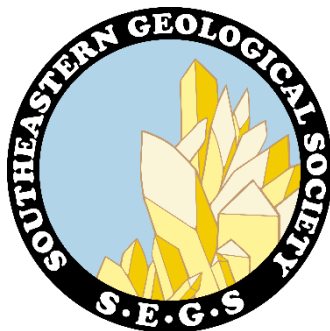


The Everglades

Southeastern Geological Society Guidebook No. 66

February 13, 2016



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Field Trip February 13, 2016

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Guidebook Edited and Compiled by:

Tom Scott, Ph. D, P.G., and Harley Means, P.G.

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P.O. Box 1636

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Introduction and Acknowledgements

This field trip guidebook was modified from a field trip guidebook that was compiled for the 99th meeting of the Association of American State Geologists (AASG), which was held in Key Largo, Florida, in June 2007. The meeting was held in conjunction with the 100th anniversary of the creation of the Florida Geological Survey (FGS). The FGS played an integral role in the creation of the SEGS and continues to support the organization in many ways.

We would like to thank and acknowledge Dr. Don McNeill of the University of Miami, RSMAS, for providing a digital copy of his Miami Geological Society field trip guidebook (McNeill, 2000). It provided the basis for much of this guidebook with only a few modifications and additions.

The SEGS would also like to thank Dr. Hal Wanless for giving our members a lecture on the geology of south Florida in preparation for the field trip.

Southern Florida is a geologically interesting area despite the very low relief! The Everglades are often described as an analog for the ancient coal-forming environments. Florida Bay is a modern carbonate-producing environment that has been intensively studied and compared to ancient carbonates. The Florida Keys display living and fossil coral reefs. The southern mainland and the lower Keys are fossil oolite shoals.

There are very few natural exposures where one can examine the rocks that underlie the Everglades. The Miami Limestone is comprised of two facies: an oolitic phase and a bryozoan-rich phase. There are several classic localities where the Miami Limestone can be observed in section. One of these localities is at the intersection of South LeJune Road and Old Cutler Road where the road crosses over a canal at Cartagena Park. There are several 3 – 5 meter exposures of the Miami Limestone, oolite phase, which can be observed along the canal. The oolite here is cross bedded reflecting the tidal channel currents that were active during the deposition of the Miami Limestone at this location.

The Miami Limestone is a valuable commodity and is actively being mined along the western flank of the Atlantic Coastal Ridge in northern Miami-Dade County. As you head south on the Ronald Reagan Turnpike you will see the active quarrying operations along the west side of the road. Most of the quarries are mining through the Miami Limestone and into the underlying Ft. Thompson Formation. Interbedded with the marine limestones of the Miami and Ft. Thompson Formations are beds of fresh water limestone which represent past periods of sea-level low stands when fresh water wetlands similar to the modern Everglades existed. See discussion regarding sea-level fluctuations below.

A photograph of a vast wetland landscape, likely a marsh or swamp, with tall, golden-brown grasses and shallow water reflecting the sky. The horizon is flat and distant. The sky is a deep blue, filled with large, fluffy white clouds. The text "Everglades National Park Field Trip Guide" is overlaid in a blue, serif font in the upper center of the image.

Everglades National Park Field Trip Guide

PHOTO BY TOM SCOTT

EVERGLADES FIELD STOP HIGHLIGHTS

Drive-by Highlight – Miami Limestone/Key Largo Limestone Mining

Site: East of US 1, between Key Largo and the mainland.

Highlights – Cemex mining operation. Mining predominantly Miami Limestone. Occasionally mining encounters Key Largo Limestone.

Drive-by Highlight Redlands

Site: Between Florida City and the Everglades National Park (ENP).

Highlights: Red soils (terra rossa) exposed in the fields along the road. The reddish color results from the dissolution of the Miami Limestone leaving a residue of Saharan dust. The dust is the result of dust storms in the Sahara putting large amounts of dust in the atmosphere. The dust is then blown across the Atlantic settling in the Caribbean and southern Florida.

Stop 1 ENP Visitor Center – (RESTROOMS AVAILABLE)

Highlights: Overviews of the park, logistics, physiography of the Park, biological and geological interaction, restoration overview

Stop 2 Pinelands

Site: Stop located on the last part of the Pleistocene oolitic limestone as the Atlantic Coastal Ridge bends away from the coast, ridge ends ~8 miles to the west.

Highlights: Observe the Pleistocene limestone that makes up the "bedrock" of ENP, the oolitic facies of the Miami Limestone.

Observe karstic limestone surface, called micro-karst, formed through acidic water and mucky peat, surface is extremely rough and irregular due to surficial karstification

Brilliantly colored tree snails can be seen in the trees along the trail.

The pine forests here and elsewhere in the park occur on slightly elevated outcrops of the Miami Limestone. The elevation of the pinelands helps to protect them from the effects of flooding, and they are rarely inundated more than several weeks each year (McPherson and others, 1976). At this stop organic soils are thin or absent. They may, however, thicken in certain of the abundant solution holes that riddle the Miami Limestone in the vicinity.

At this stop the forest undergrowth is relatively open. The upper branchy layer (canopy) of the pine forest is also open, and pine straw accumulates on the forest floor. These characteristics aid the initiation and spread of

fires necessary to maintain the pine forest community (Schomer and Drew, 1982).

The dominant pineland species observed is Caribbean slash pine (*Pinus elliotii* var. *densa*). Periodic fires prevent tropical hardwoods from out competing the pines by checking the growth of hardwood seedlings and saplings. In addition, slash pine seeds need the stimulus of fire for germination. Mature pines are characterized by thick, moist bark that tends to protect them from milder fires (Schomer and Drew, 1982). (From Bond, 1986).

Drive-by Highlight - Rock Reef Pass

Site: Subtle elongate limestone ridge (elevation ~3 ft, [0.9 m]) that rises 1-2 feet (0.3-0.6 m) above surrounding limestone plain. Origin of these elongate ridges remains a mystery.

Highlights: The narrow (15-20 ft [4.6-6.1 m] wide), elongate limestone ridge rises from the surrounding limestone, these partially control local drainage.

Heavily karstified surface on the elevated topography

Vegetation changes associated with subtle elevation change along the ridge.

Origin proposed as: faulting, fractures, diagenetic features, karstic features, or an original topographic (depositional) feature in an ancient lagoon setting.

Stop 3 Pa-Hay-Okee Overlook

Site: Hardwood hammock adjacent to freshwater slough where sawgrass (mucky) peat is accumulating.

Highlights: Calcareous periphyton, a community of algae, fungi, microbes and associated plants and animals that grow in shallow water habitats, create calcareous muds. These carbonate muds are well represented in Florida's Plio-Pleistocene sediments.

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 varies from <1 foot (0.3 m) near the Pleistocene bedrock to >8 feet (2.4 m) in the middle of Shark River Slough.

Sawgrass peat contains no silica, although it is present in the leaf blades of living sedge grass, only other mineral common is a calcium oxalate called weddellite.

Sawgrass peat section often includes charcoal layers from dry-season

(drought) fires.

Slough contains elongate, bullet-shaped tree islands or hammocks that are aligned with the direction of drainage.

Origin of hammocks appears to be irregular - some form on elevated limestone, while others occur in limestone depressions and rest on a thick (8-12 feet [2.4-3.7 m]) foundation of freshwater peat.

This stop is included to provide a view of the environment that most typifies the "true" Everglades. Sawgrass (*Mariscus jamaicensis*) is, in actuality, a sedge. Sawgrass marsh accounts for approximately 70 percent of the remaining Everglades (McPherson and others, 1976) and is also the most important peat-forming environment in southern Florida (Spackman and others, 1964). Sawgrass marsh is generally higher in elevation than sloughs and lower than hardwood hammocks. The marsh is inundated to depths ranging from a "few inches to several feet." The optimum period for flooding is on the order of months (McPherson and others, 1976). In addition to sawgrass, muhley grass (*Muhlenbergia filipes*), beardgrass (*Andropogon* sp.), arrowhead (*Sagittaria lancifolia*), and many other true grasses grow here.

Spackman and others (1964) note the character of sawgrass is such that its peat is grossly amorphous and shows no woody, fibrous, or coarse granular texture. They further note that even though the leaf blades of sawgrass contain abundant silica in the sawtooth margin and covering some leaf veins, its peat does not show a concentration of silica. (From Bond, 1986).

Drive-by Highlight - Paurotis Pond Area

Site: This site is freshwater marl being deposited at the transition between the marl prairie and the coastal mangrove belt.

Highlights: Site of freshwater marl (low-Mg calcite) formation through biological precipitation by filamentous cyanobacteria in periphyton mats.

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

Cyanobacteria precipitate, in response to photosynthesis during daylight hours, small (10-20 micron) equant low-Mg calcite crystals which form in a sheath structure around the filamentous strand.

Note: there is an absence of peat in the areas away from the freshwater sloughs (except in solution holes).

Marl environment also includes aragonitic pulmonate gastropods.

We will discuss the preservation potential of these deposits during subsequent marine transgression (i.e., beneath Florida Bay).

Note vegetation change at about this locality, begin to find small mangrove plants that are brought in during extreme storm events, low nutrient levels keep these inland plants relatively small compared to the coastal areas we will see at the next Drive-by Highlight.

Stop 4 West Lake (Restroom Break)

Site: This trail wanders through a forest of white mangrove, black mangrove, red mangrove and buttonwood to the edge of West Lake.

Highlights: Mangroves with an amazing series of prop roots.

West Lake provides an opportunity to observe a mangrove community developed around a brackish-water lake. A short core taken from the eastern north shore of West Lake shows approximately 6 in (15 cm) of undifferentiated marl, nearly 2 ft (0.6 m) of red mangrove (*Rhizophora mangle*) root peat, and approximately 1 ft (0.3 m) of sawgrass (*Cladium jamaicensis*) peat (Gleason and others, 1974).

