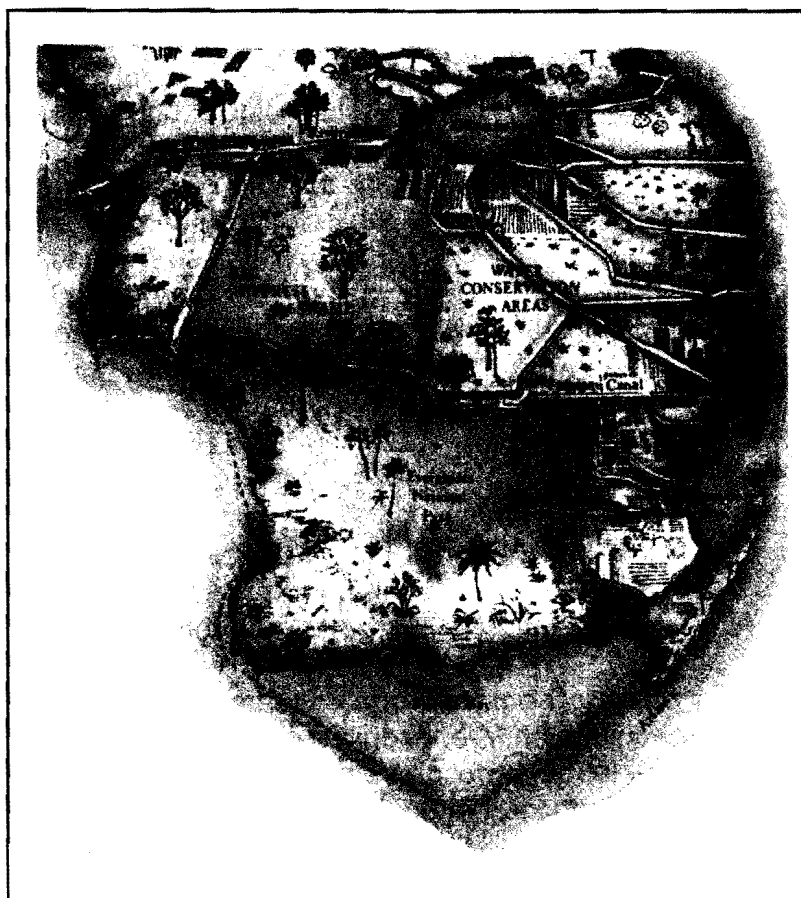


Record # 121901

Hydrogeologic Fieldtrip Everglades National Park, Southeastern Florida

January, 2005



**Compiled by:
Kevin J. Cunningham**

**With contributions by:
Don Hickey
Donald F. McNeill
Laura Guertin**

TABLE OF CONTENTS

Fieldtrip Stops

- 1 Stop 1 Royal Palm Area – Pinnacle karst
- 2 Stop 2 Old Ingraham Road – Holocene sinkhole and cave
- 3 Stop 3 Daniel Baird Road – Miami Limestone trench exposure
- 4 Stop 4 Long Pine Key Nature Trail – Subterranean habitats
- 5 Stop 5 Rock Reef Pass – Rock ridges
- 6 Stop 6 Pa-Hay-Okee Overlook – The River of Grass
- 7 Stop 7 Paurotis Pond – Freshwater marl

South Florida Climate

Temperature

Rainfall

Hurricanes and Tropical Storms

Physiography of South Florida

The Everglades Province

The Atlantic Coastal Ridge

The Big Cypress Swamp Province

The Coastal Marshes and Mangrove Swamp Province

Sea Level History

Pleistocene Sea Level

Holocene Sea Level

Geologic History of the Southern Florida Peninsula

Deep Basement of South Florida

History of the Florida Platform

Stratigraphy of the Subsurface and Surface Deposits of ENP

Arcadia Formation (Late Oligocene-Middle Miocene)

Peace River Formation (Late Miocene-Pliocene)

Long Key Formation (Late Miocene-Pliocene)

Fort Thompson Formation (Pleistocene)

Miami Limestone (Late Pleistocene)

Surficial Geology of Everglades National Park

Pleistocene Bedrock – Miami Limestone

Subaerial Exposure and Karstification

Holocene Deposits

Freshwater Peat and Organic Muck

Freshwater Marl and Cyanobacteria Mats

Coastal Mangrove Sedimentation

Marine Marl (Flamingo Marl)

References

Supplemental Figures

Selected Recent Publications on the Subsurface Geology of South Florida

FIELDTRIP STOPS

Stop 1: Royal Palm Area

Site: Last part of Pleistocene oolitic limestone as the Atlantic Coastal Ridge bends away from the coast, ridge ends about 12 miles to the west

Highlights: Small-scale surficial pinnacle karst at the upper surface of the Miami Limestone

Stop 2: Old Ingraham Road

Site: Eastern side of Old Ingraham Road

Highlights: Sinkhole and cave developed in the Miami Limestone

Sinkholes and pits like this collect organic material, which produces water of relatively low pH that causes further dissolution

Stop 3: Daniel Baird Road

Site: Exposure of Miami Limestone in trench on north side of road

Highlights: Irregular network of large-scale porosity

Comparison of highly porous, non-bedded, homogeneous peloidal grainstone to low-amplitude radar facies

Stop 4: Long Pine Key Nature Trail

Site: Transition between "finger glades" and pinelands

Highlights: View monitor wells drilled for sampling of subterranean animals by biologists from the USGS Biological Research Discipline and Everglades National Park

Examine ground-penetrating radar line collected at site that shows a paleo-sinkhole

Examine digital borehole images and caliper logs to compare porosity development at a well drilled into the sinkhole and a well drilled to the southeast of the sinkhole.

Stop 5: Rock Reef Pass

Site: Subtle elongate limestone ridge (elevation ~3 ft) that rises 1-2 feet above surrounding limestone. Origin of these elongate ridges is uncertain

Highlights: Observe the thin, elongate limestone ridge that rises from the surrounding limestone – control local drainage

Note heavily karsted surface on the elevated topography

View vegetation change associated with subtle elevation change along the ridge

Proposed origins include faulting, fractures, diagenetic features, karstic features, paleotopographic features that developed in a lagoon or bay

Stop 6: Pa-Hay-Okee Overlook

Site: Hardwood hammock adjacent to freshwater slough where sawgrass peat is accumulating

Highlights: Overlook is on the southeast border of the Shark River Slough where abundant sawgrass fills this topographic depression in the underlying limestone

Sawgrass accumulation forms a black, fine-grained freshwater peat, thickness of the peat accumulation is usually between 1 and 3 ft

Sawgrass peat section often includes charcoal from dry-season

Slough contains elongate tree islands or hammocks that are aligned with the direction of drainage

Origin of hammocks appears to be irregular – some form on elevated limestone, others in limestone depressions, and the remainder on a thick (10-15 ft) foundation of freshwater pond

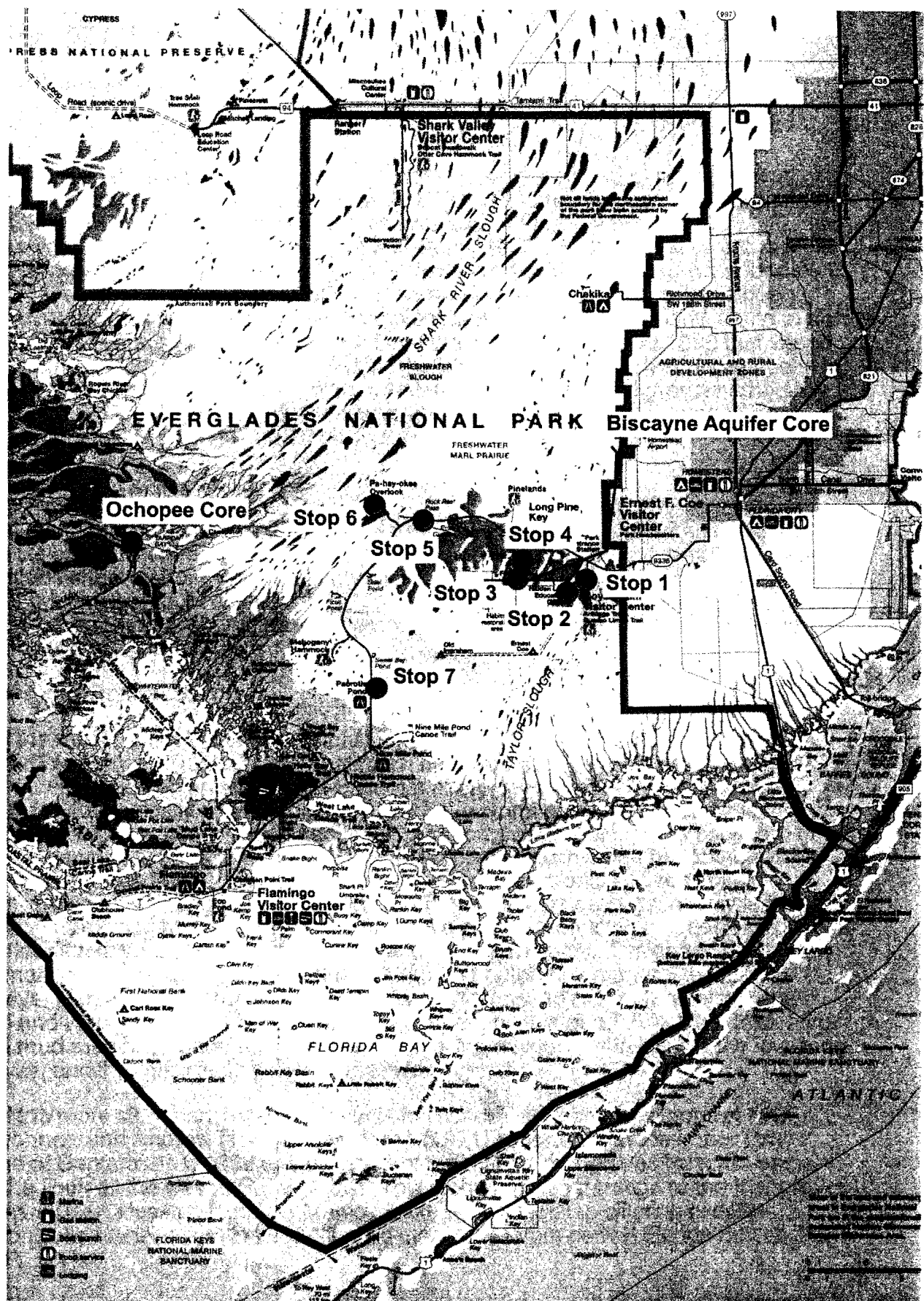


Stop 7: Paurotis Pond

Site: Roadside stop at the transition between the freshwater marl prairie and the coastal mangrove belt

Highlights: Site of freshwater marl (low-mg calcite) formation through biological precipitation by filamentous cyanobacteria

Two main cyanobacteria: genus *Scytonema* and *Schizothrix*, they form a mat-like configuration that floats on the water surface during the wet season



Field trip stop location map.

REGIONAL SETTING

South Florida Climate

Temperature

South Florida climate is dominated by warm, humid conditions typical of its subtropical location. Average temperatures are in the mid-70° for the area comprising Everglades National Park. Average daily summer temperature is about 80°F, while winter temperatures average near 60°F (Schomer and Drew, 1982). Winter freezes are rare on the southernmost peninsula, as temperature is moderated by the adjacent water bodies, the Atlantic Ocean and the Gulf of Mexico. Several severe freeze events have been recorded over the past century and have impacted many of the tropical plants found in and around ENP. Craighead (1971) reports on severe freezes in 1894 and 1895 that wiped out much of the regional citrus industry. Within the ENP boundaries, a destructive freeze in 1899 at Flamingo and Cape Sable was reported to have killed many full grown mahogany trees (Craighead, 1971). Several other severe events that inflicted tree damage are detailed by Craighead (1971) in his book *The Trees of South Florida*.

Rainfall

Rainfall in south Florida in the vicinity of Everglades National Park has an annual average of between 52 and 60 inches (Water Resources Atlas of Florida, 1984). Monthly average rainfall values show a strong seasonal pattern. The months of May through October produce the highest amount of rainfall in south Florida. The dry season, where rainfall is 3 inches or less per month, spans from November through April (records from the South Florida Water Management District, 1993).

Hurricanes and Tropical Storms

Some of the most severe weather to impact Everglades National Park result from tropical storms and hurricanes. Tropical storms that reach hurricane strength (>75 mph winds) impact areas of south Florida on an average of once per every seven years (Neumann et al., 1978; 1981). Geologically, these storms usually have storm surges that flood coastal areas with sediment-laden waters. These sediment transport events tend to add sediment to the coastal levees and inland peat swamps. Depending on the path of the hurricane, wind-driven waves can erode local shallow marine and beach sediments and redistribute sediment landward. Other geological effects include vegetation damage, mainly in the form of uprooting hardwood trees and killing of mangrove plants, producing a sudden infusion of organic debris and potential mobilization of that decaying material. Craighead describes coastal mangrove die-off from a hurricane in 1960 and noted that mangroves below a certain level were killed, relative to those slightly more elevated (>1 foot) or inland, that survived and were refoliated. He suggests that the deposition of a 0.5 to 1.0 ft thick layer of storm mud may have been responsible for reducing oxygen availability in the low-lying mangroves, and thus smothering their chances for regrowth.

Three of the more significant hurricane events to impact ENP were the storms of 1935, 1960 (Donna), and Andrew (1992). Craighead (1971) reported that the Labor Day hurricane of September 1, 1935 destroyed all of the mature mangroves from the eastern side of the Park all the way to Cape Sable. This storm did little damage to the mangroves in the Shark River areas and north to Marco Island, likely a result of differing coastline orientation. Hurricane Donna in 1960 affected mangroves from central Florida Bay all the way to Ft. Myers.

Physiography of South Florida

The physiographic provinces that compose the Everglades and surrounding areas are summarized in Figure 1.

The Everglades Province

The Everglades province forms a low lying area between the Atlantic Coastal Ridge to the east, the Sandy Flatlands area to the north, and the Big Cypress Swamp to the west (Figure 2). The Everglades basin has an extremely low slope from its elevation at the northern end (12-14 feet) near Lake Okeechobee to sea level at its southern end near Florida Bay. This subtle topographic relief, prior to human alteration, formed a slow drainage system from north to south.

The Atlantic Coastal Ridge Province

The Atlantic Coastal Ridge, bounding the Everglades on the east, ranges in elevation from about 5 to 20 feet in its southernmost part. This coastal ridge is composed of Pleistocene marine limestones with a discontinuous, thin veneer of quartz sands. The Atlantic Coastal Ridge is about 3 to 5 miles wide through much of its length in Martin, Palm Beach, Broward, and Miami-Dade Counties. At its southern terminus in southern Miami-Dade County, it widens to almost 10 miles. This southern part of the ridge is breached in places by lower elevation sloughs that are oriented perpendicular to the trend of the ridge. These sloughs, or transverse glades as they are called, represent former tidal channels in the ooid sand shoals that formed in the late Pleistocene Miami Limestone.

The Big Cypress Swamp Province

The Big Cypress Swamp forms much of the western boundary for the Everglades physiographic province and part of the western component of Everglades National Park. The Big Cypress Swamp occupies land that is slightly higher than the Everglades basin. The higher elevation is related to the occurrence of the Tamiami Formation, a Pliocene limestone deposit, containing coral reefs, that accumulated during elevated sea level highstands some 3 to 4 million years ago. The Tamiami Formation outcrops in large areas of this province, and in shallow pockets has a thin, marly soil developed (Parker and Cooke, 1944). Overall, drainage in Big Cypress is to the south and southwest. Standing water and organic accumulation is less widespread than in the Everglades basin.

The Coastal Marshes and Mangrove Swamp Province

The southern parts of the Everglades and Big Cypress Swamp provinces are bordered by the Coastal Marshes and Mangrove Swamp physiographic province (Parker and Cooke, 1944). This area is composed of a band of swamps and brackish marshes, at or just above sea level. This province spans from the northeastern part of Florida Bay, around the southern peninsula, and into the Gulf of Mexico up to the Ten Thousand Island region. This coastal rampart is often inundated by freshwater runoff as well as by saline water related to normal tidal exchange. Thus, vegetation is dominated by mangroves, capable of withstanding extremes in salinity, from completely freshwater to hypersaline water.

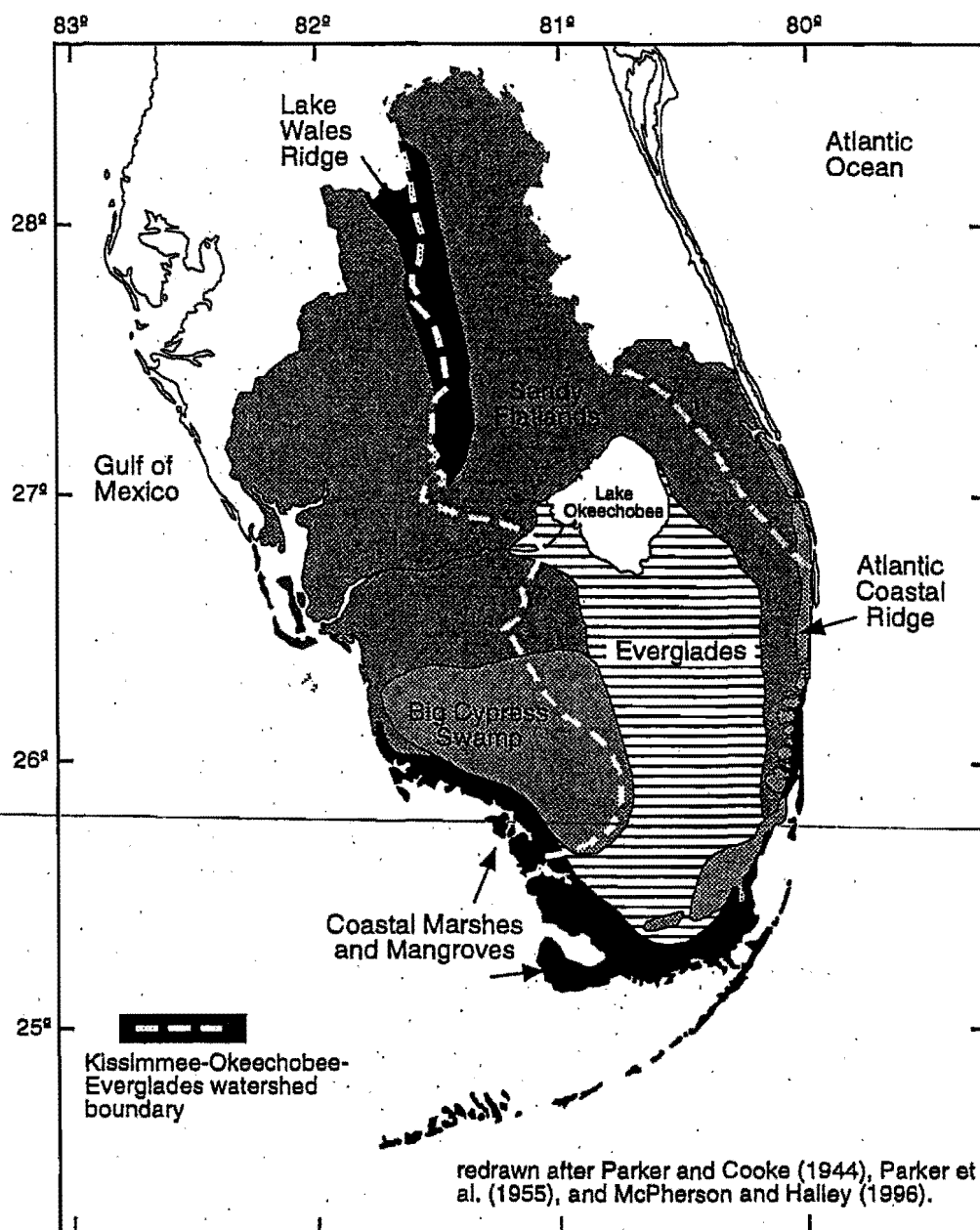


Figure 1. Physiographic regions of comprising Everglades National Park and south Florida.

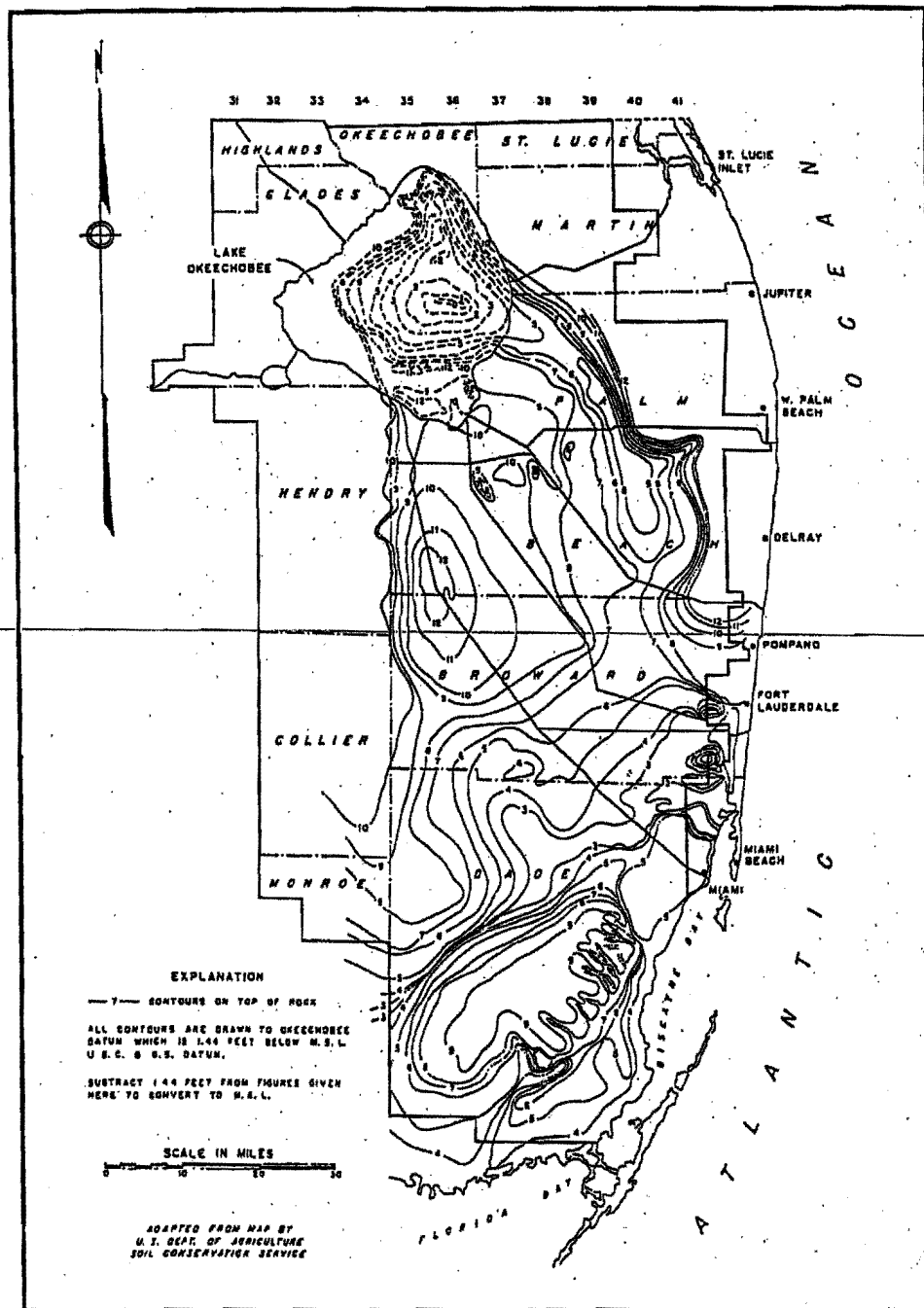


Figure 2. Depth to rock floor in the Everglades. Figure from Parker and Cooke (1944)

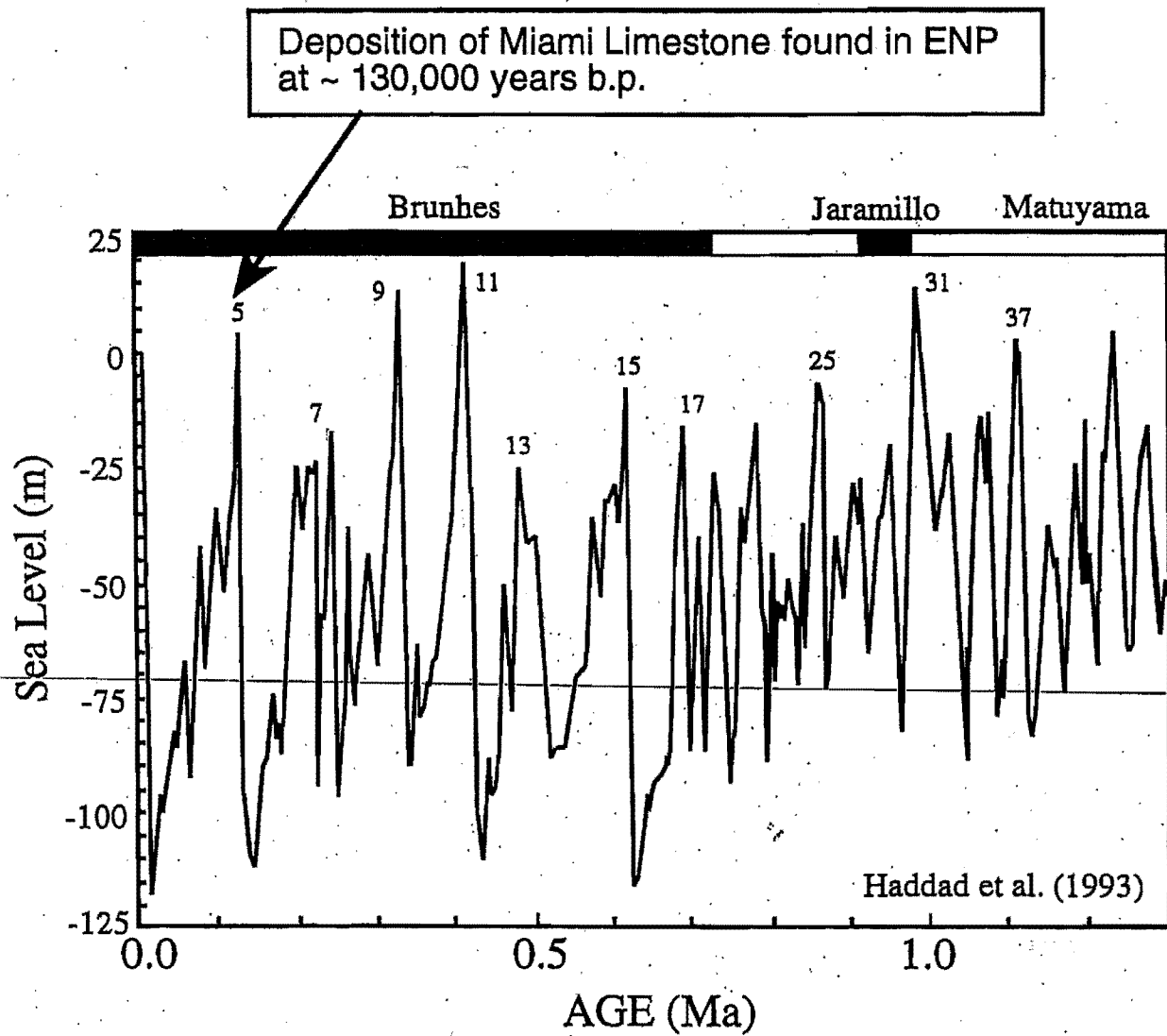


Figure 3. Proxy sea level curve for the past 1.3 m.y. based on oxygen isotopic values from deep sea cores.

Sea Level History

Pleistocene Sea Level

Sea-level changes during the late Pleistocene were responsible for deposition of the limestones that form the foundation of ENP. The Pleistocene changes in sea level are directly related to the buildup and decay of polar ice sheets. This process is thought to have occurred numerous times over the past 1 million years (see Figure 3). These climate and related sea level changes are thought to have been driven by astronomical factors such as the angle of tilt of the earth's axis, the wobble of the earth's spin axis, and the path of rotation around the sun. These astronomical factors combined to alter the heat balance of the earth and thus produced glacier formation and glacial ice decay.

The south Florida platform recorded intermittent marine deposition during the periods of deglaciation where sea level rose high enough to flood the antecedent topography. The intervening periods of lower sea level exposed the local Florida Platform to subaerial conditions, and karst processes were widespread. Core that recover the Pleistocene section in south Florida record these sequences of deposition and subaerial exposure as intervals of limestone with marine fossil capped by karstic features including calcretes (paleo-soil features), soil breccias, evidence of root structures, oxidized surfaces, and remains of surface fires (blackened pebbles, Shinn, 1988). Perkins (1977) has mapped out many of these cycles across south Florida and they are locally referred to as "Q units" for their Quaternary age.

Holocene Sea Level

The last glacial period was shown to have reached a maximum approximately 18,000 yrs ago. Since that time, the glaciers have retreated supplying meltwater to the world's oceans. The rise in sea level over the past 18 ky period has been documented from several locations in south Florida and the nearby Caribbean (Scholl, 1964; Scholl et al., 1969; Wanless, 1976; Robbin, 1984; Lighty et al., 1982; Fairbanks 1989). Scholl (1964) and Scholl et al., (1966) developed the first sea level curve for south Florida. This record was based on carbon-14 dating of terrestrial and/or mangrove peats that are now located below sea level in Florida Bay.

Regional sea level data (Figure 4) show that between ~18 ky and 7 ky sea level rose rapidly (>100 cm/100 yr) up the rim of the Florida platform. Starting between about 7 and 6 ky, the top of the Florida platform began to be flooded. As this flooding proceeded, shorelines were either abandoned (drowned) or migrated landward with the transgression. At about this same time, the rate of sea level rise slowed, from a rate of ~100 cm/100 yr to something on the order of 20 cm/1000 yr.

As sea level continued to rise with this reduced rate, much of the areas underlying Florida Bay were flooded between about 5000 to 3000 ybp. The Pleistocene bedrock underlying Florida Bay likely had a similar configuration to that of the modern Everglades National Park. Numerous solution holes, some filled with peat, are sometimes recovered in push cores on the islands and mudbanks of Florida Bay.

From about 3000 year to present the rate of sea level rise further decreased (Figure 4), and have averaged about 4 cm/100 yr. This deceleration of sea level has allowed many of the island in Florida Bay, reefs on the reef tract, and Everglades coastlines to become more stabilized and infill up to the position of modern sea level. In ENP, this has meant that the coastal levees have had the opportunity to buildup above sea level, and as mentioned

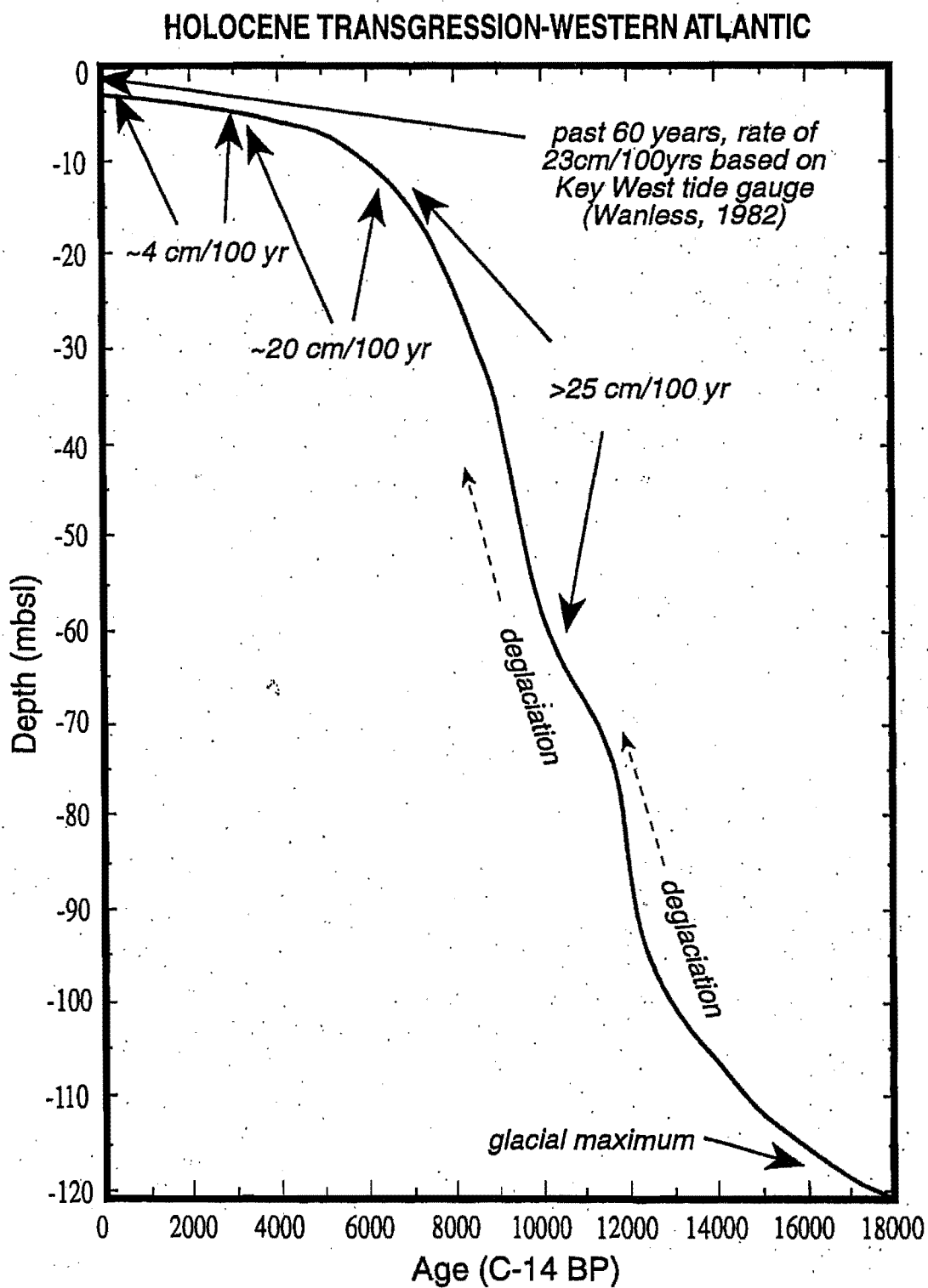


Figure 4. Sea-level curve of the Holocene transgression constructed from data collected by Lighty et al., (1982) and Fairbanks, (1989) from Florida and the western Atlantic.

above, begin to prograde seaward (Cottrell, 1989). On the western shoreline of ENP, Parkinson (1987) and Wanless and Tagett (1989) have shown that the mangrove shoreline stabilized at about 3,200 ybp and has grown vertically. Likewise, offshore oyster banks developed, became stabilized and were eventually colonized by mangroves that prograded seaward (Parkinson, 1987).

