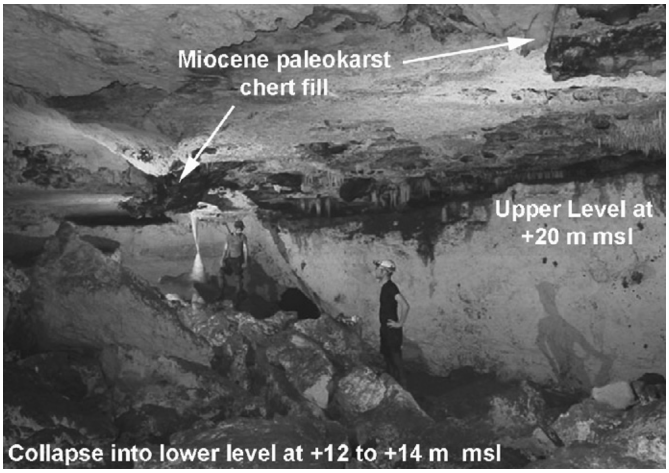


Fig. 10. Collapse feature in Briar Cave that connects the laterally continuous upper level at +20 m msl with the lower level at the modern water table which ranges between +12 and +14 m msl. Miocene paleokarst fill is visible as chert pendants hanging from the ceiling (Photo by Sean Roberts).

The strongest mode in the underwater spot-elevation data is at −15 m. This water depth matches with a sediment-smeared mode in the bathymetric data offshore of the panhandle at a depth of 10–15 m (Fig. 9). This bathymetric mode in our data agrees with paleoshoreline features identified by Rodriquez et al. (2000) at −15 m from the Texas shelf.

Paleoshoreline indicators provide additional evidence of paleosea-level elevations at other sites. For example, traces of ancient barrier islands are visible at a depth of 37 m in the Steamboat Lumps data (Fig. 3). In another example, an ancient, drumstick-shaped barrier island, complete with accreted beach ridges and a re-curved spit, is visible in the Pulley Ridge data (Fig. 4) at a depth of 70 m (Jarrett et al., 2005). This depth corresponds to the strongest mode in the bathymetric data (Fig. 9) and is within the depth range of the paleoshorelines identified by Locker et al. (1996). Smaller modes at −73 and −80 m in the Pulley Ridge data correspond to the depth to the lagoon behind the barrier