Here red mangrove, white mangrove (*Laguncularia racemosa*), black mangrove (*Avicennia germinans*), and buttonwood (*Conocarpus erectus*) may be seen. Red mangrove, which dominates this site (Spackman and others, 1964), can grow in salt, brackish, or fresh water (McPherson and others, 1976). The black mangrove grows on surfaces that become submerged only at high tide (Wanless, 1974). The white mangrove also requires periodic saltwater inundation, while the buttonwood thrives on higher, drier ground (McPherson and others, 1976).

Florida's coastal mangrove forests act to buffer uplands from the effects of storms (McPherson and others, 1976). The coastal mangrove forest acts to break both wind and high tides. The mangroves also serve as baffles that aid in keeping inland waters free of suspended sediment and floating debris (McPherson and others, 1976). (From Bond, 1986).

Stop 5 Flamingo- Florida Bay and coastal levee

Site: Examine the coastal storm levee constructed by marine mud from the adjacent Florida Bay. Overlook for Florida Bay.

Highlights: Coastal storm levee made from marine mud (mostly aragonite) and mollusc shells deposited during strong storm events (tropical storms and hurricanes) with storm surges that flood over the 1-2 foot (0.3-0.6 m) elevation coastal level.

Shoreline outcrop shows evidence of rip-up clasts indicative of earlier storm events and mud accumulation on the levee.

Levee sediment is light brown to tan as it is oxidized from its position above sea level.

Levee structure is thought to have prograded a couple of miles (several kilometers) seaward in the west-central part of Florida Bay where sediment supply is high. Eastern Florida Bay has a lower sediment supply and shows no seaward progradation, and in some cases landward erosion of the coastal level.

Stop 6 Mahogany Hammock

Site: This site is a tropical hardwood hammock containing sensitive and beautiful vegetation.

Highlights: An abundance of tropical foliage in its natural setting.

You will notice a unique odor in the hammock. It often reminds people of a faint, but not unpleasant, skunk odor. The smell comes from a small tree called the white stopper that was used in “stopping” diarrhea.

You will see more examples of karstified Pleistocene limestone.

The classic Everglades sawgrass marsh is punctuated by numerous small forested areas. Mahogany Hammock is an accessible example of a hardwood hammock. Rare paurotis palms (*Paurotis wrightii*) and massive mahoganys (*Swietenia mahagoni*) occur at this locality. Craighead (1974) notes that the distinctive dome-shaped profile of the hammock is functional in that it may deflect hurricane winds up and over the hammock itself. He theorizes that construction of the boardwalk through Mahogany Hammock left it vulnerable to rampant destruction during Hurricane Donna in 1960 (Craighead, 1974). Hardwood hammocks develop on slightly elevated areas that contain solution holes that are grouped together. The solution holes are frequently filled with peat, which may be deposited directly on bedrock or onto a layer of marl that lies directly above bedrock (Craighead, 1974; Spackman and others 1964). (From Bond, 1986).

Stop 6 Royal Palm Anhinga Trail (RESTROOMS AVAILABLE)

Site: Trail boardwalk traverses the northern portion of Taylor Slough.

Highlights: Willow thickets and other native vegetation.

Hérons, egrets, other wading birds.

Alligators, turtles, snakes, fish.

Anhinga Trail traverses the northern part of Taylor Slough. Taylor Slough, is similar to a river in that it delivers fresh water to several small bays bordering Florida Bay. The flow of water through sloughs, however, is slower than the flow through rivers; that feature, combined with the biological character and shallow nature of the sloughs, allows removal of

pollutants and excess nutrients so that degradation of estuaries is alleviated (McPherson and others, 1976).

This stop focuses on a willow (*Salix caroliniana*) thicket that is characteristic of the relatively deeper waters of the slough. Ecologically, willow thickets serve as feeding, nesting, and roosting habitats for many herons, egrets, and other wading birds (Schomer and Drew, 1982).

The sediments that accumulate in Taylor Slough are primarily various types of peat and calcitic mud. A coring program in the slough (Gleason and others, 1974) showed the "deep" central trough to contain entirely peat. The well-drained flanks of the slough primarily contain calcitic mud with minor peat layers. The mouth of the slough, near Florida Bay, contains red mangrove (*Rhizophora mangle*) peat above calcitic mud suggesting a marine transgression (Gleason and others, 1974). (From Bond, 1986)

SOUTHERN FLORIDA SETTING AND GEOLOGIC OVERVIEW

Southern Florida Climate

Temperature

Southern Florida climate is dominated by warm, humid conditions typical of its subtropical location. Average temperatures are in the mid 70s for this portion of the state. 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 were detailed by Craighead (1971) in his book *Trees of South Florida*.

Rainfall

Rainfall in southern Florida has an annual average of between 40 and 60 inches (102-152 cm) (Fernald and Purdum, 1998). The lowest average rainfall occurs in the lower keys with Key West averaging just 40 inches (102 cm). Monthly average rainfall values show a strong seasonal pattern. The months of May through October produce the highest amount of rainfall in southern Florida. The dry season, where rainfall is 3 inches (7.6 cm) or less per month, spans from November thru April (records from the South Florida Water Management District, 1993)

Hurricanes and Tropical Storms

Some of the most severe weather to impact southern Florida result from tropical storms and hurricanes. Tropical storms that reach hurricane strength (>74 mph (119 kph) winds) impact areas of southern 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 affects 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 (1971) 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 [0.3 m]) or inland which survived and were re-foliated. He suggests that the deposition of a 0.5 to 1.0 ft (0.15-0.3 m) thick layer of storm mud may have been responsible for reducing oxygen availability in the low-lying mangroves, thus smothering their chances for regrowth.

Three of the more significant hurricane events to impact southern Florida were the storms of 1935 (unnamed), Donna (1960), 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 ENP 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. For further hurricane history visit <http://www.sun-sentinel.com/news/weather/hurricane/sfl-aug2001hurricanehistory,0,5857394.storygallery>

Physiography of Southern 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. The Everglades basin has an extremely low slope from its elevation at the northern end (12-14 feet [3.7-4.3 m]) near Lake Okeechobee to sea level at its southern end near Florida Bay. This subtle topographic relief, prior to human alteration, formed a slow, sheet-flow 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 (1.5 to 6.1 m) in its southernmost part. This coastal ridge is composed of Pleistocene Miami Limestone with a discontinuous, thin veneer of quartz sands. The Atlantic Coastal Ridge is about 3 to 5 miles (4.8 to 8.1 km) 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 (16.1 km). 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 complex Pliocene deposit, containing coral reefs that accumulated during elevated sea level highstands some 3 to 4 million years ago. The Tamiami Formation crops out 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.

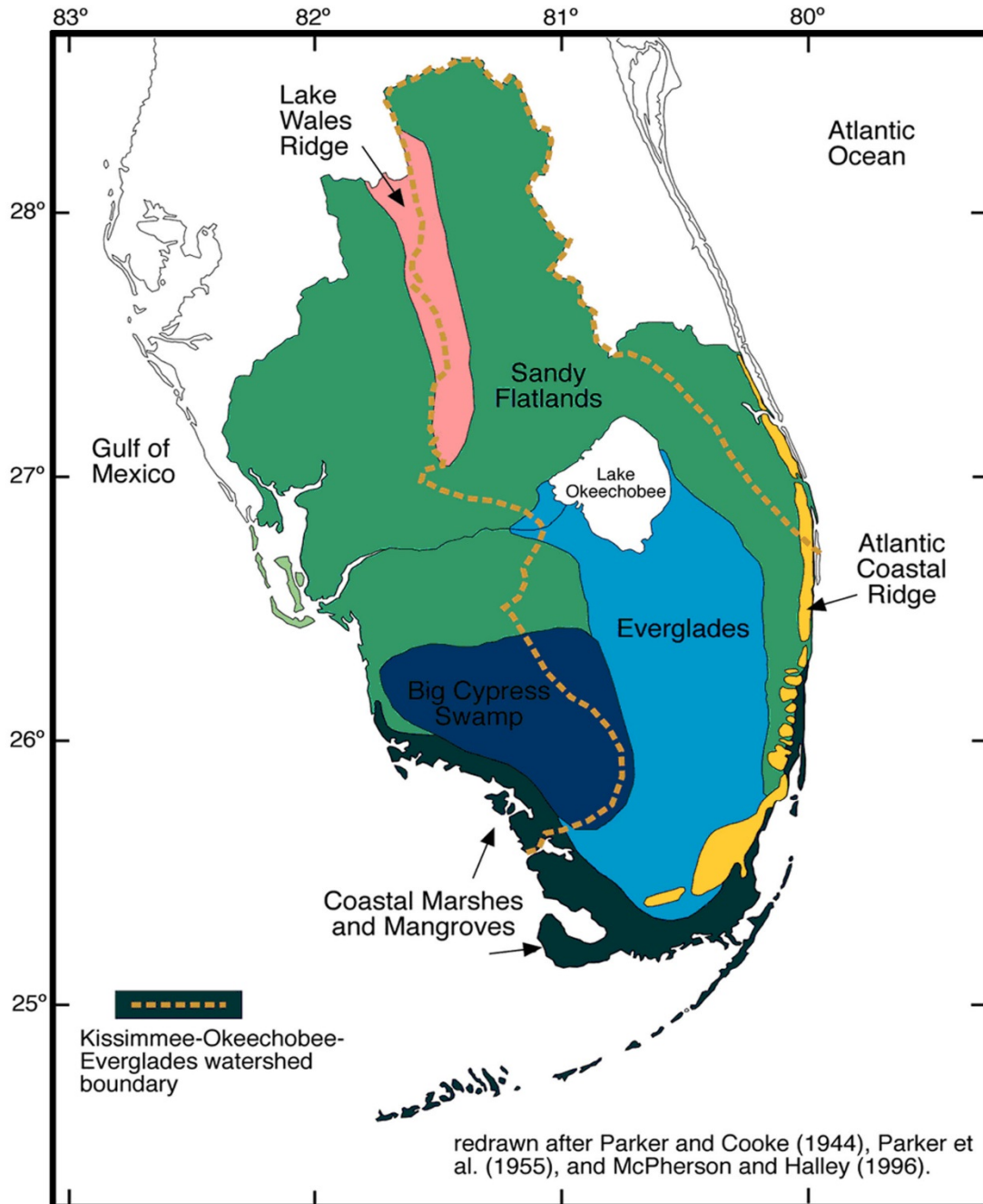


Figure 1 - Physiographic Provinces

The Florida Keys

The Florida Keys are a narrow chain of small islands extending from Soldier Key near Miami to Key West and the Dry Tortugas on the south. Most of the land in the keys is very low lying with mangrove swamps occupying an estimated one-half of the total area of the Keys (Hoffmeister, 1974). The highest point in the Keys is 18 feet (5.5 m) above sea level on Windley Key.