The modern coastline system around ENP is mainly a result of this 300 year period of relatively slow sea level rise. It is worth noting however, that sea level rise over the past ~70 years shows signs of significant increase. Tide gauge records from Key West have been analyzed by Wanless (1982) who has measured a rate of rise of about 23 cm/100 yrs. This instrumental record may be recording high-frequency changes that are incorporated into the averaged geological rates, or it may signify a significant change in rate related to further deglaciation (natural or anthropogenic?). Either way, changes of this type will have significant affects on the present-day configuration of sedimentary facies and ecological habitats within Everglades National Park.

Geologic History of the Southern Florida Peninsula

Deep Basement of South Florida

Volcanic rocks are thought to form the deep basement in the area underlying ENP based on samples collected from a deep (5.7 km) core hole in Collier County. These rocks are thought to be mainly early Mesozoic rhyolites (Thomas et al., 1989). Geochemical fingerprinting of these volcanic rocks indicates a composition characteristic of continental rifting environments within a mantle plume (Heatherington and Mueller, 1991). Little is known, however, about the pre-Jurassic rock underlying south Florida, mainly due to its depth and lack of drill holes (see Figure 5).

The volcanic nature and mantle plume setting for the basement of the southern Florida Platform is consistent with the rifting of Pangea and the formation of the Atlantic Ocean basin. Based on late Paleozoic and Mesozoic plate reconstructions of Pangea, south Florida likely was positioned at the junction of the North American, South American, and African plates. Plate rifting that eventually formed the Atlantic Ocean is thought to have initiated from hot spots located off the southern tip of the Florida Platform. This hot spot rifting is supported by the isotopic signatures in the volcanic rocks in the south Florida basin (Mueller and Porch, 1983; Heatherington and Mueller, 1991; Heatherington and Mueller, 1997).

History of the Florida Platform

Following rhyolitic basalt emplacement during rifting, the areas that is currently the southern peninsula was likely subaerially exposed and underwent weathering to form a series of late Triassic to middle Jurassic continental redbeds. As the Atlantic Ocean began to develop, siliciclastic of deltaic and shallow marine origin were deposited in the late Jurassic. Restricted marine deposition likely followed, resulting in the intermittent accumulation of evaporates and shallow marine carbonates (Figure 6).

During the early Cretaceous, as marine circulation began to improve, the Florida Platform was underwent the transition from restricted evaporites and carbonates to more widespread deposition of normal marine limestones and reefs (Figure 7). The reefs were mostly constrained to the edges of the Florida Platform along the margin of the ancestral Gulf of Mexico. A major marine transgression during the late Cretaceous transformed almost the entire Florida Peninsula to open marine deposition of carbonates. The late Cretaceous also

Depth to Pre-Mesozoic Rocks in Florida

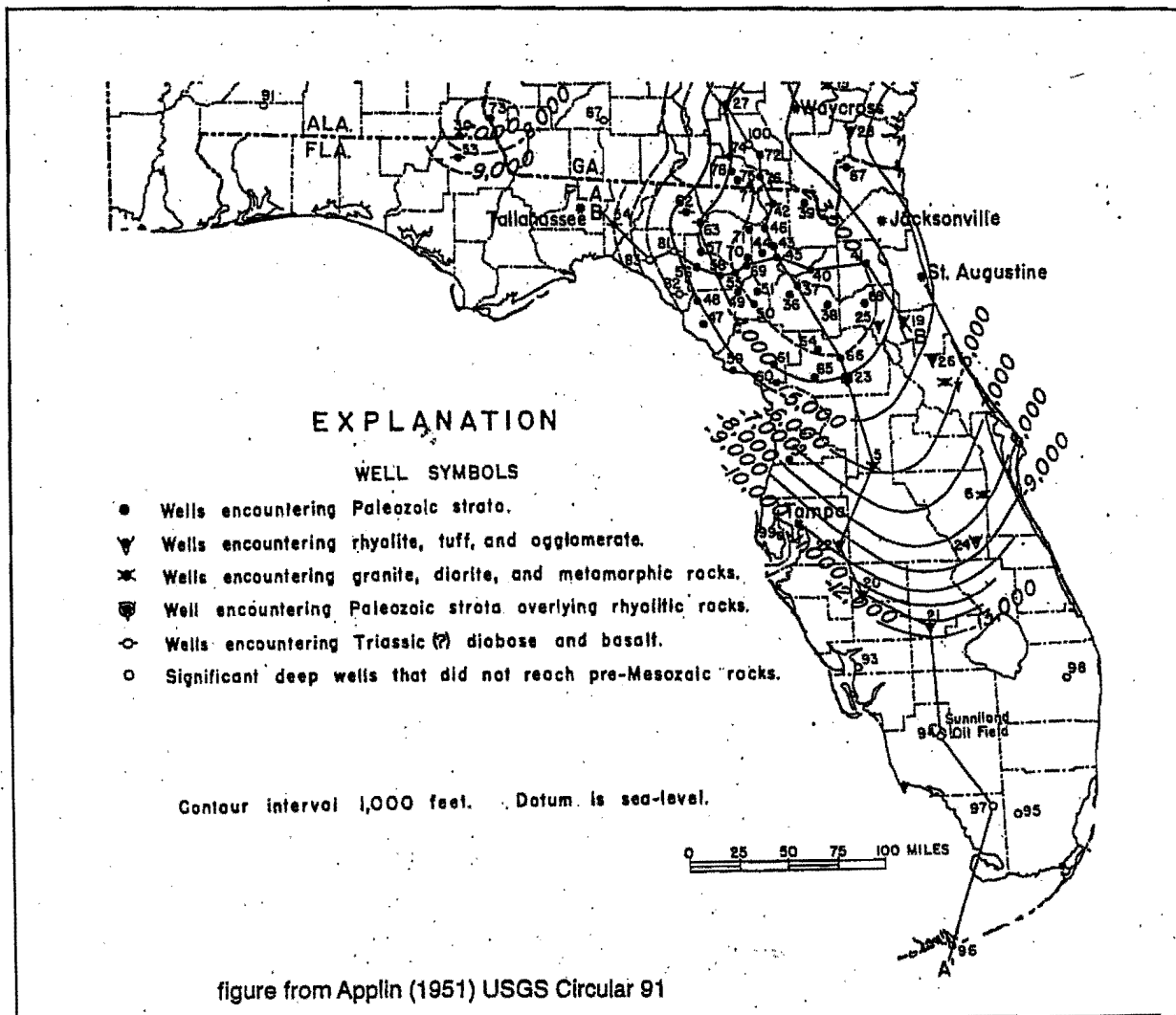


Figure 5. Depth to pre-Mesozoic rock in Florida.

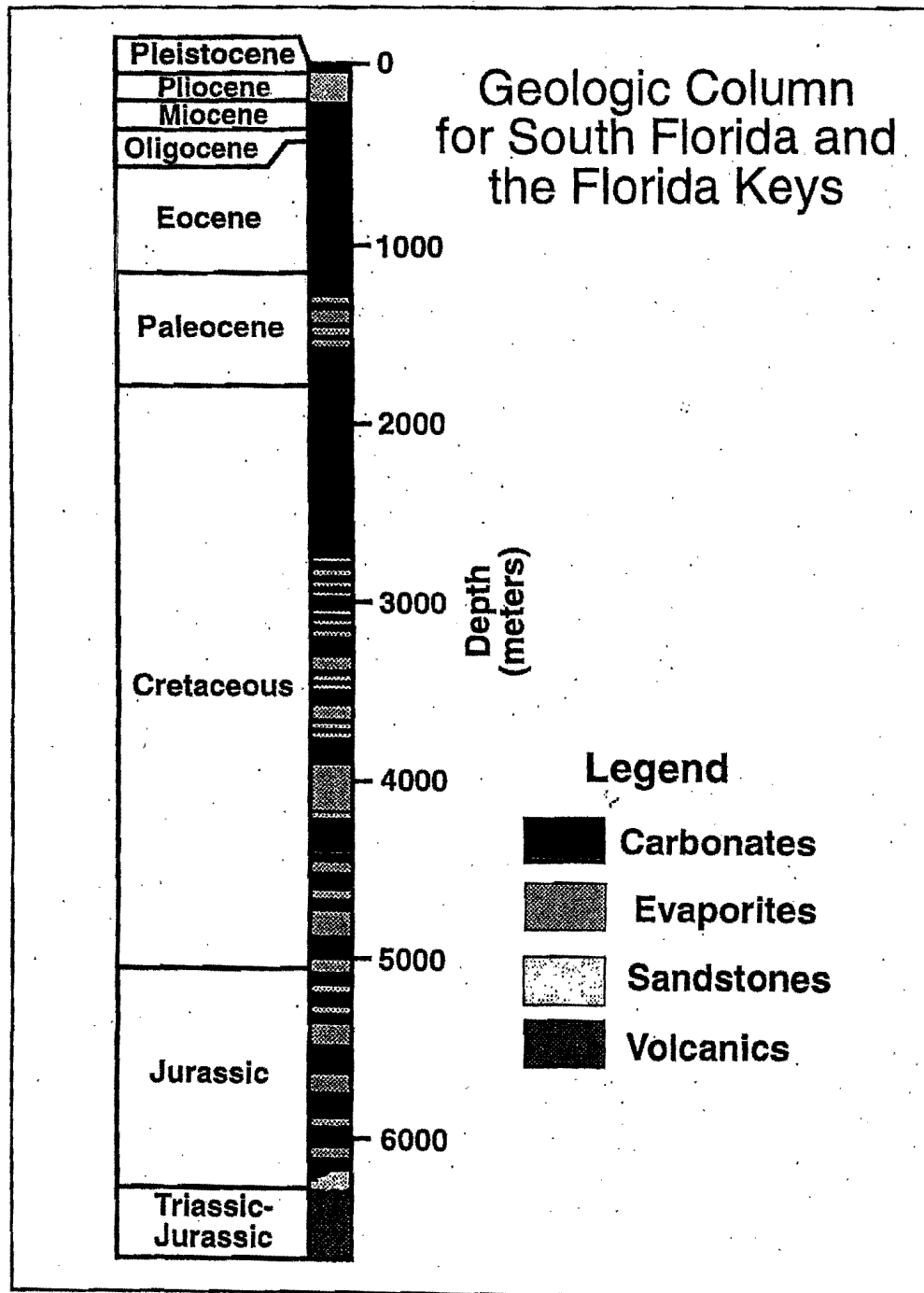


Figure 6. Summary of the sedimentary column underlying south Florida and Everglades National Park. Figure compiled from data of George Winston.

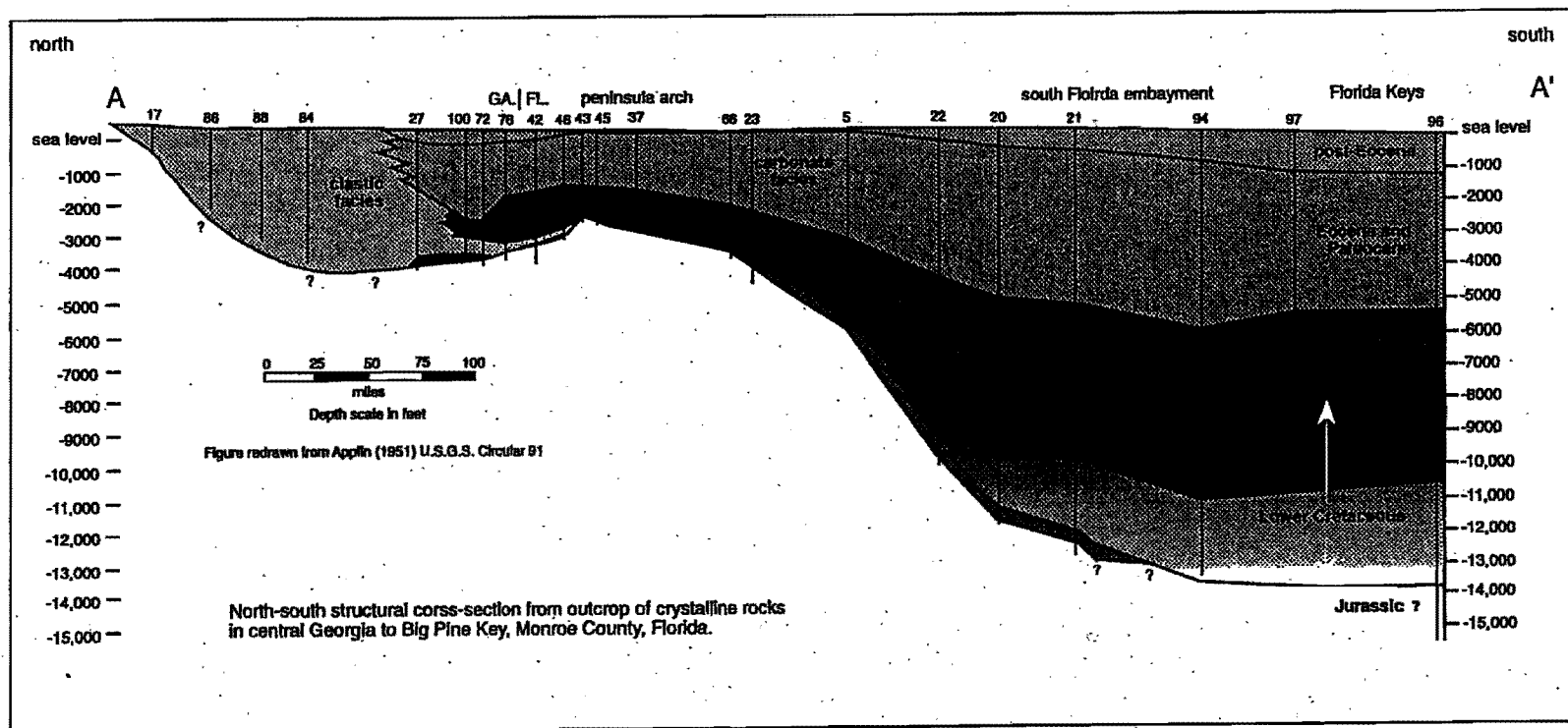


Figure 7. Cross-section from north to south through the Florida peninsula.

marked the development of widespread reefal (rudistid bivalves) deposition around the southern margin of the Florida Platform.

Cenozoic development of the Florida Platform was marked by additional deposition of marine carbonates and the reintroduction of siliciclastics (Figure 6). Marine regression in the Paleocene produced somewhat restricted marine conditions over much of the peninsula. This restriction resulted in the deposition of mixed carbonates and evaporites, except for the very southeastern part of the peninsula around the modern ENP. Paleocene deposits in Miami-Dade and Monroe counties suggests a more normal, open marine setting. Shallow-water carbonate deposition resumed throughout the Eocene and Oligocene for the southern Florida platform. Carbonate deposition was intermittent, punctuated by periods of subaerial exposure associated with falls in sea level.

The Miocene era marked a distinct change in the depositional history of south Florida with the introduction of widespread siliciclastic sedimentation. Fluvio-deltaic siliciclastics likely prograded down the peninsula supplied by weathering of the southern Appalachian mountains. Much of the southern peninsula experienced mixed carbonate-siliciclastic deposition during the Miocene. The Arcadia Formation was a carbonate ramp deposit in the southeastern peninsula during the early and middle Miocene. This unit is overlain by siliciclastic deposits comprising the Peace River Formation. The Miocene period is also marked by widespread phosphate deposition throughout the peninsula. During the Pliocene, many of the Miocene siliciclastic deposits were reworked and/or eroded. Southward transport of siliciclastic to the area of ENP and the Florida Keys was especially active as a thick pile of sands (Long Key Formation) were emplaced beneath ENP and the Florida Keys. Recent drilling by the University of Miami, the Florida Geological Survey, and the USGS has mapped out the stratigraphy of these siliciclastic deposits on the southern peninsula (Cunningham et al., 1998; Guertin et al., 1999; see Guidebook appendix for copies). The Pliocene in south Florida also had periods of localized carbonate deposition. For example west of the ENP, mid-Pliocene reef facies have been described by Meeder (1979). South of ENP, Pliocene carbonates of the Stock Island Formation (Cunningham et al., 1998) were deposited near the lower Florida Keys and the southwest Florida shelf, perhaps associated with currents originating in the Gulf of Mexico and flowing into the Straits of Florida.

The Pleistocene era marked the transition from siliciclastics (early Pleistocene?) back to widespread carbonate sedimentation (Late Pleistocene), with an intervening interval of mixed carbonate-siliciclastic sedimentation. This sequence of Pleistocene deposition is likely related to the development of high-frequency and high-amplitude sea-level changes driven by glacioeustasy. The Fort Thompson Formation of mixed carbonate and siliciclastic intervals forms the shallow subsurface unit of Everglades National Park. This unit interfingers with late Pleistocene carbonate units that form the surficial geological units for the Park: the Miami Limestone; the Key Largo Limestone; and the Anastasia Formation. These three formations outcrop in southern Florida and have been age-dated at 130 kyr (Figure 8).

Stratigraphy of the Subsurface and Surface Deposits of ENP

The stratigraphy of the geological units beneath ENP has been determined by information collected by core drilling (Figure 9). Although many areas of the Park have no core information, a revised stratigraphy (Figure 10) has recently been proposed based on a deep, continuous core (W-17232) drilled near the ENP Research Center south of Long Pine Key (Cunningham et al., 1998, see Appendix)(Figure 11). Please see the core workshop section for a lithology log and additional information on core W-17232.

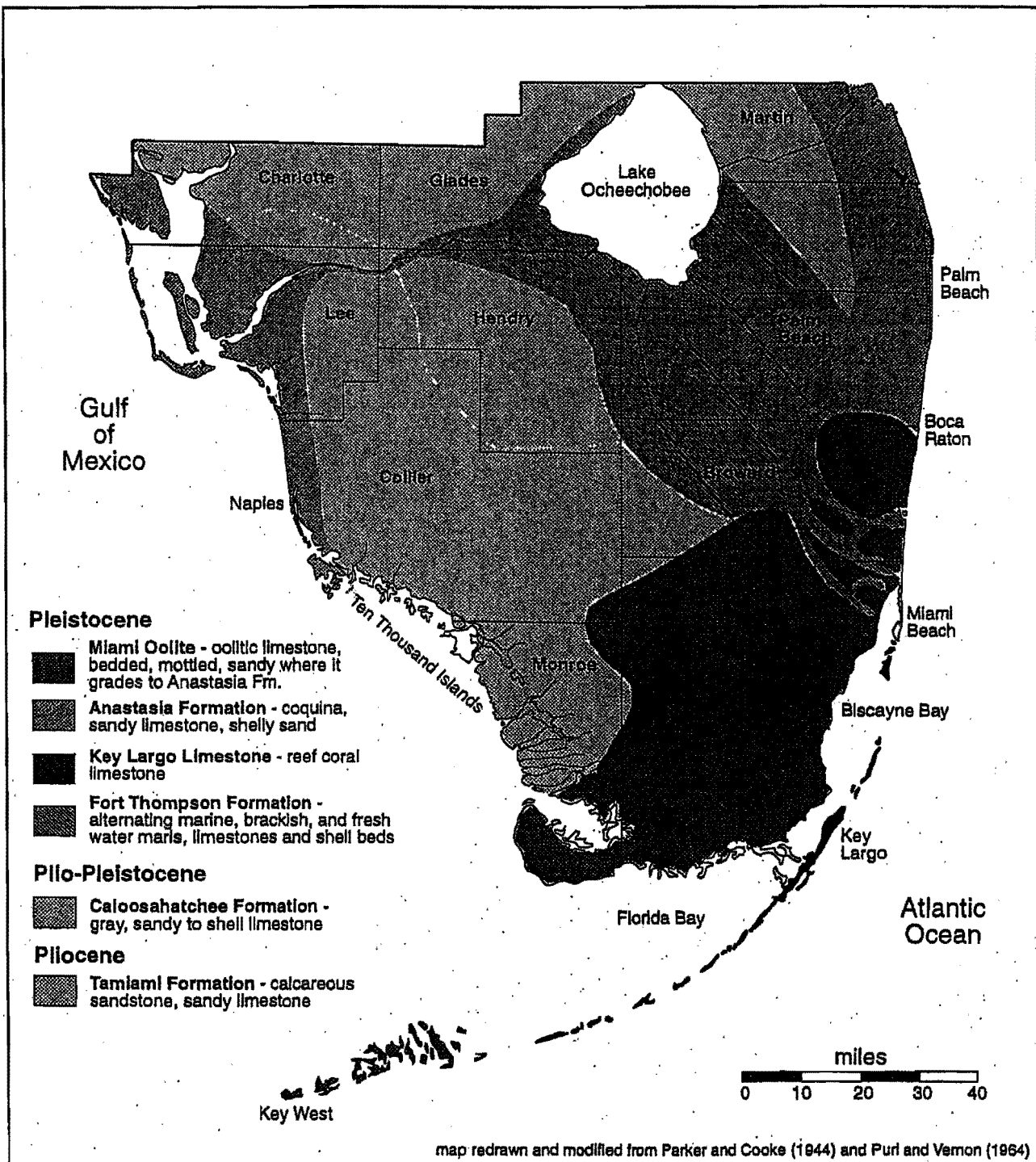


Figure 8. Geologic map of southern Florida exclusive of surficial sands.

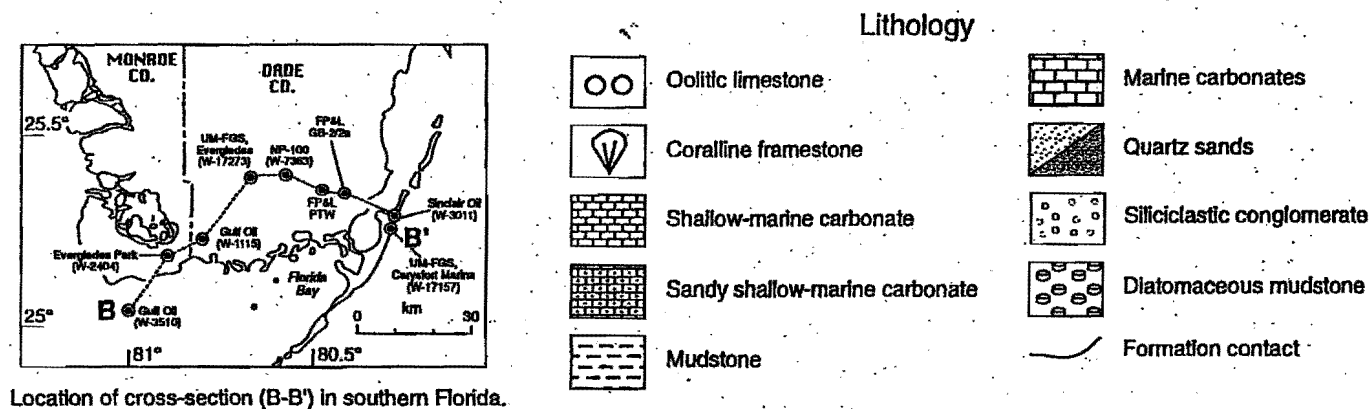
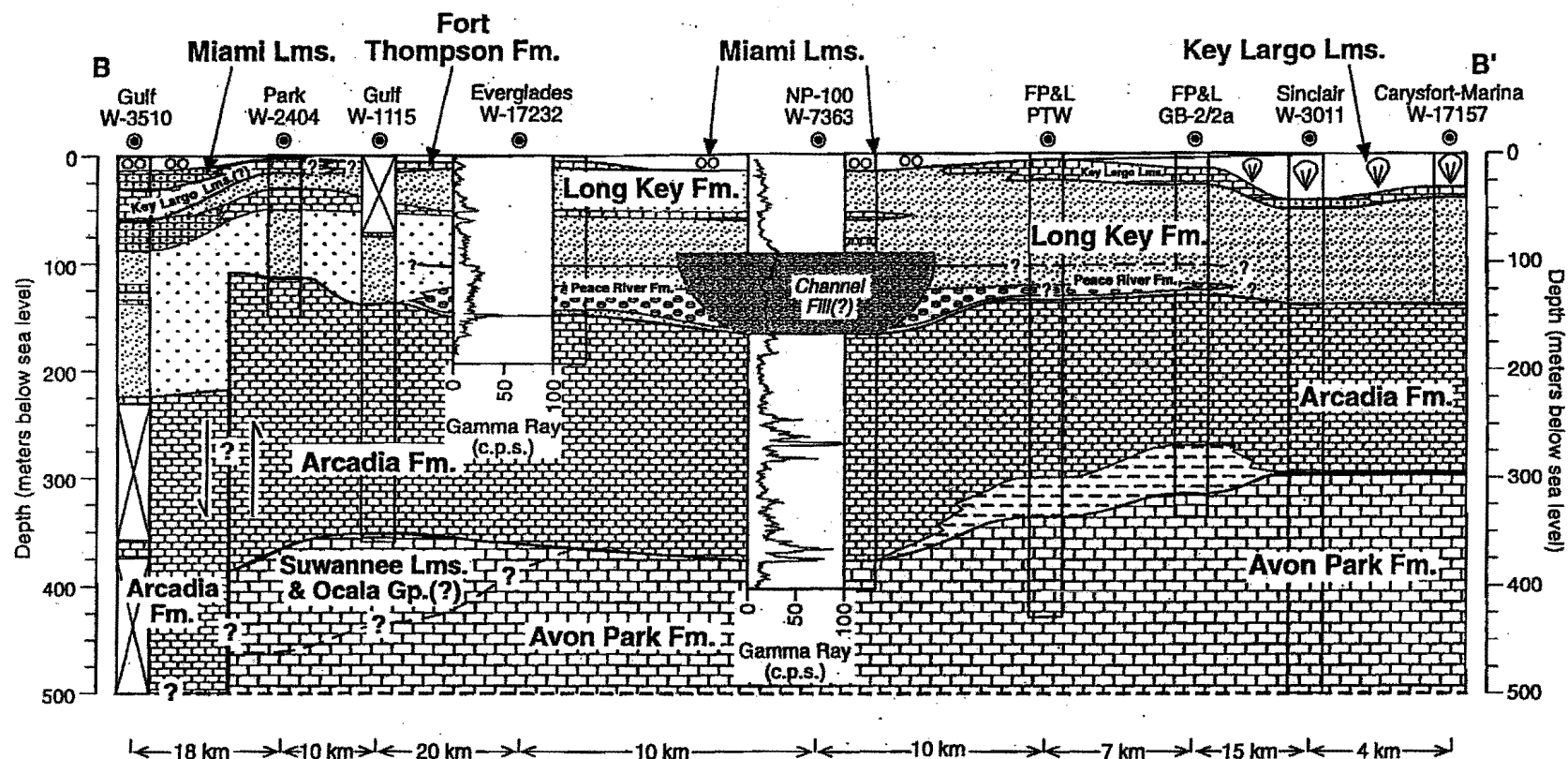


Figure 9. Cross-section across the southernmost Florida peninsula. Figure from Cunningham et al. (1998).

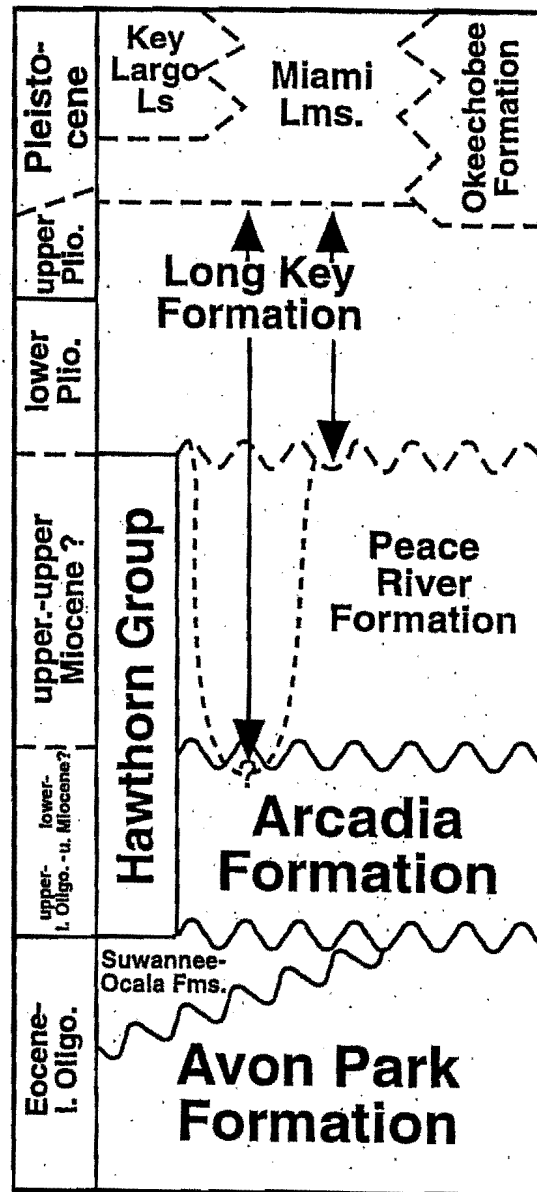


Figure 10. Stratigraphic nomenclature for the Tertiary deposits of south Florida (after Cunningham et al., 1998).

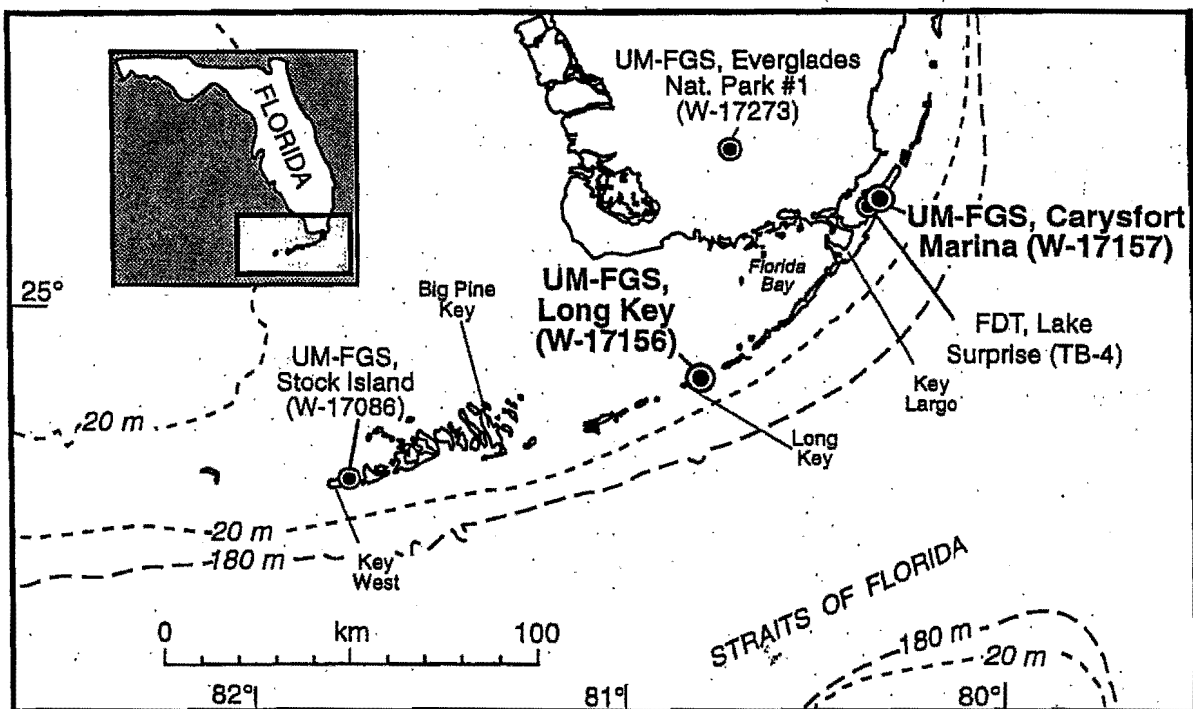


Figure 11. Location map of core holes from the South Florida Drilling Project. This study utilized cores from Long Key and Carysfort Marina. FGS = Florida Geological Survey; UM = University of Miami; FDT = Florida Department of Transportation.

Arcadia Formation (Early/Middle Miocene)

Everglades core W-17232 penetrated the top of the Arcadia Formation at approximately 147 m below land surface (Figure 12). The contact marking the top of the Arcadia Formation is a major disconformity (sequence boundary) (Figure 13) and is marked by a phosphatized surface.

The Arcadia Formation in south Florida is a predominantly carbonate unit that likely represents a ramp setting in a middle to outer neritic environment (Cunningham et al., 1998). The mineralogy of the Arcadia Formation is principally low-magnesium calcite, although subordinate amounts of dolomite and aragonite occur. Dolomite is especially prevalent in the lower part of the formation as recovered in the Long Key core boring. Quartz grains in the Arcadia Formation are a very minor component in the cores from the Florida Keys but increase northward. For example, the Everglades core (W-17232) has up to 20% quartz grains. Likewise, phosphate grains seem to increase northward from the Keys to the peninsula, where the Everglades core has up to 10% black phosphorite grains contained in thin beds (Cunningham et al., 1998).

Peace River Formation (Middle/Late Miocene)

The Peace River Formation was recovered between 98.8 and 147 m depth in the Everglades core (McNeill et al., 1996; Cunningham et al., 1998). This unit is correlated to the Peace River Formation based on the presence of swelling clays (probably smectite); a phosphate content ranging from 2-5%, and similarity of age (Figure 13) with the deposits near the type section.

The Peace River Formation overlies the Arcadia Formation in the central part of Everglades National Park. In the Florida Keys, the Peace River Formation is absent, either never deposited or eroded during the latest Miocene or earliest Pliocene. Thus, the southernmost extent of the Peace River is likely in the southern part of the terrestrial portion of ENP or perhaps beneath Florida Bay.