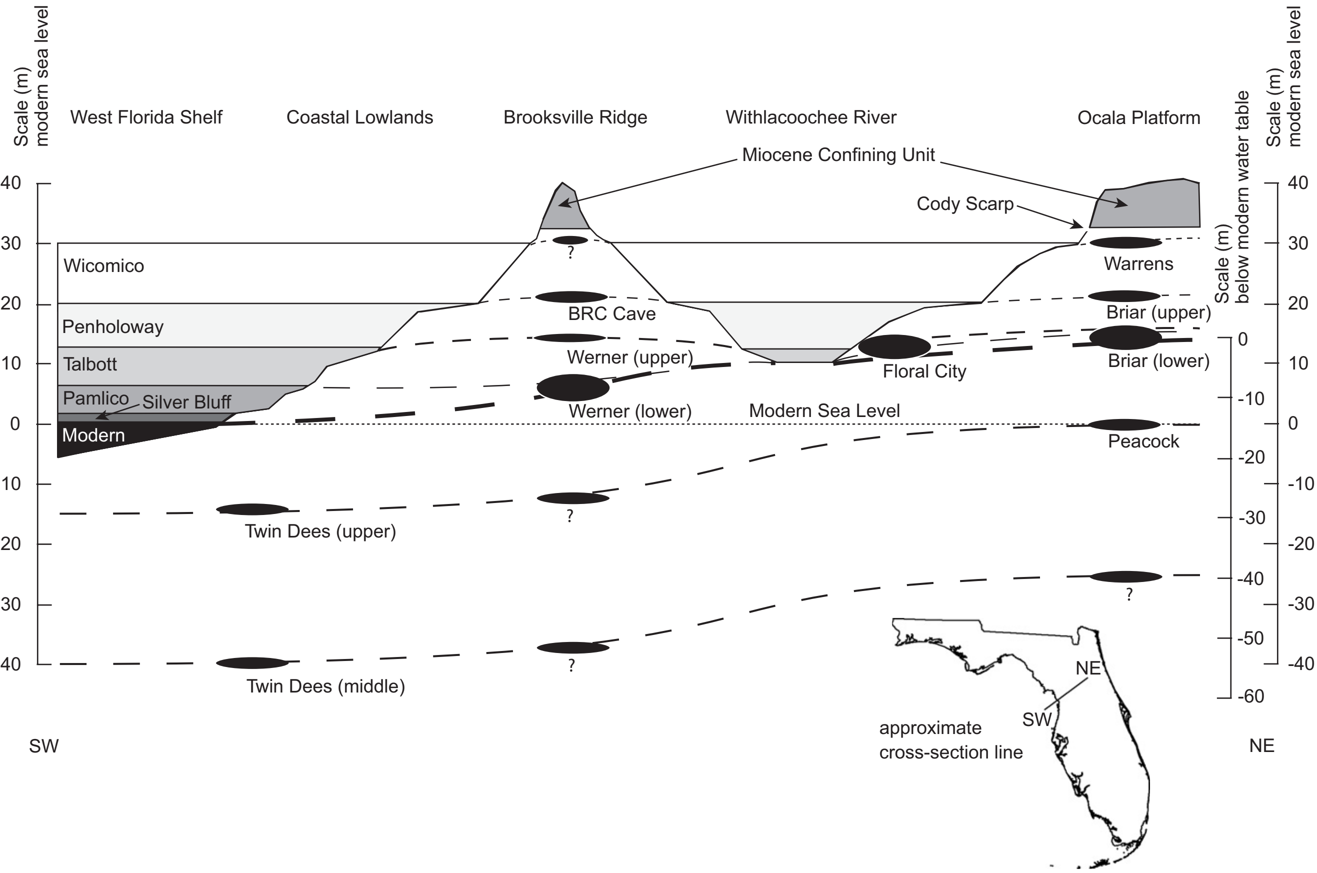


Fig. 11. Concept sketch of the how cavernous porosity in the upper part of the Floridan aquifer of west-central Florida connects to paleowater tables and paleoshorelines. Index map at lower right indicates the approximate location of the vertically exaggerated cross-section which is not to scale. Note 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. Paleosea levels relative to Cooke's terraces are identified. Black ovals identify 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 paleowater tables that intersect the caves. Note that multiple paleowater tables may occupy some cavernous horizons, as in the case of the lower level of Briar Cave. Also note that the paleowater tables are not horizontal surfaces. Rather, they grade to their contemporaneous paleoshorelines. The inflection in the paleowater tables beneath the Withlacoochee River reflects recharge to the Floridan aquifer by the river and reduced permeability in the aquifer caused by sediments that infiltrate karst features in the river bed.

island and the depth to the near-shore wave-base, respectively (Fig. 4). The −70 m modes in the bathymetric data, in particular, correspond with the broad −70 m mode in the underwater-cave spot-elevation data.

We have no offshore bathymetric data below 100 m. Small modes in the spot-elevation and well-cavity data (Fig. 9) and a strong mode in the well-cavity data of Wilson (1988), however, suggest one or more cave levels at depths that range between 100 and 120 m below the water table. Cave levels at this depth are also visible in Fig. 5. Such deep cave levels are in the range of the lowest paleoshoreline identified by Locker et al. (1996) and suggest a match with the well-known −120 m sea-level lowstand during the last glacial maximum (Fairbanks, 1989) as suggested by Wilson (1988). These deeper cave levels, however, potentially result from the cumulative effects of multiple sea-level lowstands, not just dissolution associated with the sea level of the last glacial maximum. Precise data from deep, underwater caves can be expected to be meager because of the extreme technical challenges of deep cave diving. Underwater cave data are biased toward the shallower and easier-to-explore levels.