The Keys are divided in to two parts, the upper Keys or coral keys and the lower

Keys or oolitic keys. The upper Keys extend from Soldier Key to Big Pine Key, a distance of 110 miles (177 km) (Hoffmeister, 1974). The Lower Keys extend from Big Pine Key to Key West, a distance of 40 miles (64.4 km). The Dry Tortugas are nearly 70 miles (112.6 km) further west.

Sea Level History

Pleistocene Sea Level

Sea-level changes during the late Pleistocene were responsible for deposition of the limestone that forms 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 (Figure 2). These climate and related sea level changes are thought to be 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 southern 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. Cores that recover the Pleistocene section in southern Florida record these sequences of deposition and subaerial exposure as intervals of limestone with marine fossil capped by karstic features including calcretes (duricrusts) (paleo-soil features), soil breccias, evidence of root structures, oxidized surfaces, and remains of surface fires (blackened pebbles, Shinn and Lidz, 1988). Perkins (1977) has mapped out many of these cycles across southern 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 years ago (yr bp). Since that time, the glaciers have retreated supplying melt water to the world's oceans. The rise in sea level over the past 18,000 yr bp period has been documented from several locations in southern 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., (1969) developed the first sea level curve for southern 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 3) show that between ~18,000 and 7,000 yr bp sea level rose rapidly (>40 inches (100 cm)/100 yr) up the rim of the Florida platform. Starting between about 7,000 and 6,000 yr bp, the top of the Florida platform began to be flooded. As this flooding proceeded, shoreline 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 ~40 inches (100 cm)/100 yr to something on the order of 7.9 inches (20 cm)/100 yr.

As sea level continued to rise with this reduced rate, much of the areas underlying Florida Bay was flooded between about 5,000 to 3,000 yr bp. 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 3,000 yr bp to present, the rate of sea level rise further decreased (Figure 3), and has averaged about 1.6 inches (4 cm)/100 yr. This deceleration of sea

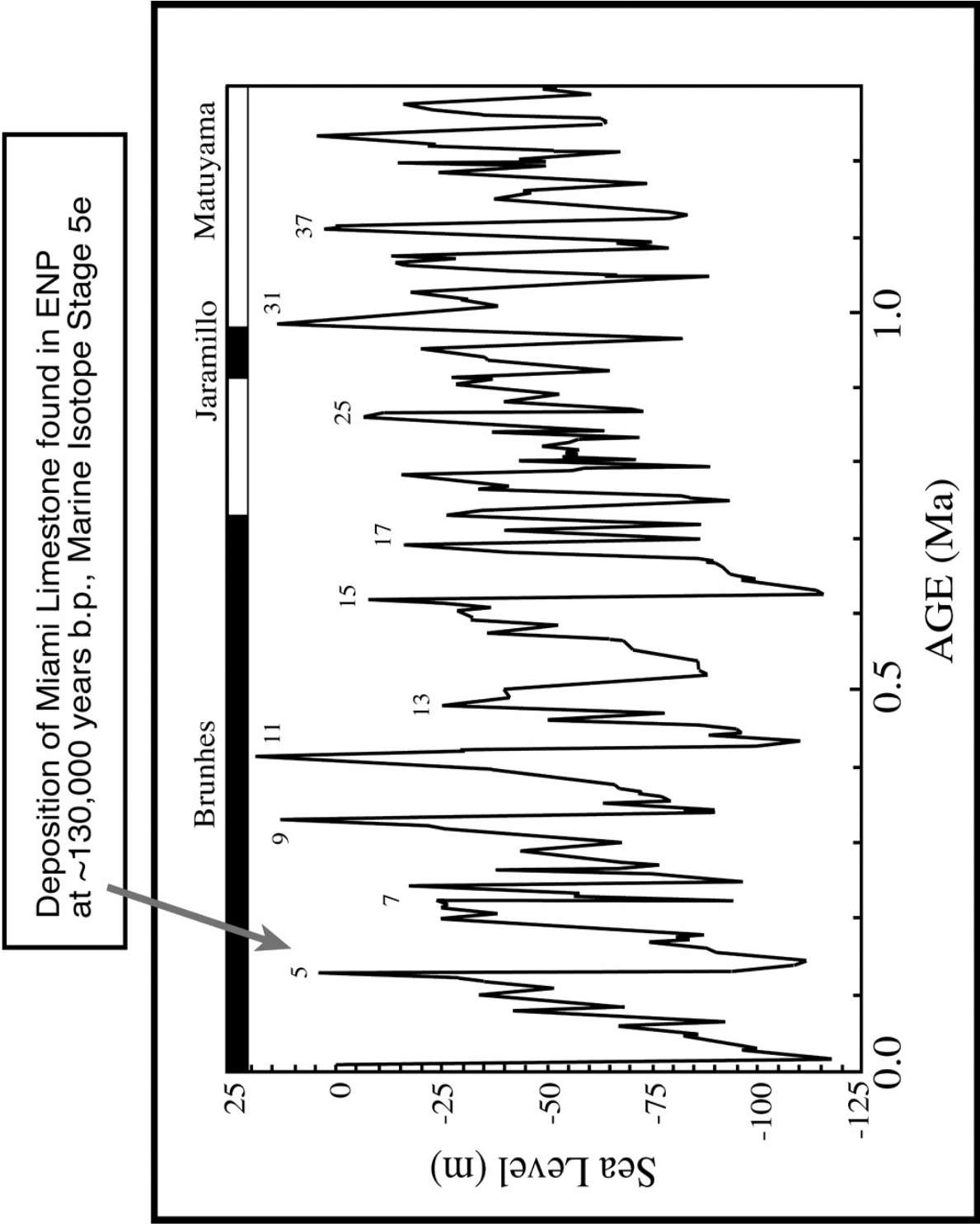


Figure 2 - Sea level changes during the last one million years (from McNeill, 2000)

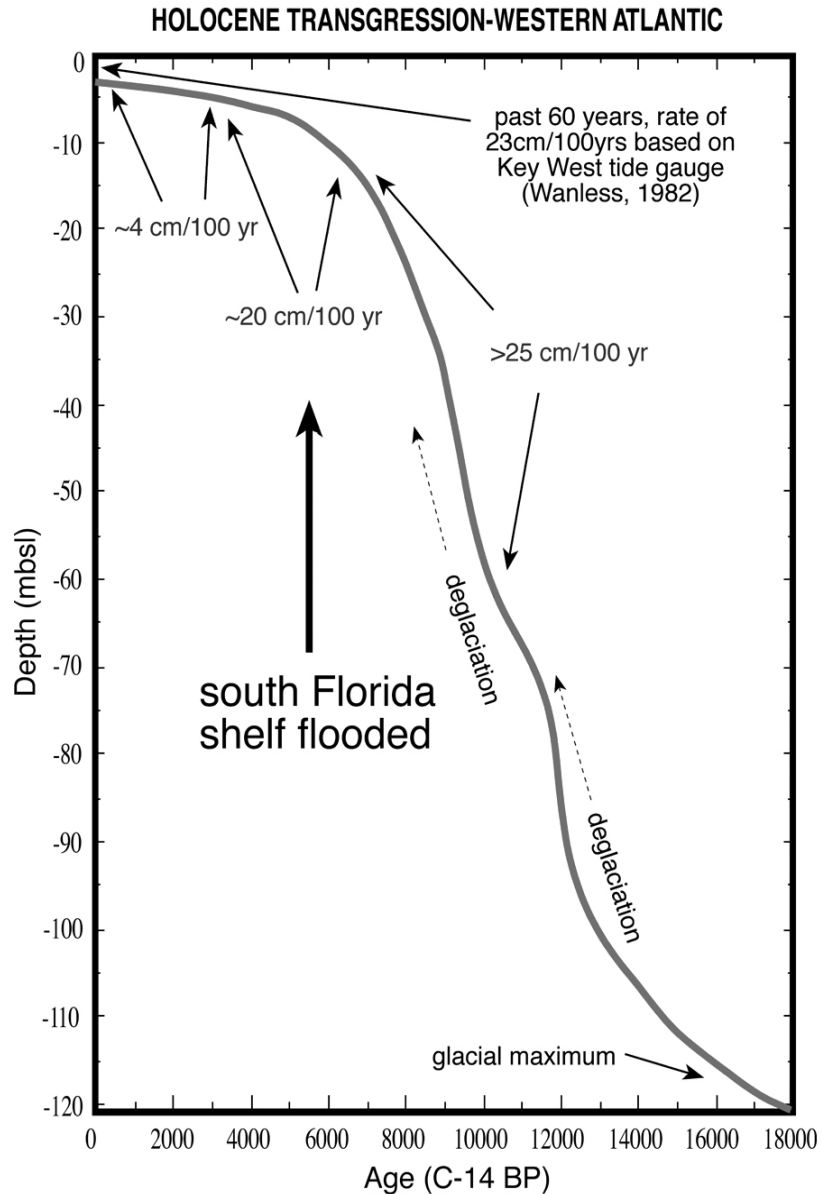


Figure 3- Regional sea level data.

level has allowed many of the islands 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 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 yr bp 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 9.1 inches (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 effects on the present-day configuration of sedimentary facies and ecological habitats within Everglades National Park.