The Peace River Formation beneath ENP is composed of two distinct lithologic units: a lower diatomaceous mudstone unit and an upper unit of very-fine to fine quartz sandstone with abundant mud matrix (Cunningham et al., 1998). The diatomaceous mudstone (comprised of silicoflagellates, diatoms, and radiolarians) was likely formed by upwelling based on the occurrence of a polar to subpolar silicoflagellates in combination with tropical to temperate radiolarians and abundant biogenic opal (high productivity). The occurrence of diatomaceous mudstones in the Everglades core is related to transgressive to early highstand conditions and upwelling onto the Florida Platform during the late Miocene.

Long Key Formation (Pliocene)

The Long Key Formation was a new formational name proposed for subsurface siliciclastics underlying southernmost Florida (Cunningham et al., 1998) (Figure 10). The type section for the Long Key Formation has been designated as Core W-17156, FGS-Long Key No. 1, located just northeast of the island of Long Key, Monroe County, in the Florida Keys.

The Long Key is suprajacent to the Arcadia or Peace River Formation and subjacent to the Miami Limestones, Ft. Thompson Formation and the Key Largo Limestone. The unit is laterally equivalent to, and coeval with the Stock Island Formation of the lower Florida Keys

Everglades National Park No. 1 Log & Lithologic Correlations

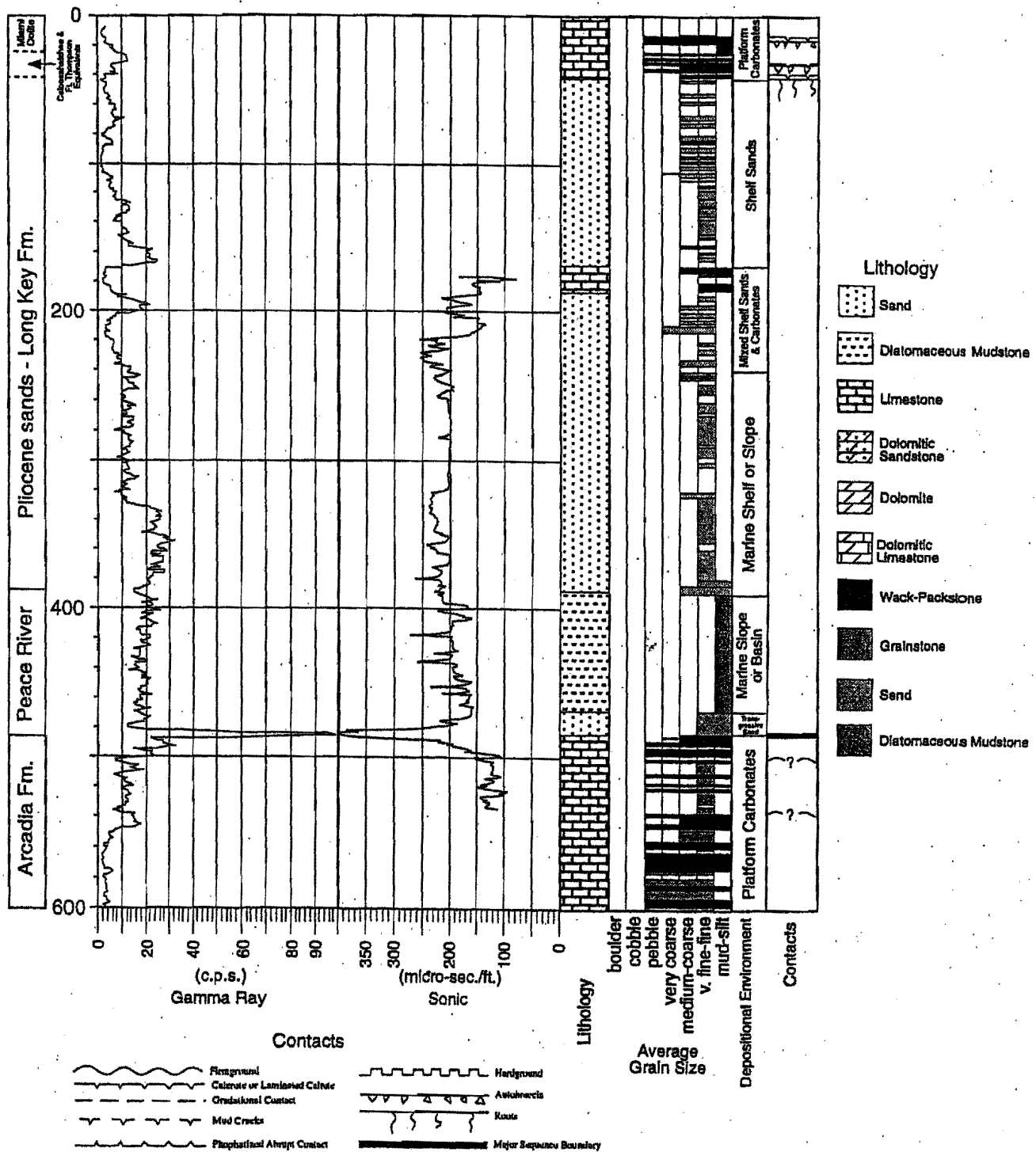


Figure 12. Log and lithology summary for ENP No. 1. Figure from Cunningham et al., 1998.

Everglades National Park #1 Core (W-17273)

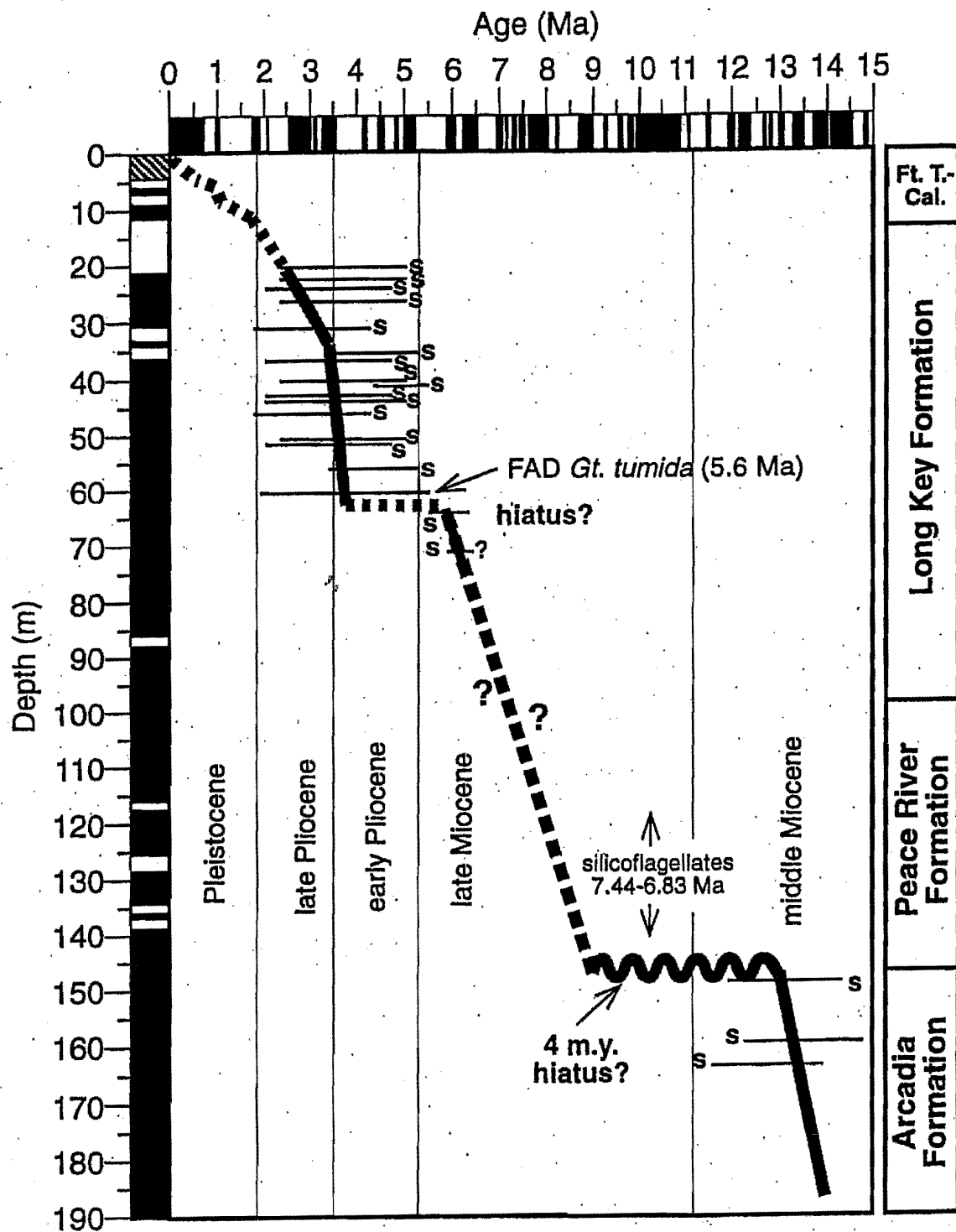


Figure 13. Age-depth relationship in ENP No. 1 based on biostratigraphy, magnetostratigraphy, and strontium-isotope stratigraphy. Figure from Guertin (1998).

subsurface (Cunningham et al., 1998; Guertin et al., 1999). The basal contact of the Long Key Formation is either with the Peace River Formation or with the Arcadia Formation where the Peace River Formation has been eroded. A regional unconformity and subaerial exposure surface on top of the Arcadia Formation separates the two units. This unconformity represents a temporal hiatus best constrained to be at least 5 my (Figure 13). Warzeski et al. (1996) showed from marine seismic profiles that the siliciclastics of the Long Key Formation progrades southward to eastward over the unconformity at the top of the Arcadia Formation (Figure 14).

In the Everglades core, the Long Key Formation ranges from ~17.4 to 98 m depth (Figure 12). The age of the Long Key siliciclastics in the Everglades core is poorly constrained by the lack of age diagnostic planktic foraminifera. The base of the formation has been partially constrained by the use of silicoflagellates, and suggest a maximum age of late Miocene (Messinian)(Figure 13). The age of the Long Key Fm sediments in the northern and central Florida Keys is much better constrained use planktic foraminiferal biostratigraphy (Guertin et al., 1999)(see Appendix). From cores on northern Key Largo (Carysfort Marina W-17157) and Long Key (W-17156) it has been proposed that the siliciclastics were deposited in three pulses, ranging in age from late Miocene, early Pliocene, and latest Pliocene/earliest Pleistocene (Guertin et al., 1999).

The paleodepth of the Long Key Formation, based on benthic foraminiferal assemblages, indicates deposition in a fluctuating outer shelf (150-180 m depth) and inner shelf (10-50 m depth) setting (Guertin et al., 1999). These fluctuations in water depth likely represent a combination of eustatic sea level changes and differential infilling of the basin with the siliciclastics.

The geometry of the Long Key Formation siliciclastics is intriguing. Warzeski et al. (1996) and Cunningham et al. (1998) have mapped out a north-south corridor of coarse-grained siliciclastics the runs from west of Lake Okeechobee southward through Hendry and Collier Counties, continuing southward through northern Monroe County and western Miami-Dade County. The spatial distribution of these coarse-grained sands (>1 mm) includes most of the area under central ENP (Figure 15), and southward beneath Florida Bay and the Florida Keys. This channelized morphology suggests southward transport of the sands from areas north of Lake Okeechobee, perhaps via the outcropping Lake Wales Ridge. The exact distribution of these sand beneath ENP remains uncertain and additional core borings are needed to definitively constrain their spatial extent (especially on the western side of ENP).

Fort Thompson Formation (Pleistocene)

The uppermost 17 m of the Everglades core consists predominantly of shallow-water limestone (Figure 12). These limestones likely represent a combination of Ft. Thompson Formation and a capping unit of the Miami Limestone.

The Ft. Thompson Formation has been informally included as a member within the Okeechobee formation by Scott (1992)(see Figure 10). The Ft. Thompson Fm is characterized by a predominantly carbonate lithology deposited as a slightly restricted, lagoonal facies during successive sea level highstands during the Pleistocene. The unit is rich in marine bivalves and includes a subordinate amount of quartz sand.

In ENP, the thickness of the ranges from ~3 to 15 m (Fish and Stewart, 1991). An west-east cross-section (E-E'), constructed by Fish and Stewart (1991) based on shallow borings, suggests that the Ft. Thompson thickens slightly to the east where it underlies the

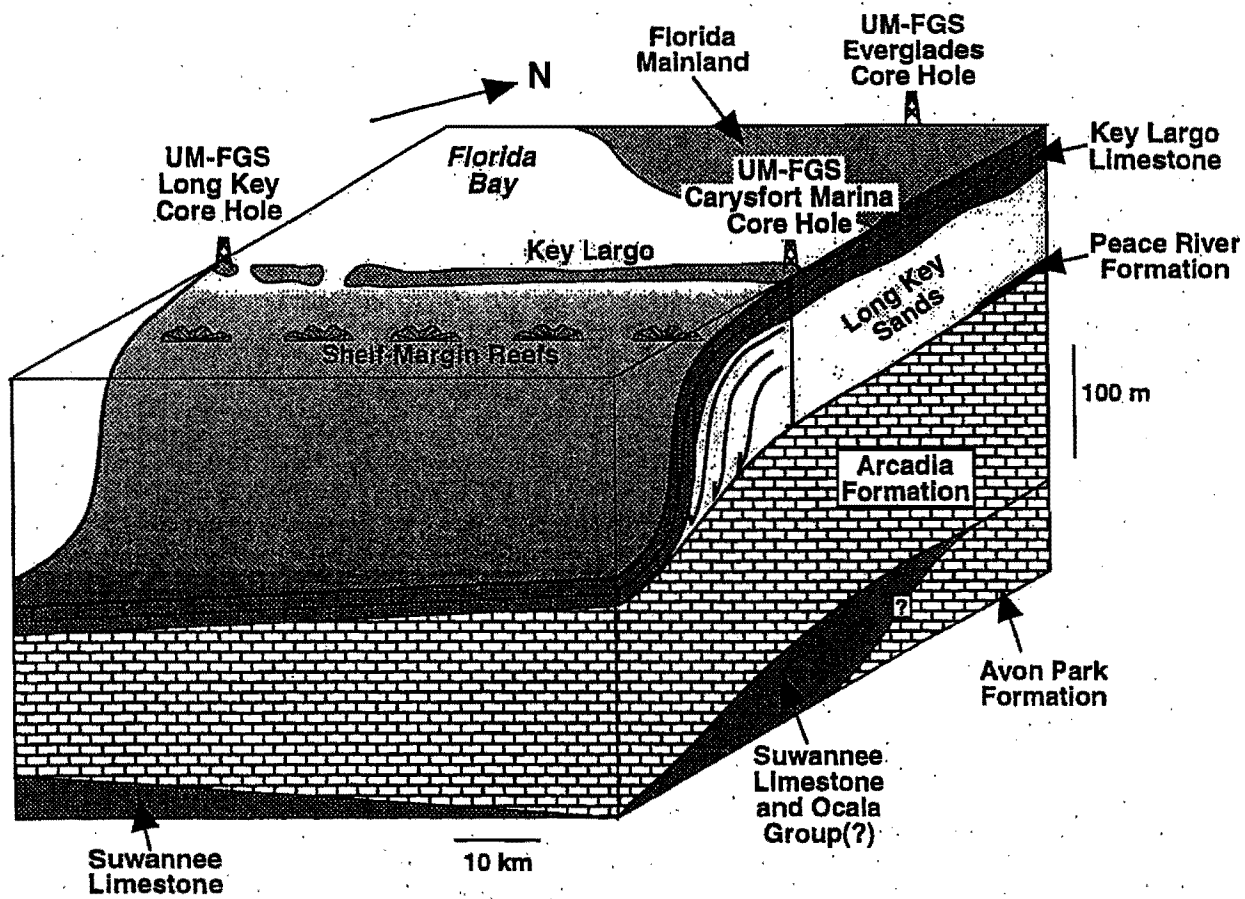


Figure 14, Cartoon depicting the stratigraphy and geometry of the geologic units underlying the Quaternary carbonates of the Florida Keys. Figure from Cunningham et al. (1998)

Miami Limestone.

Miami Limestone (Late Pleistocene)

The surficial geology of the terrestrial part of ENP has been mapped as Miami Oolite (Limestone) since at least 1944 (Parker and Cooke, 1944)(see Figure 8). The age of the Miami Limestone is late Pleistocene and has been dated at ~125 to 130 ky (Osmond et al., 1965; Broecker and Thurber, 1965). This age is correlative with an interglacial period that is had sea level elevations about 5 to 7 m higher than present sea level.

The eastern part of ENP has been mapped by Hoffmeister et al. (1967) to contain the "oolitic facies" of the Miami Limestone (Figure 16). This facies of the Miami Limestone contains a mixture of oolitic and pelloidal carbonate sands. The Miami Limestone that constitutes "bedrock" in the western part of the Park is thought to contain a more restricted, low-energy facies of the Miami Limestone (see Figure 16). This lithology was termed the "bryozoan facies" by Hoffmeister et al. (1967) due to the occurrence of colonies of the bryozoan *Schizoporella floridana*. These invertebrate marine animal secrete a calcareous shell in which they live, these grow together to form colonies that can become up to or slightly greater than a foot (30 cm) to form a knobby structure (Hoffmeister, 1974). These bryozoans are encrusting animals the often attach to sea grass roots and blades.

The lithofacies that form most of the outcrops in ENP consist of a combination of bryozoan remains, some ooids, and a significant component of lime peloids.

Surficial Geology of Everglades National Park

The surficial geology of ENP is dominated by Holocene sediments resulting from both terrestrial and marine processes (Figures 17 and 18). Most of the Holocene sedimentary environments are strongly influenced by the underlying geology, the modern physiography of those units, and the position of sea level over the past 5000 years. Thus, the modern "facies" found in Everglades National Park reflect the underlying geology, the position of today's sea level, the regional climate regime, and the type of vegetation occupying different habits. The modern ecology of ENP is an important reminder of the linkages to underlying geology and physiography.

Below is a short summary of the main facies found in Everglades National Park.

Pleistocene Bedrock - Miami Limestone

As discussed above, Pleistocene rock crops out along the eastern margin of ENP and is locally known as the "rocky glades". This areas represents the more elevated portion of the Park and is sometimes referred to as the southern most extent of the Atlantic Coastal Ridge. These exposed rocky areas are the "oolitic facies" of the Miami Limestone, although the oolitic component of the outcropping rock is often very minor, more often dominated by lime peloids (cryptocrystalline mud aggregates often formed by either flocculation of suspended aragonite needles, or by biological processes: filter feeding organism such as worms).

The elevation of the top of the Pleistocene rock (Figure 19) has important influence on the subsequent surface water hydrology, drainage, and thus much of the modern environments

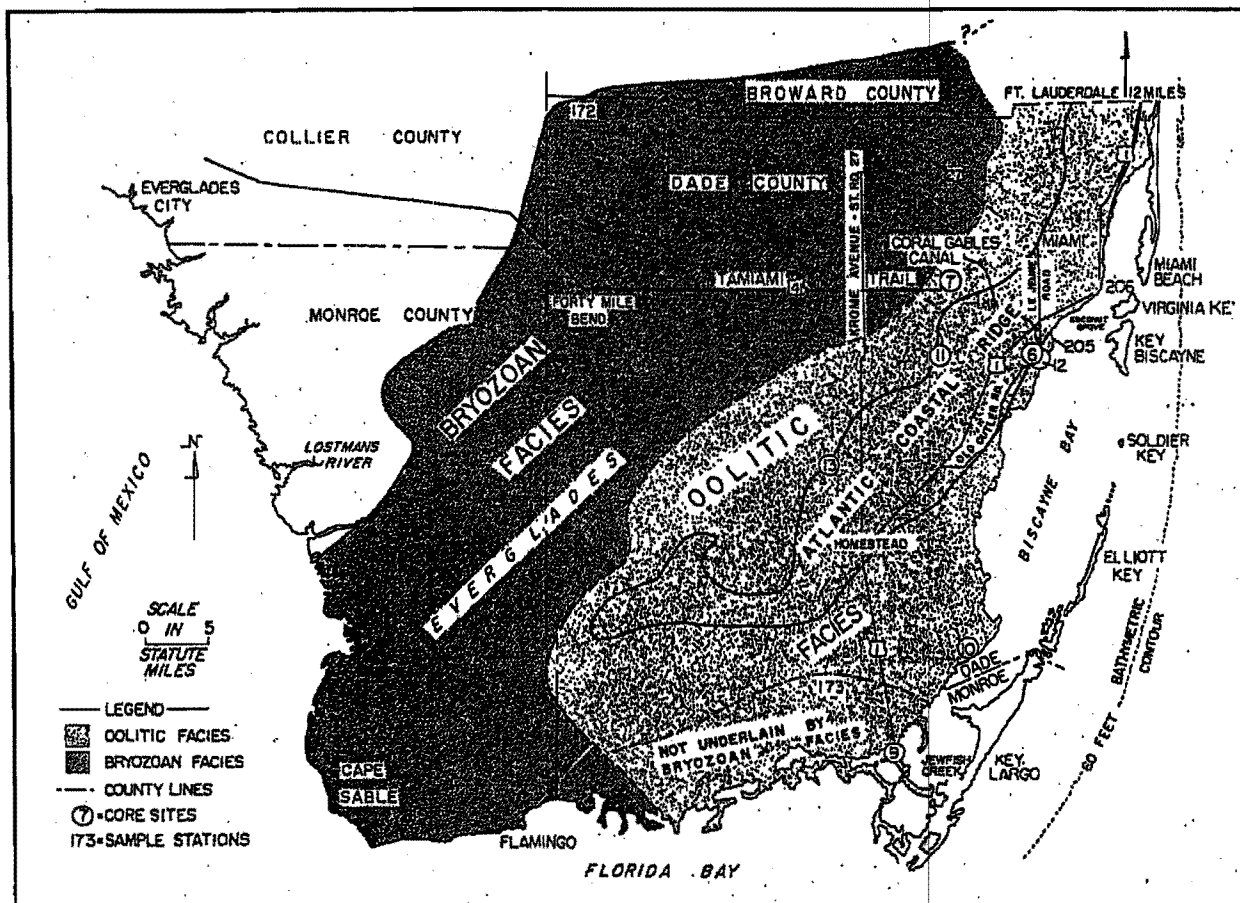
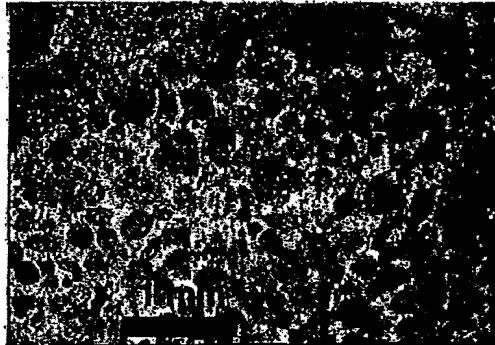


Figure 16. Distribution of "oolitic facies and "bryozoan facies" within the Miami Limestone as mapped by Hoffmeister et al. (1967).

sample location Long Pine Key, ENP

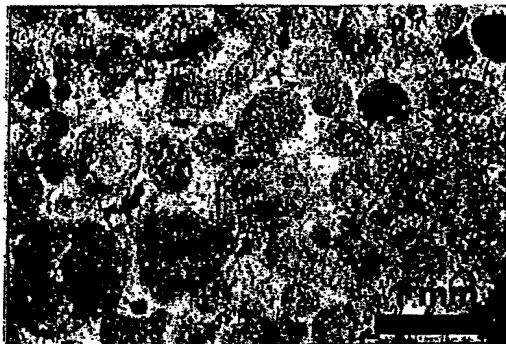


**peloidal-grainstone/packstone facies
at Long Pine Key**

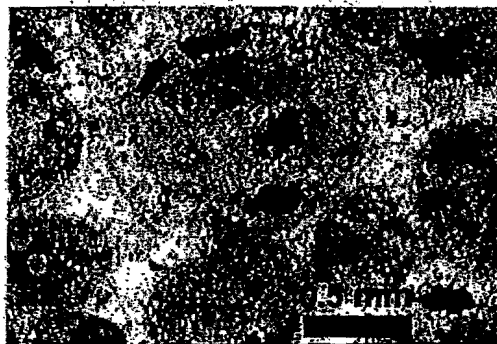


**Miami Limestone Outcrop
at Long Pine Key**

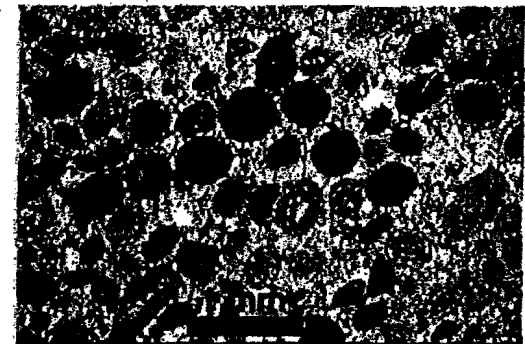
**peloidal-oolitic grainstone/packstone
outcrop at Long Pine Key, ENP**



**enlargement of peloidal-oolitic grainstone/
packstone facies at Long Pine Key**



**oomoldic porosity in peloidal-oolitic
grainstone/ packstone facies at Long Pine Key**



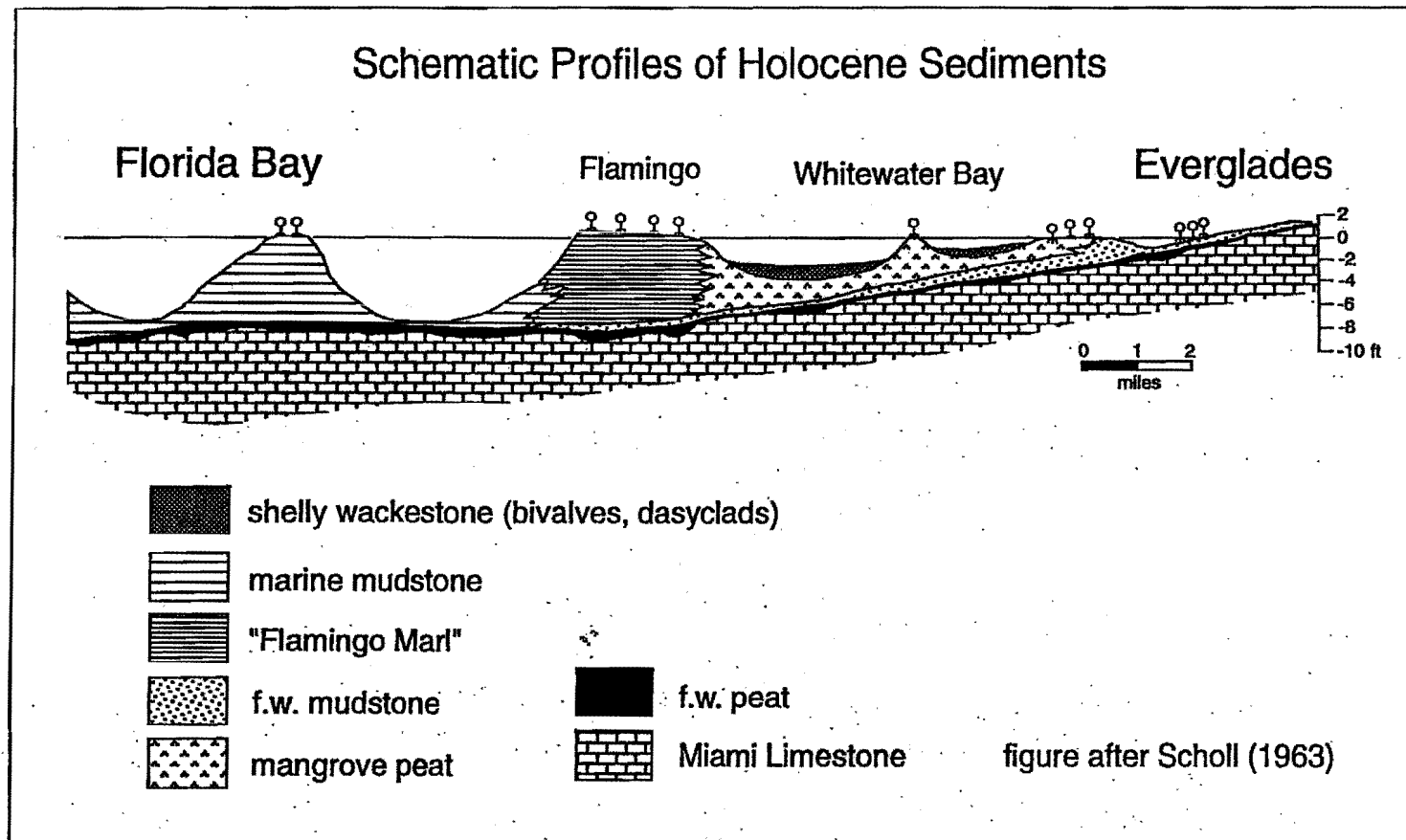


Figure 17. Schematic cross section from Florida Bay to ENP.

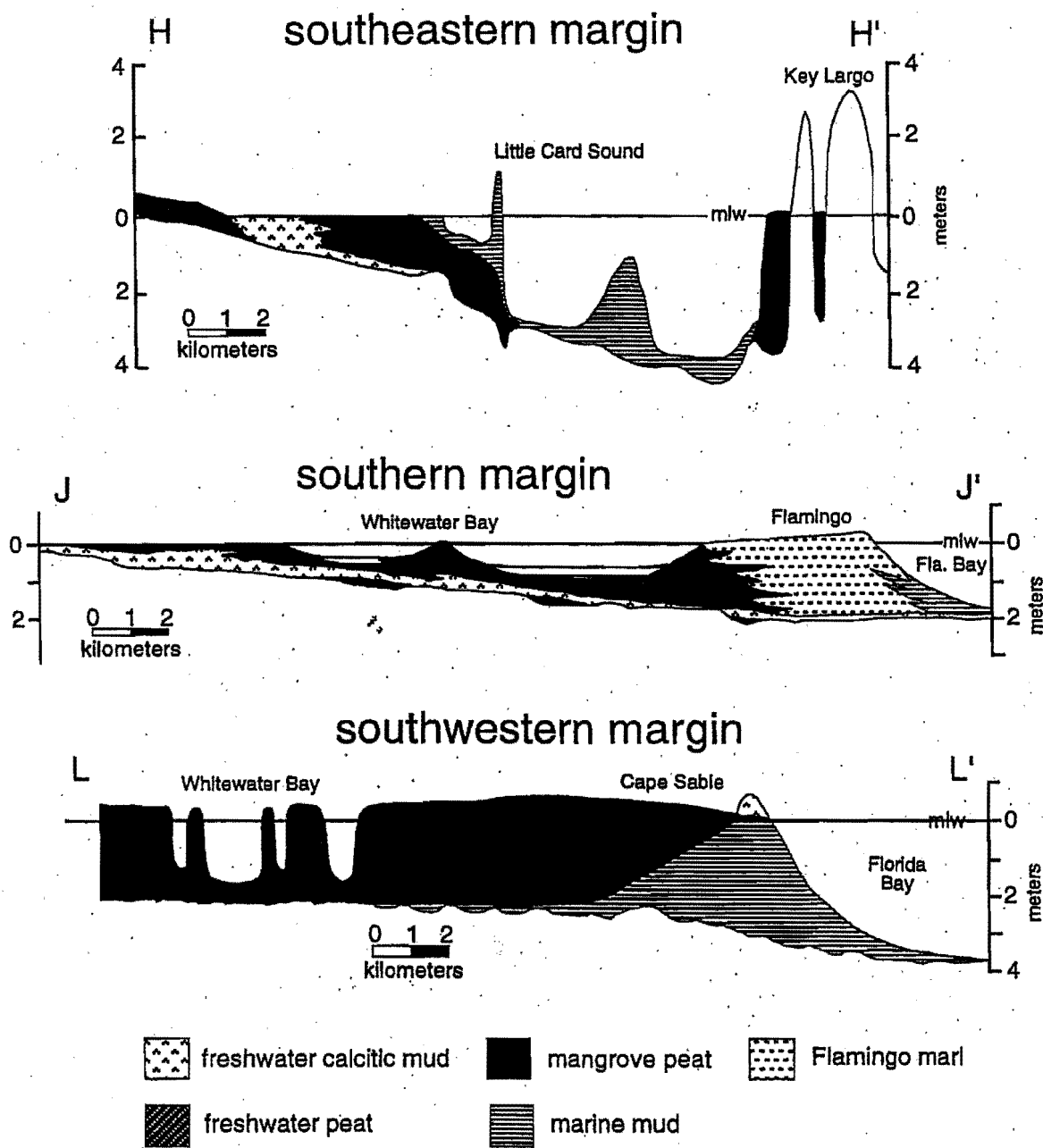


Figure 18. Cross-sections of Holocene sedimentary accumulations along the southern margin of Everglades National Park. Figures redrawn from Wanless (1974) based on shallow cores.