7. Discussion

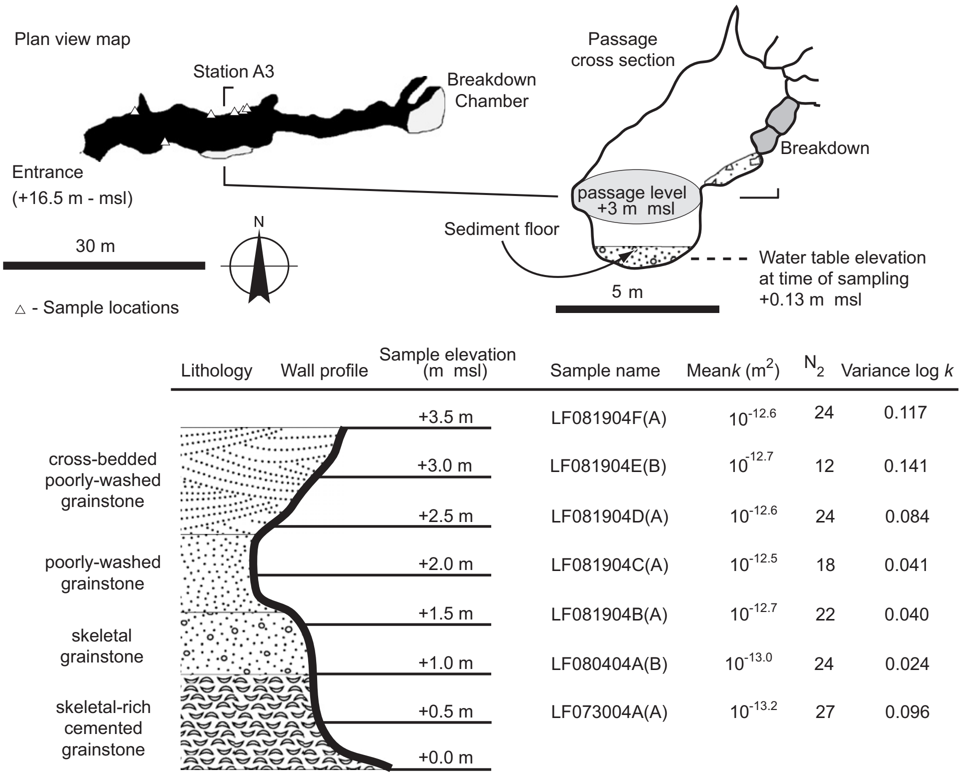
As predicted by Stringfield and LeGrand (1966), caves in the Florida Peninsula occur in levels and, judging from their alignment with terraces, they accord with the hypothesis that speleogenesis occurred along paleowater tables grading to Quaternary paleosea levels. The case can be best made from the highest, air-filled caves, which align with the Wicomico and Penholoway terraces.

When paleosea level was at the elevation of the 30-m Wicomico terrace nearly all of west-central Florida was flooded (Fig. 2B). Limestone exposed beneath dry land was limited, and therefore so was cave development. The shoreline must have been close to the site of water-table dissolution, and the water table must have been at the level of sea level or only a little higher. This is the level of Warren's Cave, which contributes to the ~30-m mode in the spot-elevation data of Fig. 9 and is the only cave in our compilation with passages at this high level. With more than 6 km of mapped passage, Warren's Cave, which is along the Cody Scarp at the edge of the unconfined aquifer (Fig. 2A), is currently the longest surveyed air-filled cave in Florida. Much of Warren's Cave formed in a semi-confined environment just below the contact with siliciclastics of the Miocene Hawthorn Group. In fact, the ceilings of the highest passages in Warren's Cave are composed of the Hawthorn Formation. With that contact ranging between elevations of +20 and +40 m in the northern half of peninsular Florida (Scott et al., 2001), there should be few if any horizontal cave passages higher than the Wicomico terrace.