GEOLOGY OF SOUTHERN FLORIDA AND EVERGLADES NATIONAL PARK

Geologic History of the Southern Florida Peninsula

Deep Basement of Southern Florida

Volcanic rocks are thought to form the deep basement in the area underlying ENP based on samples collected from a deep (3.5 mile [5.7 km]) oil test well 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 southern Florida, mainly due to its depth and lack of drill holes.

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, southern 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. The isotopic signatures in the volcanic rocks in the south support hot spot rifting in the 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 area that is currently the southern peninsula was likely subaerially exposed and underwent weathering to form a series of Upper Triassic to Middle Jurassic continental red beds. As the Atlantic Ocean began to develop, siliciclastics 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.

During the Early Cretaceous, as marine circulation began to improve, the Florida Platform underwent the transition from restricted evaporites and carbonates to more widespread deposition of normal marine limestones and reefs. 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 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 (see Scott, 1988). 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.

Beginning in the Late Oligocene and through the Miocene, a distinct change in the depositional history of southern Florida occurred with the introduction of widespread siliciclastic sedimentation. Siliciclastics prograded down the peninsula supplied by erosion of the southern Appalachian Mountains (Scott, 1988). Much of the southern peninsula experienced mixed carbonate-siliciclastic deposition during the Miocene. The Arcadia Formation (Hawthorn Group) was a carbonate ramp deposit in the southeastern peninsula during the early and middle Miocene. Siliciclastic deposits comprising the Peace River Formation (Hawthorn Group) overlie this unit. The Miocene period is also marked by widespread phosphate deposition throughout the peninsula.

During the Pliocene, many of the Miocene siliciclastic deposits further north in the peninsula were reworked and/or eroded. Southward transport of siliciclastics to the area of ENP and the Florida Keys was especially active as a thick pile of sands (Long Key Formation) was 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). The Pliocene in southern Florida also had periods of localized carbonate/siliciclastic deposition forming the Tamiami Formation. 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 Epoch marked the transition from siliciclastics (early Pleistocene?) back to widespread carbonate sedimentation (middle to 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 Plio-Pleistocene sediments of mixed carbonate and siliciclastic intervals form the shallow subsurface units of Everglades National Park. The upper portion of 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 crop out in southern Florida and have been age-dated at 130,000 yr bp.

A Brief Discussion of the Cenozoic Stratigraphy of Southern Florida

Paleocene to Lower Oligocene Carbonates

The Cenozoic stratigraphic section in southern Florida is dominated by a thick accumulation of carbonates containing variable percentages of evaporites. These sediments were deposited under restricted to open marine carbonate ramp conditions. The sediments are variably fossiliferous limestone and dolostone. The units defined in this section include the Paleocene Cedar Keys Formation, the Lower Eocene Oldsmar Formation, the Middle Eocene Avon Park Formation, the Upper Eocene Ocala

Limestone, and the Lower Oligocene Suwannee Limestone (see Scott, [1992a] for more complete discussion and references). The surficial geology of southern Florida is shown in Figure 4.

Hawthorn Group (Upper Oligocene/Lower Pliocene)

The Hawthorn Group in Florida is composed of a number of different formations and members (Scott, 1988). Most of the formations are defined from subsurface evaluations. As a result, for mapping purposes, all the component formations are not recognized on the geologic map.

In southern peninsular Florida, the Hawthorn Group formations include the Upper Oligocene to Middle Miocene Arcadia Formation including the Tampa and Nocatee Members and the Middle Miocene to Lower Pliocene Peace River Formation with its Bone Valley Member and Wabasso beds (Scott, 1988). The Nocatee Member of the Arcadia Formation and the Wabasso beds of the Peace River Formation were not recognized at or near land surface and do not appear on the geologic map.

Arcadia Formation (Upper Oligocene/Middle Miocene)

Florida Geological Survey Everglades core W-17232 (core numbers are Florida Geological Survey accession numbers) penetrated the top of the Arcadia Formation (Hawthorn Group) (Scott, 1988) at approximately 482 feet (147 m) below land surface. The contact marking the top of the Arcadia Formation is a major unconformity (sequence boundary) and is marked by a phosphatized surface.

The Arcadia Formation in southern 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 (W-17156). Quartz grains in the Arcadia Formation are a very minor component in the cores from the Florida Keys but increase northward. For example, in the Everglades core (W-17232), the Arcadia Formation carbonates have 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).

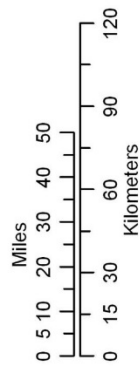
Peace River Formation (Middle Miocene/Lower Pliocene)

The Peace River Formation (Hawthorn Group) (Scott, 1988) was recovered between 324 feet (98.8 m) and 482 feet (147 m) depth in the Everglades core (W-17232) (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 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 siliciflagellates, diatoms, and radiolarians) was likely formed by upwelling based on the occurrence of a polar to subpolar silicoflagellates in +

Geology of Southern Florida



Legend

- Everglades National Park
- County Boundaries

Geologic Stratigraphy

- Holocene**
 - Oh - Holocene Sediments
- Pleistocene/Holocene**
 - Qal - Alluvium
 - Qbd - Beach ridge and Dune
 - Qu - Undifferentiated Sediments
- Pleistocene**
 - Ok - Key Largo Limestone
 - Qm - Miami Limestone
 - Qtr - Anastasia Formation
- Pliocene/Pleistocene**
 - TQsu - Shell-bearing sediments
 - TQd - Dunes
 - TQuc - Reworked Cypresshead Formation
- Pliocene**
 - Tc - Cypresshead Formation
 - Tt - Tamiami Formation
- Oligocene/Miocene**
 - Tha - Hawthorn Group, Arcadia Formation
 - Thp - Hawthorn Group, Peace River Formation
 - Thpb - Hawthorn Group, Peace River Formation, Bone Valley Member

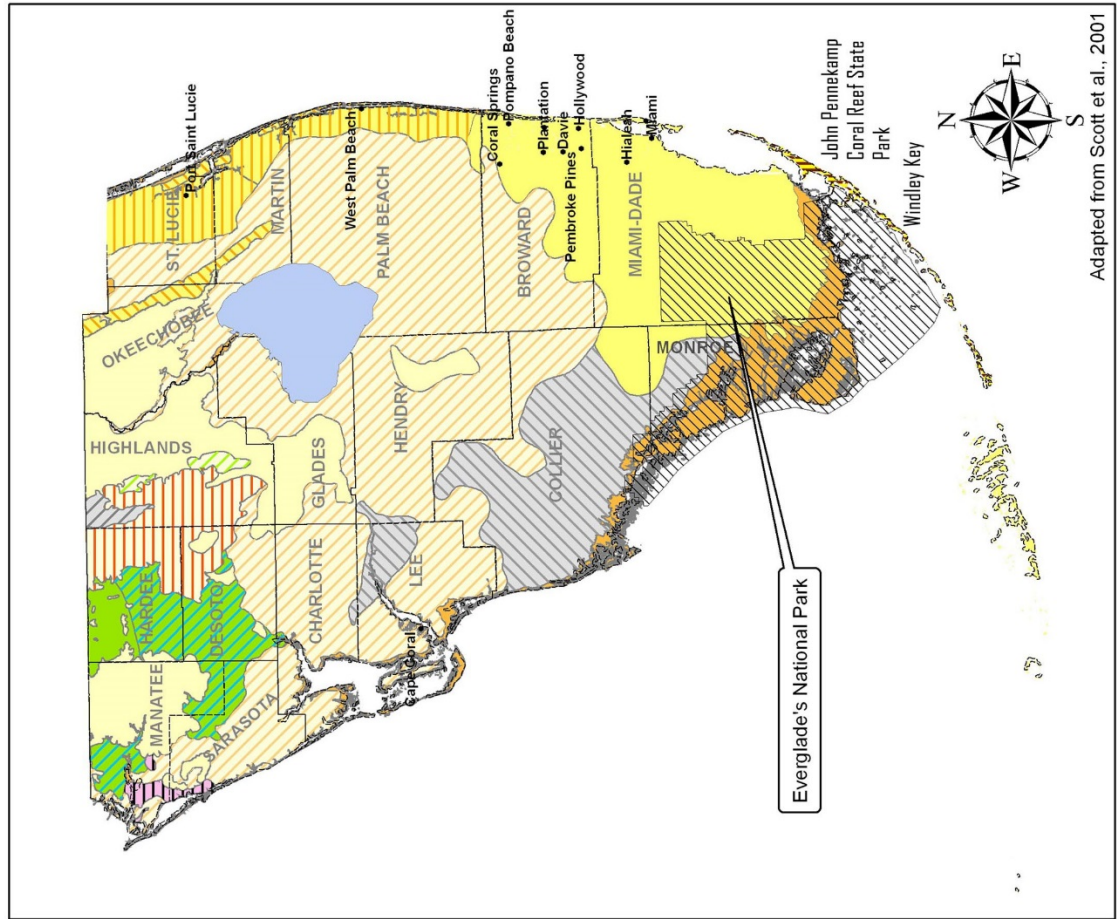


Figure 4 - Geologic map of southern Florida

Adapted from Scott et al., 2001

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). The type section for the Long Key Formation has been designated in, FGS-Long Key No. 1 Core (W-17156), 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, in part subjacent to the Plio-Pleistocene carbonates and siliciclastics, in part (upper Long Key Formation to the lower portion of the Plio-Pleistocene carbonates and siliciclastics) laterally equivalent to the Plio-Pleistocene carbonates and siliciclastics and subjacent to the Miami Limestone and the Key Largo Limestone. The unit is laterally equivalent to, and coeval with the Stock Island Formation of the lower Florida Keys 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. Warzeski et al. (1996) showed from marine seismic profiles that the siliciclastics of the Long Key Formation prograded southward to eastward over the unconformity at the top of the Arcadia Formation. This siliciclastic deposit provided the substrate for the development of the Florida Keys and the coral reefs.