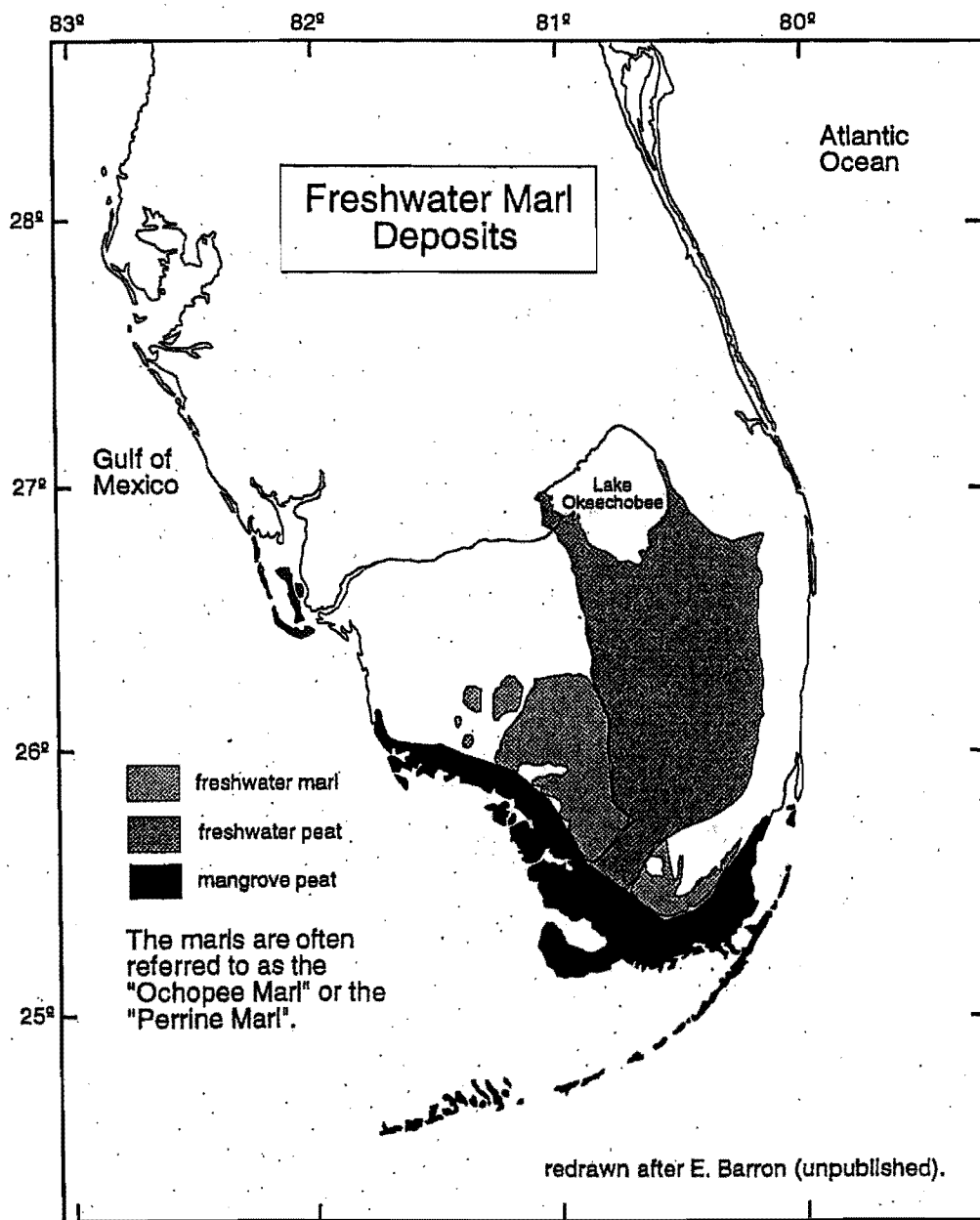


Figure 19. Map showing the distribution of freshwater marl, freshwater peat, and mangrove peat.

and vegetation found in the Park today. The exposed Pleistocene rock is evident on the color-coded visitors map provided at the Park's Visitor Center. Referred to as "Pinelands", the rocky glades provide a habitat suitable for pine vegetation relative to the surrounding lower lying wetlands.

Rock Reef Pass- the Mystery of the Rock Ridges

contributed by Don Hickey (USGS)

The south Florida landscape is ornamented with more than a dozen northwest-southeast trending ridges that have typical lengths of 10 - 20 km, widths usually 100 m or less, and topographic relief generally 0.5 - 1.5 m (Froehlich, 1979, Steinen et al., 1995). Eight ridges have been mapped and named (see USGS topographic maps), however, many others are arguably present. The ridges are locally referred to as rock reefs and are especially noticeable in aerial photographs of Everglades National Park and south Florida. The elevated relief (one meter on average) retards southward flow of surface water and is responsible for the change in vegetation observed along the axis of the ridge. Several processes have been suggested for the origin of the rock reefs. These theories include (1) structural features due to Pleistocene faulting (Steinen et al., 1995), (2) structural features due to the development of fine fractures inducing preferential cementation and/or dissolution (White, 1970), (3) the preservation of depositional shoreline features (Craighead, 1971) and (4) depositional lagoonal features (paleo-mud banks) (Froehlich, 1979, Jenkins, 1984). The origin of these geologic features remains a mystery. The evolutionary processes responsible for the origin of the ridges, however, may be determined by observing subsurface structure. Rotary core drilling and ground penetrating radar (GPR) surveys hopefully will provide enough lithologic and subsurface structural information on the geologic history of the rock reefs to enable a conclusive determination of their origin.

The exposed bedrock lithology throughout the study area comprises of the bryozoan facies (named for the high concentration of *Schizoporella floridina*) of the late Pleistocene age Miami Limestone (Hoffmeister et al., 1967). Subsurface lithology is composed of alternating sequences of marine and fresh water units separated by discontinuity surfaces (Q1 - Q5) that record periods of subaerial exposure (Perkins, 1977, Steinen et al., 1995). The southward-deepening South Florida Basin lies beneath the "Q" units and is comprised of younger phosphatic and siliciclastic rocks and older carbonates. The basement beneath the basin is more than 4.5 km (14,764 ft) deep in the vicinity of the Grossman Hammock rock reef (DuBar, 1991). A test well south of Cape Sable and west of Sandy Key penetrated approximately 3.4 km (11,200 ft) of post lower Cretaceous sediment.

The five Q (Quaternary) units present in the Pleistocene alternate between marine and fresh water lithologies. Perkins and Mitterer determined the age dates of the five distinct units and recognized they corroborate with one another. Therefore, the age dates of Perkin's five Q units coincide with Mitterer's five marine units and are as follows: Unit V/Q5 - 134,000 B.P., Unit IV/Q4 - 180,000 B.P., Unit III/Q3 - 236,000 B.P., Unit II/Q2 - 324,000 B.P., and Unit I/Q1 - absolute age not published.

Steinen and others (1995) tentatively interpreted drill cores as indicating 1 m or more of late Pleistocene and possibly Holocene, vertical offset on a southwest-dipping normal fault that strikes along the rock reef. Since the tentative inference of Steinen and others (1995), additional data from recent drilling and ground penetrating radar indicates little evidence suggestive of late Pleistocene and/or Holocene faulting. The transect of bore holes drilled perpendicular, with respect to the northwest-southeast trending Grossman Ridge, reveal no displacement indicative of Quaternary seismic activity resulting in faulting. The 100MHz and

Craighead's Rock Reefs

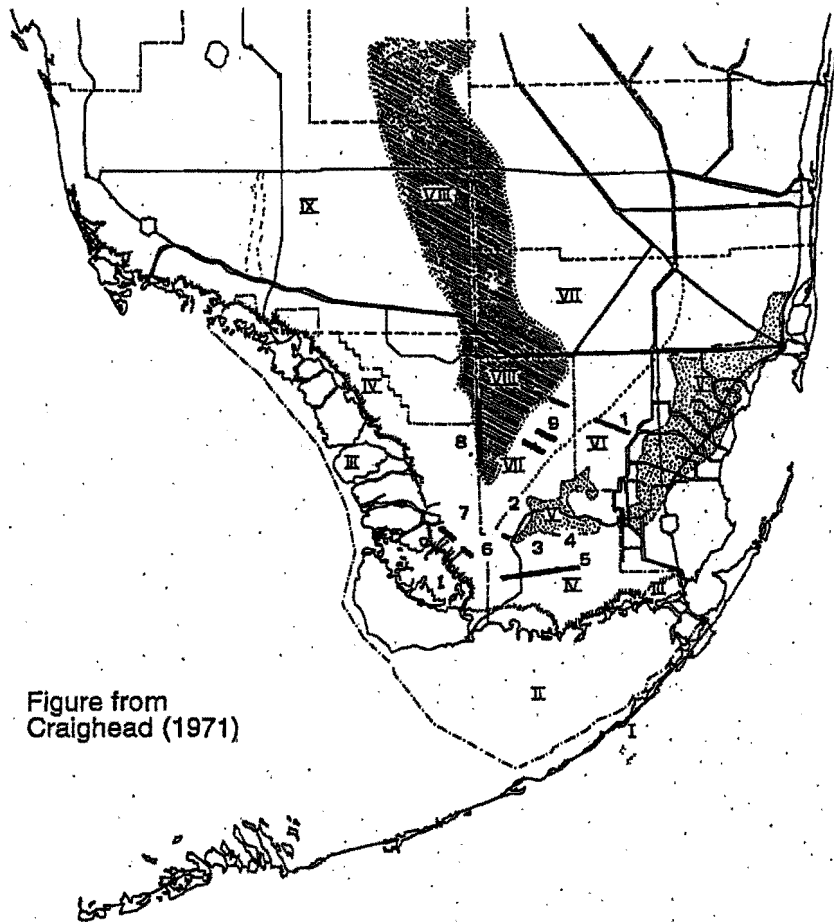


Figure from
Craighead (1971)

- | | |
|---------------------------------|-----------------------------|
| 1 - Grossman Hammock | 2 - Joe Ree Rock Reef |
| 3 - Ficus Hammock Rock Reef | 4 - Pineland Rock Reef |
| 5 - Whiskey Creek Rock Reef | 6 - Watson River Rock Reef |
| 7 - Squaw Creek Rock Reef | 8 - West Boundary Rock Reef |
| 9 - Shark River Slough remnants | |

50MHz ground penetrating radar profiles verify the absence of displacement along the Q4 discontinuity surface, which is consistently observed at approximately four meters below the rock surface. The rock reefs of south Florida, including Grossman Hammock, provide inadequate geologic evidence suggestive of tectonic activity within the Quaternary resulting in fault displacement.

White's (1970) hypothesis of preferential cementation along the ridge axis due to water percolating through fine fractures caused by structural movement has been addressed and not completely rejected. Froehlich (1979) presents observations against the theory, but admits the evidence is not conclusive either way.

Froehlich (1979) discounted Craighead's (1971) paleo-depositional shoreline features hypothesis on the basis of their geomorphology. Field observations related to directional relationships with known depositional features in south Florida seem to contradict shoreline processes. Grain size and texture of the sediments do not appear to vary within the rock reef features, as they should, if they were depositional shoreline features.

There are no sedimentologic differences found in any of the marine units (especially the Q5) of the cores (provided by E.A. Shinn and R.B. Halley) logged by the researchers interested in the origin of the rock reefs. In other words, Steinen (1995) states there is no support for the Froehlich (1979) and Jenkins (1984) hypothesis that the modern topography is relict topography formed during deposition of the Q5 unit. Thin sections prepared for Steinen are thought to show the Q5 unit is better cemented in the core sampled from the ridge axis than in any of the cores sampled flanking the ridge.

The origin of the south Florida rock reefs is still an unanswered question. Interested researchers are anxious to have the perplexing dispute satisfactorily explained: Structural or Depositional- which process is responsible for the evolution of the most noticeable and curious geological feature in Everglades National Park? Along with determining the origin of the rock reefs, ongoing research will investigate the effects of the ridges on subsurface water flow. The enigmatic ridges have long been known to pond surface water on their north sides and effect spatial distribution of the local flora. Since the narrow ridges are many kilometers in length, it is likely they may also inhibit subsurface water flow toward the south, especially during periods of drought.

Subaerial Exposure and Karstification

The Pleistocene rocks in the rocky glades or pinelands have been exposed to terrestrial influences for a period of approximately 130 ky. Deposition at ~130 ky was the last time glaciers melted to the extent sufficient to provide water for sea level to rise high enough to flood the Florida Platform. During the intervening period, exposure of the marine rocks to freshwater has altered much of the original metastable aragonite mineralogy to more stable low-magnesium calcite through reprecipitation and cementation. Much of the original rock has, however, been lost to dissolution as it is exposed to rainwater and groundwater undersaturated with respect to calcium carbonate. These corrosive waters have filtered through the Miami Limestone during period when sea level was considerably lower and the groundwater table was deeper beneath the surface. It is likely that many of the larger solution holes were formed at this time. Subsequently, as Holocene sea level has risen over the past 5000 years, the water table has moved very close to the surface, as we see it today. This high water table has allowed the lower elevation solution holes to fill with organic material and marl. Continual decay of this organic matter and the production of CO₂ contributes to the formation of carbonic acid in the organic-filled solution holes. These

corrosive water serve to further dissolve the near surface limestones.

The formation of small subsurface caves, and their collapse, is likely responsible for many of the larger solution holes found in the pinelands. The degree of connectivity between subsurface conduits has not been explored fully in the local area.

A good example of these organic-filled solution holes can be seen at our stop along the road to Long Pine Key. A second form of karstification in the rocky glades occurs by the surficial boring of fungi and algae at the surface of the exposed limestone. This form of bioerosion may be responsible, in conjunction with exposure to rainwater, for the pitted and pocketed nature of the Pleistocene limestone. The relative contribution of both types of weathering has not been determined.

A classic example of weathering on the Miami Limestone was the photograph by F.C. Craighead of the limestone sidewalk at the home of Mrs. W.J. Krome. Apparently, blocks of the local Miami Limestone were set in a sidewalk level with the concrete matrix. At the time of the photograph, some 45 years after emplacement, the blocks of the Miami Limestone had been lower about 1 inch (2.54 cm).

Holocene Deposits

Overlying the karstic surface of the Miami Limestone bedrock throughout the Park are a series of Holocene deposits related to both terrestrial depositional processes and the interaction of the rising sea level along the coastal areas (Figures 17 and 18).

Freshwater Peat and Organic Muck

The accumulation of organic material in areas of the Everglades covered most of the year by freshwater have formed mucky or peaty soils. Most of the freshwater peat occurs in the slightly lower sloughs and solution holes in the bedrock. These mucky soils are usually black, and generally fine-grained based on a predominantly saw grass composition. With lowering of the natural water levels through drainage, much of this freshwater peat has been destroyed by oxidation or exposure to fire.

A more woody peat is found in association with tree islands and hammocks. This peat is often referred to as hammock peat (Craighead, 1971). This peat contains woody materials as a result of its deposition under the tree islands. This type of peat provides a good habitat for several species of tree, including buttonwood, poisonwood, wax myrtle, spicewood, mahogany, and randia (Craighead, 1971).

Freshwater Marl and Cyanobacteria Mats

One of the most spatial extensive modern "facies" is that of the freshwater marl (Figure 19). The open prairies surrounding the pinelands and the deeper sloughs (Shank and Taylor) host conditions favorable for the *in situ* precipitation and accumulation of freshwater calcium carbonate. These carbonate deposits are known locally as "marls".

Several investigators have examined the distribution and formation of these marls in the Everglades (Gleason, 1972; Gleason and Spackman, 1974; Merz, 1992). The precipitation of small crystals (10-20 microns) is a result of extracellular precipitation by cyanobacteria mats during the standing water part of the annual hydro-period.

from the infilling of the nearshore marine basin (perhaps by storm accumulation?) and subsequent mangrove colonization. Parkinson (1987) developed a slightly different model for the Ten Thousand Island area, where oyster banks expand and eventually join, are infilled by fine sediment, and form the substrate for mangrove expansion.

One additional type of sediment that has been described in the coastal bays within the mangrove swamp has been termed 'liver mud'. Davis (1940) and Spackman et al., (1966) used this term to describe a soupy, reddish, organic-rich mud found within the (now) brackish ponds of the saline mangrove zone. Spackman et al. (1964, 1966) thought these muds formed by the erosion of mangrove peat and the onset of oxidation of the organic material. Good examples of this sediment type are found in small ponds surrounding Coots Bay.

Marine Marl (Flamingo Marl)

An elevated levee (1.5 to 2.0 ft, 45 to 60 cm) rims the southern terrestrial boundary of ENP (northern shore of Florida Bay). This levee structure is composed of marine mud and shell that is thought to have been swept landward from Florida Bay during hurricanes and strong tropical storms. Locally, this coastal deposit is referred to as the "Flamingo Marl". This deposit is dominated by aragonitic mud, as it is easily scoured from Florida Bay and suspended during strong wind events, and it is readily transported by the storm or wave surge.

Cottrell (1989) cored much of the coastal levee and the immediate offshore area in Florida Bay. His findings showed that in the eastern part of Florida Bay the levees are relatively narrow, usually arcuate, and often erosional. This is most likely related to the sediment starved nature of northeastern Florida Bay. The north central and northwestern parts of Florida Bay have great sediment productivity and a more stable coastal levee is formed, and it has been shown to be progradational (Cottrell, 1989). In the area between Flamingo and Cape Sable the seaward progradation is in excess of 2 km during the past 3 to 4 ky.

The prograding coastal levee is built above sea level by the piling up of sediment during flooding events related to strong storms. As such, the sediment is readily oxidized and shows evidence of storm related rip-up clasts, root structures from terrestrial vegetation, and bioturbation by crabs burrow excavation.

COMBINED REFERENCES

- * Broecker, W.S., and D.L. Thurber, 1965, Uranium-series dating of corals and oolites from Bahamian and Florida Keys limestones: Science, v. 159, p. 58-60.

Cottrell, D.J., 1989, Holocene evolution of the coast and nearshore islands, northeastern Florida Bay, Florida. Ph.D. dissertation, University of Miami, Coral Gables, FL, 194 p.

- * Craighead, F.C., Sr., 1971, The Trees of South Florida, Vol. 1., The Natural Environment and their Succession. U. of Miami Press, Coral Gables, p. 212.

Cunningham, K.J., McNeill, D.F., Guertin, L.A., Ciesielski, P.F., Scott, T.M., and de Verteuil, L., 1998, New Tertiary Stratigraphy for the Florida Keys and Southern

A recent study by Merz (1992) found that precipitation occurs for 6-8 months per year when the freshwater prairies are flooded. It is these areas that contain vegetation which can withstand several months of complete desiccation, for example: sawgrass (*Cladium jamaicensis*), some mangroves, and extensive cyanobacteria mats. The cyanobacteria mats are reactivated with the onset of the seasonal flooding cycle and produce small carbonate crystals during daytime precipitation, a response to photosynthesis by the cyanobacteria. The main calcifying species of filamentous cyanobacteria are *Schizothrix* and *Scytonema*. The water in which the cyanobacteria occur are supersaturated with respect to carbonate and the precipitation occurs within a sheath structure around the filamentous strand. The formation of calcite crystals within the sheath structure produces a size (5-20 microns) and shape (equant) distinct crystal morphology.

In the southern Everglades, freshwater carbonate marls reach thicknesses of up to 50 cm depending on relief of the underlying Pleistocene carbonates. The stratigraphy of the freshwater marl consists of: the upper few centimeter of dark brown material due to high organic content, with depth the marl becomes light brown to gray, and is sometimes underlain by freshwater peat. The marl portion of the sequence often contains plant roots and freshwater gastropods.

Coastal Mangrove Sedimentation

The coastal mangrove swamp environment rims the seaward edges of Everglades National Park (Figure 19). These coastal swamp environments are formed where the Holocene sea level has transgressed upon the Pleistocene limestones and freshwater sloughs and marl prairies.

Sediment produced from the coastal prairies results mainly from the decay of mangrove plants and the formation of mangrove peat. The red mangrove (*Rhizophora mangle*) is the dominant plant in the coastal swamp area, and reproduces via a elongate seedling. These thin, rod-shaped seedling, slightly bigger than a pencil are distributed by wind and tidal currents. Strong tropical storms and hurricanes likely play an important role in the distribution of mangrove seedlings.

Once established, mangrove plants produce abundant organic material through the production of root hair beneath the sediment surface and through extensive root systems. These organic fibers remain wet and are slow to decay through oxidation. As more and more organic material accumulates acid conditions evolve in the pore waters of the coastal swamp and become very corrosive to carbonate grains. Usually, carbonate material that is incorporated in the mangrove system is dissolved. The resulting sedimentary sequence is nearly 100% mangrove peat, with occasional subordinate amounts of quartz sand.

Wanless (1974) has cored many of the coastal mangrove deposits within ENP and has described the succession of low-energy shoreline development. Wanless (1974) has shown that for the eastern margins of ENP the Holocene transgressive sequence overlying the Pleistocene bedrock consists of a basal freshwater marl or peat that grades upward to predominantly red mangrove peat. Later, as sea level floods the area, the mangrove peat may be capped by transgressive marine sediments. Alternatively, the mangrove peat can form a more vertically aggrading deposit, where it keeps up with the rise of sea level instead of eroding as it transgresses.

For the southern part of the ENP coastline (northwestern Florida Bay) and much of the areas along the western coastline (Ten Thousand Islands) has been prograding seaward during the past 4000 years (Wanless, 1974; Parkinson, 1987). Seaward growth likely results

Peninsula of Florida. Geological Society of America Bulletin, v. 110, p. 231- 258.

Davis, J.H., Jr., 1940, The ecology and geologic role of mangroves in Florida. Carnegie Institution, Washington D.C., no. 517.

DuBar, J.R., 1991. Quaternary geology of the Gulf of Mexico Coastal Plain- Florida Peninsula. In Quaternary nonglacial geology, edited by R.B. Morrison, 595-604. The Geology of North America, vol. K-2. Geological Society of America.

* Fairbanks, R.G., 1989, A 17,000 year glacio-eustatic sea level record - Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation: Nature, v. 342, p. 637-642.

Fish, J.E., and Stewart, M., 1991, Hydrogeology of the Surficial Aquifer System, Dade County, Florida, USGS WRI Report 90-4108, 50 pp.

* Froehlich, D.J., 1979, The rock reefs of the Everglades of South Florida. Unpubl. Masters thesis, Syracuse University, Syracuse, N.Y., 128p.

Gleason, P.J., 1972, The origin, sedimentology, and stratigraphy of a calcitic mud located in the southern fresh-water Everglades. Unpubl. Ph.D. Dissertation, Penn State Univ., State College, PA, 355 p.

* Gleason, P.J. and Spackman, W., 1974, Calcareous periphyton and water chemistry in the Everglades. Miami Geological Society, Memoir 2, p. 146-181.

Guertin, L.A., McNeill, D.F., Lidz, B.H., and Cunningham, K.J., 1999, Chronology and Transgressive/Regressive Signatures in the Late Neogene Siliciclastic Foundation (Long Key Formation) of the Florida Keys. Journal of Sedimentary Research, v. 69, p. 653-666.

Heatherington, A. L., and Mueller, P.A., 1991, Geochemical evidence for Triassic rifting in southwestern Florida. Tectonophysics 188: 291-302.

Heatherington, A.L., and Mueller, P.A., 1997, Ch. 3 Geochemistry and Origin of Florida Crustal Basement Terranes in The Geology of Florida. Univ. Press of Florida, Gainesville, p. 27-38.

Hoffmeister, J.E., Stockman, K.W., and Multer, H.G., 1967. Miami limestone of Florida and its recent Bahamian counterpart: Geol. Soc. American Bull., v. 78, p. 175-190.

Hoffmeister, J.E., 1974, Land from the sea - The geologic story of south Florida: Coral Gables, Fla., University of Miami Press, 143 p.

* Jenkins, R.V., 1984, The origin of the Rock Reefs of the Everglades. Unpubl. Master's thesis, Wichita State Univ., Kansas, 137p.

Lighty, R.G., Macintyre, I.G., and Stuckenrath, R., 1982, Acropora palmata reef framework: a reliable indicator of sea level in the Western Atlantic for the past 10,000 years. Coral Reefs, v. 1, p. 125-130.

McNeill, D.F., Cunningham, K.J., Guertin, L.A., Melim, L.A., Warzeski, E.R., Anselmetti, F.S., Ginsburg, R.N., Eberli G.P., and Swart P.K., 1996, Data report: Tertiary-

Quaternary cores from the Florida Keys and Everglades. Miami Geological Society, South Miami, Florida, 98 p.

Meeder, J. F., 1979, Field guidebook to a Pliocene reef of Southwest Florida. Miami Geological Society, 19 p.

* Merz, M.U., 1992, The Biology of Carbonate Precipitation by Cyanobacteria. Marburg, Facies, v. 26, p. 81-102. MARINE LIB.

Mitterer, R.M., 1975, Ages and diagenetic temperatures of Pleistocene deposits of Florida based on isoleucine epimerization in Mercineria: Earth and Planet. Sci. Letters, 28:275-282.

Mueller, P.A., and Porch, J., 1983, Tectonic implications of Paleozoic and Mesozoic igneous rocks in the subsurface of peninsular Florida. Transactions of the Gulf Coast Association of Geological Societies 33: 169-74.

Neumann, C.J., Jarvine, B.R., and Pike, A.C., 1981, Tropical cyclones of the North Atlantic Ocean 1871-1981: Asheville, N. C., National Climatic Center: Historical Climatology Series 6-2, 174 p.

Neumann, C.J., Cry, G.W., Caso, E.L., and Kerr, J.D., 1978, Tropical cyclones of the North Atlantic Ocean, 1871-1977. National Climatic Center, Asheville, N.C., U.S. Govt. Printing Office, 170 p.

Osmond, J.K., Carpenter, J.R., and, Windom, H.L., 1965, $^{230}\text{Th}/^{234}\text{U}$ age of the Pleistocene corals and oolites of Florida: Jour. Geophys. Res., v. 70, p. 1843-1847.

Parker, G.G., and Cooke, C.W., 1944, Late Cenozoic Geology of Southern Florida, with a Discussion of the Ground Water. Florida Geological Survey, Tallahassee.

Parkinson, R.W., 1987, Holocene sedimentation and coastal response to rising sea level along a subtropical low energy coast, Ten Thousand Islands, southwest Florida. Unpubl. Ph.D. Dissertation, Univ. Miami, Coral Gables, FL, 224 p.

Perkins, R.D., 1977, Depositional framework of Pleistocene rocks in south Florida, in Enos, Paul, and Perkins, R.D., Quaternary Sedimentation in south Florida, Geol. Soc. America Memoir 147:131-197.

Robbin, D.M., 1984, A New Holocene Sea Level Curve for the Upper Florida Keys and Florida Reef Tract. Miami Geological Society, Miami, p. 437-458.

Shinn, E.A., and Lidz, B.H., 1988, Blackened Limestone Pebbles: Fire at Subaerial Unconformities. Springer-Verlag, New York, p. 117-131.

* Scholl, D.W., 1964, Recent sedimentary record in mangrove swamps and rise in sea level over the southwestern coast of Florida, parts I and II. Marine Geology, v. 1, p. 344-366, v. 2, p. 343-364.

* Scholl, D.W., Craighead, F.C., Sr., and Stuiver, M., 1969, Florida submergence curve revised: its relation to sedimentation rates. Science, v. 163, p. 562-564.

Scott, T.M., and Allmon, W.D., 1992, The Plio-Pleistocene stratigraphy and paleontology of southern Florida. Florida Geological Survey Special Publication no. 36. 194 p.

South Florida Water Management District, 1993, Lower East Coast Regional Water Supply Plan: West Palm Beach, Fla., 193 p.

Spackman, W., Scholl, D.W., and Taft, W.H., 1964, Field guidebook to environments of coal formation in southern Florida. Geological Society of America Field Trip, 67 p.

Spackman, W., Doldon, C.P., and Reigel, W., 1966, Phytogenic organic sediments and sedimentary environments in the everglades mangrove complex. Paleontographica Abt. B 117, p. 135-152.

Steinen, R.P., Shinn, E.A., Halley, R.B., 1995, Hypothesized fault origin for the rock reefs of South Florida: GSA annual meeting, New Orleans, Book of Abstracts, A p. 229.

Thomas, W.A., T.M. Chowns, D.L. Daniels, T.L. Neatherly, L. Glover, and R.J. Gleason, 1989, The subsurface Appalachians beneath the Atlantic and Gulf coastal plains. The Geology of North America, v. F-2. Geological Society of America.

Wanless, T.L., 1974, Mangrove sedimentation in geologic perspective, In, Gleason, P. (ed.), Environments of South Florida: Present and Past. Miami Geol. Soc. Mem, 2, p. 190-200.

Wanless, H.R., 1982, Sea level is rising -- so what?. J. Sed. Petrology, v. 52, p. 1051-1054.

Wanless, H.R., 1976. Geological setting and Recent sediments of the Biscayne Bay region, Florida. In, Thorhaug, A., and Volker, A., (eds.), Biscayne Bay: Past, Present, and Future. Univ. of Miami Sea Grant Spec. Publ. No. 5, p., 1-32.

Wanless, H. R., and Tagett, M. G., 1989, Origin, growth and evolution of carbonate mudbanks in Florida Bay. Bulletin of Marine Science, v. 44, no. 1, p. 454-489.

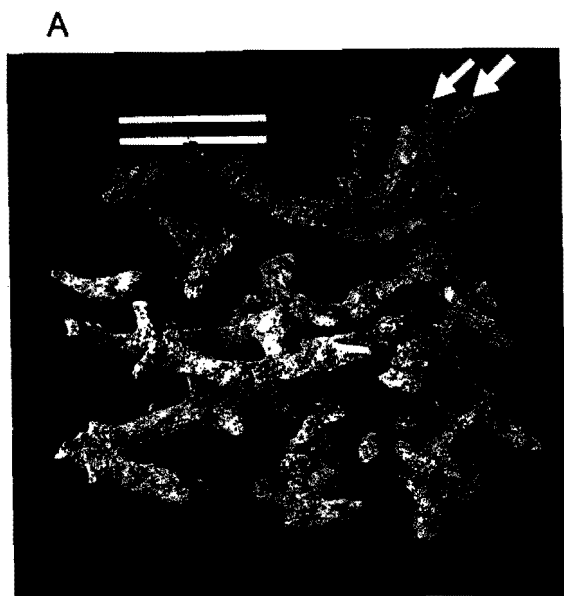
Warzeski, E. R., Cunningham, K. J., Ginsburg, R. N., Anderson, J. B., and Ding, Z. D., 1996, Neogene Mixed Siliciclastic and Carbonate Foundation for the Quaternary Carbonate Shelf, Florida Keys. J. Sedimentary Research, v. 66, p. 788-800.

White, W.A., 1970, The Geomorphology of the Florida Peninsula: Florida Geol. Surv. Bull. no. 51, 164p.

Supplemental Figures

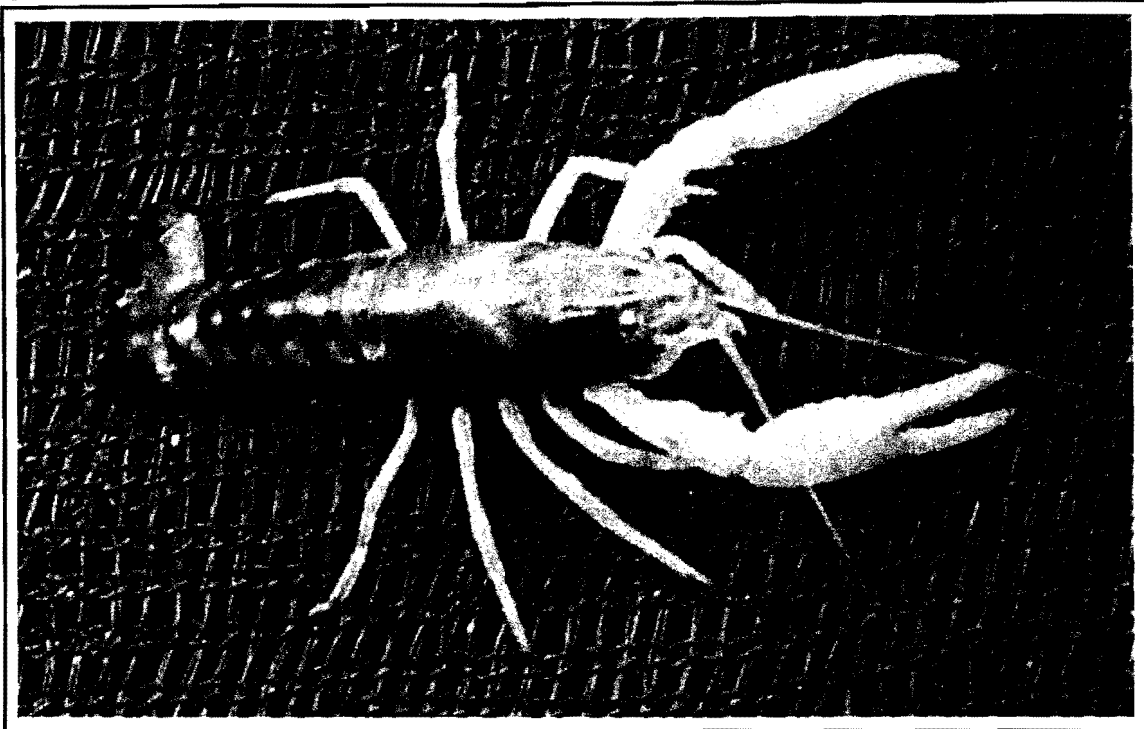
Epoch		Fish & Stewart (1991)	Causarus (1987)	Perkins (1977)
Miocene	Pliocene	Surficial Aquifer System Semiconfining Unit or Sand Aquifers Gray Limestone Aquifer Semiconfining Unit Biscayne Aquifer	Peat and Marl	
			Miami Limestone	Q5
	Fort Thompson Formation		Q4	
			Q3b	
			Q3a	
			Q2	
	Peace River Formation		Q1	

Shallow hydrostratigraphy, lithostratigraphy and cyclostratigraphy of southeastern Florida.

