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Controls on Late Quaternary Coral Reefs of the Florida Keys

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2.1 Regional Setting and Early Cultural History

The Florida Keys is an arcuate, densely populated, westward-trending island chain at the south end of a karstic peninsular Florida Platform (Enos and Perkins 1977; Shinn et al. 1996; Kindinger et al. 1999, 2000). The “keys” mark the southernmost segment of the Atlantic continental margin of the United States. The islands are bordered by Florida Bay to the north and west, the Atlantic Ocean to the east and southeast, Gulf of Mexico to the west, and Straits of Florida to the south. Prevailing southeasterly trade winds impinge on the keys, creating a windward margin. The largest coral reef ecosystem in the continental United States rims this margin at a distance of ~5–7 km seaward of the keys and occupies a shallow (generally <12 m), uneven, westward-sloping shelf (Parker and Cooke 1944; Parker et al. 1955; Enos and Perkins 1977). The platform is tectonically stable at present (Davis et al. 1992; Ludwig et al. 1996; Toscano and Lundberg 1999). The reefs and 240-km-long island chain parallel the submerged shelf margin, corresponding roughly to the 30-m depth contour that marks the base of a fossil shelf-edge reef (studies cited use the same criterion). The modern reef tract extends west-southwest from Soldier Key southeast of Miami (25°60′ N, 80°20′ W) to the Dry Tortugas in the Gulf of Mexico (24°40′ N, 83°10′ W). Reef-tract habitats lie within the protective domain of the Florida Keys National Marine Sanctuary (Fig. 2.1a–c; Multer 1996).

Prehistoric Paleoindians inhabited the Floridan Peninsula around 12 ka (Zeiller 2005). The Archaic Period of human progress followed (from ~7 to 2 ka) as aboriginal tool making became more sophisticated. The Formative or Ceramic Period (from ~2 ka to AD 1513) was next as the creation of pottery for transportation and storage of food and water became important. The Historic Period began in 1513. By the mid-1500s, Florida had become part of a Spanish monopoly in the Americas. Conquistadors first settled in La Florida in St. Augustine on the East Coast in 1567. In 1763, England took Canada from France, and Spain ceded all of La Florida to England. Spain again took possession of La Florida in the 1783 Treaty of Paris (Zeiller 2005).

The United States acquired Florida from Spain by treaty in 1821 largely for the potential military advantage that the Florida Keys offered (see articles in Gallagher et al. 1997, and selected human-interest notes in Appendix 2.A). The government recognized a need to protect shipping between the Atlantic and Gulf Coasts, and the keys were natural sites for military bases for this purpose. The US Army and US Navy established bases on several islands, and upon admission to the Union as the 27th State in 1845, forts were built at Key West (Fort Zachary Taylor) and the Dry Tortugas (Fort Jefferson). The Florida Keys played major roles in the Second Seminole War (1835–1842), the Spanish-American War (April–August 1898), World War I (1916–1918, when Key West first became a major naval training base), World War II (1941–1945), the Cuban Missile Crisis (1962), the war on drugs