In the Everglades core (W-17232), the Long Key Formation ranges from ~57 feet (17.4 m) to 324 feet (98.8 m) depth. 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). The age of the Long Key Formation sediments in the northern and central Florida Keys is much better constrained through the use of planktic foraminiferal biostratigraphy (Guertin et al., 1999. From cores on northern Key Largo (Caryfort 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 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 that 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) include most of the area under central ENP and southward beneath Florida Bay and the Florida Keys. This channelized morphology suggests southward transport of the sands from areas north of Lake Okeechobee. The exact distribution of this sand beneath ENP remains uncertain and additional core borings are needed to definitively constrain their spatial extent.

Tamiami Formation (Pliocene)

The Tamiami Formation is a poorly defined lithostratigraphic unit containing a wide range of mixed carbonate-siliciclastic lithologies and associated faunas (Missimer, 1992). It occurs at or near the land surface in Charlotte, Lee, Hendry, Collier and

Monroe Counties in the southern peninsula. The Tamiami occurs only in the western most portion of ENP. A number of named and unnamed members are recognized within the Tamiami Formation. These include: the Buckingham Limestone Member; an unnamed tan clay and sand; an oyster (*Hyotissa*) facies, a sand facies, the Ochopee Limestone Member, the Bonita Springs Marl Member; an unnamed limestone facies; the Golden Gate Reef Member; and the Pinecrest Sand Member (Missimer, 1992). The individual members of the Tamiami Formation were not separately mapped on the geological map.

Lithologies of the Tamiami Formation in southern Florida include: 1) light gray to tan, unconsolidated, fine to coarse grained, fossiliferous sand; 2) light gray to green, poorly consolidated, fossiliferous sandy clay to clayey sand; 3) light gray, poorly consolidated, very fine to medium grained, calcareous, fossiliferous sand; 4) white to light gray, poorly consolidated, sandy, fossiliferous limestone; and 5) white to light gray, moderately to well indurated, sandy, fossiliferous limestone. Phosphate is present in virtually all lithologies as limited quantities of sand- to gravel-sized grains. Fossils present in the Tamiami occur as molds, casts and original material and include barnacles, mollusks, corals, echinoids, foraminifers and calcareous nannoplankton.

Plio-Pleistocene Carbonates and Siliciclastics

The uppermost 56 feet (17 m) of the Everglades core (W-17232) consists predominantly of shallow-water limestone. These limestones likely represent a combination of Ft. Thompson Formation and a capping unit of the Miami Limestone but may include carbonate and siliciclastic facies equivalent to the Caloosahatchee and Bermont Formations.

The Caloosahatchee, Bermont and Ft. Thompson Formations have been informally included within the Okeechobee formation by Scott (1992b). These units are characterized by a predominantly carbonate lithology although the siliciclastic component is highly variable and deposited as a slightly restricted, lagoonal facies during successive sea level highstands in the Plio-Pleistocene. The unit is rich in marine bivalves.

Miami Limestone (upper Pleistocene)

The surficial geology of the southeastern peninsula has been mapped as Miami Limestone (formerly Miami Oolite) since at least 1944 (Parker and Cooke, 1944). The age of the Miami Limestone is late Pleistocene and has been dated at ~125,000 to 130,000 yr bp (Osmond et al., 1965; Broecker and Thurber, 1965). This age is correlative with an interglacial period that had sea level elevations about 16 to 23 feet (5 to 7 m) higher than present sea level.

As defined by Hoffmeister et al. (1967) the Miami Limestone contains two facies: an oolitic facies and a bryozoan facies. The oolitic facies contains a mixture of oolitic and pelloidal carbonate sands. The bryozoan facies has an abundance of the bryozoan *Schizoporella floridana*. These invertebrate marine animal secrete a calcareous shell in which they live and 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 seagrass roots and blades. This unit may exceed 40 feet (14 m) in thickness (Hoffmeister, 1974).

Key Largo Limestone (upper Pleistocene)

The Key Largo Limestone is exposed at the surface in the Florida Keys from Soldier Key on the northeast to Newfound Harbor Keys near Big Pine Key on the southwest (Hoffmeister, 1974). It occurs along the eastern and southeastern boundaries

of ENP. This unit is a fossil coral reef much like the present day reefs offshore from the Keys. An exceptional exposure of the Key Largo Limestone occurs in the Windley Key Quarry State Geological Site in the upper Florida Keys. Exposures of the limestone containing large coral heads are in a series of old quarries.

The Key Largo Limestone is a white to light gray, moderately to well indurated, fossiliferous, coralline limestone composed of coral heads encased in a calcarenitic matrix. Little to no siliciclastic sediment is found in these sediments. Fossils present include corals, mollusks and bryozoans. It may exceed 200 feet (61 m) in thickness (Hoffmeister, 1974).

A Brief Hydrogeologic Discussion of Southern Florida

The hydrogeologic framework of southern Florida consists of a basal sub-Floridan confining unit, the Floridan aquifer system, the intermediate aquifer system and the surficial aquifer system (Southeastern Geological Society, 1986). The sub-Floridan confining unit occurs in the Cedar Keys Formation. The Floridan aquifer system is comprised of Eocene and Oligocene carbonate sediments of the Oldsmar Formation, Avon Park Formation, Ocala Limestone, Suwannee Limestone and, in some areas, the lower Arcadia Formation (Hawthorn Group). The intermediate aquifer system consists of the Hawthorn Group (Arcadia and Peace River Formations) and, in some areas, the Tamiami Formation. The surficial aquifer system is made up of the Plio-Pleistocene carbonates and the Miami Limestone. In the Keys, the surficial aquifer system is developed in the Key Largo and Miami Limestones.

The Floridan aquifer system in southern Florida is non-potable. It can provide source water for desalination plants supplying this area's burgeoning population. Zones within the Floridan are utilized for the disposal of treated effluent.

The intermediate aquifer system is little used in southern Florida at this time. In southwestern Florida counties, the intermediate is an important source of potable water.

The surficial aquifer system is widely utilized in southern Florida. The Biscayne Aquifer of the surficial aquifer system is one of the most transmissive aquifers in the world. The Biscayne Aquifer provides water for many of the municipalities along Florida's southeastern coast. (see Scott [1992a] for further discussion and references).

Surficial Geology of Everglades National Park

The surficial geology of ENP is dominated by Holocene sediments resulting from both terrestrial and marine processes. 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. For further information concerning the geology, flora, fauna and history of exploration, see Gleason (1984).

Pleistocene Bedrock - Miami Limestone

Pleistocene rock crops out along the eastern margin of ENP and is locally known as the "rocky glades". This area 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 exposed 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 organisms such as worms). 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.

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

The Miami Limestone underlies the Florida Bay portion of ENP. Holocene carbonate mud and sand cover it. There are only scattered submarine exposures of the Miami Limestone.

Rock Reef Pass- the Mystery of the Rock Ridges

(contributed by Don Hickey [USF and USGS])

The southern Florida landscape is ornamented with more than a dozen northwest-southeast trending ridges that have typical lengths of 6.2-12.4 miles (10-20 km), widths usually 330 feet (100 m) or less, and topographic relief generally 1.6-4.9 feet (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 southern 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 Miami Limestone bryozoan facies. 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 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 yr bp, Unit IV/Q4 - 180,000 yr bp, Unit III/Q3 - 236,000 yr bp, Unit II/Q2 - 324,000 yr bp, and Unit I/Q1 - absolute age not published.

Steinen and others (1995) tentatively interpreted drill cores as indicating 3.3 feet (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 boreholes 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 50MHz ground penetrating radar profiles verify the absence of displacement along the Q4 discontinuity surface, which is consistently observed at approximately 13 feet (4 m) below the rock surface. The rock reefs of southern 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 southern 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 that 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 southern 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 affect 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 130,000 yrs. Deposition around ~130,000 yr bp began as the 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 the period when sea level was considerably lower and the ground-water 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 5,000 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 carbon dioxide contributes to the formation of carbonic acid in the organic-filled dissolution holes. These corrosive waters 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 dissolution holes found in the pinelands. The degree of connectivity between subsurface conduits has not been explored fully in the local area.

Another form of erosion 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.

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 5 and 6).

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 sawgrass 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 Cyanobacterial Mats (Periphyton mats)

One of the most spatially extensive modern “facies” is that of the freshwater marl. The open prairies surrounding the pinelands and the deeper sloughs (Shark 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). The precipitation of small crystals (10-20 microns) is a result of extracellular precipitation by cyanobacterial mats during the standing water part of the annual hydro-period. 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 cyanobacterial (periphyton) mats. The cyanobacterial 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 produce a size (5-10 microns) and shape (equant) distinct crystal morphology.