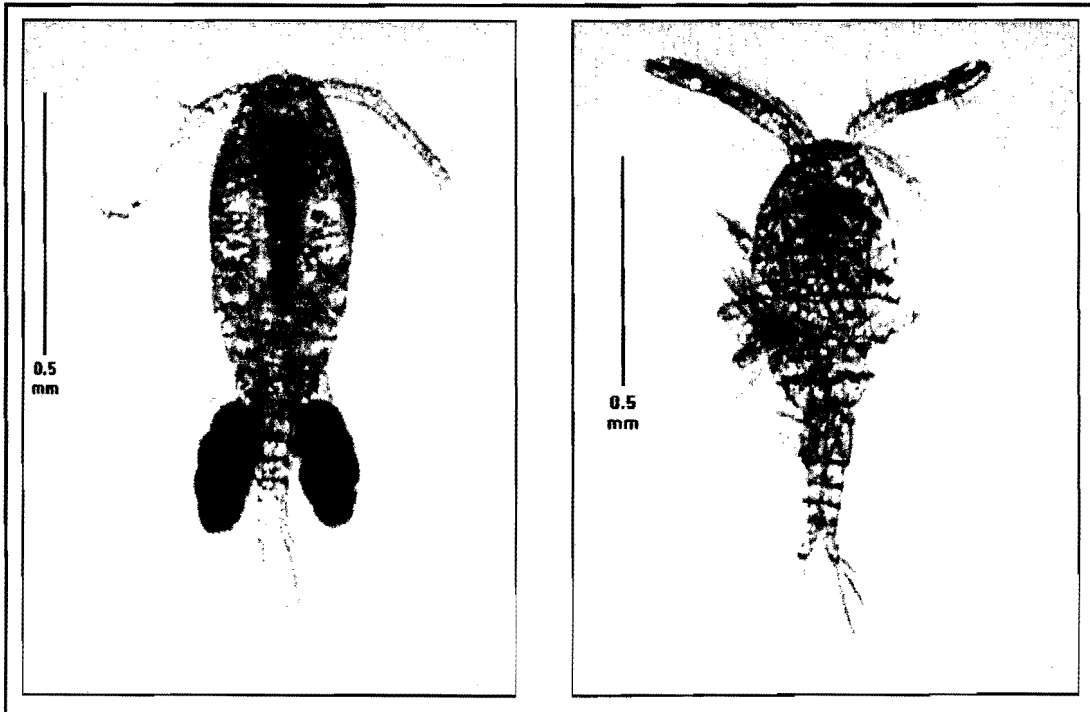


(A) Plastic cast of *Alpheus* shrimp burrows (Shinn, 1965). Burrows like these riddle the mottled facies (Evans, 1984) of the Miami Limestone. (B) Cut face of boulder sized sample of mottled facies of the Miami Limestone showing channel porosity (Evans, 1984). Burrowing such as that shown in photo A contribute to this irregular framework of relatively more highly cemented peloid-oid grainstone and resulting extremely high transmissivities for the Miami Limestone.

A



B



(A) A Miami cave crayfish. (B) Female and male copepods, female has eggs attached. These are examples of aquatic animals biological researchers hope to trap in large-scale porous zones of the limestone of the Biscayne aquifer located by ground-penetrating radar and tested with coreholes drilled by WRD in the Everglades National Park.

Selected Publications

Part 1



Application of ground-penetrating radar, digital optical borehole images, and cores for characterization of porosity hydraulic conductivity and paleokarst in the Biscayne aquifer, southeastern Florida, USA[☆]

Kevin J. Cunningham^{*}

U.S. Geological Survey, Water Resources Discipline, 9100 NW 36th Street, Suite 107, Miami, FL 33178, USA

Abstract

This paper presents examples of ground-penetrating radar (GPR) data from two study sites in southeastern Florida where karstic Pleistocene platform carbonates that comprise the unconfined Biscayne aquifer were imaged. Important features shown on resultant GPR profiles include: (1) upward and lateral qualitative interpretative distribution of porosity and hydraulic conductivity; (2) paleotopographic relief on karstic subaerial exposure surfaces; and (3) vertical stacking of chronostratigraphic high-frequency cycles (HFCs). These characteristics were verified by comparison to rock properties observed and measured in core samples, and identified in digital optical borehole images. Results demonstrate that an empirical relation exists between measured whole-core porosity and hydraulic conductivity, observed porosity on digital optical borehole images, formation conductivity, and GPR reflection amplitudes—as porosity and hydraulic conductivity determined from core and borehole images increases, formation conductivity increases, and GPR reflection amplitude decreases. This relation allows for qualitative interpretation of the vertical and lateral distribution of porosity and hydraulic conductivity within HFCs. Two subtidal HFCs in the uppermost Biscayne aquifer have significantly unique populations of whole-core porosity values and vertical hydraulic conductivity values. Porosity measurements from one cycle has a median value about two to three times greater than the values from the other HFC, and median values of vertical hydraulic conductivity about three orders of magnitude higher than the other HFC. The HFC with the higher porosity and hydraulic conductivity values is shown as a discrete package of relatively low-amplitude reflections, whereas the HFC characterized by lower porosity and hydraulic conductivity measurements is expressed by higher amplitude reflections. Porosity and hydraulic conductivity values measured from whole-core samples, and vuggy porosity identified on digital borehole images from shallowing-upward, peritidal HFCs show that the highest porosity occurs at the base of the cycles, moderate porosity at the middle of the cycles, and lowest porosity occurs at the top of cycles. Hydraulic conductivity is also highest at the base of the peritidal cycles and lowest in the middle to upper parts of cycles. This change in porosity and hydraulic conductivity from bottom to top is visible as an upward variation in reflection amplitude on GPR profiles—lowest amplitudes at the base and highest at the cycle tops. This study demonstrates that GPR can be used to show the qualitative distribution of porosity and hydraulic conductivity within a cycle-stratigraphic framework composed of carbonate HFCs. The distribution of porosity and

[☆] The use of brand names in this paper is for identification purposes only and does not constitute endorsement by the author, the U.S. Geological Survey, or the Journal of Applied Geophysics.

^{*} Tel.: +1-305-717-5813; fax: +1-305-717-5801.

E-mail address: kcunning@usgs.gov (K.J. Cunningham).

hydraulic conductivity within HFCs is related to depositional textures. The upward and lateral patterns of the rock facies within the HFCs can be translated to geophysical-log properties and radar facies configurations that could aid in interpretation and prediction of ground-water flow through a carbonate aquifer.

© 2003 Elsevier B.V. All rights reserved.

Keywords: Ground-penetrating radar; Porosity; Biscayne aquifer; Carbonates; Karst; Southeastern Florida

1. Introduction

Ground-penetrating radar (GPR), combined with a precisely defined cycle stratigraphy from cores and digital borehole images, and the detection of vuggy porosity from digital borehole images of near surface karst limestone, can provide a robust visualization of karst aquifer architecture, encompassing the spatial distribution of aquifer bodies, barriers, conduits, and connectivity. Calibration of high-resolution borehole data to GPR attributes for complex karst carbonate lithologies requires continuously cored boreholes and digital-image logs. The high-resolution study of the shallow, karstic Biscayne aquifer serves as a guide for developing improved and more realistic geology-based karst-carbonate aquifer models.

Although the geologic application of GPR is most common for siliciclastic strata (e.g., Beres and Haeni, 1991; Smith and Jol, 1992; van Overmeeren, 1998) and crystalline rocks (e.g., Grasmueck, 1996; Lane et al., 2000), its use in karst-carbonate rocks is becoming more common (Ballard, 1983; Beck and Wilson, 1988; Barr, 1993; McMechan et al., 1998; Beres et al., 2001; Cunningham and Aviantara, 2001). GPR has been applied to near-surface carbonate rocks, but the combined use of GPR and digital borehole images is a new application (Cunningham and Aviantara, 2001). No published examples have been found that demonstrate the use of GPR to delineate porosity within a carbonate high-frequency cycle stratigraphy. Other lithologic and hydraulic features that can be inferred from GPR profiles include sediment types and thickness (Beres and Haeni, 1991), karst features (Barr, 1993; McMechan et al., 1998), subaerial-exposure surfaces (Kruse et al., 2000), and depth to water table and clay beds (Johnson, 1992; Barr, 1993). McMechan et al. (1998) used GPR to image a near-surface paleocave system in the Lower Ordovician Ellenberger dolomites in central Texas. Martinez et al. (1998) showed that small-scale (less than 0.01 m) lithologic heterogeneity could be

identified with GPR imaging of Pennsylvanian cyclic limestone outcrops in Kansas. The lithologic heterogeneity, which affects permeability, can provide quantitative data for use in fluid-flow modeling. Dagallier et al. (2000) showed that GPR could be used to identify the internal organization of lithologic units within Jurassic limestone in France. Kruse et al. (2000) have shown that GPR can be effective in mapping the altitude and structure of shallow limestone cap rock in the prairie, cypress swamp, and hardwood hammock of the Fakahatchee Strand State Preserve in southwestern Florida. Beres et al. (2001) demonstrated that GPR is an excellent tool for identifying and delineating shallow subsurface cavities in karstified Jurassic limestone in Switzerland.

2. Purpose and scope

The purpose of this paper is to demonstrate how the combined use of GPR, borehole-geophysical logs, and continuously drilled cores can be used to characterize the spatial distribution of porosity and identify karst features within shallow carbonate aquifers. In this paper, it is shown that GPR profiles combined with cores and digital optical borehole image logs can contribute powerfully to characterizing hydrogeologic properties of shallow karst-carbonate aquifers. This investigation demonstrates the effective use of the relation between porosity and high-frequency carbonate cycles and amplitude of reflections in GPR profiles, to characterize a karst-carbonate aquifer. Results from this study have improved the understanding of the distribution of porosity in young (Pleistocene) platform carbonates that comprise an unconfined surficial aquifer.

GPR profiles and data from test coreholes were collected at two sites, the north-central Miami-Dade site and the Rocky Glades site, in southeastern Florida (Fig. 1). To enhance the data set, whole-core porosity

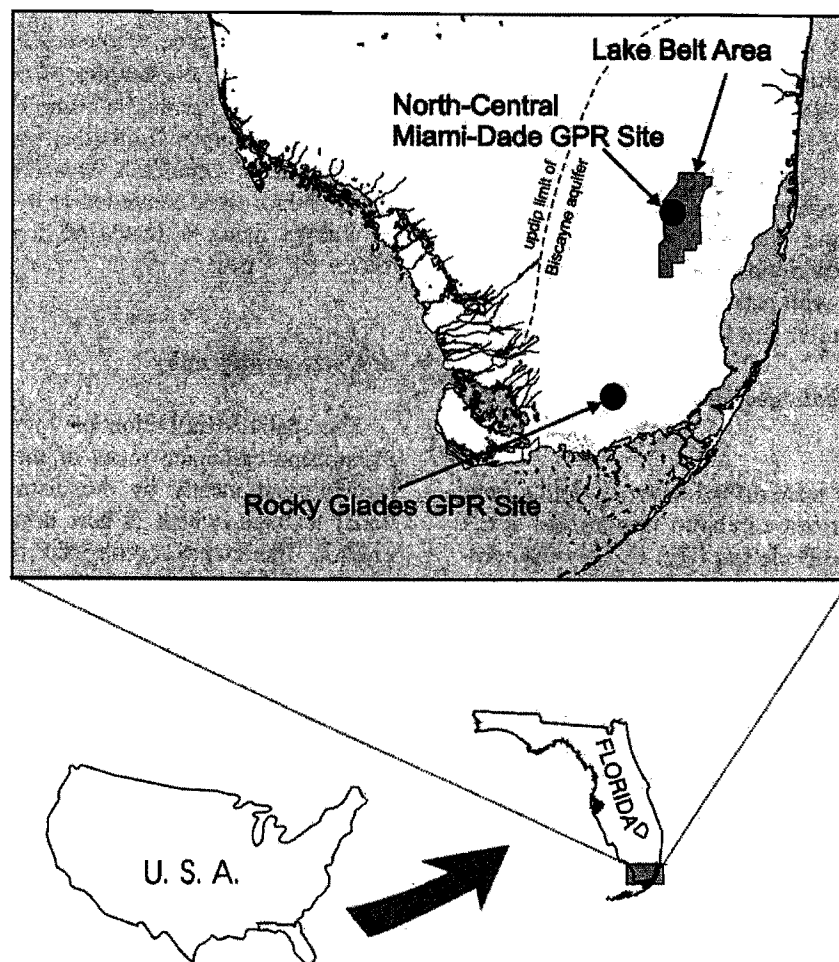


Fig. 1. Map of locations of the north-central Miami-Dade and Rocky Glades ground-penetrating radar (GPR) sites, and the Lake Belt Area.

values were used from ongoing research of the surficial aquifer in the Lake Belt Area (Cunningham and Aviantara, 2001), which includes the north-central Miami-Dade site (Fig. 1).

3. Methods

3.1. GPR surveys

Two types of GPR field surveys were conducted for this project: (1) continuous measurement common-offset reflection surveys and (2) common mid-point (CMP) velocity surveys (Annan and Davis, 1976; Davis and Annan, 1989). The common-offset

reflection surveys were performed to produce two-dimensional profiles of the GPR reflections, and the CMP surveys were used to calculate radar velocities propagating through the solid and fluid material comprising the Biscayne aquifer. All GPR data was collected using a Geophysical Survey Systems (GSSI) SIR™ System-10A+ with a dual 100-MHz antenna array. The common-offset reflection surveys were collected while towing the antennas 17 m behind a truck at a rate of about 0.8 km/h. The separation between the center points of the antennas was 89 cm. Velocities were calculated by correlating depths to reflectors, which could be determined from positive correlation with corehole lithologies and the CMP surveys. Processing included a horizontal filter pass

and, for some GPR profiles, a constant-velocity migration of the continuous survey data using GSSI RADAN™ for WinNT software. Identification of GPR reflection amplitudes also was accomplished using the software GSSI RADAN™. Interpretations of profiles were made using the RADAN™ for WinNT software and RADAN™-to-bitmap conversion utility. The descriptions of radar-reflection patterns are consistent with patterns described for seismic profiles by Mitchum et al. (1977).

3.2. Drilling, borehole geophysical logs, and whole-core porosity

Seven test wells were drilled to verify results from GPR surveys. Four test coreholes were drilled at the north-central Miami-Dade site (Fig. 1). Two test coreholes and one rotary roller-bit test well were drilled at the Rocky Glades site (Fig. 1). Borehole-geophysical logs were collected by the U.S. Geological Survey (USGS) for all seven test wells and included conductivity, natural gamma ray, caliper, and digital borehole image logs. The digital borehole image logs were run using either a RaaX™ Borehole Image Processing System (BIPS™) or an ALT OBI-40™ digital optical logging tool in the test wells filled with clear, ambient

freshwater. Sixty-nine whole-core porosity measurements were made on samples of core drilled at both the north-central Miami-Dade and Rocky Glades GPR sites, and on samples from other test coreholes drilled throughout the Lake Belt Area (Fig. 1). Air-permeability values were converted to hydraulic conductivity values using a factor of 1 millidarcy equals 9.67×10^{-9} m/s.

4. Cycle stratigraphy

The spatial distribution of vuggy porosity in the Pleistocene carbonate rocks of the Biscayne aquifer is controlled mostly by the distribution of depositional textures, which is best described by a stratigraphic framework comprised of high-frequency cycles (HFCs). Using a modified definition by Lucia (1999), the HFC is a chronostratigraphic unit composed of an unconformity-bounded succession of genetically related textures contained in beds or bed-sets. The upper and lower bounding surfaces of the HFC are surfaces of subaerial exposure caused by a relative fall in sea level.

Two types of HFCs are present in the Biscayne aquifer. One is a subtidal cycle formed by vertical

Series	Hydrogeologic Unit		Lithostratigraphic Unit	"Q Units"	HFC	Cycle Type
Holocene	Surficial Aquifer System	Biscayne Aquifer	Peat or Marl or Both			
Pleistocene			Miami Limestone	Q5	Q5	Subtidal
				Q4	Q4	
			Fort Thompson Formation	Q3	Q3 Q3a Q3b	Peritidal
				Q2	Q2	
				Q1	?	

===== surface of subaerial exposure

Fig. 2. Shallow time stratigraphic units, hydrostratigraphy (Fish and Stewart, 1991), lithostratigraphy (Causaras, 1987), "Q units" of Perkins (1977), and high-frequency cycles (HFC) used in this report for southeastern Florida.

aggradation of high-energy shoals or shallow-marine, peloidal, highly burrowed sand flats. The Miami Limestone contains two unconformity bounded subtidal HFCs (Fig. 2). The second type of HFC, a peritidal cycle, is composed of a succession of depositional textures that decrease in grain size upward, that shallow upward, and is capped by a tidal-flat deposit or freshwater limestone or a stacking of both. Three peritidal HFCs are recognized in the upper part of the Fort Thompson Formation (Fig. 2). The delineation of HFCs in the lower part of the Fort Thompson is currently under investigation. The “Q” terminology of the HFCs is modified from Perkins (1977), who first recognized that the Miami Limestone and Fort Thompson Formation of south Florida are composed of five unconformity-bounded, time-stratigraphic marine units (Fig. 2). These units were informally termed, from oldest to youngest, Q1 through Q5 (Q for Quaternary). Fig. 2 shows the relation between the “Q units” of Perkins (1977) and the HFCs of this study.

5. Results of GPR surveys

5.1. Rocky glades site

At the Rocky Glades site (Fig. 1), the radar reflections from the Q5 subtidal HFC typically have poor horizontal continuity or hummocky configurations (Fig. 3). These reflection patterns image highly bioturbated, massive beds (without well-defined bedding planes) composed of pelmoldic grainstone and packstone that have very high porosities and hydraulic conductivities (Figs. 4–6). The reflections of the Q5 HFC are mostly lower amplitude than reflections in the underlying uppermost limestone of the Q4 HFC (Fig. 3). Amplitude analysis demonstrates that a reflection representing the base of the Q5 HFC has substantially lower amplitude than amplitudes of the top layers of the Q4 HFC (Fig. 7a). The basal reflection of the Q5 HFC averages about 6 decibels (dB) lower than amplitudes at the top of the Q4 HFC

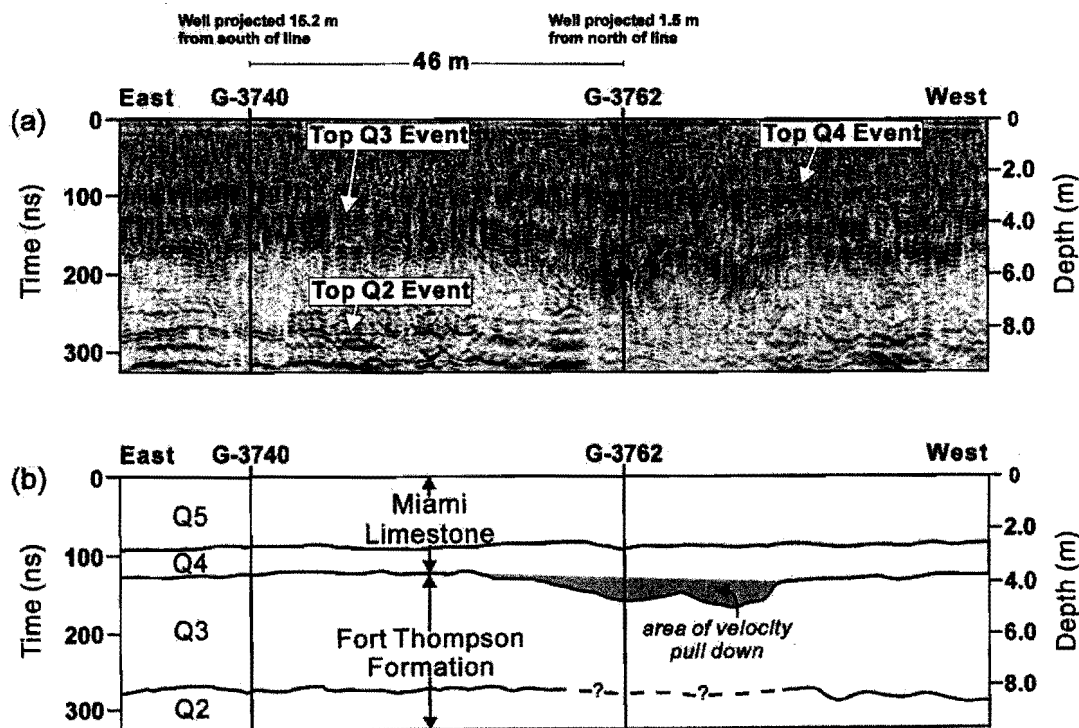


Fig. 3. GPR line 286 at the Rocky Glades site, Everglades National Park. (a) 100-MHz profile across zones of very high porosity in high-frequency cycles Q4 and Q3. A horizontal-filter pass has been applied to the profile. (b) Line drawing of GPR profile. Q5, Q4 and Q3 correspond to the high-frequency cycle stratigraphy shown in Fig. 2.

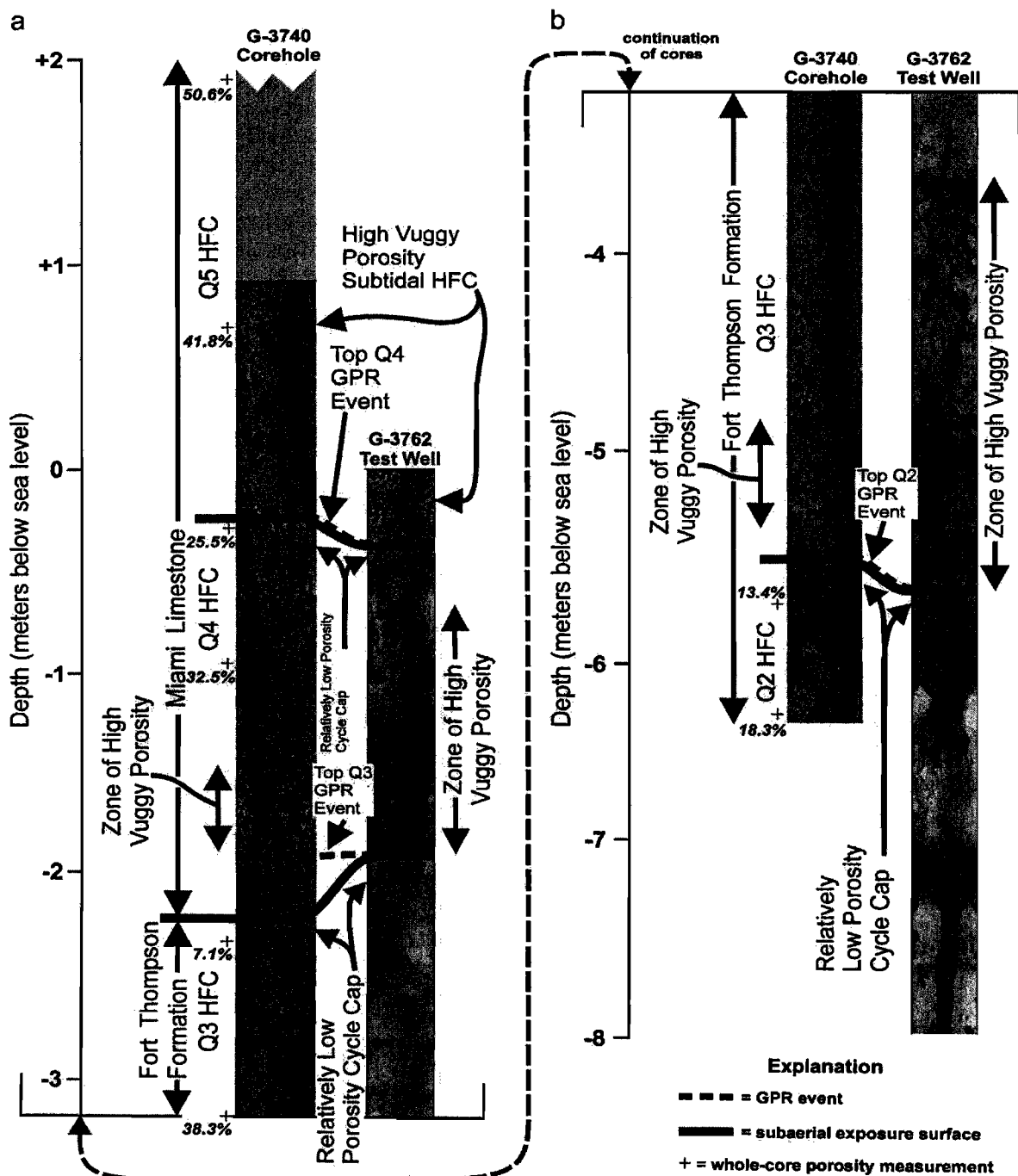


Fig. 4. (a) Digital optical borehole images of the G-3740 and G-3762 test coreholes (Fig. 3) with base of borehole images continued. (b) Continuation of base of borehole images in (a). Depths of ground-penetrating radar events are interpreted from common mid-point velocity surveys and correlation to test-corehole lithology. Zones of relatively high vuggy porosity are shown. HFC = high-frequency cycle.

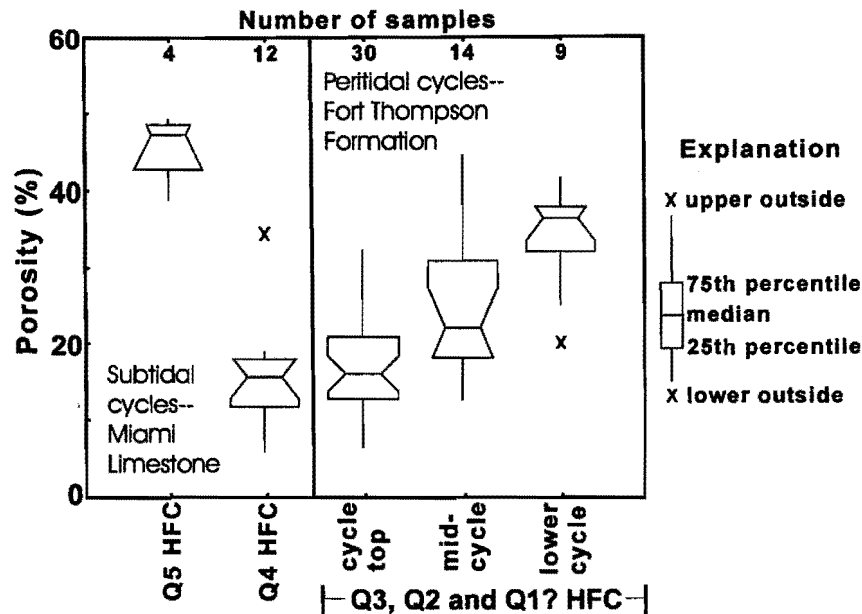


Fig. 5. Box-whisker plots of laboratory-measured porosity of whole-core samples from the Rocky Glades GPR site and Lake Belt Area. In the box plot, the upper and lower quartiles of the data are portrayed by the top and bottom of the polygon, and the horizontal line segment within the polygon represents the median. When comparing the notches on two boxes, if the notches do not overlap, this indicates a difference in the median of porosity populations at about a 95% confidence level. Where there is overlap of notches, there is not a significant difference in the medians. Roughly 99% of the data is contained between the limits of the whiskers and the remaining 1% of the data are plotted as individual points. The plots for the two subtidal high-frequency cycles of the Miami Limestone indicate that the upper Q5 high-frequency cycle (HFC) has significantly higher values of porosity than the lower cycle (Q4 HFC). The three plots to the right indicate that the porosity values within the high-frequency peritidal cycles of the Fort Thompson Formation decreases upward from cycle base to cycle cap.

(Fig. 7a). The relatively low amplitudes of the reflections of the Q5 HFC are consistent with a very high pelmoldic matrix porosity, high solution-enlarged burrow porosity, and high hydraulic conductivity that are characteristic of the Q5 HFC (Figs. 5 and 6). The relatively high reflection amplitudes of the Q4 HFC correlate with a micrite-rich rock fabric that has a characteristically lower porosity and hydraulic conductivity (Figs. 5 and 6). Whole-core porosity values of the Q5 HFC from the Lake Belt Area and Rocky Glades site (Fig. 1) range from 40% to 50%, and values from the Q4 HFC are two to three times lower (Fig. 5). The average median whole-core vertical hydraulic-conductivity value of the Q5 HFC averages about three orders of magnitude higher than the median value from the Q4 HFC (Fig. 6a) and the median whole-core maximum horizontal hydraulic-conductivity value of the Q5 HFC averages about one order of magnitude higher than the median value from the Q4 HFC (Fig. 6b).

The lower amplitudes of the reflections in the Q5 HFC relative to higher reflection amplitudes in the top layers of the Q4 HFC are probably caused by much higher porosities, and thus higher freshwater content in the Q5 HFC. Fig. 8 shows that the formation conductivity of the Q5 HFC is higher than the formation conductivity of the top layers of the Q4 HFC. The attenuation of electromagnetic (EM) waves increases as the electrical conductivity of a medium increases (Lane et al., 2000). Thus, there is an empirical relation between formation porosity, hydraulic conductivity, formation conductivity, and reflection amplitudes—as porosity increases, hydraulic conductivity and formation conductivity increases, and reflection amplitude decreases. This relation is observed throughout the entire vertical and lateral section of the Biscayne aquifer represented in Figs. 3 and 4.

The top of the Q4 subtidal HFC has a relatively low porosity limestone cap and much of the bottom

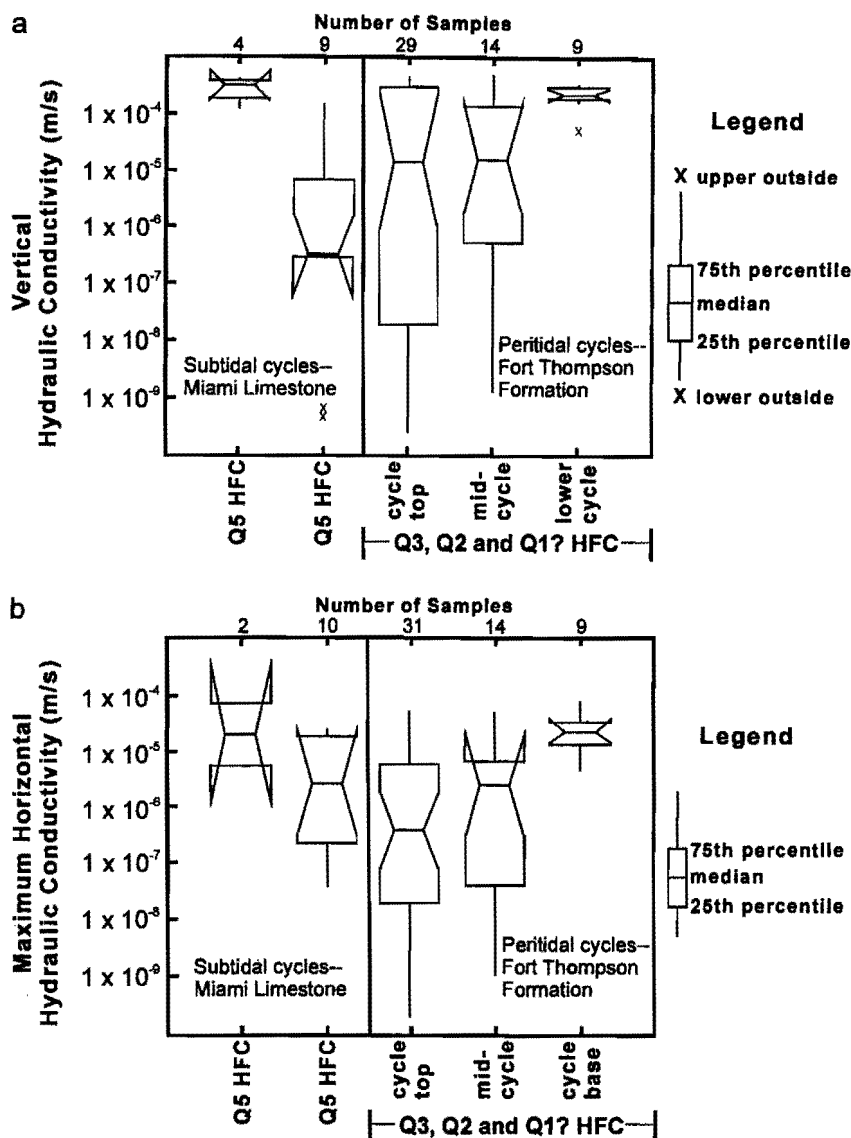


Fig. 6. Box-whisker plots of hydraulic conductivity of most of the same samples displayed in Fig. 5. See Fig. 5 for an explanation of the box-whisker plots. Hydraulic conductivities were calculated from laboratory-measured air-permeability values using a factor of 1 millidarcy equal to 9.67×10^{-9} m/s. (a) Vertical hydraulic conductivity and (b) maximum horizontal hydraulic conductivity.

section of the Q4 HFC is characterized by higher matrix and vuggy porosity (Fig. 4). On the GPR profile shown in Fig. 3, the reflections in the top layers of Q4 HFC have relatively higher amplitude than the reflections in the bottom section of the Q4 HFC. In the area of the G-3762 test corehole, high vuggy porosity in the bottom section of the Q4 HFC is developed best (Fig. 4). This high porosity at the

G-3762 test corehole is expressed as a thick zone of relatively low amplitude reflections in the bottom section of the Q4 HFC on the GPR profile shown in Fig. 3. Comparison of Q4 HFC reflection amplitudes in Fig. 7a and b confirms that the reflection amplitudes at the top of the Q4 HFC are about 9 dB higher than at the base of the Q4 HFC. Formation conductivity in the top layers of the Q4 HFC is also

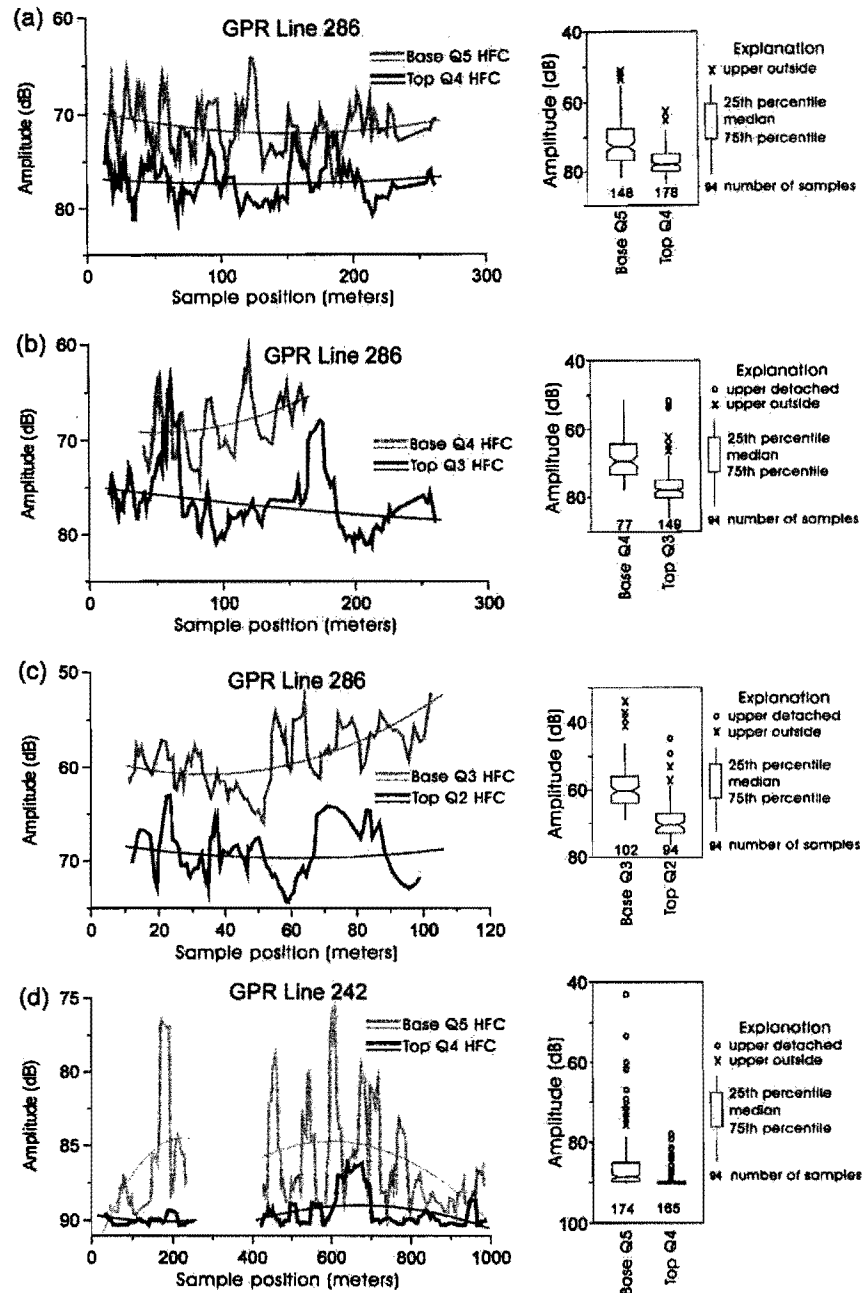


Fig. 7. Changes in ground-penetrating (GPR) reflection amplitudes over GPR survey distance, and corresponding box-whisker plots showing reflection amplitude sample populations for GPR reflection events at the base and tops of high-frequency cycles (HFCs). Uses data from GPR line 286 from the Rocky Glades site and GPR line 242 from the north-central Miami-Dade site. Reflection amplitudes at cycle bases are mostly lower than the reflection amplitudes from underlying cycle tops as shown by comparison of amplitude between (a, d) the base of Q5 high-frequency cycle (HFC) and top of Q4 HFC, (b) the base of cycle Q4 HFC and top of the Q3 HFC, and (c) the base of the Q3 HFC and the top of the Q2 HFC. Box-whisker plots show that there is a significant difference between median values of reflection amplitudes for values from contiguous cycle tops and cycle bases. The two very irregular curves in the graphs are based on running averages and the two smooth curves are based on a polynomial averaging. See Fig. 5 for an explanation of box-whisker plots.

