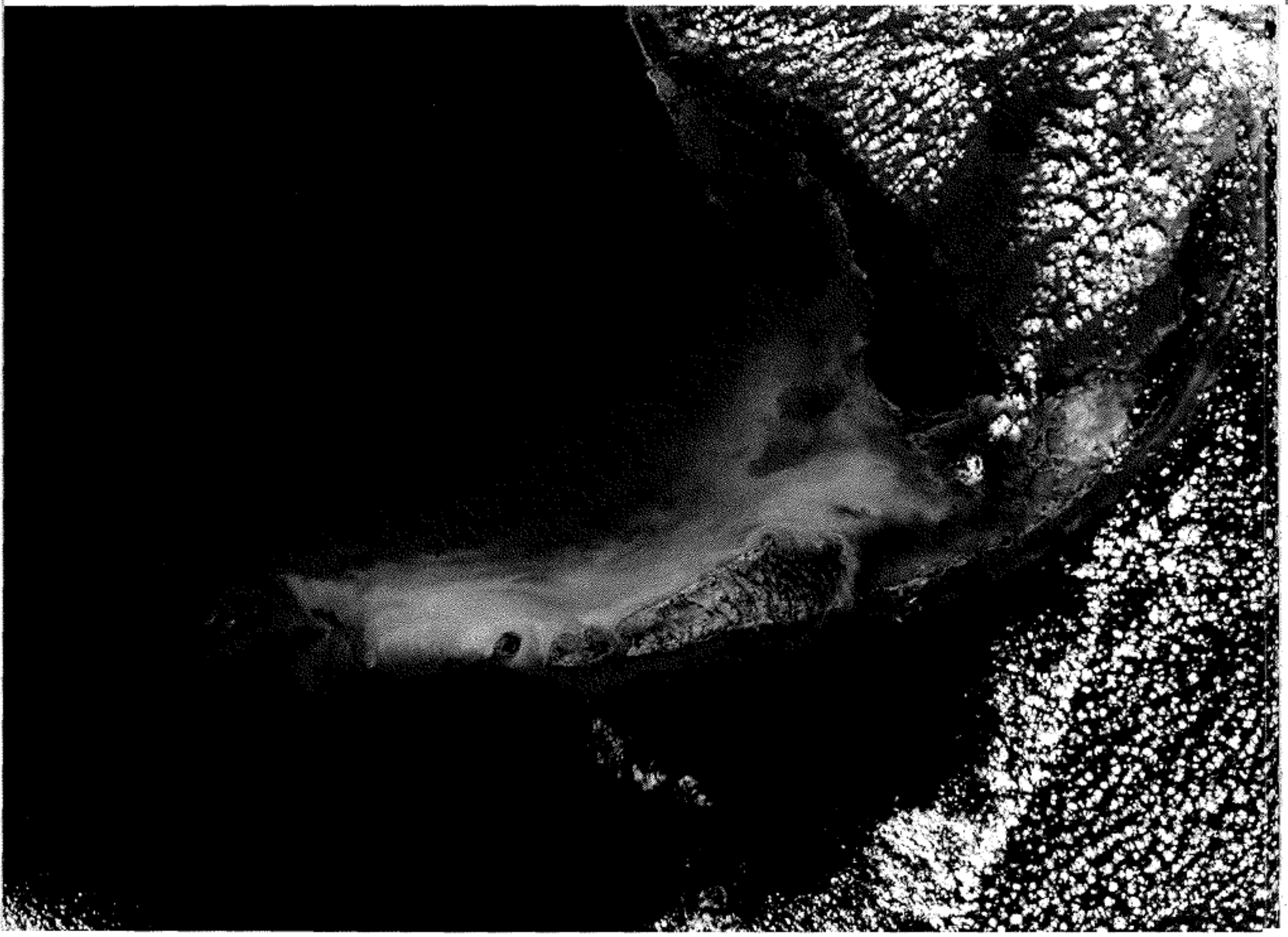

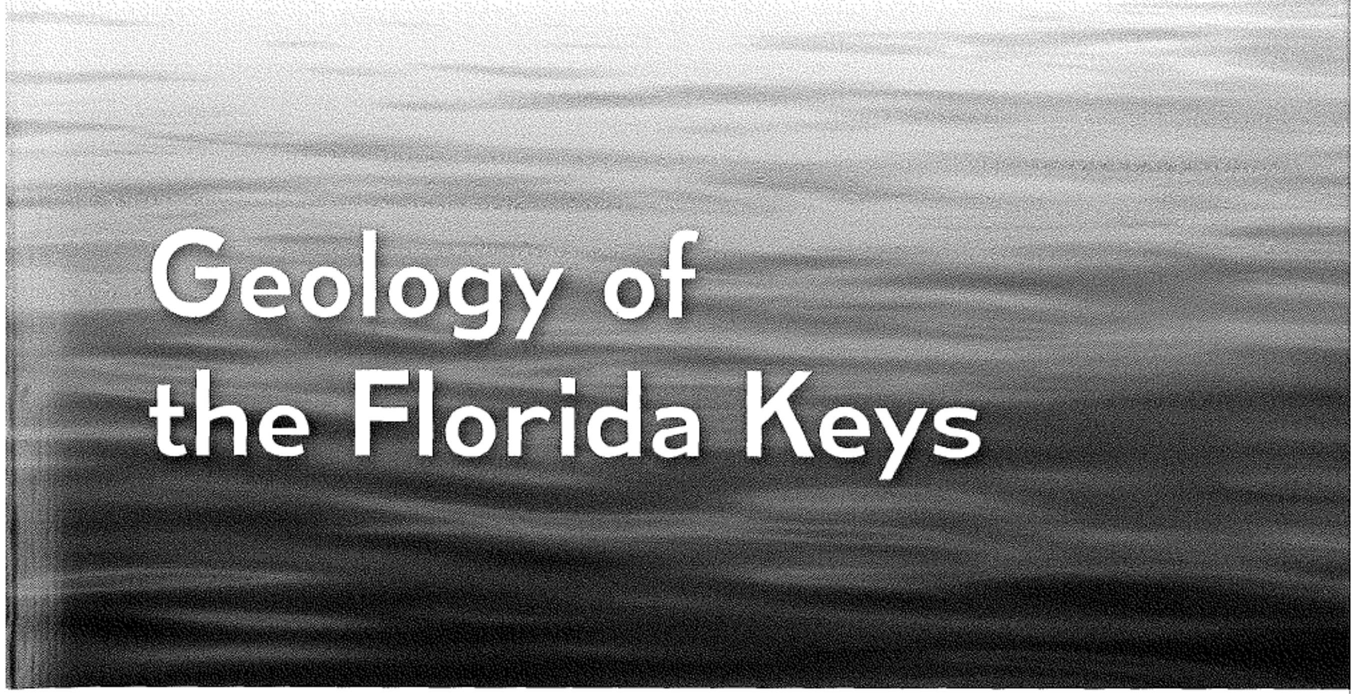

Geology of the Florida Keys

Eugene A. Shinn and Barbara H. Lidz

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Introduction

The purpose of this book is to examine the ongoing geologic processes inherent in the evolutionary history of the Florida Keys over the past approximately 125,000 years. In language as nontechnical as possible, supplemented by notes where necessary, we discuss the processes that created the coral reefs, lime mud, and ultimately the limestone found in the geologic record anywhere on our planet. Included are significant unanswered questions regarding the geology and biology of the Florida Keys that still need research to resolve.

The book is a virtual guide for those interested in natural history, especially for the carbonate biologists, geologists, sedimentologists, and students who frequent the Keys in great numbers. The Keys and their coral reefs have long provided a premier natural laboratory for scientific investigations of modern and ancient limestone and sedimentary environments. Our focus is primarily on those areas made famous beginning in the 1950s by Robert N. Ginsburg, Twenhofel medalist[1] and considered the father of modern comparative carbonate sedimentology. They remain classic areas for field courses centered on sedimentary processes that aid in understanding formation of ancient limestones anywhere on Earth.