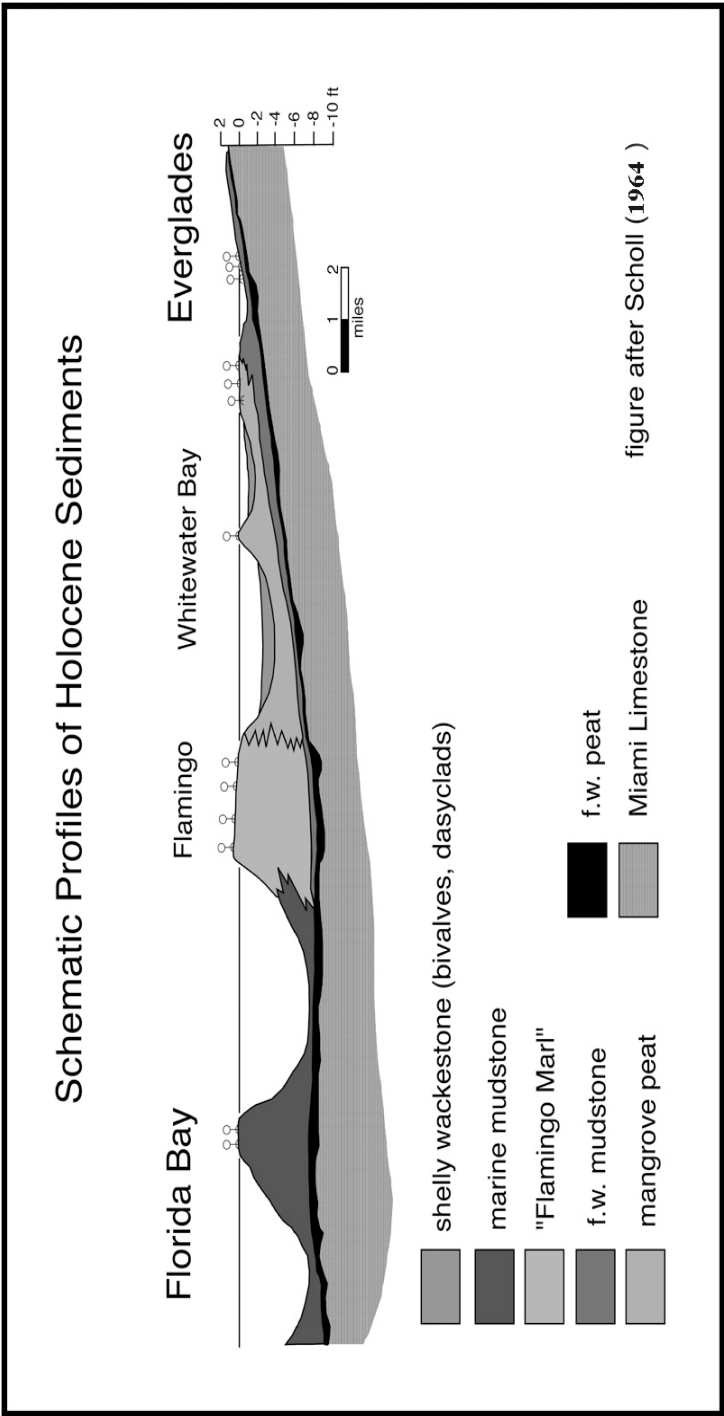


Figure 5 - Schematic profile of Holocene sediments

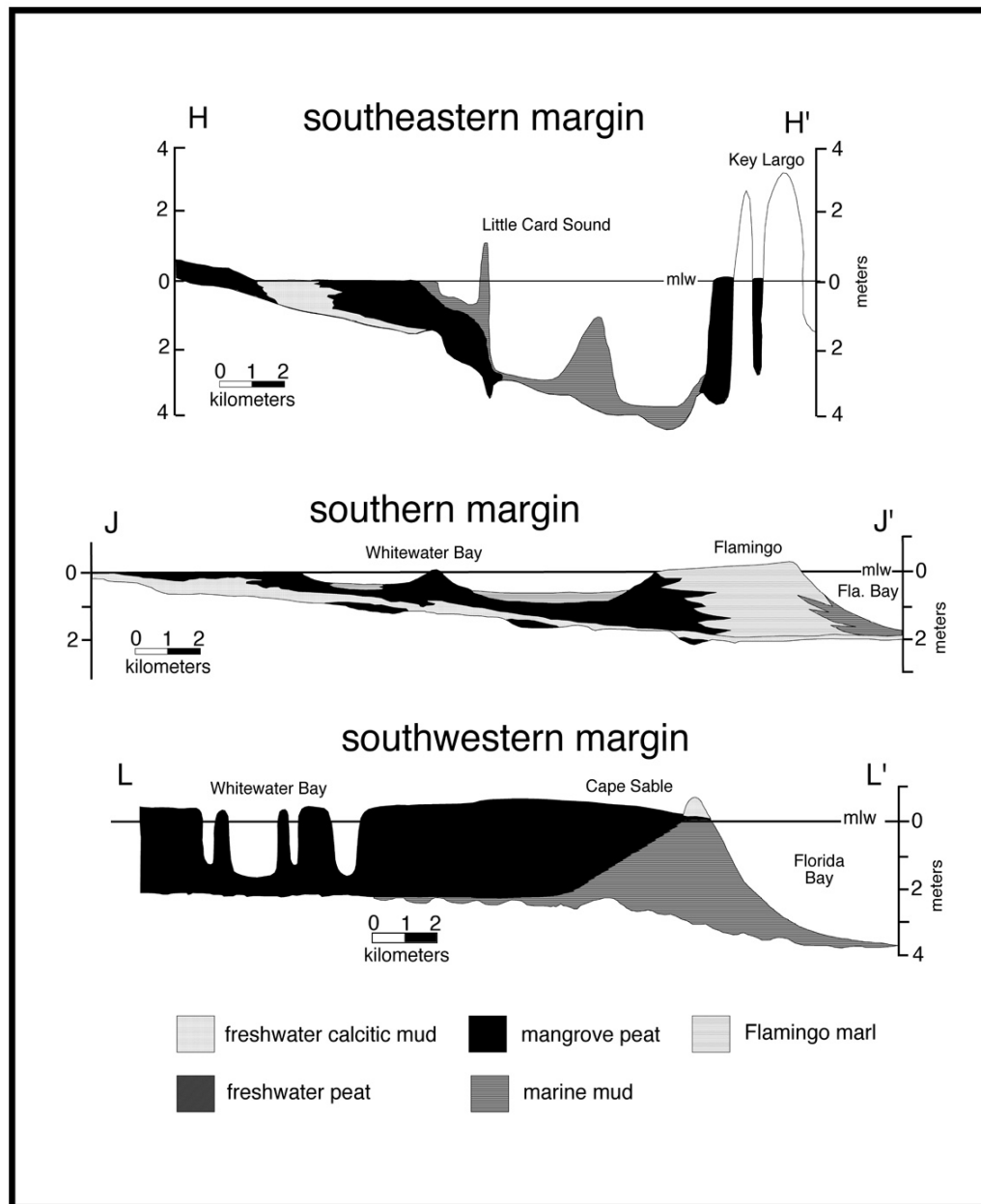


Figure 6 - Holocene sediments of the southern tip of Florida (from McNeill, 2000)

In the southern Everglades, freshwater carbonate marls reach thicknesses of up to 1.6 feet (50 cm) depending on relief of the underlying Pleistocene carbonates. The stratigraphy of the freshwater marl consists of the upper inch or so (few centimeters) 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. 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 an elongate seedling. These thin, rod-shaped seedlings, 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.

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 4,000 years (Wanless, 1974; Parkinson, 1987). Seaward growth likely results 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 this mud 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 (informally the 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 informally referred to as the "Flamingo Marl". This deposit is dominated by aragonitic mud, is easily scoured from Florida Bay and suspended during strong wind events and 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 formed that is progradational (Cottrell, 1989). In the area between Flamingo and Cape Sable the seaward progradation is in excess of 1.2 miles (2 km) during the past 3,000 to 4,000 yrs.

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.

Florida Bay Overview

Florida Bay is an 850 mi² (2,200 km²), roughly triangular area bordered on the north by the Florida mainland, the east and south by the Keys and open to the Gulf of Mexico on the west. The bay is very shallow with very few areas exceeding 9 feet (2.7 m). One of the most interesting features of Florida Bay is the existence of a sinuous, anastomosing topographic arrangement of elongate mudbanks (Hoffmeister, 1974).

Florida Bay began developing approximately 4,000 yr bp as sea level rose and encroached on to the land. The land surface was much like the present day Everglades. Mangrove peat is found beneath the carbonate mud in many areas and the surface of the underlying Miami Limestone is karstified. Much of the carbonate mud originates within the bay as the result of the growth and breakdown of calcareous algae (*Halimeda*, *Penicillus* and others).

Plant and animal communities in the South Florida ecosystem have undergone striking changes over the past few decades. In particular, Florida Bay has been plagued by seagrass die-offs, algal blooms, and declining shellfish and sponge populations. These alterations in the ecosystem have traditionally been attributed to human activities and development in the region. Currently, under the [South Florida Initiative of the Ecosystem Program](http://sofia.usgs.gov/) (<http://sofia.usgs.gov/>) scientists at the USGS are studying the paleoecologic changes taking place in Florida Bay in hopes of understanding the physical environment and restoring the region to a more pristine, natural state. Restoration efforts include changes in agricultural and land development practices, which began in the early 1900s, and the restructuring of the present levee and canal system established to control the flow of water throughout southern Florida. Before recommending the use of such efforts, however, scientists must first determine which changes are part of the natural variation in Florida Bay and which resulted from human activities. To answer this question, scientists study both modern samples and deeper piston cores which reveal paleoecologic changes over the past 150-200 years. These two types of cores compliment each other by providing information about the current state of the Bay, changes that have occurred over time, and patterns of change. (From <http://sofia.usgs.gov/flaeco/hist/floridabay.html>).

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Windley Key Fossil Reef State Park

Field Guide



PHOTO BY HARLEY MEANS

The Geology of Windley Key

The Florida Keys, extending approximately 150 miles (240 km) from Soldier Key on the north to Key West on the south, are an arcuate string of islands composed of late Pleistocene limestone (approximately 125,000 years before present). The surface of the upper keys from Soldier Key to Big Pine Key is composed of the Key Largo Limestone while the lower keys' surface is Miami Limestone. The Key Largo Limestone is a fossil reef while the Miami Limestone in the keys is made up of oolites - small spheres of calcium carbonate formed on shoals affected by tidal fluctuations. Windley Key, located in the upper keys (Figure 1), is composed of Key Largo Limestone.