Many of the known caves above the modern water table in Citrus and Hernando Counties occur at the elevation of the 20-m Penholoway terrace which marks another time of extensive submergence with relatively narrow emergent land areas and, therefore, a small difference between water table and sea level. One of these Penholoway-level caves is BRC Cave, which has more than 1 km of surveyed passage (Table 1). Several caves along the Cody Scarp also formed at the elevation of the Penholoway terrace. One is Briar Cave, which also has more than 1 km of surveyed passage. Briar Cave has two distinct levels, which connect by collapses and solution-enlarged fractures (Fig. 10). The upper level averages +20 m msl. All these observations agree with the matching of the Penholoway terrace with the major mode in the air-filled cave-level data of Fig. 9.

Matching terraces and cave levels below the Penholoway terrace is less straightforward. The next terrace in the succession is the 12.8-m Talbott terrace (Table 2). The mode in the cave-survey data come principally from the two caves near the Withlacoochee River—Floral City and Thornton Caves—although there are several caves in the Brooksville Ridge with passages near this position (e.g., Fig. 5). Many other caves in peninsular Florida contain passages at the elevation of the Talbott terrace, particularly along the Cody Scarp to the north and east of the Withlacoochee River. One such example is Briar Cave where the lower level of Briar Cave is at 12–14 m. In analogy with the Wicomico and Penholoway levels, such caves may represent a former water table close in elevation to the Talbott paleosea level at a position close to the Talbott paleoshoreline.

The lower level of Briar Cave and the entirety of Floral City and Thornton Caves, however, are occupied by the modern water table, which suggests another possibility. Given how the water table can be captured by the infinite-permeability horizon of a cave passage near the top of the saturated zone (Rhodes and Sinacori, 1941; LeGrand and Stringfield, 1971), it is possible that the formative water table at the Talbott elevation in these three caves was graded, at one time or another, to one or more of the Talbott, Pamlico, or Silver Bluff paleoshorelines, just as the modern water table in Briar Cave is graded now to the present shoreline. In other words, the lower level of Briar



Sample elevation (m msl)	Sample name	Mean k (m^2)	N_2	Variance log k
+3.5 m	LF081904F(A)	$10^{-12.6}$	24	0.117
+3.0 m	LF081904E(B)	$10^{-12.7}$	12	0.141
+2.5 m	LF081904D(A)	$10^{-12.6}$	24	0.084
+2.0 m	LF081904C(A)	$10^{-12.5}$	18	0.041
+1.5 m	LF081904B(A)	$10^{-12.7}$	22	0.040
+1.0 m	LF080404A(B)	$10^{-13.0}$	24	0.024
+0.5 m	LF073004A(A)	$10^{-13.2}$	27	0.096

Fig. 12. Matrix permeability of wall samples in Morris Cave (Florea, 2006b). Note that the sample with the greatest matrix permeability (LF081904C(A), $10^{-12.5}$ m^2) aligns with the elevation of principal passage development at +2 m msl.