Geologic Context

In spite of, or because of, the uniqueness of the Keys, their reefs and geology have long attracted scientists of many disciplines. As early as 1905 to 1939, a world-famous research laboratory operated on a remote island in the Dry Tortugas, an atoll-like group of islands west of Key West. In addition, because of natural diversity, the Keys hosted many scientific studies during the 1900s. Their distinct geology (composition) and geometry (orientation) allow the island chain to be divided into the lower, middle, and upper Keys (fig. i.1). Based on historic events, often shipwrecks, many Keys coral reefs have acquired individual names. Some are also named after people. In recent years, the authors had the honor of formally designating such a reef in the

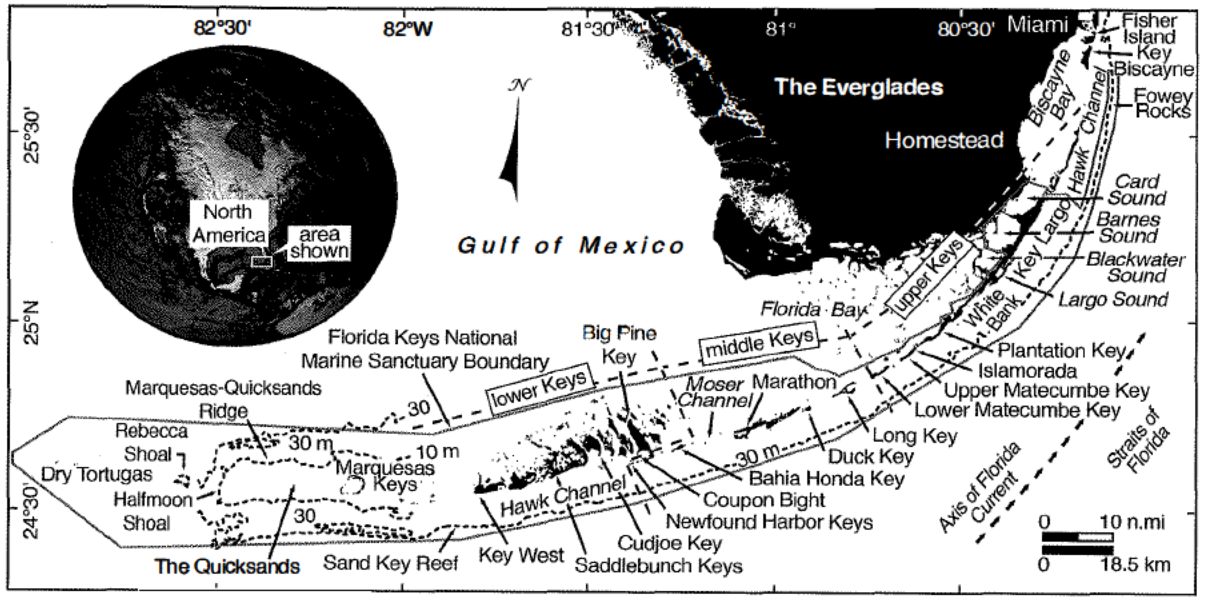


Figure i.1. Index map of the Florida Keys shows major geomorphologies and orientation of the reefal upper and middle Keys and parallel alignment of the linear oolitic bars of the lower Keys. Labeled sites are referred to in text, notes, or figure captions.