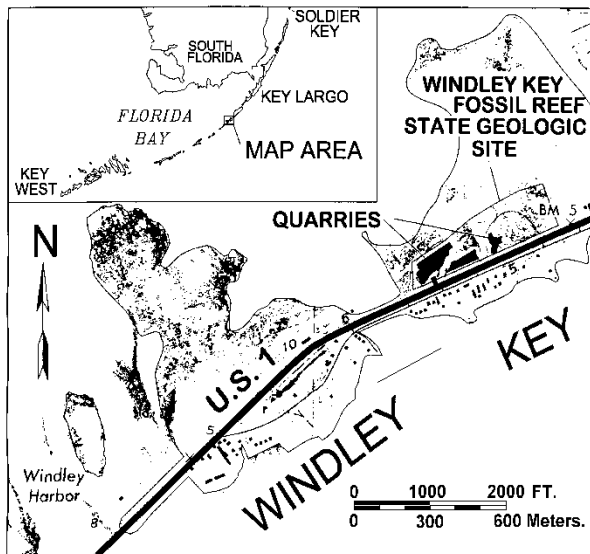


Figure 1. Windley Key location map.

There are two main sediment types that make up the Keys: biogenic and chemical. Here at Windley Key, Key Largo Limestone is biogenic. The Key Largo Limestone, named by Sanford (1909), extends in the subsurface north of Soldier Key under the Miami Limestone to at least Miami Beach. It extends in the subsurface southward to Key West, also beneath the Miami Limestone. Harrison and Coniglio (1985) discuss the origin of the Key Largo Limestone. The limestone exposed in the Windley Key Fossil Reef State Geological Site consists of a framework of corals

surrounded by or encased in a calcium carbonate (CaCO_3) sediment. Virtually all of the coral species found today in the patch reefs of the Florida reef tract occur in the Key Largo Limestone (Hoffmeister and Multer, 1968). There are five primary coral species forming the Key Largo Limestone: -Star coral (*Montastrea annularis*), Porous coral (*Porites astreoides*), Brain corals (on Windley trip cover) (*Diploria stigosa*, *Colpophyllia natans*, *Diploria labyrinthiformis*) (Stanley, 1966). These corals make up approximately 30 percent of the limestone of which *Monatstrea annularis* comprises nearly half (Stanley, 1966) Figure 2). The calcium carbonate sediment matrix of the limestone is sediment trapped between the corals. This sediment, which comprises about 70 percent of the limestone, is made of calcium carbonate mud and skeletal material. The most common of the skeletal material is *Halimeda*, a calcareous green algae. Other skeletal grains present include mollusks (snails and clams) and foraminifers (single celled organisms with a CaCO_3 shell). The Key Largo Limestone is characteristically moderately hard. The rock is cemented together by calcite (CaCO_3). Ground water dissolved some of the original sediment and calcite precipitated in the pore spaces. Much of the porosity has been filled by calcite near the present land surface forming a dense and harder cap rock. The original reef line was over 220 miles long, and the Key Largo limestone ranges from 75 to over 200 feet thick throughout the Keys.

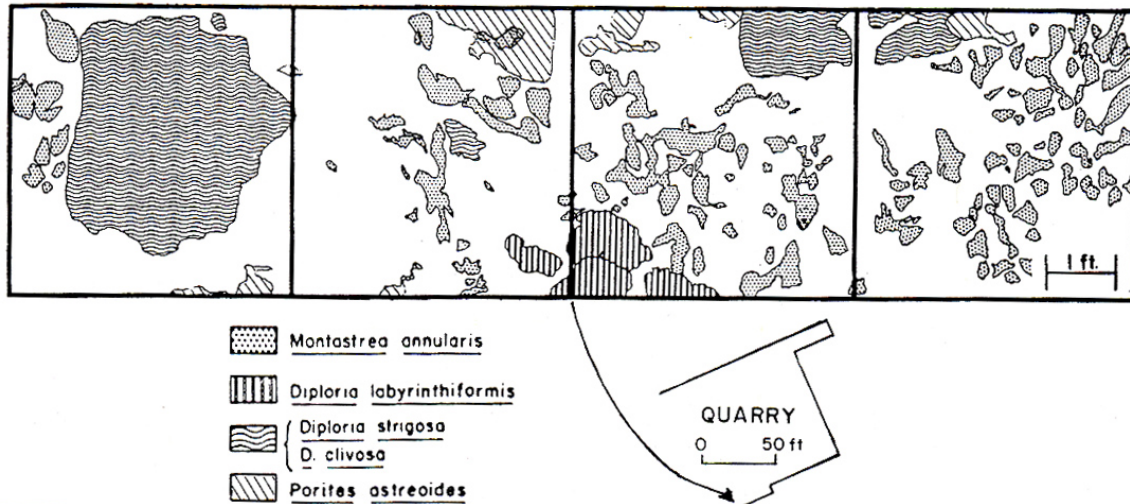


Figure 2. The distribution of corals in a section on the south wall of Windley Key quarry. At the extreme right is a tangential section through a branching *Montastrea* colony. At the extreme left is a large head of *Diploria* brain coral. *Porites astreoides* exhibits an encrusting habit (seen near the top of the section) (From Stanley, 1966).

The second type of sediment, Miami Limestone oolite facies, is not found here at Windley Key. Ooids are spherical, chemically precipitated carbonate grains formed by concentric layers of CaCO_3 deposited around a nucleus as the ooid is moved back and forth by tidal currents. The Miami Limestone, in part an oolitic carbonate, forms the surface and near surface deposits in southern Florida and the lower Keys. Oolitic sediments are no longer forming in the Keys but still can be found in some areas of the Bahamas.

Rain water is naturally slightly acidic and becomes more acidic as it seeps through decomposing organic debris. The acidic water slowly dissolves limestone forming dissolution pits, cavities and voids of varying size. Numerous examples of limestone dissolution can be seen in the walls of the quarries on Windley Key. The dissolution pits are usually at least partially filled by organic debris and a reddish residual sediment. The reddish residual sediment was left following the dissolution of the limestone. Some of the reddish residual sediment originated in Africa. The dust was blown across the Atlantic Ocean and deposited along with the carbonate sediments. The agricultural fields on the mainland west of Miami are named the "Redlands". A terra rossa soil developed as a result of dissolution of the Miami and Key Largo Limestones leaving an insoluble residue consisting mainly of African dust.

For further information on the geology of southern Florida's carbonate environments see Bond (1986) and the regional geologic discussion in the Everglades Field Trip (this volume).

Visitors to the Windley Key Fossil Reef Geological State Park have a unique opportunity to explore the fossilized reef exposed through mining activities. In and surrounding the quarries, you can experience the tropical nature of the native habitats found in the upper Florida Keys.

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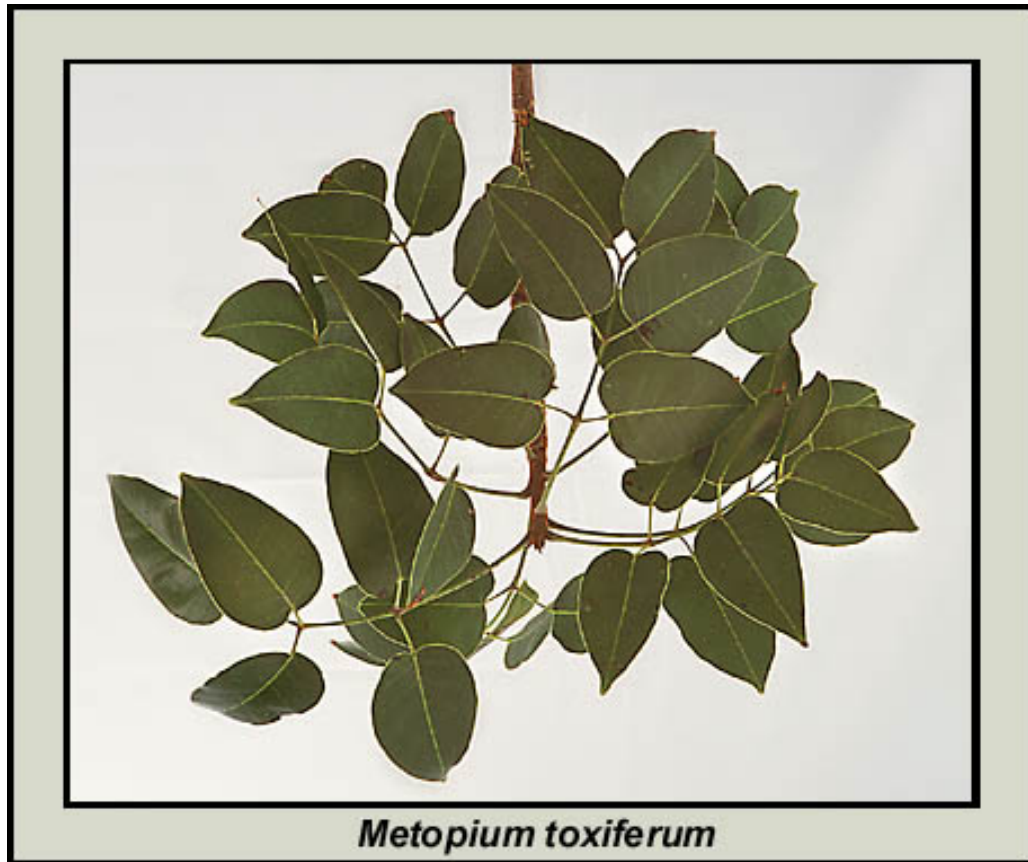
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A Brief History

Various tribes of Indians inhabited the Keys before the first European explorers arrived, and middens and other remains are located in the immediate area. One midden has been identified at the Northern boundary of the Quarry tract.