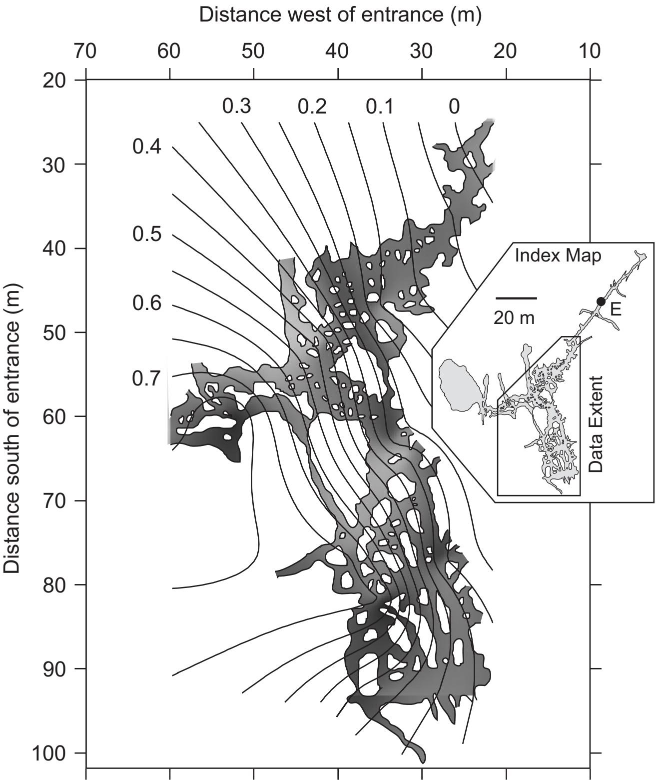


Fig. 13. Map of a portion of Floral City Cave (see index map inset). Contours on the map designate the elevation of a 0.5-m tall laterally continuous horizon with respect to a water table datum of 10.8 m msl (contour interval is 0.05 m). The northern and eastern sections of the cave are principally tall, narrow fractures where the laterally continuous horizon plunges beneath the level of passage.

Cave may be multigenerational. By implication, lower cave levels would have a similarly complicated history.

Based on such considerations, Fig. 11 summarizes our conception of how caves, paleowater tables, and paleoshorelines connect in the karst of central Florida. The sketch illustrates four concepts regarding the nature of the connection:

1. The levels in air-filled caves occur at consistent elevations above modern sea level over widespread areas. For example, BRC Cave and Briar Cave, separated by more than 60 km, both have levels at the elevation of the Penholoway terrace. The paleoshoreline was close to both of these caves at the time the level of passage formed along a paleowater table elevation close to paleosea level.
2. Submerged cave levels organize according to depth below the modern water table. For example, passage levels in both Peacock Springs and Twin Dees, separated by approximately 150 km, occur at a water depth of 15 m. The paleoshoreline was much further from Peacock Springs than from Twin Dees at the time the level of passage formed along a sloping paleowater table.
3. Because the paleowater tables are not horizontal surfaces and grade to their contemporaneous paleoshorelines, some cave levels at or below the modern water table may represent multiple generations of passage development. This may be the case of Floral City, Thornton's, and the lower level of Briar Cave, which occur at the elevation of the Talbott terrace yet remain partially flooded in the modern water-table configuration.
4. Finally, a single paleowater table can pass through cave levels associated with different terraces. Such stair-stepping occurs because later water tables reoccupy zones dissolved by earlier water tables, and, as the shoreline occupies new positions with different sea-level stands, the configuration of the shoreline changes causing a single location to be a vastly different distance from the new shoreline. As a result, the present water table can pass through a Talbott-associated cave level in the Ocala Platform and a Pamlico-associated cave level beneath the Brooksville Ridge while at the same time connecting to modern sea level at the present shoreline.

In the same way that a single paleowater table can connect caves dating in part from various sea-level stands, it is possible, indeed likely, that cave levels can step between various favored intervals within the stratigraphy (Klimchouk, 2003). The limestones of the Floridan aquifer retain their depositional permeability (Budd and Vacher, 2004), and the karst of west-central Florida is eogenetic karst (Florea and Vacher, 2006). Matrix permeability of the Floridan aquifer is anything but homogeneous; it correlates with depositional texture and ranges over three orders of magnitude. The overall preponderance of the matrix transmissivity occurs within grainstones that aggregate to a minority of the total bed thicknesses (Budd and Vacher, 2004). Therefore, even though our data affirm the hypothesis that the caves occur in levels that formed along former water tables connected to paleoshorelines, it is altogether possible that the levels of individual caves also correlate with favorable stratigraphic or lithologic positions.

Two lines of evidence from this study support the potential for lithologic control on cave levels. The first is from Morris Cave where seven core samples of the wall rock that align along a vertical profile reveal a higher matrix permeability at the level of primary passage development in the cave (Fig. 12; Florea, 2006b). The second line of evidence comes from the map of Floral City Cave (Fig. 13) where the passages have two distinct morphologies: solution-enlarged fractures up to 4 m tall and less than 1 m wide, and a laterally continuous horizon that averages 50 cm tall and supported by rock pillars. The laterally continuous horizon in Floral City is inclined to the water table, but is everywhere in the cave within the seasonal range of the water table which can fluctuate in the karst of Florida by more than 2 m (Florea and Vacher, 2007). In the northern and eastern sections of Floral City, the laterally continuous horizon disappears as it plunges beneath the level of cave development and fracture passages dominate (Fig. 13).