upper Keys.[2] At the time (2002), the reef patch consisted of large, pristine heads of *Monstastraea annularis.*

In the following pages, we discuss the geomorphology and limestone origin and composition of major land- and seascape features in the Florida Keys. Because details of the origin and geology deep beneath the Keys are complex and beyond the scope of this book, we focus mainly on the more recent part of their geologic past, specifically, the last approximately 130,000 years of time. This interval comprises the later

Table i.1. Nomenclature for the most recent intervals of the geologic time scale as reported by the International Commission on Stratigraphy

Cenozoic	
Quaternary Period	
Holocene Epoch	4th interglacial stage
Pleistocene Epoch	
Wisconsinan	4th glacial stage
Sangamonian	3rd interglacial stage
Illinoian	3rd glacial stage
Yarmouthian	2nd interglacial stage
Kansan	2nd glacial stage
Aftonian	1st interglacial stage

Note: Note the four cycles of glacial and interglacial stages for North America.

part of the Pleistocene Epoch known as the Ice Ages, and the most recent epoch, called the Holocene. The Ice Ages, or global intervals of glacial stages, were separated by intervals of much warmer (interglacial) phases (table i.1). The Pleistocene began approximately 2.6 million years ago and was followed by the Holocene. According to earlier literature, the Holocene is said to have begun 10,000 years ago, but the interval is now considered to be about 11,500 years old. Many geologists regard the Holocene as simply a continuation of the Pleistocene, though it can rightly be called the era of modern man. The Florida Keys islands on which we walk and live were formed during the later part of the Pleistocene about 125,000 years ago, when sea level was higher than at present. The mantra of the geologist is, "The present is a key to the past." This book demonstrates how and why this mantra is so true and so important.

Social History of the Keys

The Florida Keys are unique, having once been home to several Native American tribes, among them one called the Tequesta. When the Spanish conquistadors discovered the Keys during the sixteenth century, they conquered the Tequesta who had existed there for the preceding 2,000 years. Many were taken to Cuba for conversion to Christianity and where most died. The Tequesta people are no more, but their shell mounds and pottery shards can still be found throughout the Keys and south Florida. Co-occurrence of the mounds and artifacts with intact shells of the gastropod *Cittarium pica* provided important clues to the type of Tequesta lifestyle.[3]

Spain ceded Florida to Britain in 1763, repossessed Florida in 1784, and again ceded Florida in 1821, this time to the United States. During the American Revolution and the war of 1812 with Britain, many European Loyalists fled to Canada and the Bahamas, where life on craggy limestone islands still under British rule was less than ideal. Some, mostly shipwrights, later migrated to the Keys and Key West, which the Spaniards had named Cayo Huecos[4] (Island of Bones). These early English settlers, known as Conchs (pronounced konks), became "wreckers,"[5] salvaging goods, people, and ships grounded on coral reefs.[6] Those who moved to the island were known as "Freshwater Conchs." Folks born there were "Saltwater Conchs." The Keys and especially Key West share a unique, fascinating, and sometimes bizarre social history ranging from rum and drug smuggling to human trafficking.[7] The arrival at Key West of the Flagler Railroad in 1912[8] and the U.S. Navy during WWII added more character to this most unusual island. To this day, Key West and the Keys remain a magnet for unique individuals, including such people as treasure hunters, smugglers, and retired scientists.

Science Comes to the Keys

Alfred Goldsboro Mayer, who held a degree in engineering, decided to study zoology at Harvard University early in the 1900s. While he was there, Alexander Agassiz, director of the Harvard Museum of Comparative Zoology, invited him to coauthor a book on medusae, the umbrella-shaped cnidarians most commonly represented by jellyfish. In 1904, the Carnegie Institution approved Mayer's proposal to establish a laboratory on Loggerhead Key at Dry Tortugas (fig. i.2) some 70 miles (113 kilometers) west of Key West. Mayer succeeded admirably, attracting noted scientists to pursue important marine research and conduct studies of their own design. The Carnegie Laboratory opened for business on this remote island in 1905. Although Mayer, who had changed the spelling of his name to Mayor, died on Loggerhead Key in 1922, scientists continued to conduct research there until 1939. The studies completed on corals by people such as Alexander Agassiz, T. Wayland Vaughan, John W. Wells, and others are known the world over. Most marine science disciplines practiced today were instituted at the Tortugas Laboratory, and the world's first underwater color photograph was taken there in 1926. In all, 146 researchers worked at the laboratory between 1905 and 1939. Subsequent hurricanes have destroyed the buildings, and only remnants of cement sea tanks remain, along with a memorial monument to Mayor placed there in 1923 (figs. i.3A-B, i.4). Mayor's artist wife designed the