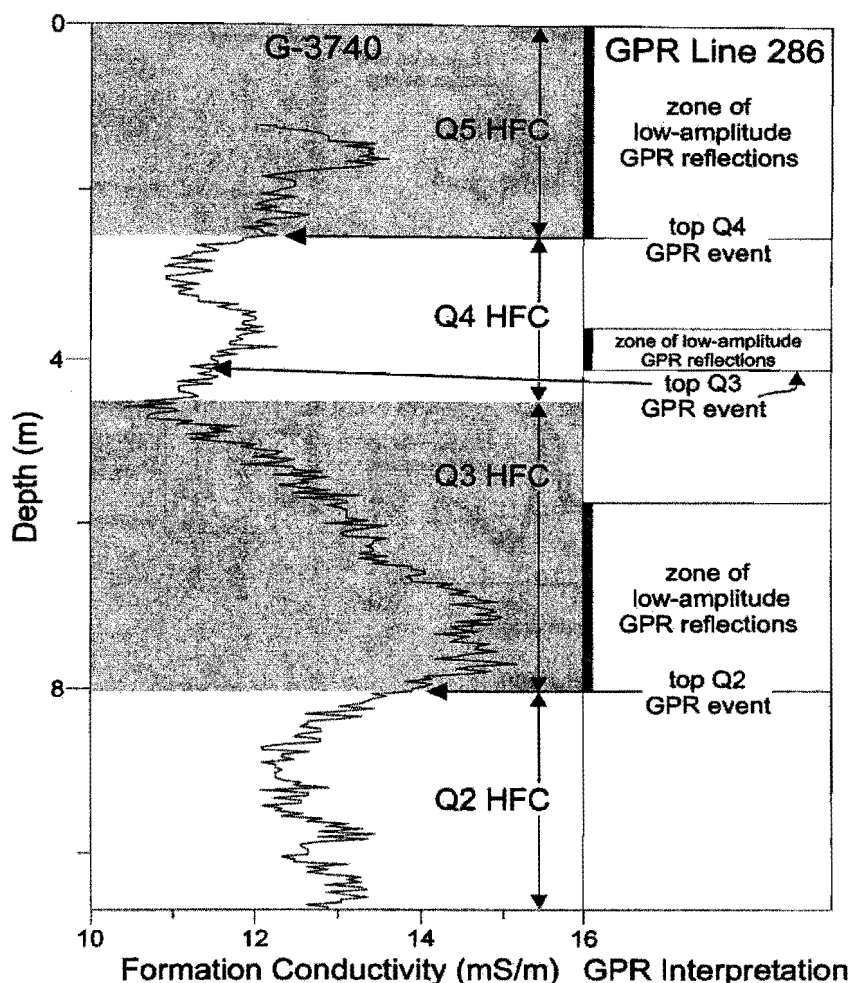


Fig. 8. Formation conductivity measured by an induction-resistivity borehole-geophysical tool for the G-3740 test corehole and ground-penetrating radar (GPR) events interpreted from GPR line 286 (Fig. 3). Zones of relatively higher electrical conductivity correspond to zones of relatively high vuggy porosity on digital optical borehole images and zones of relative low-amplitude reflections on the GPR line 286. High-frequency cycles (HFC) determined from stratigraphic analysis of cores and digital borehole images.

higher than in much of the bottom section of the cycle (Fig. 8).

The high water saturation of the thick zone of high vuggy porosity in the bottom section of the Q4 HFC near the G-3762 test corehole (Fig. 4) produces a velocity pulldown in the reflections of the upper surface of the Q3 HFC (Fig. 3). The velocity of EM waves in freshwater (0.033 m/ns) is considerably slower than that of limestone (0.12 m/ns) according to Davis and Annan (1989). The interval velocity between the ground surface and top layers of the Q4, Q3 and Q2 HFCs was determined by correlation

of a CMP analysis (Fig. 9a) with layers identified in test corehole G-3740 (Fig. 3). The computed velocity, 0.06 m/ns, is about half of Davis and Annan's (1989) limestone velocity. The lower south Florida velocities are probably due to very high limestone porosity and almost complete ground saturation.

These data suggest that the apparent structural low on the upper surface of the Q3 HFC (Fig. 3) was caused by a relatively slow two-way traveltime of EM waves through the vuggy porosity zone. Correlation of the top of the Q3 GPR anomaly between the G-3740 and G-3762 test coreholes shows that

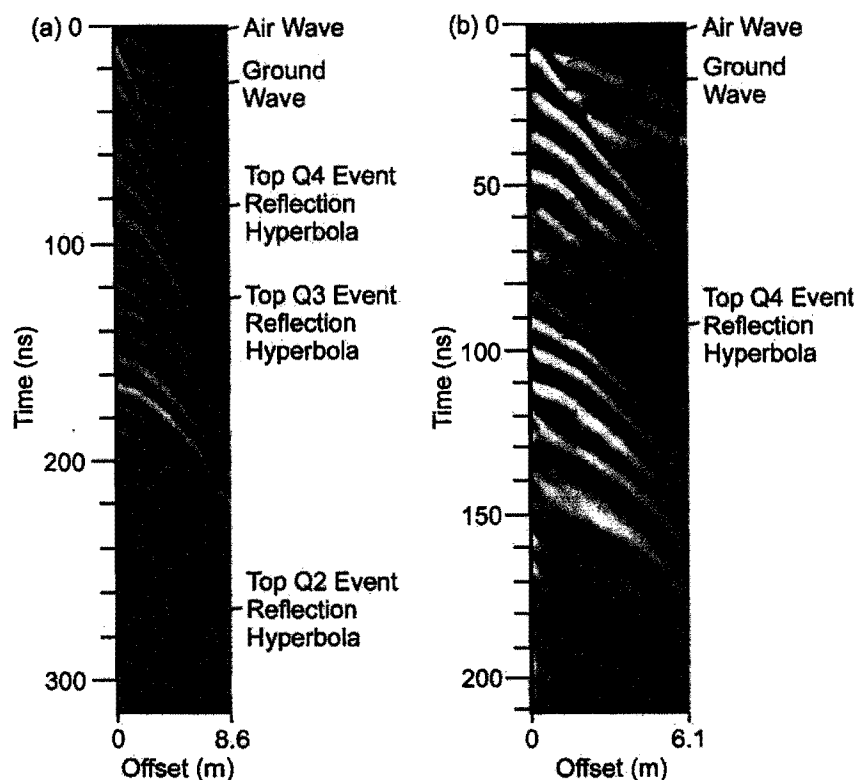


Fig. 9. Common mid-point velocity surveys. (a) Survey from due north of the G-3740 test corehole (Fig. 3) and (b) survey from near the G-3710 test corehole (Fig. 10).

there is almost no difference in the altitude of the Q3 GPR event between the test coreholes (Fig. 4). The roughly 1-m thick structural “sag” in the altitude of the top of the Q3 GPR event near the G-3762 corehole, is thus attributed to a decrease in velocity (Fig. 3). Further evidence of the velocity pulldown is the similar in vertical distance between the top Q4 GPR event and top Q3 GPR event at the G-3762 test corehole relative to the G-3740 test corehole (Fig. 4).

The GPR reflections at the tops of the Q3 and Q2 HFCs have amplitudes averaging about 9–11 dB higher than overlying reflections at the bases of the Q4 HFC and Q3 HFC, respectively (Fig. 7b and c). Low porosity lime mudstone and wackestone cap both the Q3 and Q2 HFCs (Fig. 4), whereas vuggy, pelecypod floatstone and rudstone compose the bases of these cycles. Fifty-three whole-core samples from the Q3 and Q2 peritidal HFCs from both the Rocky

Glades GPR site and the Lake Belt Area (Fig. 1) confirm that porosity values decrease upward from the base to the tops of peritidal cycles (Fig. 5). Further, core-scale hydraulic conductivity values decrease upward from the base to the tops of peritidal cycles (Fig. 6). This upward trend in decreasing porosity and hydraulic conductivity reflects a decrease in grain size and an increase in matrix micrite upward within the HFCs, and is expressed as an upward decrease in conductivity within the Q3 HFC (Fig. 8). Similar to the Q4 HFC, the upper part of the Q3 HFC has higher reflection amplitudes than the lower part of the Q3 HFC (Figs. 3 and 7) that are apparently related to an upward decrease in porosity and freshwater saturation. The highly porous zones in the Q4 and Q3 HFCs (Fig. 4) could be a laterally well-connected, incipient dissolutional cave system that is similar to more evolved cave systems described by Ford (1988).

5.2. North-central Miami-Dade site

Two high-frequency carbonate cycles (Q5 and Q4 HFCs) of the Miami Limestone and the uppermost high-frequency cycle (Q3b HFC) of the Fort Thompson Formation are imaged on GPR profile 242, which was collected at the north-central Miami-Dade GPR site (Figs. 1, 2 and 10). A thin calcrete layer at the top of each HFC provides evidence that a surface of subaerial exposure, which was related to a relative fall in sea level, caps each HFC (Fig. 11). A prominent karstic exposure surface that shows evidence for significant dissolution along the surface separates HFCs Q5 and Q4, as shown in Fig. 11. This buried karstic surface has up to 1 m of paleorelief and, locally, karstic dissolution has almost entirely removed the Q4 HFC (Figs. 10 and 11). Digital optical borehole images and continuously drilled cores confirm that the Q4 HFC is relatively thick to almost absent (Fig. 11). Verification of the interpretation shown in Fig. 10 would not have been possible with only cores because of incomplete recovery and the associated error in depths. Only with the digital optical borehole images (Fig. 11) was it possible to verify unambiguously the interpretation shown in Fig. 10.

Typical reflection configuration patterns and lithofacies in the Q5 HFC are like those described earlier for the Q5 HFC at the Rocky Glades site. Fig. 10 shows that the GPR reflections of the Q5 HFC are lower amplitude than reflections of the Q4 HFC and

upper part of the Q3b HFC. Comparison of amplitudes of a GPR reflection at the base of the Q5 HFC and a reflection at the top of the Q4 HFC indicate that the median amplitude of the Q5 HFC reflection is about 7 dB less than the upper reflection of the Q4 HFC (Fig. 7d). This difference is significant at about a 95% confidence level (Fig. 7d). The relatively low amplitudes of the Q5 reflections are probably related to a very high pelmoldic matrix porosity and solution-enlarged burrow porosity, which are characteristic of the Q5 HFC, relative to lower matrix porosity (Fig. 5) and more micrite-rich peloidal facies of the Q4 HFC. These relations between the GPR reflection amplitudes and porosity of the Q5 HFC, and the amplitudes and porosity of the Q4 HFC are almost ubiquitous in the data collected at the Rocky Glades GPR site and throughout the Lake Belt Area (Fig. 1). Relatively low-amplitude reflections assigned to the Q5 HFC shown in Fig. 10 correspond to a zone of relatively high formation conductivity in test corehole G-3713 (Fig. 12). This observation corroborates the empirical relation between porosity, hydraulic conductivity, formation conductivity, and reflection amplitudes—as porosity increases, hydraulic conductivity and formation conductivity increases, and reflection amplitude decreases.

The interval velocity between the ground surface and top of the Q4 HFC is 0.06 m/ns as determined by CMP analyses near test coreholes G-3710 and G-3711 at the north-central Miami-Dade site (Figs. 9b and

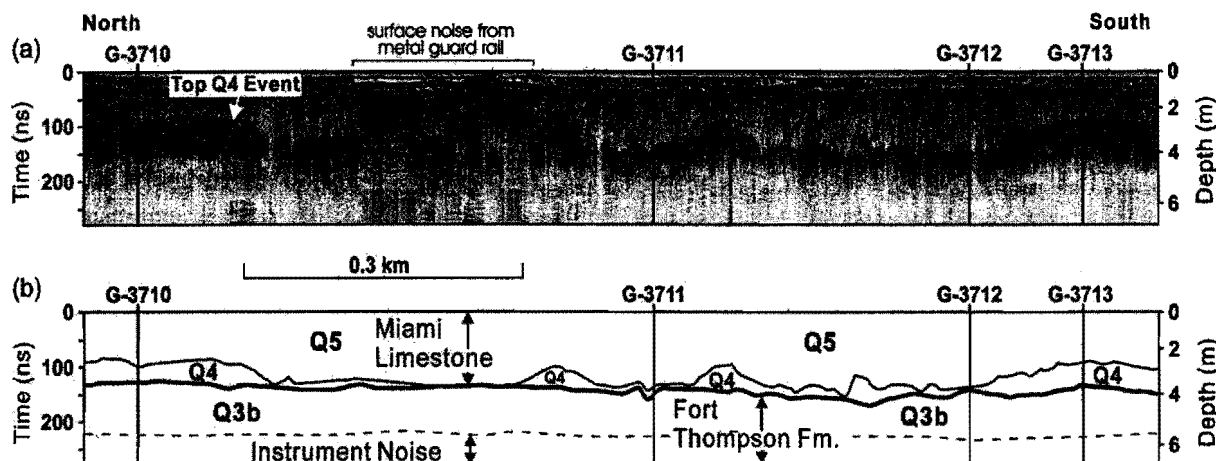


Fig. 10. Ground-penetrating radar (GPR) line 242 at the north-central Miami-Dade GPR site. (a) 100-MHz GPR profile. (b) Line drawing of GPR profile. Q5, Q4 and Q3b correspond to the high-frequency cycle stratigraphy shown in Fig. 2.

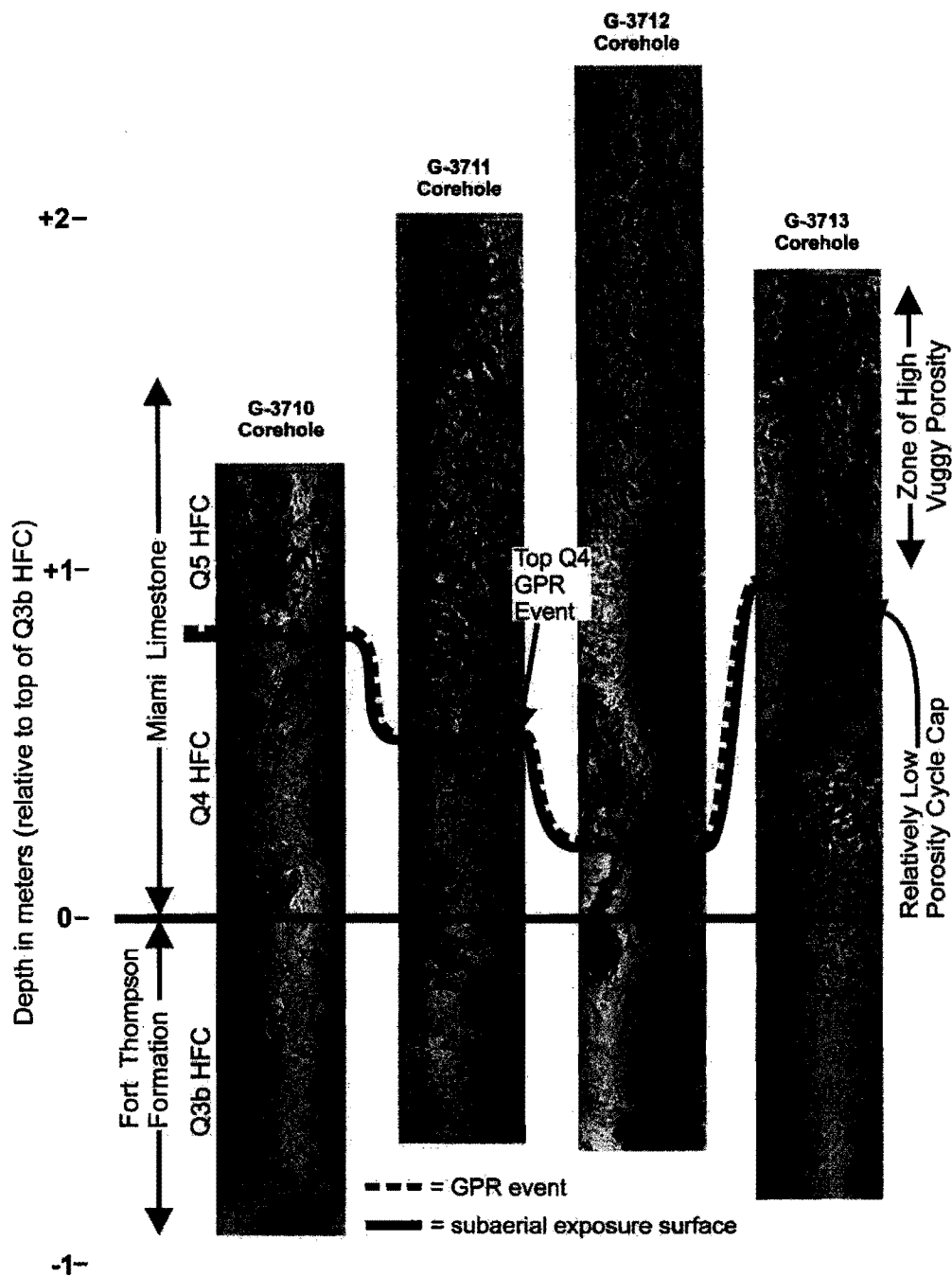


Fig. 11. Correlation of four digital optical borehole image logs from test coreholes G-3710, G-3711, G-3712, and G-3713 used to verify ground-penetrating radar at the north-central Miami-Dade GPR site (Fig. 10).

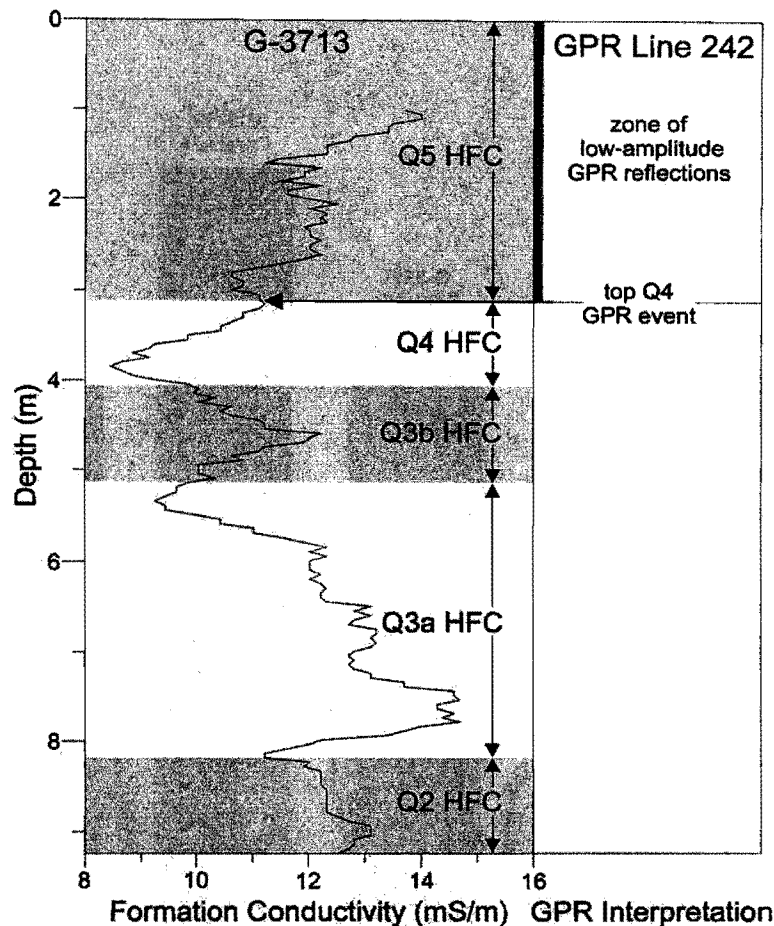


Fig. 12. Formation conductivity measured by an induction-resistivity borehole-geophysical tool for the G-3713 test corehole and ground-penetrating radar (GPR) events interpreted from GPR line 242 (Fig. 10). The zone of relatively high electrical conductivity within the Q5 high-frequency cycle (HFC) corresponds to a vertical and lateral zone of relatively low-amplitude reflections assigned to the Q5 HFC shown on the ground-penetrating radar line 242 (Fig. 10). High-frequency cycles determined from stratigraphic analysis of cores and digital borehole images.

10). This velocity is the same as the velocity determined at the Rocky Glades site and similar to a velocity (0.05 m/ns) calculated by Kruse et al. (2000) for the limestone of the upper Biscayne aquifer in an area of Everglades National Park (ENP).

6. Discussion and conclusions

Ground-penetrating radar (GPR) is a useful tool in the hydrogeologic characterization of shallow carbonate aquifers. This technique was applied to karstic Pleistocene platform carbonates of the upper Biscayne aquifer in southeastern Florida. Geologic features

shown on resultant GPR profiles include: (1) two-dimensional, qualitative distribution of porosity on hydraulic conductivity; (2) paleotopographic relief on karstic subaerial exposure surfaces; and (3) vertical stacking of chronostratigraphic high-frequency cycles (HFCs). These characteristics were verified by comparison to rock properties observed and measured in rock samples from continuously drilled cores, and identified in digital optical borehole images.

An empirical relation exists between measured whole-core porosity, observed porosity on digital optical borehole images, formation conductivity, and GPR reflection amplitudes—as porosity determined from core and images increases, formation conductivity

ity increases, and reflection amplitude decreases. A plausible explanation is that attenuation of GPR-EM waves increases as the freshwater saturation of the medium increases. Borehole-conductivity logs show that highly porous limestone of the Biscayne aquifer with relatively high freshwater saturation has a higher conductivity than low-porosity limestone with relatively low freshwater saturation. Thus the highly porous, highly conductive zones within the limestone of the Biscayne aquifer have low reflection amplitude, because as the electrical conductivity of a medium increases the attenuation of the GPR-EM waves increases.

The stratigraphic framework of the uppermost part of the Biscayne aquifer is composed of two high-frequency subtidal carbonate cycles that form the Miami Limestone. Whole-core porosity values from the upper subtidal HFC are typically about two to three times higher than whole-core porosity measurements from the underlying subtidal HFC. GPR profiles show that overall, the higher porosity of the upper HFC generates lower amplitude reflections than the underlying lower porosity HFC. Also, measured basal reflection amplitudes of the upper subtidal HFC are significantly lower than measured reflection amplitudes of the lower subtidal HFC.

The Fort Thompson Formation underlies the Miami Limestone and forms the middle to lower part of the Biscayne aquifer. The upper Fort Thompson Formation is composed of multiple high-frequency peritidal carbonate cycles. Porosity values measured from whole-core samples show that the lowest porosity occurs at HFC tops, moderate porosity at the middle of the HFCs, and the highest porosity at the base of the HFCs. This change in porosity from bottom to top is visible as an upward variation in reflection amplitude on GPR profiles—lowest amplitudes at the base and highest at the HFC tops. Using a 100-MHz source, amplitudes of reflections of relatively low-porosity cycle tops typically have median values about 2–11 dB higher than amplitudes of reflections in overlying relatively high-porosity cycle bases.

This study demonstrates that GPR can be used to show the qualitative distribution of porosity within a cycle-stratigraphic framework composed of carbonate HFCs. The distribution of porosity within HFCs is mostly controlled by depositional textures. The upward and lateral patterns of rock facies within the

HFCs can be translated to borehole geophysical properties and radar facies configurations that could aid in interpretation and prediction of ground-water flow through a carbonate aquifer. Furthermore, the highly porous zones identified in HFCs at the Rocky Glades site could be a laterally well connected, incipient dissolutional cave system that is similar to more evolved cave systems described by Ford (1988).

Acknowledgements

This project was funded by the South Florida Water Management District and Critical Ecosystems Studies Initiative. Robert Zepp is thanked for permits to drill in the ENP. Bill Loftus, Sue Perry, and Cristina Bruno are thanked for initiating the ENP portion of the project. Anthony Brown, Jean-Claude Poix, David Schmerge, Marc Stewart, and Diane Riggs assisted with field activities. Peter Joesten, Ron Reese, John Lane, and Carole Johnson are thanked for early critical reviews. The Branch of Geophysics, USGS, provided essential geophysical instrumentation.

References

- Annan, A.P., Davis, J.L., 1976. Impulse radar soundings in permafrost. *Radio Science* 11, 383–394.
- Ballard, R.F., 1983. Electromagnetic (radar) techniques applied to cavity detection. U.S. Army Corps of Engineers Water Way Experimental Station Technical Report GL-83-1, Report 5. 90 pp.
- Barr, G.L., 1993. Applications of ground penetrating radar methods in determining hydrogeologic conditions in a karst area, west-central Florida. U.S. Geol. Surv. Water-Resources Invest. Report 92-4141. 26 pp.
- Beck, B.F., Wilson, W.L., 1988. Interpretation of ground penetrating radar profiles in karst terrane. *Proceedings of the Second Conference on Environmental Problems in Karst Terranes and their Solutions*, Nashville, TN, November 16–18, 1988. National Water Well Association, pp. 347–367.
- Beres Jr., M., Haeni, F.P. 1991. Application of ground-penetrating radar methods in hydrogeologic studies. *Ground Water* 29, 375–386.
- Beres, M., Luester, M., Olivier, R., 2001. Integration of ground-penetrating radar and microgravimetric methods to map shallow caves. *J. Appl. Geophys.* 46, 249–262.
- Causaras, C.R., 1987. Geology of the surficial aquifer system, Dade County, Florida. U.S. Geol. Surv. Water-Resources Invest. Report 86-4126. 240 pp., 3 sheets.
- Cunningham, K.J., Aviantara, A., 2001. Characterization of the

- karstic Biscayne aquifer in southeastern Florida using ground-penetrating radar, digital optical borehole images and core (abstract), In: Kuniansky, E.L. (Ed.), U.S. Geological Survey Karst Interest Group Proceedings St. Petersburg, Florida, February 13–16, 2001. U.S. Geol. Surv. Water-Resources Invest. Report 01-4011, p. 134.
- Dagallier, G., Laitinen, A.I., Malartre, F., Van Campenhout, I.P.A.M., Veeken, P.C.H., 2000. Ground penetrating radar application in a shallow marine Oxfordian limestone sequence located on the eastern flank of the Paris Basin, NE France. *Sediment. Geol.* 130, 149–165.
- Davis, J.L., Annan, A.P., 1989. Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy. *Geophys. Prospect.* 37, 531–551.
- Fish, J.E., Stewart, M., 1991. Hydrogeology of the surficial aquifer system, Dade County, Florida: U.S. Geol. Surv. Water-Resources Invest. Report 90-4108. 50 pp.
- Ford, D., 1988. Characteristics of dissolutional cave systems in carbonate rocks. In: James, N.P., Choquette, P.W. (Eds.), *Paleokarst*. Springer-Verlag, New York, pp. 25–57.
- Grasmueck, M., 1996. 3-D ground-penetrating radar applied to fracture imaging in gneiss. *Geophysics* 61, 1050–1064.
- Johnson, D.G., 1992. Use of ground-penetrating radar for water-table mapping, Brewster and Harwick, Massachusetts. U.S. Geol. Surv. Water-Resources Invest. Report 90-4086. 27 pp.
- Kruse, S.E., Schneider, J.C., Campagna, D.J., Inman, J.A., Hickey, T.D., 2000. Ground penetrating radar imaging of cap rock, caliche and carbonate strata. *J. Appl. Geophys.* 43, 239–249.
- Lane Jr., J.W., Buursink, M.L., Haeni, F.P., Versteeg, R.J., 2000. Evaluation of ground-penetrating radar to detect free-phase hydrocarbons in fractured rocks—results of numerical modeling and physical experiments. *Ground Water* 38, 929–938.
- Lucia, F.J., 1999. *Carbonate Reservoir Characterization*. Springer-Verlag, Berlin. 226 pp.
- Martinez, A., Kruger, J.M., Franseen, E.K., 1998. Utility of ground-penetrating radar in near-surface, high-resolution imaging of Lansing-Kansas City (Pennsylvanian) Limestone reservoir analogs. *Current Research in Earth Sciences. Kansas Geol. Surv. Bull.*, vol. 241, part 3, pp. 43–59.
- McMechan, G.A., Loucks, R.G., Zeng, X., Mescher, P., 1998. Ground penetrating radar imaging of a collapsed paleocave system in the Ellenburger dolomite, central Texas. *J. Appl. Geophys.* 39, 1–10.
- Mitchum Jr., R.M., Vail, P.R., Sangree, J.B., 1977. Seismic stratigraphy and global changes of sea level, part 6: stratigraphic interpretation of seismic reflection patterns in depositional sequences. In: Payton, C.E. (Ed.), *Seismic Stratigraphy—Applications to Hydrocarbon Exploration*. Amer. Assoc. Petrol. Geol. Mem., vol. 26, pp. 117–133.
- Perkins, R.D., 1977. Depositional framework of Pleistocene rocks in south Florida. In: Enos, P., Perkins, R.D. (Eds.), *Quaternary Sedimentation in South Florida, Part II*. Geol. Soc. Am. Mem., vol. 147, pp. 131–198.
- Smith, D.G., Jol, H.M., 1992. Ground-penetrating radar investigation of a Lake Bonneville delta, Provo level, Brigham City, Utah. *Geology* 20, 1083–1086.
- van Overmeeren, R.A., 1998. Radar facies of unconsolidated sediments in The Netherlands: a radar stratigraphy interpretation method for hydrogeology. *J. Appl. Geophys.* 40, 1–18.



ELSEVIER

Journal of Applied Geophysics 43 (2000) 239–249

JOURNAL OF
APPLIED
GEOPHYSICS

www.elsevier.nl/locate/jappgeo

Ground penetrating radar imaging of cap rock, caliche and carbonate strata

S.E. Kruse ^{a,*}, J.C. Schneider ^a, D.J. Campagna ^b, J.A. Inman ^a, T.D. Hickey ^c

^a Department of Geology, University of South Florida, 4202 E. Fowler Ave., Tampa, FL 33620-5200, USA

^b Department of Geology, The College of William and Mary, Williamsburg, VA 23187, USA

^c U.S. Geological Survey, Center for Coastal Geology, 600 4th St. South, St. Petersburg, FL 33701, USA

Received 23 September 1998; received in revised form 17 February 1999; accepted 23 February 1999

Abstract

Field experiments show ground penetrating radar (GPR) can be used to image shallow carbonate stratigraphy effectively in a variety of settings. In south Florida, the position and structure of cap rock cover on limestone can be an important control on surface water flow and vegetation, but larger scale outcrops (tens of meters) of cap rock are sparse. GPR mapping through south Florida prairie, cypress swamp and hardwood hammock resolves variations in thickness and structure of cap rock to ~3 m and holds the potential to test theories for cap rock–vegetation relationships. In other settings, carbonate strata are mapped to test models for the formation of local structural anomalies. A test of GPR imaging capabilities on an arid caliche (calcrete) horizon in southeastern Nevada shows depth penetration to ~2 m with resolution of the base of caliche. GPR profiling also succeeds in resolving more deeply buried (~5 m) limestone discontinuity surfaces that record subaerial exposure in south Florida. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Ground penetrating radar; Cap rock; Caliche; Carbonates; South Florida

1. Introduction

Ground penetrating radar (GPR) has been widely used to map shallow stratigraphy in siliciclastic environments (e.g., Davis and Annan, 1989; Smith and Jol, 1992; McGeary et al., 1998; Rea and Knight, 1998; Sauck, 1998). The dominant use of GPR in carbonate environments has been the detection of sinkholes or bedrock cavities filled with air, water or sediment (e.g., Beck and Sayed, 1991; Stewart and

Parker, 1992; Barr, 1993; Buursink, 1995; Mellet, 1995). We tested the ability of GPR to map carbonate units that form through the dissolution and recrystallization of calcium carbonate on exposed surfaces, including cap rock, caliche and now-buried discontinuity surfaces.