After Key West was settled, Conch families moved up the Keys to establish small farming and fishing communities and in the mid 1800's the Russell family homesteaded the "Umbrella Keys," Windley Key's earlier name. In 1908, the Russell family sold the tract to the Florida East Coast Railway. Three separate quarries subsequently operated in the Windley quarry complex: The Windley Quarry, the Flagler Quarry and the Russell Quarry. Flagler reportedly paid the Benjamin Russell family \$852.80 for the area. From that time until the final completion of the Overseas Railroad, the quarries on the tract were used to supply rock for the railbed and the bridge approaches. After the railway was completed, "Quarry Station" at Windley Key was a regular stop for local passengers, for the delivery of fresh water from the mainland, and for the shipment of "Keystone" back to the mainland. When the railway was destroyed by the 1935 hurricane, Quarry Station was also leveled along with the local camp and infirmary for railroad workers. The completion of the Overseas Highway in 1938 encouraged resumption of the quarrying of Keystone and the quarry was leased to a succession of companies. During the early 60's the last commercial quarrying ceased.

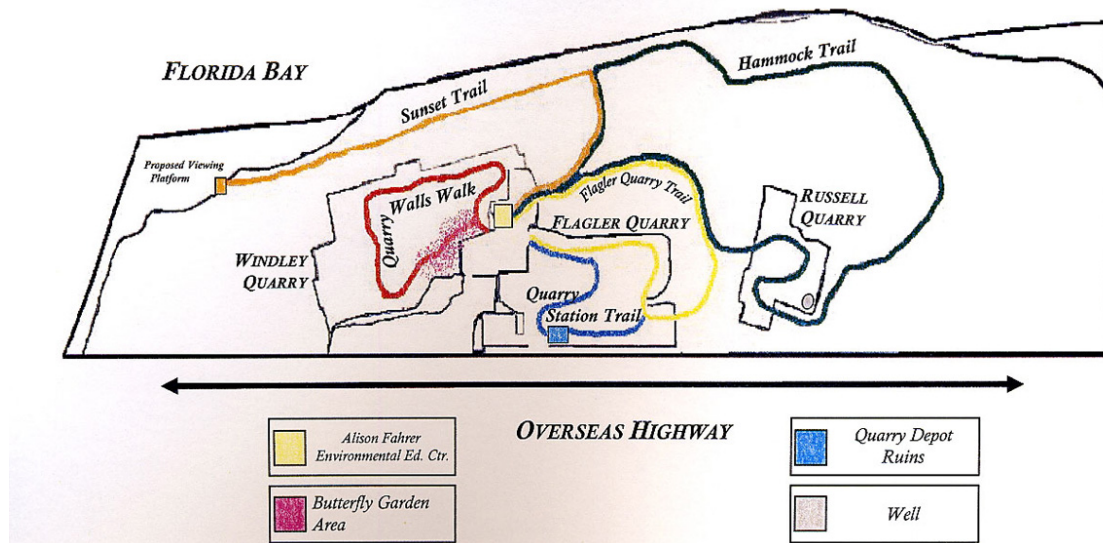
If you only learn one native tree during your visit to Windley Key... let it be this



Poisonwood (*Metopium toxiferum*)

Before walking along any Keys nature trail, everyone should learn to recognize this relative of poison sumac & poison oak. To the right of the channeling machine is a twenty-five foot tall poisonwood tree. The leaves are compound, meaning each is composed of several leaflets. Poison ivy has three leaflets, poisonwood may have five or seven. Poisonwood leaves have dark green upper surfaces, but are lighter below, and have yellowish mid-ribs and edges. The sap of poisonwood turns black after being exposed to air. Small sap stains on the leaves and larger blotches on the bark help make this tree easier to identify. Berries produced by the tree are the main diet for our endangered white crowned pigeon population. Adult pigeons eat a variety of fruits but young hatchlings rely solely on the high fat content in the nutritious berries. The availability of berries affects the number and health of white crowned pigeon offspring. **Brushing up against poisonwood can cause "contact dermatitis," an allergic skin irritation. Poisonwood is said to be 5x stronger than poison ivy! Even standing under the trees in the rain can affect sensitive individuals.**

Map of Quarries & Trails



The Trails

STATIONS 1 & 2

This begins the HAMMOCK, FLAGLER QUARRY, QUARRY STATION and SUNSET TRAILS.

Station 1) This channeling machine was used to quarry Keystone here as early as World War I, and into the 1960s when the quarrying operation ceased. Chisels on either side of the machine were driven into the rock by a belt driven engine. This action cut channels to a depth of about two or three inches with each pass of the machine, which moved back and forth from one end of the track to the other. By repeating this process over and over, the chisels were capable of digging to a depth of eight feet into the rock. Notice the track running perpendicular to the machine's track. Once the channel was cut in one direction, the machine was transferred to the other track. This allowed a cross cut of the same depth to be made. Workers then used steel wedges to pry the huge slabs of rock loose. Each slab is estimated to weigh many tons. The limestone blocks were then removed and transported for use in decorating the faces of buildings such as John Deering's home in Miami called Vizcaya, post offices in Key West, Miami and St. Louis, the altar of a New York church, and the faces of many buildings in South Florida. It was even used in the Space Needle Monorail Station in Seattle, Washington. Along U.S. 1 in Islamorada, you can visit a monument dedicated to victims of the 1935 Labor Day Hurricane which is constructed with Keystone.

Station 2) Once you enter the hardwood hammock, it will become difficult to separate tree canopies, so take a look over-head now. Above this intersection stand four of the most common tall trees of Windley Key's hammocks: Jamaican dogwood, West Indian mahogany, poisonwood and short leaf fig. The word "hammock" has several meanings, such as shady place" or "island forest." The hardwood hammock you are now entering can be a safe and quiet place to spend some time. Notice the understory foliage lining the trail in this clearing. Once the trail enters the full shade of these hammock canopy trees, understory plants thin out. Also notice how canopy trees

insulate the hammock interior from the heat of Florida's summer sun and the chilling effect of winter winds. A little further down this path, the trails split and go in different directions. We would encourage you to take every trail, as there are different features and native species throughout the park. The trails contain marked stations, grouped in numerical order as follows:

FLAGLER QUARRY TRAIL

Yellow Markers: #3-#17

This trail (approximately 1/4 of a mile [0.4 km]) offers a gentle walking experience in the park. It complies with ADA accessibility guidelines.

QUARRY STATION TRAIL

Blue Markers; #18-#24

This trail (approximately 1/8 of a mile [0.2 km]) offers a slightly more difficult walk.

HAMMOCK TRAIL

Green Markers: #25 - #53

This is the longest trail (approximately 1/2 mile [0.8 km]), and leads through several habitats and features.

SUNSET TRAIL

Orange Markers: #54 - #72

This trail (approximately 1/3 mile [0.5 km]) leads close to the waters edge. Future plans include an observation platform at the end of the trail.

QUARRY WALLS WALK

Red Markers: #73-#85

This trail (approximately 1/8 mile [0.2 km]) tours Windley Quarry and allows close up viewing of the walls.

Quarry Walls Walk

Corals are formed by colonies of tiny animals called polyps. These animals secrete a calcium carbonate skeleton. Some of coral corallites are tiny and difficult to see. If you look closely at the wall, you may see scattered in it the very small corallites of finger coral (*Porites porites*). Other corals found here have larger corallites such as some types of star coral (*Montastrea*), which can be several millimeters across, making them much easier to see.

73) As you walk along the eastern wall you will see very dark colored rock in some places. This is caused by algae which takes hold and begins to grow on these vertical rock faces.

74) Since this old coral reef was exposed as an island, very little soil has developed upon its surface. The trees growing here must send their roots into nooks and crannies in the rock. These harsh growing conditions prevent the trees from getting very tall.

75) The machinery here was used to cut the large rough pieces of stone into much smaller, more manageable pieces that were then cut and polished in a building that had been located behind this cutter.

76) The gin pole featured was used to lift the heavy stone and maneuver on to the cutter and/or to the railroad cars.

77) The exposed reef walls here are composed of mostly brain coral (*Diploria*), star coral (*Montastrea*) and loose debris. This debris comes from a variety of things including mollusks and echinoids. Calcareous mud derived from the disintegration of the calcareous algae *Halimeda*, mollusk shells and other biogenic debris. In some

areas of the quarry walls, the biogenic debris and carbonate mud can contribute more to the total makeup than corals do

78) Geologists have apparently hacked away at this brain coral trying to get unaltered coral in order to date it. Corals are made up of aragonite which is a form of calcium carbonate. Around the edge of this disturbance, you can see coral that has been altered to calcite. Unaltered material from the interior fossil is required for accurate age.

79) For thousands of years, rainwater has been dissolving the exposed Key Largo limestone. The calcium carbonate-rich waters are drawn upward beneath the thin soil by capillary action. The CaCO_3 is deposited as the water evaporates leaving a thin crust called a duricrust or calcrete.

80) Looking at the wall here, you will see a hole bored by a giant date mussel (*Lithophaga*). This mollusk ranges in size from one to five inches in length. It lives in the tube which it bores into the coral. The tube can be as much as a foot deep. The clam burrows through coral by using an acid solution which results in a very smooth wall. Along with holes made by the giant date mussel, you may see holes made by boring barnacles, tiny crabs, other mollusks. The borings can contribute to the breakdown of large coral heads.

81) The top of the wall is the surface of this ancient reef which is close to a hundred thousand years old. Dissolution has created numerous micro-karst depressions that can be seen in the quarry walls.

82) Corals grow very slowly, depending on the species and conditions in the growing environment. It is estimated that star coral grows about one foot in 28.5 years.

83) Keep in mind that when you walk in the quarry, you are walking over corals

84) These blocks are the last keystone blocks that were quarried at Windley Key. All operations ceased in the early 1960s and the blocks were never removed. When construction occurs in the Keys that requires the removal of keystone blocks, several companies are quick to cut it and remove it free of charge as it is a valuable building material!

85) High on the wall in the distance is the channeling cutter. This cutting machine was used to quarry the keystone here. It moved along the upper part of the wall chiseling grooves to a depth of eight feet.

The information presented here is taken from a pamphlet on the geology of Windley Key Fossil Reef Geological State Park by Thomas M. Scott and modified from the Trail and History Guide on sale in the park visitor center.