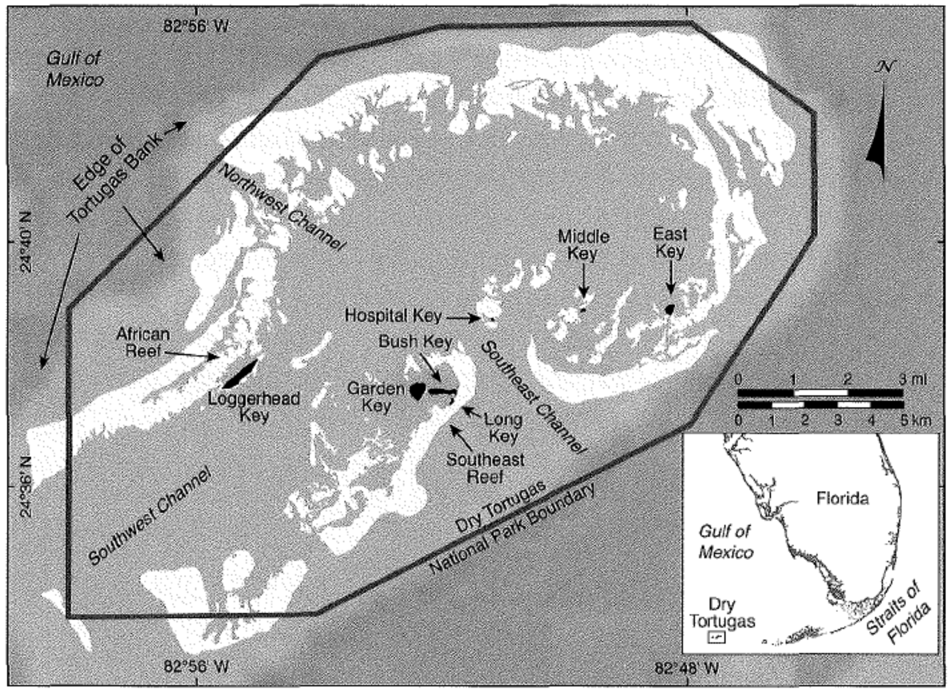


Figure i.2. Index map displays major geomorphologies of the Tortugas Bank. Inset shows location of the Dry Tortugas at the westernmost end of the Florida reef tract. Labeled sites are referred to in text, notes, or figure captions.

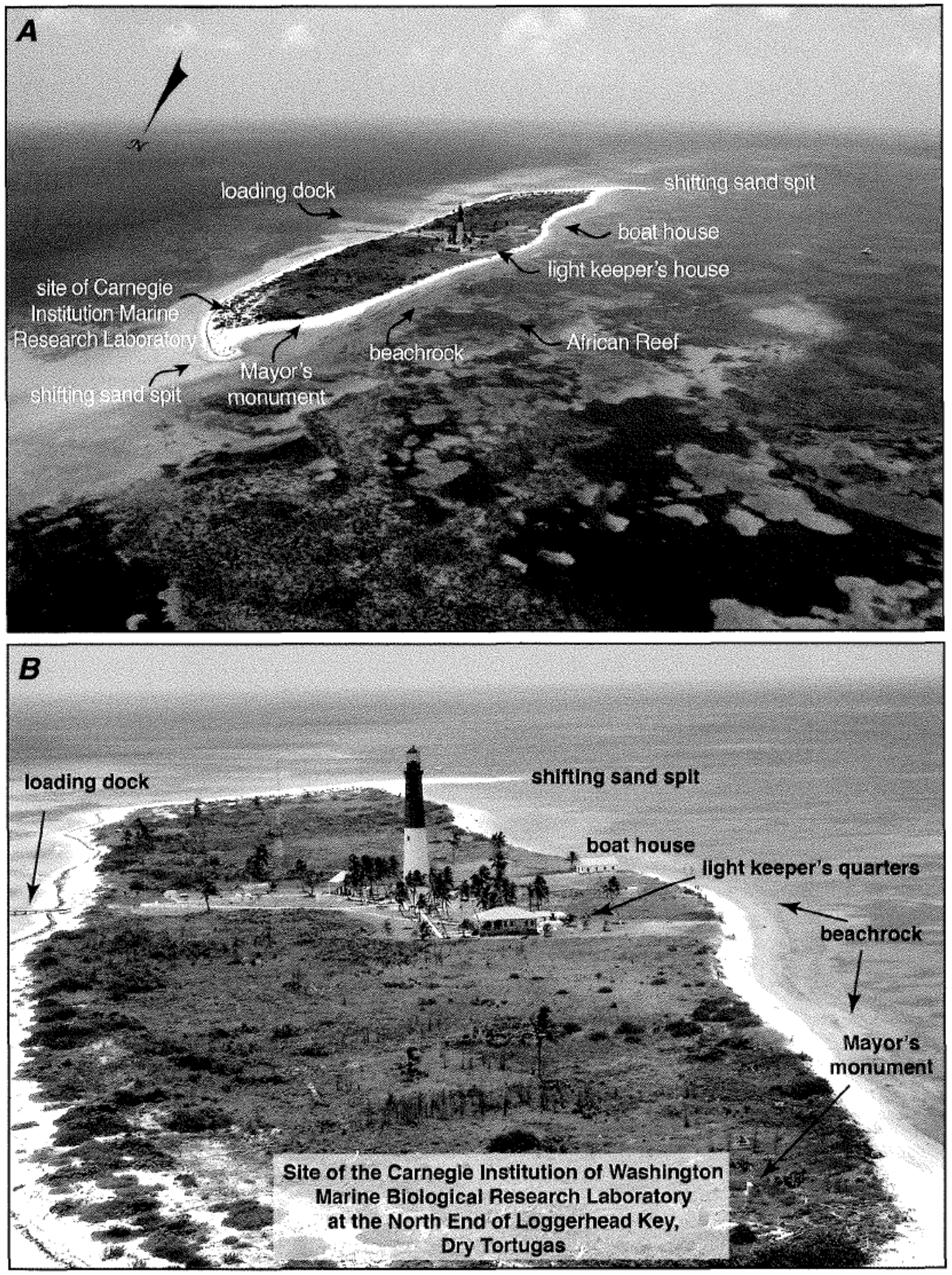


Figure i.3. *A*, Oblique aerial view (2004) looking southeast shows Loggerhead Key and the site of African Reef. *B*, Closer oblique view (2004) of Loggerhead Key looking south shows submerged beachrock on west side of island.