Karst targets that have been identified through the use of GPR include solution cavities, buried sinkholes and epikarst features such as bedrock pinnacles. With GPR, voids formed by soil piping to underlying major cavities were detected by their characteristic diffraction patterns (Benson and La Fountain, 1984); cavities of 1–2 m depth extent associated with limestone

* Corresponding author. Tel.: +1-813-974-2236; fax: +1-813-974-2654; e-mail: skruse@chuma.cas.usf.edu

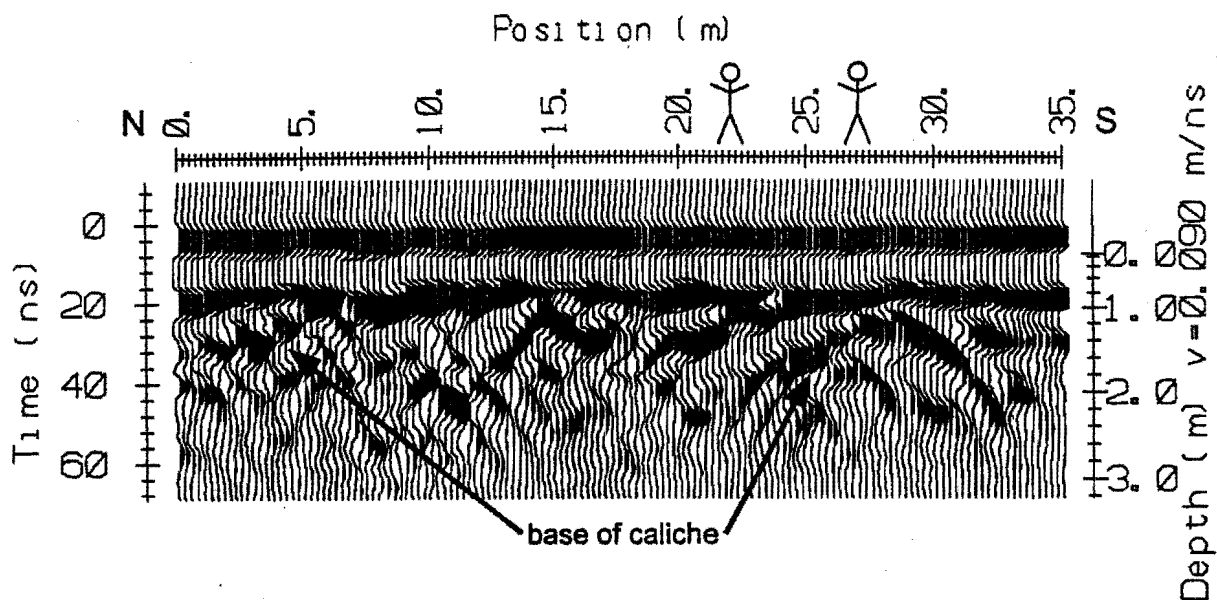


Fig. 6. 100-MHz line parallel to mesa edge. Location shown in Fig. 5. Stick figures show positions of investigators in Fig. 7. Data displayed 3-fold trace average with SEC gain with $400\times$ maximum gain and 1.0 dB/m attenuation.

3.3. Discontinuity surfaces (Everglades National Park, south Florida)

South Florida contains eight northwest-southeast trending ridges that have typical lengths of 10–20 km, widths usually 100 m or less, and topographic reliefs generally 0.5–1.5 m (Steinen et al., 1995). The ridges are locally referred to as rock reefs and are especially

noticeable in aerial photographs of Everglades National Park. Several processes responsible for the origin of the rock reefs have been suggested but not proven, including mid-Pleistocene faulting, the development of fine fractures inducing preferential cementation, and the preservation of paleo-shorelines or paleo-mud banks. In addition, the enigmatic ridges pond surface water on their north sides and affect spatial distribution



Fig. 7. Outcrop of caliche at edge of mesa. Investigators aligned with 22 and 27 m positions on survey in Fig. 6.

of plants. Since the narrow ridges are many kilometers in length, it is likely they also inhibit subsurface water flow toward the south, but the effects of the ridges on subsurface water flow have never been evaluated. The models proposed for the origin of the ridges can be tested using GPR images of subsurface structure. Therefore, we ran GPR profiles across Grossman's Ridge (Figs. 8 and 9), along a transect of bore holes.

The exposed bedrock lithology comprises the bryozoan facies of the Miami Limestone of late Pleistocene age, a marine limestone deposited during a period of higher sea level. Subsurface lithology is composed of alternating sequences of marine and fresh water units separated by discontinuity surfaces (Q1–Q5) that record sub-aerial exposure (Steinen et al., 1995, Perkins, 1977). The discontinuity surfaces are observed in the core samples as impermeable, dense sequence boundaries above and below the porous Miami Limestone sequences.

The transect of bore holes drilled across the northwest–southeast trending Grossman's Ridge, reveal no offset in Q surfaces indicative of Quaternary faulting. 100- and 50-MHz GPR profiles directly verify the absence of displacement along the Q4 mid-to-late Pleistocene Unit (180,000 years b.p.), including the Q4 discontinuity surface which is consistently observed at 4 m (165 ns) below the rock surface (Fig. 9). While we cannot distinguish the ridge formation mechanism from these data alone, the uniform depth below surface of the Q4 horizon suggests that the process responsible predates the Q4 exposure.

3.4. Velocities

The velocities at the Fakahatchee Strand and Grossman's Ridge sites (0.06 and 0.05 m/ns, respectively) are less than those typically expected for limestone (~ 0.12 m/ns (Annan, 1992)). However, our values are substantiated

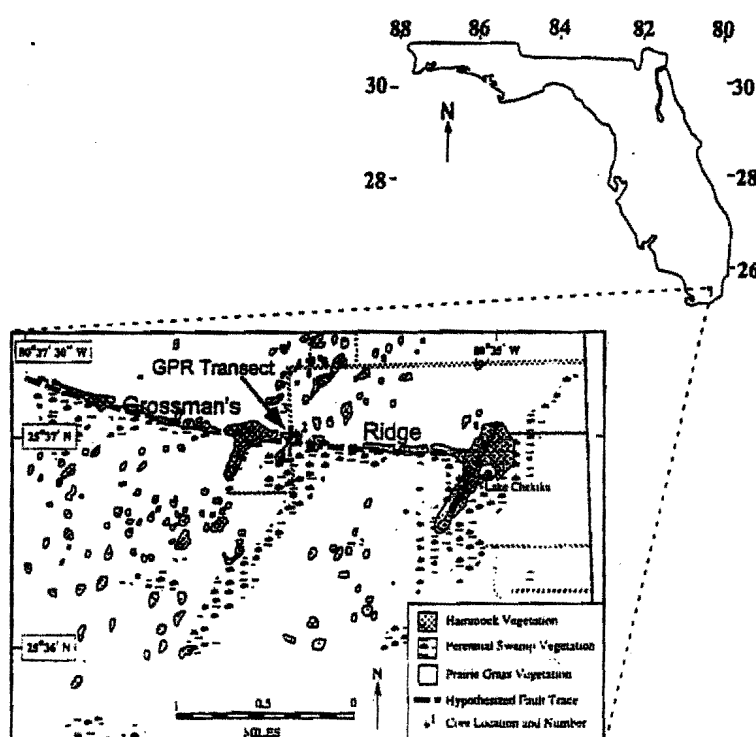


Fig. 8. Location of Grossman's Ridge which lies within Everglades National Park, Florida.

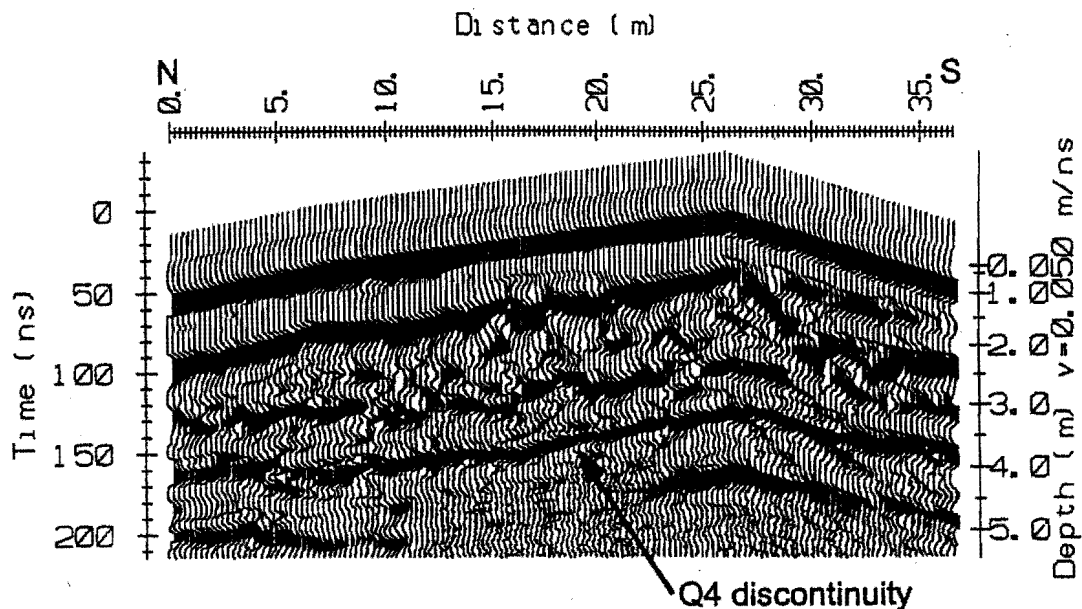


Fig. 9. 50-MHz profile across Grossman's Ridge. Location shown in Fig. 8. Data displayed with AGC with 250 $\times$ maximum possible gain, no trace averaging. Traces are corrected for topography. Common midpoint profiles and a core at the 30 m position (shown as location 2 on Fig. 8) verify the velocity and identification of the Q4 discontinuity.

by both common midpoint surveying at each site (for example, Fig. 3b) and by the good agreement between cores or augers and inferred depths to reflecting interfaces. The anomalously low velocities may be due to the high porosity of the limestone (even the highly cemented cap rock has voids and fractures) and the complete ground saturation.

4. Conclusions

Field experiments in south Florida and in southeastern Nevada demonstrate that GPR is an effective tool for imaging carbonate strata that form under subaerial conditions, such as cap rock, caliche and discontinuity surfaces. In the examples shown above, profiles with 50- and 100-MHz antennas resolve strata to 2–5 m depth. In the Fakahatchee Strand, GPR reveals that the cap rock thins in a continuous fashion toward and beneath the margin of a hardwood hammock and changes in the cap rock reflectors through a cypress swamp are inferred to repre-

sent varying amounts of rubble at the cap rock surface. GPR mapping of caliche in Mormon Mesa and the Q4 discontinuity in Everglades National Park provides stratigraphic control on the timing and mechanism of formation of enigmatic linear ridges.

Acknowledgements

We thank Suzanne Weedman, Bob Mixon, Steve Wandrei, Mike Owen, Bruce Dubendorff, Cynthia Gomez and Harry Jol for their help in the Fakahatchee Strand; Ulrich Kruse for assistance on Mormon Mesa, and Gene Shinn for proposing the work on Grossman's Ridge. The manuscript benefitted from constructive comments by anonymous reviewers.

References

- Annan, A.P., 1992. Ground Penetrating Radar Workshop Notes, Sensors and Software. Ontario, Canada.
- Barr, G.L., 1993. Applications of ground penetrating radar

Not At UMI LIBRARIES

MAKING LIB
GB 609.2.M884
1984

- methods in determining hydrogeologic conditions in a karst area, west-central Florida. USGS Water-Resources Investigations Report 92-4141, 26 pp.
- Beck, B.F., Sayed, S., 1991. The sinkhole hazard in Pinellas County: a geologic summary for planning purposes. Florida Sinkhole Research Institute Report 90-91-1, Orlando, FL.
- Benson, R.C., La Fountain, L.J., 1984. Evaluation of subsidence or collapse potential due to subsurface cavities. In: Beck, B.F. (Ed.), Sinkholes: Their Geology, Engineering and Environmental Impact. Proc. 1st Multidisciplinary Conf. on Sinkholes, Balkema, Boston, pp. 201-215.
- Bohannon, R.G., Grow, J.A., Miller, J.J., Blank, R.H., 1993. Seismic stratigraphy and tectonic development of the Virgin River depression and associated basins, southeastern Nevada and northwestern Arizona. Geol. Soc. Am. Bull. 105, 501-520.
- Buursink, M., 1995. Shallow geologic features identified in southwest Florida ground penetrating radar surveys. Abs. with Programs, Geol. Soc. of Am. Southeastern Section, April 6-7, Knoxville, TN, p. 39.
- Casas, A., Lazaro, R., Vilas, M., Busquet, E., 1996. Detecting karstic cavities with ground penetrating radar at different geological environments in Spain. Proc. 6th International Conference on Ground Penetrating Radar, pp. 455-460.
- Cranehead, F.C., Sr., 1974. Hammocks of South Florida. In: Gleason, P.J. (Ed.), Environments of South Florida: Present and Past. Miami Geological Society, Memoir 2, Miami, FL.
- Davis, J.L., Annan, A.P., 1989. Ground penetrating radar for high resolution mapping of soil and rock stratigraphy. Geophys. Prospect. 37, 531-551.
- Dominic, D.F., Egan, K., Carney, C., Wolfe, P.J., Boardman, M.R., 1995. Delineation of shallow stratigraphy using ground penetrating radar. J. Appl. Geophys. 33, 167-175.
- Duever, M.J., Carlson, J.E., Meeder, J.F., Duever, L.C., Gunderson, L.H., Riopelle, L.A., Alexander, T.R., Myers, R.L., Spangler, D.P., 1986. The Big Cypress National Preserve. National Audubon Society, Research Report No. 8, New York, NY, 444 pp.
- Gardner, L.R., 1972. Origin of the Mormon Mesa caliche, Clark County, Nevada. Geol. Soc. Am. Bull. 83, 143-156.
- Liner, C.L., Liner, J.L., 1995. Ground-penetrating radar: a near-face experience from Washington County, Arkansas. The Leading Edge 14 (1), 17-21.
- Mellet, J.S., 1995. Ground penetrating radar applications in engineering, environmental management, and geology. J. Appl. Geophys. 33, 157-166.
- McGeary, S., Daly, J.F., Kranz, D.E., 1998. High-resolution imaging of Quaternary coastal stratigraphy using ground penetrating radar. 7th Intl. Conf. Ground Penetrating Radar, May 27-30, Univ. of Kansas, pp. 273-277.
- Mixon, R.B., Schindler, J.S., in preparation. Depth to indurated rock, thickness of regolith, and character of surficial material in the Ochopsee area of Collier County, southwestern Florida, U.S. Geological Survey Open File Report.
- Monroe, W.H., 1966. Formation of tropical karst topography by limestone solution and reprecipitation. Caribb. Sci. 6, 1-7.
- Perkins, R.D., 1977. Depositional framework of Pleistocene rocks in south Florida. In: Enos, P., Perkins R.D. (Eds.), Quaternary Sedimentation in south Florida; Geol. Soc. Am., Mem. 147, p. 131-197.
- Rea, J., Knight, R., 1998. Geostatistical analysis of ground-penetrating radar data: a means of describing spatial variation in the subsurface. Water Resour. Res. 34, 329-339.
- Sauck, W.A., 1998. Long GPR profiles for geologic reconnaissance and mapping. 7th Intl. Conf. Ground Penetrating Radar, May 27-30, Univ. of Kansas, pp. 263-272.
- Smith, D.G., Jol, H.M., 1992. Ground-penetrating radar investigation of a Lake Bonneville delta, Provo level, Brigham City, Utah. Geology 20, 1083-1086.
- Steinen, R.P., Shinn, E.A., Halley, R.B., 1995. Hypothesized fault origin for the rock reefs of South Florida. GSA annual meeting, New Orleans, Book of Abstracts, p. A-229.
- Stewart, M., Parker, J., 1992. Localization and seasonal variation of recharge in a covered karst aquifer system, Florida, USA. Int. Contrib. Hydrogeol. 13, 443-460.
- Weedman, S.D., Paillet, F.L., Means, G.H., Scott, T.M., 1997. Lithology and geophysics of the surficial aquifer system in western Collier County, Florida. United States Geological Survey Open File Report 97-436, 167 pp.

HAU

93651.V32

REC'D
ELECTRONIC OR DERIVED
10/27/2000

HAU

Beck, 1989, MULTIDISCIPLINARY CONF ON SINKHOLES; GB843.M85 MAKING LIB

Spencer, FHS OFR 58, DEP. AS: F45/58 GOV INFO FLORIDA DECS 18p.

Beck, 1984, MULTIDISCIPLINARY CONF ON SINKHOLES; GB609.2.M84 MAKING LIB



New method for quantification of vuggy porosity from digital optical borehole images as applied to the karstic Pleistocene limestone of the Biscayne aquifer, southeastern Florida

Kevin J. Cunningham^{a,*}, Janine I. Carlson^b, Neil F. Hurley^b

^a U.S. Geological Survey, 9100 NW 36th Street, Suite 107, Miami, FL 33178, USA

^b Department of Geology and Geological Engineering, Colorado School of Mines, 1516 Illinois Street, Golden, CO 80401, USA

Abstract

Vuggy porosity is gas- or fluid-filled openings in rock matrix that are large enough to be seen with the unaided eye. Well-connected vugs can form major conduits for flow of ground water, especially in carbonate rocks. This paper presents a new method for quantification of vuggy porosity calculated from digital borehole images collected from 47 test coreholes that penetrate the karstic Pleistocene limestone of the Biscayne aquifer, southeastern Florida. Basically, the method interprets vugs and background based on the grayscale color of each in digital borehole images and calculates a percentage of vuggy porosity. Development of the method was complicated because environmental conditions created an uneven grayscale contrast in the borehole images that makes it difficult to distinguish vugs from background. The irregular contrast was produced by unbalanced illumination of the borehole wall, which was a result of eccentricity of the borehole-image logging tool. Experimentation showed that a simple, single grayscale threshold would not realistically differentiate between the grayscale contrast of vugs and background. Therefore, an equation was developed for an effective subtraction of the changing grayscale contrast, due to uneven illumination, to produce a grayscale threshold that successfully identifies vugs. In the equation, a moving average calculated around the circumference of the borehole and expressed as the background grayscale intensity is defined as a baseline from which to identify a grayscale threshold for vugs. A constant was derived empirically by calibration with vuggy porosity values derived from digital images of slabbed-core samples and used to make the subtraction from the background baseline to derive the vug grayscale threshold as a function of azimuth. The method should be effective in estimating vuggy porosity in any carbonate aquifer.

© 2003 Published by Elsevier B.V.

Keywords: Digital borehole image log; Vuggy porosity; Borehole geophysics; Biscayne aquifer; Carbonates; Southeastern Florida

1. Introduction

Vuggy porosity is visible “pore space that is within grains or crystals or that is significantly larger than the grains or crystals; that is, pore space that is not interparticle” (Lucia, 1995). Intraparticle pores, particle molds, fenestrals, channels, vugs, and caverns of

* Corresponding author. Tel.: +1-305-717-5813; fax: +1-305-717-5801.

E-mail address: kcunning@usgs.gov (K.J. Cunningham).

Choquette and Pray (1970) are included in this definition. These kinds of porosity are all present in the Pleistocene limestone of the Biscayne aquifer and the larger well-connected type must play an important role in the flow of ground water through the aquifer. Although detection of vuggy porosity in the subsurface is a challenge, mapping the spatial distribution of vuggy porosity could produce significant insight into ground-water flow velocities and directions, salt-water intrusion, and movement of contaminants within carbonate aquifers.

Identification of vugs and fractures by geophysical logging is normally accomplished, in the absence of image logs, by combining and interpreting several logs, including: sonic, dipmeter, laterolog and induc-

tion, density, spontaneous potential, caliper, and natural gamma-ray spectrometry (Crary et al., 1987). A frustration to the environmental scientist is that identifications of vugs and fractures using these logs are challenging and interpretive in the absence of a borehole-wall image. We found that visual interpretations of digital borehole images are the most reliable and practical method of identifying vuggy porosity in the limestone of the Biscayne aquifer. With increased verification that electronic images of borehole walls in the quantification of vuggy porosity (Hickey, 1993; Newberry et al., 1996; Hurley et al., 1998, 1999) in petroleum reservoirs and fractures in aquifers (Williams and Johnson, 2000) can lead towards identification of

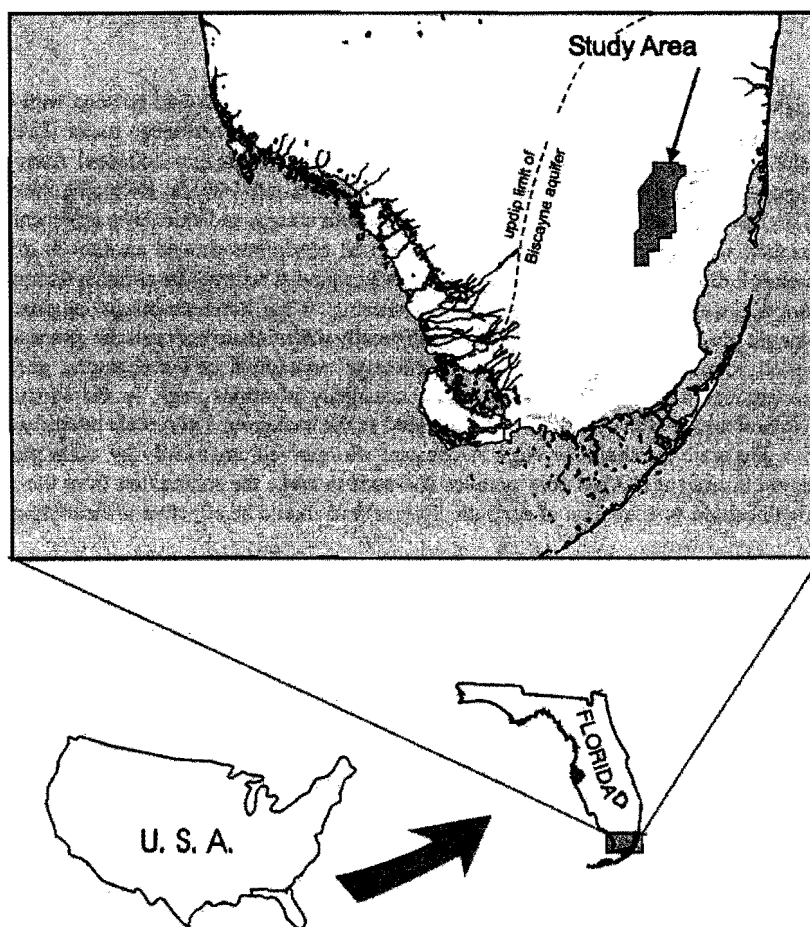


Fig. 1. Map of study area in north-central Miami-Dade County, southeastern Florida.

fluid-flow units, it was recognized that a method of quantifying digital borehole images collected in the limestone of the Biscayne aquifer needed to be developed.

The research methods presented in this paper are based on expansion of earlier work at the Institute for Resource and Environmental Geosciences at the Colorado School of Mines by Hurley and Alexander Aviantara. Carlson and Hurley developed the method of computing vuggy porosity and Carlson prepared the initial draft of the methods section. Cunningham described cores, supervised drilling of test coreholes, acquired the borehole-geophysical data, developed the high-resolution cycle stratigraphy, and participated in much of the final preparation of the manuscript and illustrations.

The purpose of this paper is to describe a new method of quantifying vuggy porosity in optical borehole images logged in coreholes drilled in the karstic Pleistocene limestone that comprises the Biscayne aquifer of southeastern Florida (Fig. 1). It is shown how an uneven illumination of the borehole wall due to eccentricity of the image tool results in unbalanced digital grayscale images and how the method can be used to correct this problem to produce realistic values of vuggy porosity.

2. Drilling and borehole geophysical logs

The U.S. Geological Survey drilled 50 continuously cored test wells for this study using either a wireline coring system or conventional rotary coring system that collected whole-core samples. Geophysical logging was conducted on most of the test wells and included induction resistivity, natural gamma ray, spontaneous potential, single-point resistivity, caliper, and digital borehole image logs. The digital borehole image logs were run in 47 of the test wells while filled with clear fresh water using a RaaX™ Borehole Image Processing System (BIPS™) digital optical logging tool. RaaX™ designs BIPS™ for clear-water borehole environments to monitor, process, and record optical images of borehole walls in digital format for geological and geotechnical analysis. Upper and lower centralizers were used on the BIPS™ tool during logging of most test wells.

3. Stratigraphic nomenclature

The spatial distribution of vuggy porosity in the Pleistocene carbonate rocks of the Biscayne aquifer is controlled mostly by the distribution of deposi-

Series	Hydrogeologic Unit		Lithostratigraphic Unit	"Q Units"	HFC	Cycle Type
Holocene	Surficial Aquifer System	Biscayne Aquifer	Peat or Marl or Both	Peat or Marl or Both	Peat or Marl or Both	
Pleistocene			Miami Limestone	Q5	Q5	Subtidal
				Q4	Q4	
			Fort Thompson Formation	Q3	Q3b Q3a	Peritidal
				Q2	Q2	
	Q1	?				

===== = surface of subaerial exposure

Fig. 2. Shallow time stratigraphic units, hydrostratigraphy (Fish and Stewart, 1991), lithostratigraphy (Causaras, 1987), "Q units of Perkins (1977), and high-frequency cycles (HFC) used in this paper for southeastern Florida.

tional textures, which is best described by a stratigraphic framework composed of high-frequency cycles (HFCs). Using a modified definition by Lucia (1999), the HFC is a chronostratigraphic unit composed of an unconformity-bounded succession of genetically related textures contained in beds or bed-sets. The upper and lower bounding surfaces of the HFC are surfaces of subaerial exposure caused by a relative fall in sea level.

Two types of HFCs are present in the Biscayne aquifer. One is a subtidal cycle formed by vertical aggradation of high-energy shoals or shallow-marine, peloidal, highly burrowed sand flats. The Miami Limestone contains two unconformity bounded subtidal HFCs (Fig. 2). The second type of HFC, a peritidal cycle, is composed of a succession of depositional textures that decrease in grain size upward, that shallow upward, and is capped by a tidal-flat deposit or freshwater limestone or a stacking of both. Three peritidal HFCs are recognized in the upper part of the Fort Thompson Formation (Fig. 2). The delineation of HFCs in the lower part of the Fort Thompson is currently under investigation by the U.S. Geological Survey. The “Q” terminology of the HFCs is modified from Perkins (1977), who first recognized that the Miami Limestone and Fort Thompson Formation of south Florida are composed of five unconformity-bounded, time-stratigraphic marine units (Fig. 2). These units were informally termed, from oldest to youngest, Q1 through Q5 (Q for Quaternary). Fig. 2 shows the relation between the “Q units” of Perkins (1977) and the HFCs of this study.

4. Quantification of vuggy porosity

The development of a method for the quantification of vuggy porosity in borehole images of the limestone of the Biscayne aquifer required first the measurement of the proportion of vugs in images of slabbed whole-core samples, second the identification of vuggy porosity in borehole images, and finally, calibration of the core-sample values and results from borehole-images. The RECALL™ software manufactured by Baker Atlas™ provided the necessary tool to analyze and derive vug porosities in images.

4.1. Quantification of vuggy porosity from slabbed core

Twenty-five slabbed whole-core samples from 11 test coreholes were prepared for black and white photography by sanding the slab face to a smooth, flat surface. The slab face was then coated with a water-soluble printing ink using a soft rubber roller, which deposits the ink on the surface but does not penetrate into small vugs that are open at the slab surface. Two coats of ink were applied, a white nonfluorescent undercoat, then a topcoat of fluorescent orange ink that produces maximum photographic contrast between the rock and open vugs at the slab surface. The prepared slab surfaces were next photographed in a wooden exposure box while illuminated with fluorescent lighting. Hurley et al. (1998, 1999) describe in detail the core-sample preparation, and photographic equipment, film, and exposure settings used to obtain photographic results such as those shown in Fig. 3.

To obtain digitally scanned images of these core samples, photographic negatives of the “inked” slabbed-core surfaces were scanned using an Agfa

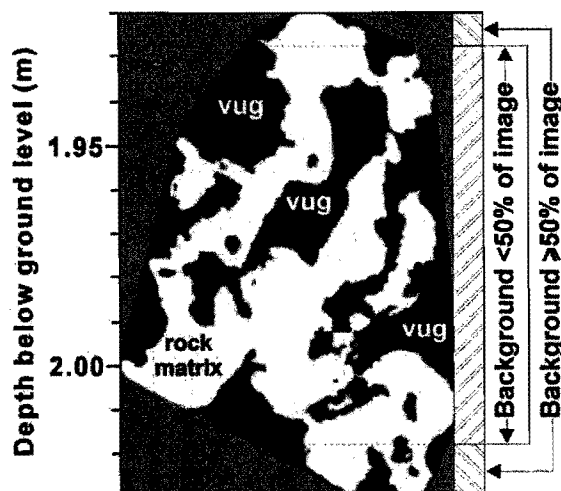


Fig. 3. Slabbed whole-core sample taken from the G-3725 test corehole in the depth interval between 1.92 and 2.03 m of the Q5 high-frequency cycle. Note the high porosity (dark gray to black) due to vugs. The rock is represented by white and surrounding background is the gray tone. Quantification of vuggy porosity was only conducted over that portion of the image where the proportion of the background was less than 50% of the sample image.

Duoscan™ flatbed scanner to produce a 230-level grayscale file of the negatives. Resulting grayscale images show the matrix as white and the vugs as dark gray to black (Fig. 3). The vug and rock-matrix image was trimmed in the software utility PHOTOSHOP™ to exclude any area outside of a polygon not defining the vug and rock-matrix image.

Images of core samples needed to be rectangular in order to facilitate processing. Fig. 3 shows the resulting core-sample image to which a background of medium-gray color has been added beyond the outside of the perimeter of the sample image (Fig. 3). Together, the background and the core-sample image form a rectangle that can be loaded into RECALL™.

RECALL™ provides an algorithm called STATISTICS™ that can analyze the proportion of vug, rock, and background according to their assigned color value at each available depth. This routine includes every available point in the scanned core image. The user provides the necessary precise thresholds: one between vug and background, and the other between background and rock matrix. Vug porosity is calculated as the proportion of the dark value divided by the sum of the dark and white portions. The results from STATISTICS™ can be plotted as a vug porosity curve beside the core image. To eliminate calculating vuggy porosities over areas that have small sample size and possibly nonrepresentative porosities, the following rule was applied using a user-defined software routine. If the gray background at each depth increment represented less than 50% of the image, then vuggy porosity was determined (Fig. 3). But, if the gray background was equal to or greater than 50% at each depth increment, vuggy porosity was not calculated. As an example, if the entire core-sample image in Fig. 3 was used, vug porosity would have been sampled from 1.92 to 2.03 m. However, the background rule reduces the interval from 1.928 to 2.018 m so that the available core interval is 0.02 m shorter (Fig. 3). For all 25 slabbed cores, approximately 92% of the available linear core depths were usable for vuggy porosity determination.

The results from STATISTICS™ can be plotted as a vug-porosity curve beside the core on a depth-by-depth basis (see column labeled COREPHI in Fig. 11) or presented as a single value that is the summation of all vug elements divided by all valid elements in the interval that defines the slabbed-core image (e.g., Fig.

3). The range of interval porosity values in Table 1 shows that the vuggy porosity values of the Q5 HFC span a much higher range than values for other HFCs. The very high porosity values contained in the Q5 HFC relative to underlying HFCs are consistent with whole-core laboratory measurement of porosity values presented by Cunningham (2003) for HFCs making up the Biscayne aquifer.

4.2. Identification of vuggy porosity in digital borehole images

Normally, defining grayscale thresholds that separate the vugs, rock matrix, and background portion of a digital image is a simple process of defining two grayscale-value cutoffs that bound the background values and applying STATISTICS™ as described in the paragraph above to calculate vuggy porosity. In the case of core-sample images, great care was taken to prevent uneven lighting of slabbed-core samples during sample photography, and the core samples were inked to create only two valid grayscale classes (dark gray to black and white) within the circumferential outline of core-sample images. However, in the case of the 47 digital borehole images, there are many valid values of grayscale that define vugs. A more critical problem is an uneven intensity of the light originating from the light source on the BIPS™ tool that illuminates the borehole wall. The differential intensity of borehole-wall illumination is due to tool eccentricity (whether centralizers were used or not), which defeats the capability of determining one grayscale cutoff that defines vug versus another that identifies rock matrix in the images. Fig. 4 shows an example of this problem, where there is a semivertical bright “stripe” along

Table 1
Interval vuggy porosity values for slabbed whole-core sample from high-frequency cycles

High-frequency cycle name	Number of cores	Range of interval vuggy porosity (%)
Q5	3	26.8–41.4
Q4	4	0.5–6.3
Q3b	3	0.01–10.4
Q3a	8	2.9–27.7
Q2 and Q1	7	0.3–7.3

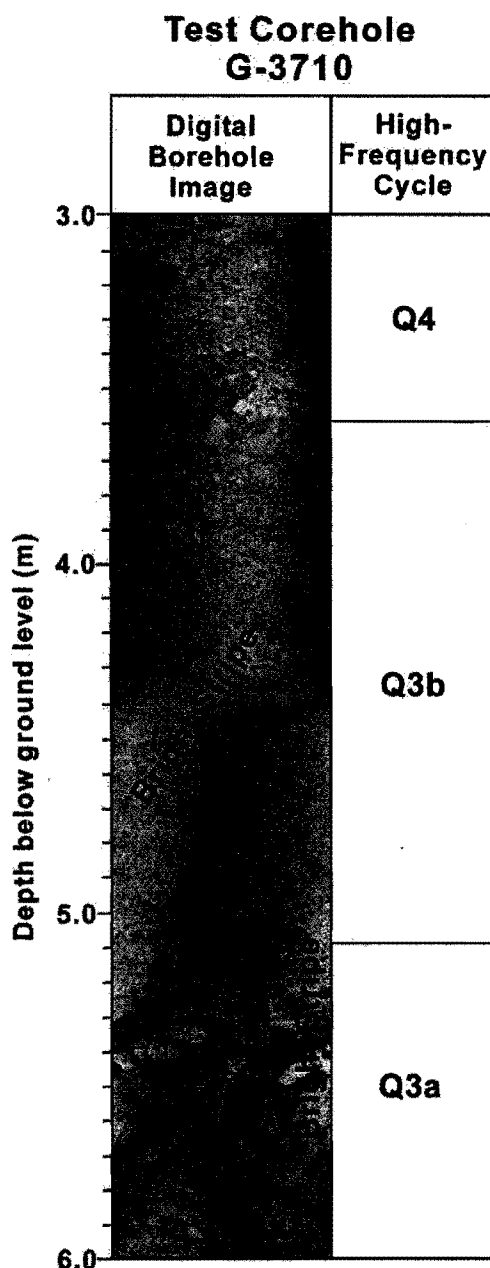


Fig. 4. Example of the digital borehole image. Note the longitudinal highlight effect that can be seen crossing the image. This effect is due to an eccentricity of the image tool relative to the corehole circumference and tends to shift as the tool is moved up or down the corehole.

much of the borehole image due to eccentricity of the tool. That portion of the borehole wall that is closer to the recording tool and light source appears brightest (Fig. 4). The eccentricity of the borehole tool, and thus the light source, may change direction as the image of the borehole wall is recorded while the BIPS™ tool moves uphole or downhole. The uneven-lighting of the borehole wall produces an additional problem—a vug identified on the bright side of the borehole wall will have far greater contrast with the rock matrix than a similar vug in the darker side of the image. The human eye can identify both vugs and rock matrix, so an algorithm was necessarily designed to simulate this judgement.