Similar to favorable lithologic horizons, Eocene paleokarst near the top of the Avon Park and Ocala Limestones, identified in core by Budd and Vacher (2004), may focus groundwater flow and influence the location of modern cave development. End-Oligocene paleokarst features in Florida, in contrast, are filled with Miocene age siliciclastics (Yon and Hendry, 1972) that can inhibit modern cave development. One such example is in the upper level of Briar Cave where paleokarst fills of chert remain as pillars and ceiling pendants (Fig. 10).

The effects of favorable stratigraphic horizons and paleokarst, combined with a larger coverage of Miocene siliciclastics in the past (Scott, 1988) may have combined to produce hypogenic flow conditions in the upper Floridan aquifer that could have initiated cave development or overprinted the morphology of existing cave passages. In fact, many of the caves in this study display features often associated with hypogenic conditions in other settings such as blind pockets, deep feeders, transverse fractures, rising cupolas, and outlet springs (Klimchouk, 2003). Furthermore, several underwater caves in Florida such as Sulphur Springs (Table 1) have deep vents that discharge sulfate-rich waters rising from a deeper source (Garmin, 2002) that clearly indicate the existence of hypogenic speleogenesis in Florida.

Finally, the location of the freshwater–saltwater mixing zone is a consideration in the formation of caves in coastal environments. The classic example comes from the Late-Pleistocene flank-margin caves of the Bahamas (Mylroie and Carew, 1995). More recently, Smart et al. (2006) demonstrated that the levels of extensive caves in the Yucatan Riviera are deeper inland than close to the coast consistent with the notion that they formed along the base of the freshwater lens. The hydrogeology of Florida, however, differs greatly from the Yucatan or the Bahamas. The freshwater lens is much thicker, a fact attributed to the presence of Miocene siliciclastics by Back and Hanshaw (1970). To the extent that caves formed along the mixing zone in Florida during sea levels equal-to or lower-than modern conditions, they would be at depths greater than that considered in this study except near the coast, where some near-shore and offshore springs discharge brackish water.

At higher than modern sea levels, particularly at the elevation of the Wicomico and Penholoway terraces, the freshwater lens would be much thinner and the paleoshoreline was relatively close to these caves. Therefore, much like the flank-margin caves of Mylroie and Carew (1995), the elevation of paleosea level, paleowater table, and the paleomixing zone may have occurred within a range not resolvable using our dataset.

8. Conclusion

The elevations of mapped caves and drilled cavities group into distinct modes in frequency graphs. This finding that caves occur in levels is consistent with Swinnerton's notion that submerged caves of the Florida peninsula formed along former water tables and Stringfield and LeGrand's more general hypothesis that the former water tables reflect Quaternary sea-level stands. Air-filled caves occur at consistent elevations relative to present sea level and align with Cooke's classic marine terraces, which lie nearby and formed during periods of higher sea level when large portions of the Florida Peninsula were submerged. The underwater caves occur at particular depths below the present water table and generally align with distant submerged terraces and offshore paleoshoreline features. In both air-filled and underwater caves, the range of elevations within particular levels are likely the product of second-order influences such as variations in lithology that include paleokarst features and confining units, and the presence of mixing zones.

The principle that cave levels connect to changing base levels was worked out in the telogenetic karst of the Mammoth Cave area. We have shown that the principle applies also to the eogenetic karst of peninsular Florida. Both are examples of glacial control: one results from the effect of Quaternary ice sheets on proglacial rivers; the other results from the effect of the ice sheets on sea level. Conceptually, cave levels can be regarded as part of Daly's (1934) "Changing World of the Ice Age."

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