Figure i.4. Alfred Goldsboro Mayor's monument as it stood near the laboratory ruins in 2004.

Placed here in 1923, a year after his death on the beach near the laboratory, Mayor's monument reads:

Alfred Goldsboro Mayor who studied the biology of many seas and here founded a laboratory for research for the Carnegie Institution directing it for XVIII years with conspicuous success brilliant versatile courageous utterly forgetful of self he was the beloved leader of all those who worked with him and who erect this to his memory

BORN MDCCCLXVIII • DIED MCMXXII

monument, yet she never visited the island. The lighthouse visible in the figures was built in 1858 and at this writing is still operational. Most major lighthouses[9] have been extinguished and replaced by tall, unmanned towers.

Although Darwin in 1842 was arguably the first to study coral reefs in general, it was Alexander Agassiz who conducted studies of the Keys reefs prior to establishment of the Carnegie Laboratory. Because of the toll on ships that wrecked on

the reefs, he studied coral reefs at the request of the Light House Service. One of his conclusions was that the reefs were too extensive to be removed! So he recommended construction of steel lighthouses to warn ships of danger. Coral reef science was thus born out of economic concerns to avoid wrecked ships. Although modern technology has reduced the number of shipwrecks, economics still play a role in reef research. Today coral reefs are magnets for tourist and sports-diver dollars.

Economics would drive reef science anew in the 1940s and 1950s, leading to an invasion of geologists and biologists in great numbers. Petroleum geologists stimulated research on coral reefs beginning in the 1950s. It was widely believed that knowing and understanding how modern reefs were initiated and were able to sustain growth would help predict the locations of ancient deeply buried hydrocarbon-bearing reefs. This notion followed the ingrained theory that the present is a key to the past.

Changing Demographics

With the beginning of World War II and an enlarging naval facility, a 12-inch-diameter (1 foot, or 30 centimeters) iron water pipe was constructed alongside Highway US 1 to import freshwater to Key West. The water came from shallow wells in the Biscayne Aquifer south of Homestead (fig. i.1). Before pipeline construction, the city and the rest of the Keys depended on rainwater stored in cisterns. In Key West, shallow wells produced barely drinkable brackish water suitable mostly for washing clothes. The freshwater floating on denser saline water throughout the Keys is thin and variable, depending on rainfall. Climate in the Keys had changed. Before the 1900s, solar salt was commercially produced in salt ponds on the south side of Key West, but wetter weather around the turn of the century prevented continuation of salt production.

WWII, the Navy, and Freshwater

With the coming of freshwater and the navy, including a Naval Air Station, Key West began to prosper like never before; however, communities along the way also tapped the water supply, so that at times only a trickle reached post-WWII Key West. Lack of water severely checked further tourism and population growth. One was lucky to have enough for a shower in the few Keys motels that survived the 1950s and 1960s. Lack of water and presence of only one gasoline filling station between Homestead and Key West, in Marathon (fig. i.1), slowed the flow of tourists. These deterrents vanished in the 1970s with installation of a 36-inch-diameter (1 meter) water pipe. Modern wider bridges that one travels today also aided development. With the arrival of abundant water, motels and housing projects flourished. Duck Key, the town of Key Colony, and other developments, constructed mainly from lime mud and sand dredged from Florida Bay, had their beginnings in the 1950s.

Yet another important factor aided building in the Keys—aerial mosquito spraying! Old DC-3 aircraft zoomed at treetop level, spraying pesticides mixed with diesel oil. Clouds of mosquitoes had always been a deterrent to tourism and population growth. Only the hardy well-tanned Conchs could survive the swarms. It was often said their darkened skin was like leather. Pale-skinned Yankees were fresh meat to the stinging hordes. Mosquitoes, lack of water, and the threat of hurricanes had successfully kept the human population in check, but by the late 1970s, everything changed yet again. The 1970s were the principal drug-smuggling years. Many struggling fishermen would soon be piloting "go-fast" speedboats and driving expensive Mercedes-Benz sedans. As a side effect of their newfound wealth, fishermen began decimating the lobster population as they purchased thousands of additional lobster traps. The traps made them look legitimate. Lobster boats and go-fasts were vital for offloading square groupers (local jargon for bales of marijuana) from mother ships offshore. Jimmy Buffett's songs *A Pirate Turns Forty* and *Margaritaville* popularized this period.

Invasion

In 1980, a human invasion floated in from the south—the Mariel Boatlift. Cuba's economy had dipped, and tobacco crops had succumbed to disease. The United States was falsely accused of practicing bioterrorism on the crops. The result? In April of that year, Cuban President Fidel Castro allowed citizens to emigrate from Cuba at the port of Mariel. He also opened his prisons and mental institutions. Thousands left by the boatloads, and Key West bore the brunt of what became known as the Marielito invasion. The exodus lasted for six months. Demographics of the Keys and south Florida were changed forever.

Oil: In the Keys?