Fig. 5 shows a model that demonstrates the lighting problem at a single borehole depth in a borehole image. In this representation of gray-scale values versus compass direction, it is assumed that the tool is eccentric and is closest to the borehole wall at 90° and farthest at 270°. The borehole surface is assumed to be completely smooth and homogeneous except for two vugs at 90° and 270°. An array of 670 elements represents all grayscale values sampled at this depth and encircling the borehole. Note the sine-like undulation of grayscale values that represents the effects of eccentric lighting with high grayscale values representing lighter grayscale tones than low values (Fig. 5). The vugs are identified as a lower value or darker grayscale tone than the neighboring background of the smooth and homogeneous borehole wall. Elements sampled at vugs on the bright side will have a greater value difference than those on the dark side (Fig. 5).

If the static STATISTICS™ technique, which was applied to core-sample images in RECALL™, was used on the depth shown in Fig. 5, both individual vugs could not be identified. For example, a threshold value of 115 for grayscale would identify the vug at 90°, but would also identify everything from 180° to 360° as a vug (Fig. 5). And, a threshold of 10 would only identify the vug found at 270° (Fig. 5).

Fig. 5 is an idealized representation of grayscale values that contrasts markedly with a much more complex graph of grayscale values at an actual depth from a digital borehole image shown by the solid-line curve in Fig. 6a. Fig. 6b shows an image of a 0.2-m-thick section of the borehole wall in test corehole G-3720. The grayscale values (670 elements sampled across the borehole-wall image) at the 5.0-m depth

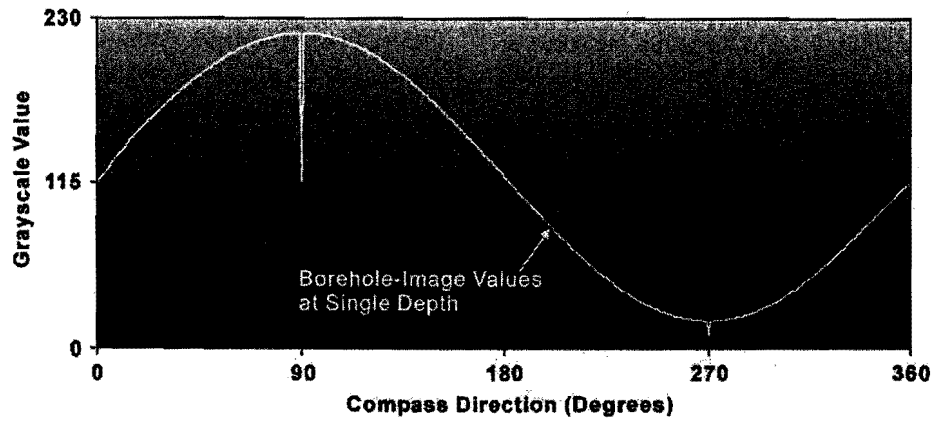


Fig. 5. Model of borehole-image grayscale values at a single depth of a digital borehole image. The sine-shaped curve shows the effects of eccentered lighting on the image and for two vugs (downward deflections of the curve). Note that the vertical distance between the peaks of the vugs and the sine-shaped background curve changes as the distance between the borehole and the tool changes.

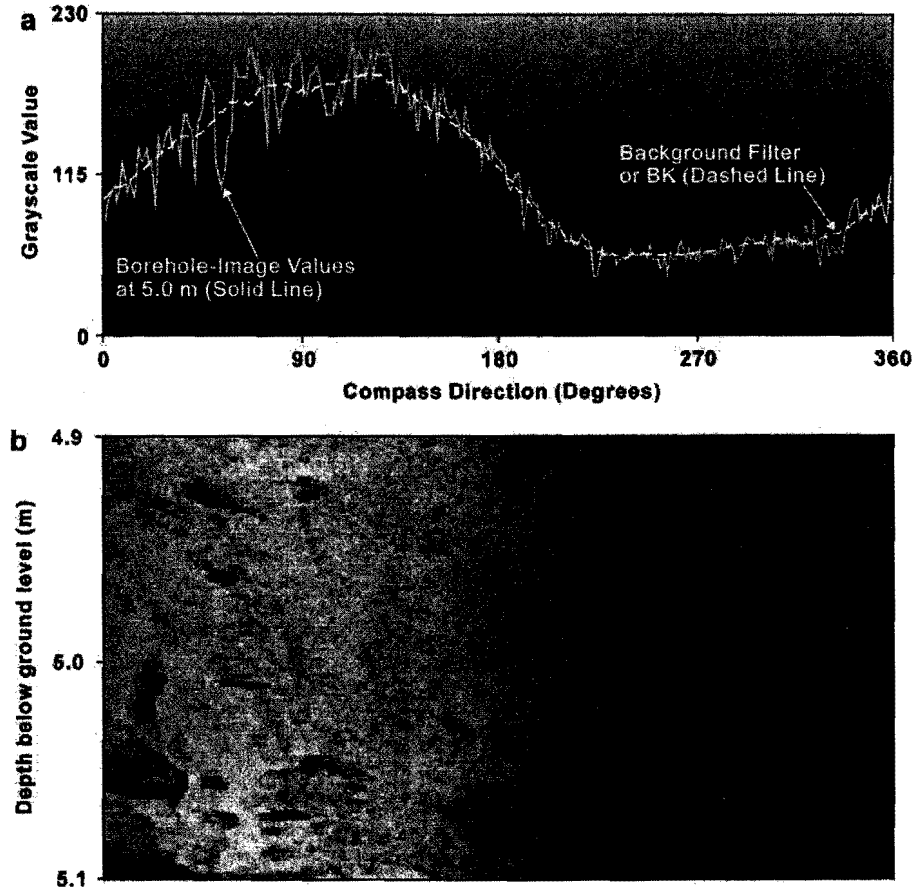


Fig. 6. Graph of the borehole-image grayscale values (solid line in (a)) at a depth of 5.0 m from the digital borehole image in (b). The background filter represented by the dashed line in (a) is called the BK curve, which is designed to remove the effects of eccentering. Any deflections of the solid line downward below the dashed BK curve are vuggy porosity candidates.

were retrieved and displayed as the solid-line curve in Fig. 6a. Vugs are represented by significant downward extensions of the solid-line curve that are more pronounced on the light side of the hole than the dark side. The grayscale curve (solid line) of the borehole-wall image in Fig. 6a is much more rugged than the smooth grayscale curve representing a model of the borehole-wall grayscale values shown in Fig. 5.

As shown in Fig. 6a, a moving-average curve (dashed line) called background (BK) was used to create a relatively smooth representation of the local variation of grayscale values along the circumference of the borehole wall. It was assumed that a moving average of the grayscale values spanning 1/8 of a borehole circumference was appropriate for normalization of BK for all borehole images. The borehole images were loaded into a matrix that was 670 elements wide, the 1/8 moving average used to approximate BK had a width of 84 elements. Local vugs represent a small percentage of the large average (84 elements) and did not, in general, affect the BK

value. Even at a depth with many or large vugs, the moving-average curve represented the local change in light intensity along the borehole wall with candidate vug values appearing below the BK values (Fig. 6). The BK curve was calculated at every depth spanning an interval 2 mm in vertical height for each borehole image.

A method of counting potential vuggy porosity was devised by using the BK curve as a threshold and counting any grayscale value as a vug that falls below the BK curve. For instance, in Fig. 6, the total proportion of vuggy porosity at the depth of 5.0 m would be equal to the summation of counts for each element along the solid line that was below the dashed line divided by 670—the total possible counts. This background porosity (BGED) calculated at each depth is an important key to calibrating vug core porosity to the digital borehole images. A display of the results of this technique is shown in track 3 of Fig. 7. Comparison of the borehole image in track 1 and the image in track 3 indicates that the black areas representing

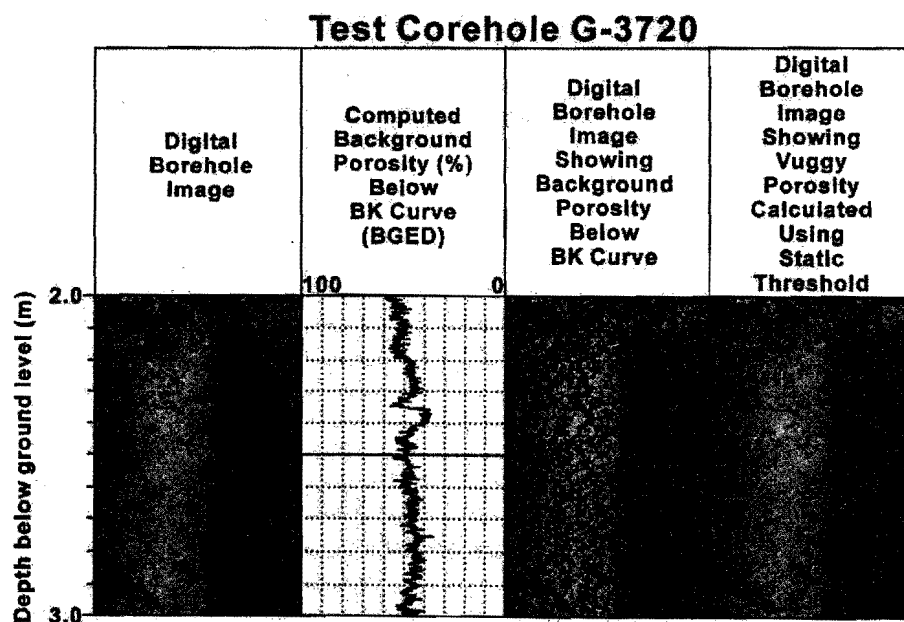


Fig. 7. Digital borehole image, computed porosity, and digital borehole images with blackened porosity from two depth intervals in test corehole G-3720. The first track shows the original digital borehole image from 2- to 3-m depth below ground level. The third track shows what the image would look like if every grayscale color below the background or BK were considered a vug. The results shown in track 3 are recorded as background porosity in track 2 and has a range of 38–60%. Track 4 shows the portion that would be considered vugs (black) in the same image if the effects of eccentricity were ignored and a static grayscale threshold was used. Note the predominance of vug incorrectly identified on the dark side of the image in track 4 while the brightest portion is almost totally devoid of vugs.

potential vugs are evenly spaced but too abundant to be considered valid vugs (Fig. 7). But, most importantly, the most poorly illuminated (darker) side of the borehole wall does not show an increased number or extent of vugs, and is not totally black, as is almost the case in track 4 where a static or single grayscale threshold provided by the STATISTIC™ algorithm was utilized. So, the attempt to neutralize the effects of uneven lighting of the borehole wall was successful and the final task was to calibrate this moving-average technique for vug computation.

Recalling that vug contrast is greater in the brighter side of the hole, the next step was to design a threshold that is below the 84-element moving average (BK) and is thicker in the bright zones and thinner in the dark zones, as shown by the thickness between the dashed and solid lines in Fig. 8. Vugs are identified as all values that fall below the dashed-line or threshold curve (Fig. 8). A percentage of the grayscale value, P , below the BK curve provides the threshold, but it requires calibration with core-sample images. Eq. (1) expresses a preliminary threshold curve.

$$\text{Threshold} = (1 - P)BK \quad (1)$$

where BK is the moving-average curve derived from 670-grayscale-image values along the circumference of the borehole-wall image at a single depth, and P is a constant that provides a vuggy-porosity threshold expressed as a fractional percentage.

Vuggy porosity is calculated as the summation of elements at a given depth that are less than the vuggy-porosity threshold (Fig. 8) divided by the number of elements evaluated (670 elements), as expressed in Eq. (2).

$$\text{Image Vuggy Porosity} = vc/ct \quad (2)$$

where vc is the count of the number of grayscale values below vuggy-porosity threshold at a single depth, and ct is the number of elements (670) evaluated around the borehole wall at a single depth.

After a reasonable value for P , the constant in Eq. (1), was established by calibration of vug porosity of the core to the digital image, vug porosity for every depth in the 47 digital borehole images could be calculated.

4.3. Calibration of vuggy porosity in digital borehole images and slabbed-core images

Deriving vuggy porosity on a depth-by-depth basis in all the digital borehole images was achieved by calibrating the vuggy porosity determined in the core-sample images with observations of the digital-borehole-image and modeled-borehole-image data. The concepts and data used to do this included: (1) a reliable calculation of vuggy porosity for the 25 core-sample images at 2-mm depth increments, (2) a model that eliminates the effects of eccentricity, (3) the calculation

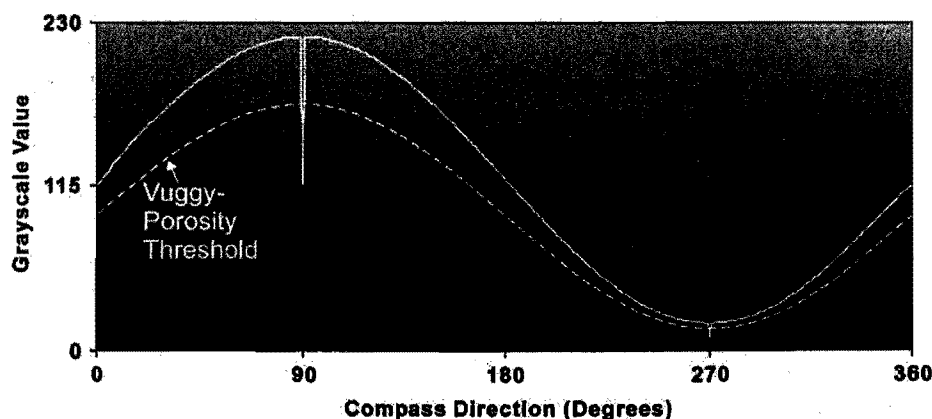


Fig. 8. A model of the data presented in Fig. 5 with the addition of a dashed line representing the threshold or cutoff (see Eq. (1)) that will identify all vugs around the borehole and eliminate the problems of an eccentric tool. All data that falls below the threshold is counted as vuggy porosity.

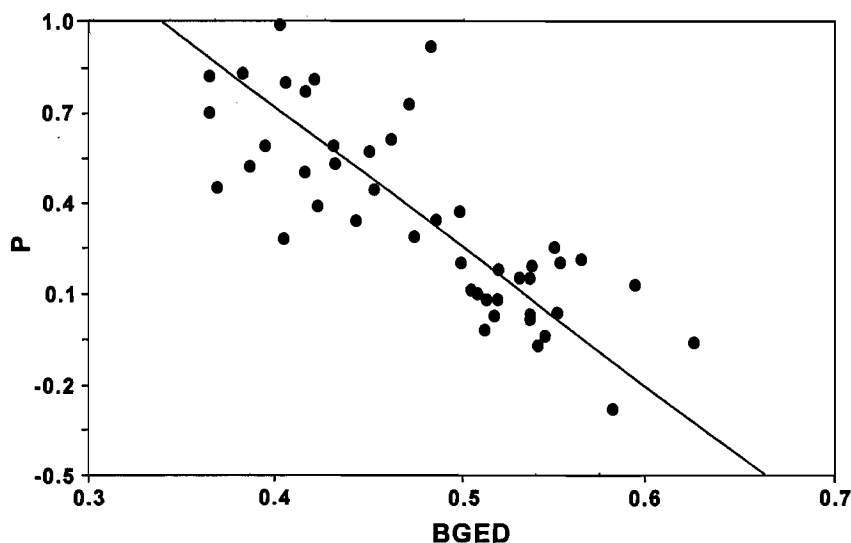


Fig. 9. Scatter plot of the background porosity or BGED versus the best value of P that will produce the same vuggy porosity in the borehole images as that found in the 25 core samples. This relationship produces the necessary value of P for Eq. (1).

of BK curves through moving averages at 2-mm depth increments in the 47 digital borehole images, and (4) an estimate of background porosity (BGED) at every

depth using the BK curve as a vuggy porosity threshold (method described earlier to produce track 2 in Fig. 7, or Eq. (2), where P is zero in Eq. (1)).

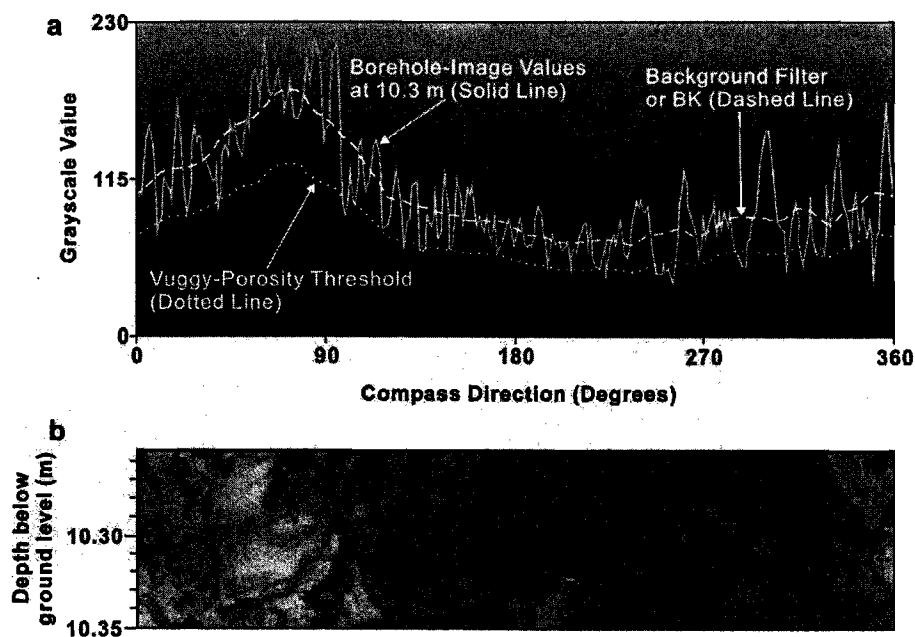


Fig. 10. (a) Graph shows the grayscale values from the depth 10.3 m (solid line) and the background curve BK (upper dashed line). Any points that fall below the vuggy-porosity threshold curve (lower dotted line) are considered vuggy porosity. (b) Digital borehole image used to generate data presented in (a).

After the calculation of the vuggy porosity in the 25 core-sample images, the next step was to establish a relationship between the vuggy porosity derived from core-sample images and the data at the same depth intervals as the digital borehole images. A vuggy porosity value calculated from an image was not expected to exactly match the vug porosity from slabbed-core images. This is because the borehole image is a circumferential view of the rock comprising a borehole wall, while the slabbed-core image is a view of a planar cross section of a cylinder of rock that has been inked and was present in the interior of the borehole wall. It is assumed that the vug porosity

derived from the slabbed-core images is highly accurate on a depth-by-depth basis. Even if slabbed-core images are correctly matched to depths of borehole-wall images, it is not expected that a peak-to-peak or trough-to-trough match between curves of vuggy porosity values of core and borehole images would exist. However, overall shapes and magnitudes of curves should be similar, as shown by comparing tracks 2 and 3 in Fig. 11. Keys (1986) presents a similar sample mismatch with comparison of porosity measured on core plotted against neutron-log values, and Paillet and Crowder (1996) discusses in detail how samplings of two different

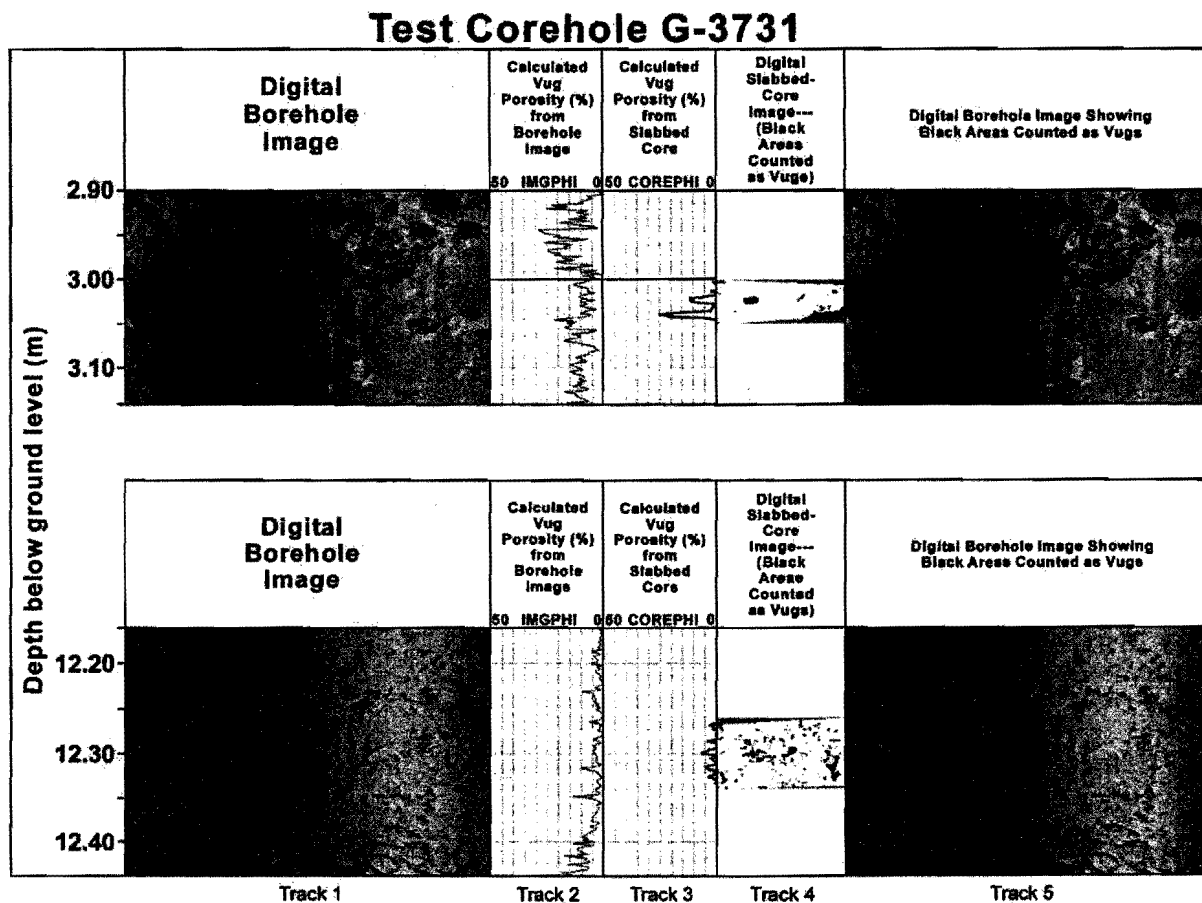


Fig. 11. Plots of two depth intervals in G-3731 showing the comparison of core to digital image and the resulting calculations of vug porosity on a depth by depth basis. Track 1 contains the original digital image. Track 5 on the far right contains the same image with the portions determined to be vugs darkened. Tracks 2 and 3 contain the vug porosity determined from the image (IMGPHI) and the vug porosity determined from the slabbed core (COREPHI). Track 4 shows the photographed slabbed core where white is rock matrix, black is vug contribution, and the gray surrounding the core is background (where no analysis can be made).

parameters at the same depth can result in different vertical distributions of log attributes.

To establish the relation between core and borehole image, it was assumed that the highest vuggy porosity value for any row of elements in a core-sample needs to match the highest BGED (an estimate of background porosity) for any row of elements in the same interval of the borehole image. An iterative test was then applied using Eqs. (1) and (2) to establish a best P that would provide the same highest vuggy-porosity value from borehole-image data as highest core-image value. The same method was applied to the minimums in each core. This exercise provided 50 points for Fig. 9 that established a relationship between BGED and P based on minimum and maximum porosities from the core-sample images.

A scatter plot of the data, BGED and P , assumes a linear relationship with a high negative correlation coefficient of -0.8 (Fig. 9). A regression line that minimizes the average of the sum of squares error in the x and y directions applied to the data predicts a value of P from BGED in Eq. (3).

$$P = 2.56764 - 4.62344 \times \text{BGED} \quad (3)$$

where P is the necessary constant needed to calibrate the background curve in Eq. (1) to produce the threshold for vug determination, and BGED is the porosity using the BK curve as a threshold at a single depth.

Fig. 10 is an example of applying P to a BK curve at a single depth (10.3 m) to produce a vuggy-porosity threshold. Elements along the 10.3-m depth are counted as vuggy porosity where the solid-line curve representing the borehole-image values is below the vuggy-porosity threshold (lower dashed line in Fig. 10).

4.4. Testing of quantification of vuggy porosity in digital borehole images

Testing of this technique was, by examination of the calculated vuggy porosity curve in the core-

Test Corehole G-3713

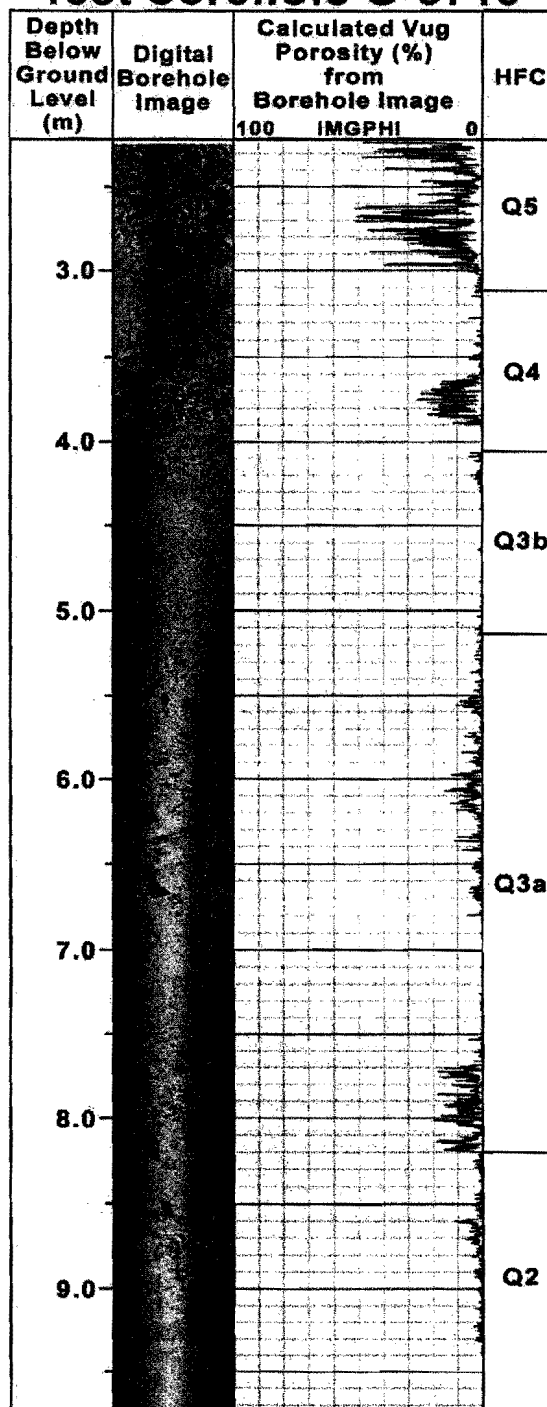


Fig. 12. An example of a vuggy porosity log display of limestone from a portion of the Biscayne aquifer showing the original digital borehole image, the calculated vug porosity (IMGPHI) from the image, and the high-frequency cycles (HFCs).

sample intervals and comparison of it to the vuggy porosity curve, calculated for the corresponding borehole image. A second test was to compare the digital borehole image with the predicted vugs darkened to the core image for visual inspection. Fig. 11 shows two core-sample images from test corehole G-3731 where the resulting estimate of vuggy porosity from the borehole image (marked IMGPHI) and the vuggy porosity from the core image (marked COREPHI) is an excellent match. Visual inspection of the size and density of vugs also look similar in the core-sample image of track 4 and the darkened areas of the digital borehole image in track 5. All 25 core-sample images were compared to the vuggy porosity predicted from the digital borehole images by reviewing the darkened borehole image and comparing the vuggy porosity curves. Approximately 90% of the predicted values looked reasonable.

5. Conclusions

A new method has been developed for quantifying vuggy porosity in digital borehole images that emphasizes removing the effects of an eccentricized image tool and extracting the darkest values from the images as vugs. It is observed that the vugs were not consistently dark in the original images and this method will not identify them, making the predicted vug porosity a conservative estimate. However, 90% of the depths yielded conservative vug porosity values that were reasonable in value and image presentation. The method should be effective in estimating vuggy porosity in any carbonate aquifer.

Fig. 12 shows a sample of the final graphical representation of vuggy porosity determined for one of the 47 borehole images processed in the southeastern Florida study area (Fig. 1). As shown in Table 1, porosity values are exceptionally high in the Q5 HFC, as noted by Cunningham (2003) for laboratory porosity measurement of whole-core samples from many of the same coreholes used herein. High porosity values were found to be common at the base of the Q3a HFC and are related to the vertical stacking of lithofacies within the Q3a HFC. This observation is consistent with data presented by Cunningham (2003) that shows the lower portions of HFCs contained within the upper Fort Thompson Formation have statistically

significant lower total porosity values than middle and upper portions of the HFCs.

Acknowledgements

This project was funded in part by the South Florida Water Management District. Jean-Claude Poix, Anthony Brown, and Marc Buursink assisted with field activities. The Branch of Geophysics, USGS, provided essential geophysical instrumentation and technical advice during field activities. Fred Paillet and James LoCoco are thanked for critical reviews.

Note: The use of brand names in this paper is for identification purposes only and does not constitute endorsement by the authors, the U.S. Geological Survey, or the Journal of Geophysics.

References

- Causaras, C.R., 1987. Geology of the surficial aquifer system, Dade County, Florida. U.S. Geol. Surv. Water Resour. Invest. Report 86–4126.
- Choquette, P.W., Pray, L.C., 1970. Geologic nomenclature and classification of porosity in sedimentary carbonates. *Am. Assoc. Pet. Geol. Bull.* 54, 207–250.
- Crary, S., Dennis, R., Denoo, S., et al., 1987. Fracture detection with logs. *Tech. Rev.* 35, 22–34.
- Cunningham, K.J., 2003. Application of ground-penetrating radar, digital optical borehole images, and cores for characterization of porosity and paleokarst in the Biscayne aquifer, southeastern Florida. *J. Appl. Geophys.* 55, 61–76 (this volume).
- Fish, J.E., Stewart, M., 1991. Hydrogeology of the surficial aquifer system, Dade County, Florida. U.S. Geol. Surv. Water Resour. Invest. Report 90–4108.
- Hickey, J.J., 1993. Characterizing secondary porosity of carbonate rocks using borehole video data [abstract]. *Abstr. Programs-Geol. Soc. Am.* 25, p. 23 (Southeastern Section).
- Hurley, N.F., Zimmermann, R.A., Pantoga, D., 1998. Quantification of vuggy porosity in a dolomite reservoir from borehole images and core, Dagger Draw Field, New Mexico. *Soc. Petrol. Engineers 49323, Annual Technical Conference and Exhibition*, New Orleans, Louisiana, September 27–30, 1998, pp. 789–802.
- Hurley, N.F., Pantoja, D., Zimmerman, R.A., 1999. Flow unit determination in a vuggy dolomite reservoir, Dagger Draw Field, New Mexico. *SPWLA Transactions*, 4 Oslo, Norway. 14 pp.
- Keys, W.S., 1986. Analysis of geophysical logs of water wells with a microcomputer. *Ground Water* 24, 750–760.

- Lucia, F.J., 1995. Rock-fabric/petrophysical classification of carbonate pore space for reservoir characterization. *Am. Assoc. Pet. Geol. Bull.* 79, 1275–1300.
- Lucia, F.J., 1999. *Carbonate Reservoir Characterization*. Springer-Verlag, Berlin.
- Newberry, B.M., Grace, L.M., Stief, D.D., 1996. Analysis of carbonate dual porosity systems from borehole electrical images. *Soc. Petrol. Engineers (SPE) Paper 35158*, Permian Basin Oil and Gas Recovery Conference, Midland, TX, 123–125.
- Paillet, F.L., Crowder, R.E., 1996. A generalized approach for the interpretation of geophysical well logs in ground water studies: theory and application. *Ground Water* 34, 883–898.
- Perkins, R.D., 1977. Depositional framework of Pleistocene rocks in south Florida. In: Enos, P., Perkins, R.D. (Eds.), *Quaternary Sedimentation in South Florida, Part II*. *Geol. Soc. Am. Mem.* 147, 131–198.
- Williams, J.H., Johnson, C.D., 2000. Borehole-wall imaging with acoustic and optical televiwers for fractured-bedrock aquifer investigations. *Proceed. Minerals and Geotech. Logging Symp.*, Golden, CO, October 24–26, pp. 43–53.