Few Keys residents, especially Freshwater Conchs, know that the Keys were once a focal point for oil exploration. The climax of exploration came in 1943 when Humble Oil Company (now ExxonMobil Corp.) struck oil at 11,500 feet (3,505 meters) near the Everglades town of Sunniland, a small agricultural village near the west coast of Florida (fig. i.5). The oil reservoir is in a Cretaceous (table i.2) reeflike formation that was quickly named the Sunniland Zone. World War II was on, and the country needed all the oil it could find. That black-gold discovery on the edge of the Everglades east of Naples set off frantic searches throughout south Florida and the Keys. Sinclair Oil Company was drilling near Homestead in what is now Cheeca Hammock in Everglades National Park (figs. i.5, i.6). Next was a series of test wells near the intersection of Card Sound Road and the old highway on North Key Largo. Coastal Caribbean Oils & Minerals, Ltd., a Bermuda-based company founded in 1953 by William F. Buckley Sr., had acquired most of the oil rights in Florida waters. Being a small company, they subleased to major companies such as Gulf Oil.

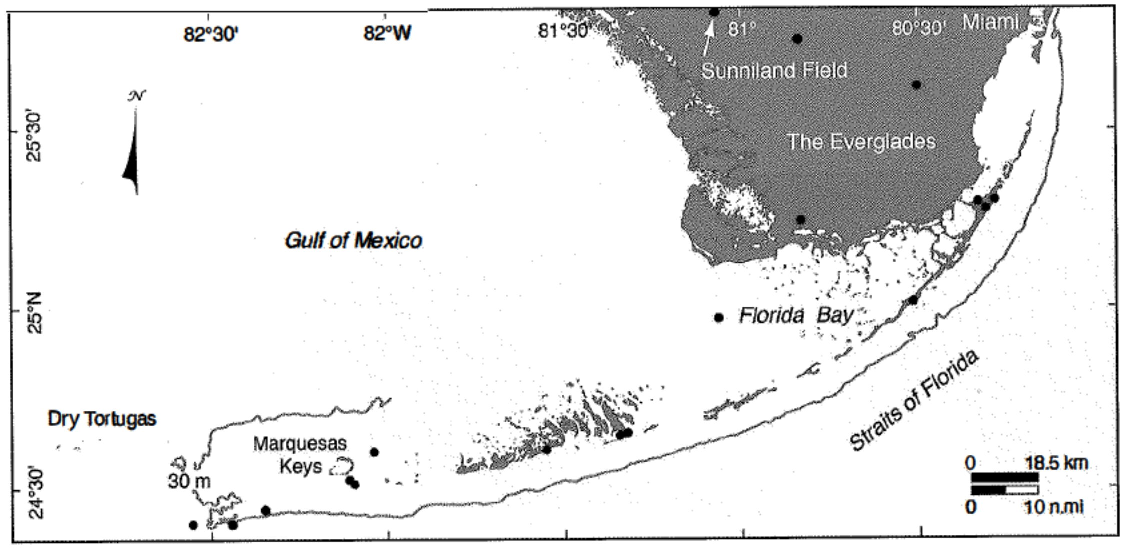


Figure i.5. Index map shows locations of 18 exploratory oil wells (red dots) drilled in south Florida and the Florida Keys between the early 1940s and 1962. Oil was discovered at Sunniland Field in 1943. The Sunniland well is still producing.

By the 1950s and war's end, test wells were drilled on a few Keys followed by a 15,000-foot (4,572-meter) well near Coupon Bight in the Newfound Harbor Keys near Big Pine Key (fig. i.1). Next came a test well about a mile west of Sandy Key in Florida Bay, followed by two test wells drilled in 1959 near the Marquesas Keys 20 miles (32 kilometers) west of Key West. The last test was drilled on the reef tract southwest of the Marquesas Keys in 1960 while Hurricane Donna was ravaging the middle and upper Keys. Two more test wells had been drilled along the outer-shelf reef tract farther west. Oil shows were found in all Sunniland Zone tests, but the amount found was insufficient to justify production at the then-prevailing price—around $5.00 a barrel!

Table i.2. Nomenclature and ages for select intervals of geologic time from the present back to 416 Ma

	Age (Ma)		Age (Ma)		Age (Ma)
Cenozoic Period	65.5–today	**Mesozoic*** Period	251.0–65.5	Paleozoic Period	542–251
Quaternary	2.6–0.01	**Cretaceous**	145.5–65.5	**Permian**	299–251
Holocene	0.01–today	Jurassic	201.6–145.5	Carboniferous	359–299
Pleistocene	2.6–0.01	Triassic	251.0–201.6	Pennsylvanian Epoch	318–299
Tertiary	65.5–2.6			Mississippian Epoch	359–318
Neogene	23.0–2.6			Devonian	416–359
Paleogene*	65.5–23.0				
Eocene Epoch*	55.8–33.9				

Note: * Other names for other periods of geologic time exist between the noncontiguous periods or epochs given. The intervals in bold are mentioned in the text, captions, or notes. Data taken from 2009 Geologic Time Scale.

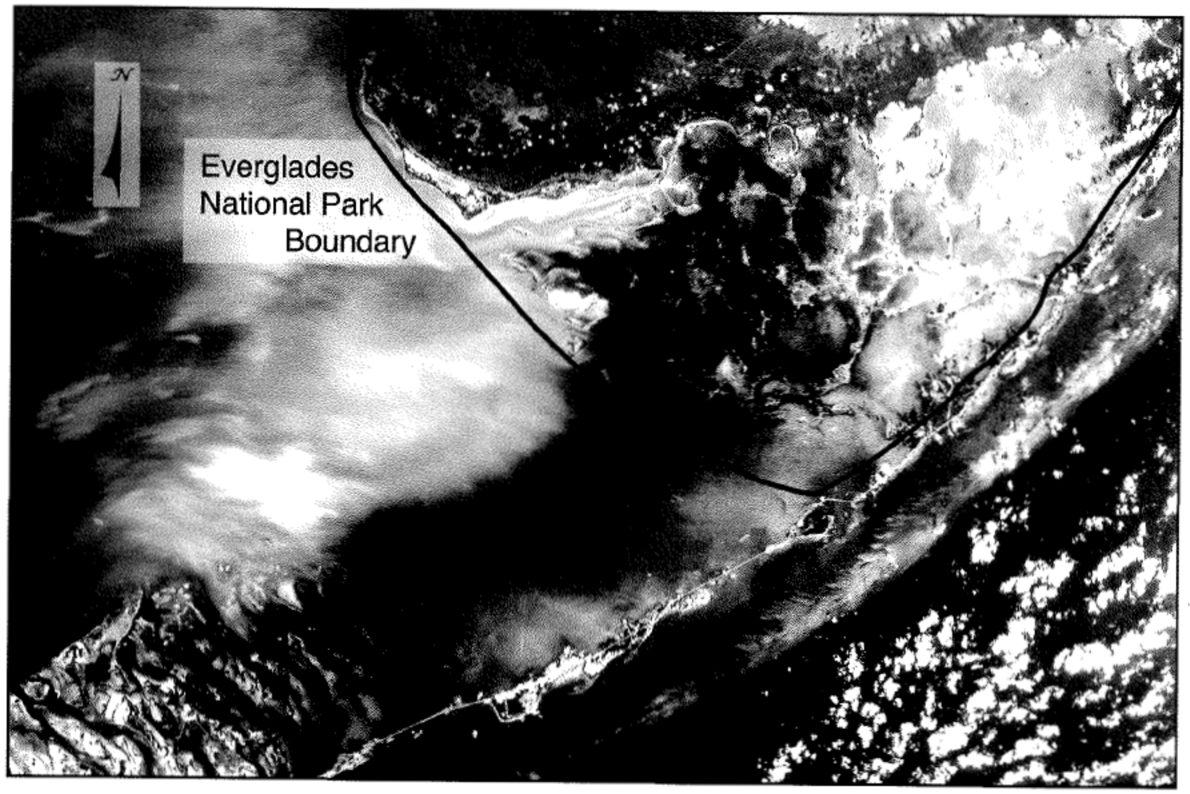


Figure i.6. Enhanced Thematic Mapper Plus image, acquired in May 2000 from the Landsat-7 satellite, shows the four geographic components of the south Florida ecosystem: the Everglades (south part), Florida Bay, the Florida Keys, and the reef tract. Note where approximate southern boundary of Everglades National Park falls. Endangered mangroves fringe virtually every visible shoreline. The upper and middle Keys are an emergent 125,000-year-old coral reef. The lower Keys are emergent fossil-ooid tidal bars of the same age. Seaward of the Keys lie habitats of the inner shelf, Hawk Channel, Holocene sands and reefs on the shallow outer shelf, and 100-foot-tall (30-meter-high) 80,000-year-old fossil reefs on an upper-slope terrace seaward of the shelf edge. The Gulf of Mexico is at left, Straits of Florida under clouds at right. Dense growth of species of the seagrass genus *Syringodium* causes the dark wide band in center.

With establishment of the Florida Keys National Marine Sanctuary and a moratorium on offshore drilling, oil exploration came to a sudden stop. The sanctuary bill was signed on November 16, 1990.

Tourism and Scuba

With completion of the new highway bridges, widened roads, freshwater, and mosquito control, a long-cherished dream for the Florida Keys took root. Tourists came in droves, and with the popularity of a self-contained underwater breathing apparatus (scuba), promoted by Captain Jacques-Yves Cousteau and his television shows, divers

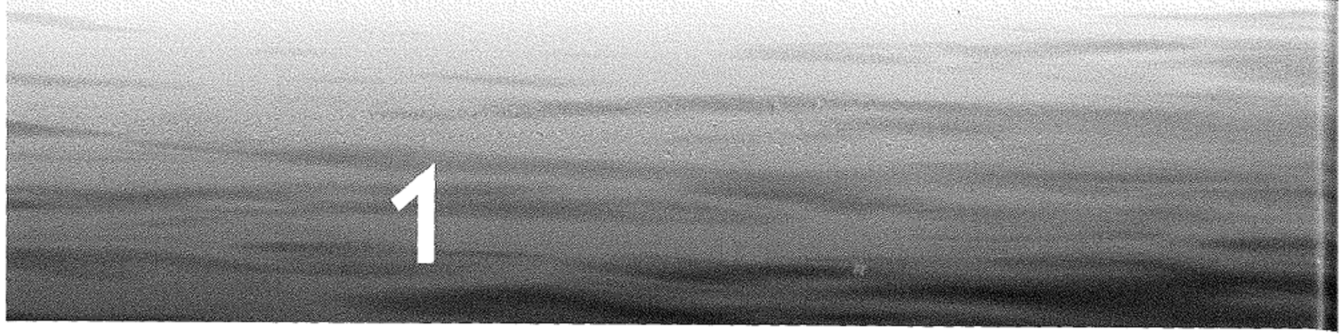
arrived and dive shops and charter boats blossomed. In the early 1970s, the first fast-food restaurants took hold, as did liquor stores, adult bookstores, bars, and gee gaw and wooden-toy shops. In the 1950s, other than Overseas Liquors in Marathon, no liquor sources existed between Homestead and Key West. Key West, of course, had always had rum smuggled in from Cuba and elsewhere, as was popularized in Ernest Hemingway's book, *To Have and Have Not*.

The Keys would never be the same. Coral reefs were being loved to death by hordes of snorkelers, scuba divers, and fishermen. Onshore development brought septic tanks, cesspools, and shallow-disposal wells. Contents all went into the porous limestone beneath the Keys.

Everglades National Park was created in 1947 (fig. i.6) at a time before rising concern over coral health. In the 1970s, John Pennekamp Coral Reef State Park was created to protect fish and stop spearfishing off Key Largo. Coral health did not become a serious issue until the late 1970s and early 1980s, when it became clear to scientists that corals were dying. Documented coral death signaled the beginning of efforts to protect the environment from the onslaught of people—and still they came. Plans to control population growth came and went.

The foregoing thumbnail history is intended to prepare visiting scientists and laypeople for a visit to the Keys; however, the real purpose of this book, as stated in the beginning, is to demonstrate the value of the Keys and immediate surroundings as an environmental scientific laboratory for naturalists, geologists, biologists, students, and sedimentologists and to stimulate ideas for further research.

What made the Florida Keys and how did they form? For that information, we go way back before the last Ice Age. It all began many millions of years earlier when the Caribbean was part of a megacontinent called Pangaea, which broke apart to form the Atlantic Ocean. But all that is well beyond the scope and purpose of this book. For that story, we recommend *Geologic History of Florida* by Hine (2013).



About the Keys

Processes I

The interaction of numerous and diverse geologic processes over time has sculpted the asymmetric geomorphologies, limestones, and sedimentary environments of the modern Florida Keys. The primary controls on reef distribution and all developmental phases and features of those depositional carbonates were antecedent topography and a fluctuating sea level. Though our focus is on the relatively thin topmost strata (layers) and the most recent part of geologic history—the last 125,000 years, which include the later part of the Pleistocene and the Holocene epochs (table i.2)—deposition in much earlier geologic times resulted in thicker underpinnings. The entire Pleistocene limestone buildup over a 2.6-million-year period is little more than 200 feet (61 meters) thick; the buildup is thickest under the lower Keys and about half as thick under the upper Keys. Below Pleistocene accumulations lies a much thicker Tertiary sequence (table i.2), which in turn rests on thick Cretaceous limestone, deposited during the time of the dinosaurs and accretion of the organic materials that produced the oil-bearing formation at Sunniland. These older rock units deep below Florida and the Keys are also beyond the scope of this book. Again see Hine (2013) for details about these rocks. The younger Pleistocene and Holocene coral reefs, lime sands, and smelly muds of the Florida Keys serve as a natural environmental (biological and geological) laboratory and attract the attention of biologists, geologists, and their students from around the world.

Following discussions of the various Holocene sedimentary processes, spiced with anecdotal stories, facts, and references to previous research, we provide comprehensive maps of the area. The maps are the fruits of extensive research conducted by early workers and most recently by the U.S. Geological Survey (USGS) and others. Over the years, starting in the 1950s, geologists began their pilgrimages to the Keys, often as part of organized water-based field trips. Those classic field trips involved slithering and slogging through smelly mud, slapping mosquitoes, and finally swimming and snorkeling over incredibly beautiful coral reefs. Because of our long history as

trip leaders, we provide details and tips on where to go and what to see, in essence a "virtual field trip." We concentrate mainly on "processes" to help put the resultant geology in better context. This virtual trip, based on many years of such field excursions, incorporates contrasting sedimentary processes and environments over a typical 3- to 5-day period. Our virtual trip is suitable for students and professionals, as well as for interested laypeople and naturalists. The reader may then decide to take an actual field trip based on what is presented here. Toward the end of the book, we outline a typical 3-day field trip for those who want the hands-on experience. Be advised, however, that this field of scientific knowledge is itself an ongoing evolving process. Many interpretations of sedimentary processes presented here may be revised by the results of future research. Before we begin, let's start with some basic information about the limestone that forms the Florida Keys and underlies the offshore sediments and reefs.

Corals, Sand Bars, Limestone, and an Impatient Sea

The middle and upper Keys as viewed on maps, satellite images, or from an automobile negotiating traffic on Highway US 1 have a distinctive slightly arcuate northeast-to-southwest profile. These Keys were a living and growing coral reef eventually entombed in reef sand when sea level was 20+ feet (6+ meters) above present (fig. 1.1). Orientation of the lower Keys, however, is clearly different (see figs. i.1, i.6). Beginning at Big Pine Key and extending on to Key West, the highway curves ever more westward, terminating in Key West. Unlike the more linear Keys to the north, the lower Keys were not coral reefs. They were sandbars sculpted by north-south–trending currents and composed of spherical sand grains called ooids.

Ooids and Oolite

Like small pearls, ooids are pinhead-size concretions of precipitated aragonite, the mineral form of calcium carbonate (generally called limestone) that forms mainly in seawater. The majority of limestone on Earth, however, is composed of calcite. Given geologic time, aragonite converts to calcite, especially when exposed to freshwater. Ooids (fig. 1.2) form around a nucleus grain rolling and tumbling in clear current-swept waters supersaturated with calcium ions (Ca^{+2}) and carbonate ions (Co_3^{-2}). When combined, these ions form calcium carbonate ($CaCO_3$). The currents that shaped these sandbars were also responsible for creation of the ooids of which the bars are composed. As with most warm tropical seas, supersaturation and agitation induce calcium carbonate to precipitate. Rolling while precipitating on a nucleus accounts for the spherical egg-shape form—hence the name "ooid." Ooids were once thought to be fossilized fish eggs, which they closely resemble. We are in fact dealing