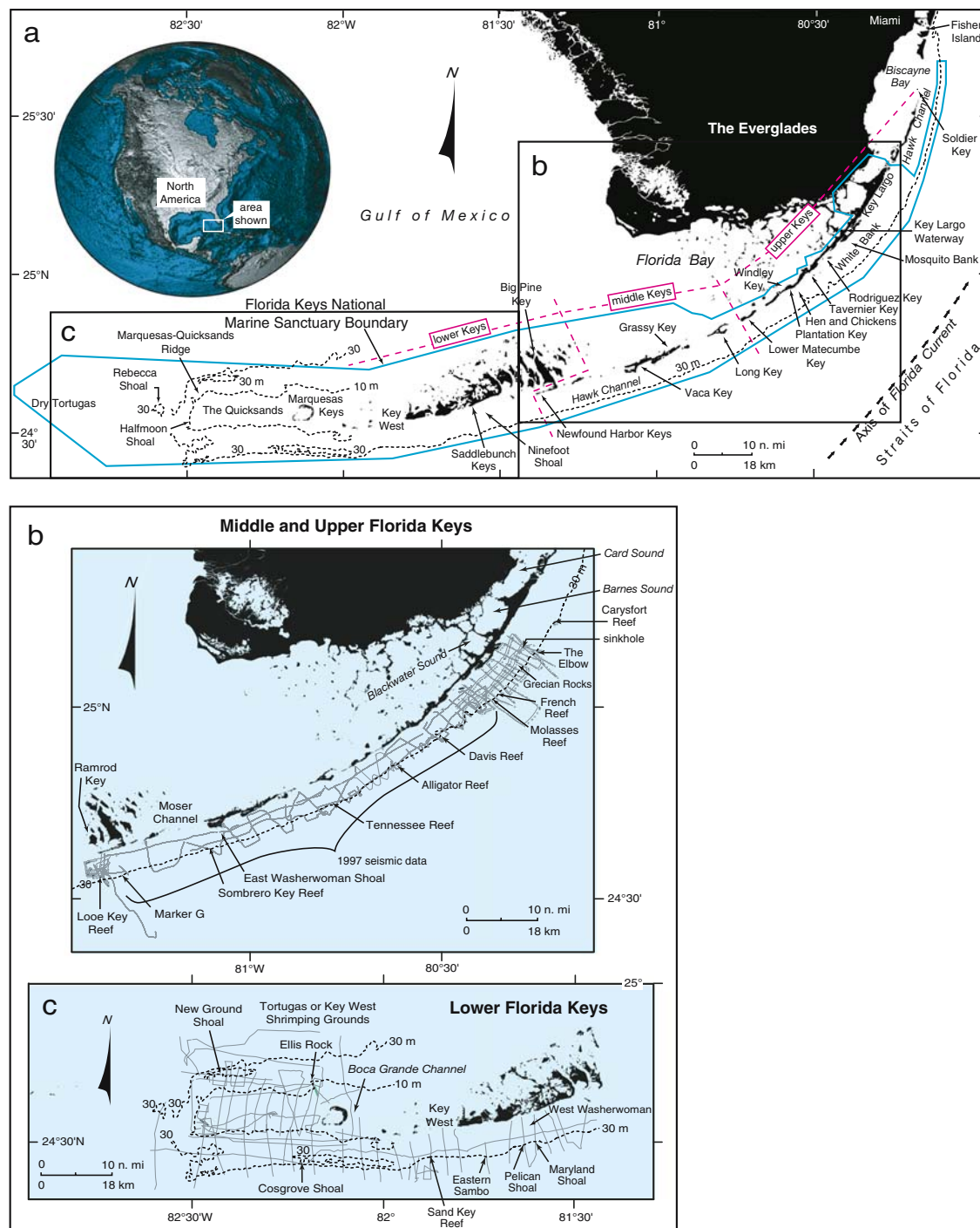


FIG. 2.1. **a** Index map of South Florida and the Florida Keys. Dashed red dogleg line separates areas of Pleistocene ooid bank (Miami Limestone) of the lower Keys and coral reef (Key Largo Limestone) of the westernmost middle Keys. An ooid bank also formed at the east end of the reef and today underlies the city of Miami (Halley and Evans 1983). Note major tidal passes in middle Keys. Dotted line (30-m-depth contour) marks the shelf margin, which lies within the Florida Keys National Marine Sanctuary boundary (blue line). **b** Index map shows locations of major Holocene coral reefs and USGS geophysical surveys (gray lines) for a portion of the upper and all of the middle Keys. Sinkhole at the northeast end is discussed in Shinn et al. (1996). **c** Index map shows survey lines for the lower Keys, Marquesas Keys, and The Quicksands areas. Contours are in meters

(1970s), and the Mariel Boatlift (1980). Financier Henry Flagler's Overseas Railroad transported tourists south to Key West and agricultural produce north from Cuba to Miami for 23 years before the Labor Day hurricane of 1935 destroyed both train and railway tracks (Parks 1968). The keys and other areas of South Florida today remain favored destinations for Caribbean immigrants seeking asylum in the US. But for the past three decades, the coral reefs have fueled the economy of the keys, providing lucrative commercial fisheries and colorful easily reachable habitats that draw tourists from around the world.

Accessibility of the shallow and emergent late Quaternary sequences to scientists makes the Florida windward margin one of the best-studied modern carbonate platforms. In the early years, Florida reefs intrigued researchers interested in the tropical marine-carbonate environments. Shinn and Jaap (2005) recount some of the classic carbonate studies that were carried out in the Dry Tortugas. Louis Agassiz mapped benthic communities in the Tortugas (Agassiz 1880). His son Alexander published the map (Agassiz 1883). In an effort to protect shipping, Louis also examined reefs for the Lighthouse Service (the US Coast Survey, predecessor of the US Coast Guard) with the intent of determining how to prevent the reefs from growing. Reefs took a heavy toll on shipping and in those days were considered a costly nuisance. Failing to discover how to halt reef growth, Louis decided the logical solution was installation of lighthouses. A 46-m-high structure was completed on Loggerhead Key in the Tortugas in 1858 and still functions today, though with updated illumination. In 1905, Alfred Goldsborough Mayer, a student of Alexander Agassiz, built and directed the Carnegie Institution's Dry Tortugas Laboratory on Loggerhead Key. To help justify the laboratory, he documented the so-called black-water event (a red tide) of 1879 that killed fish and essentially all acroporids at the Tortugas (Mayer 1903). He published his landmark treatise on medusae (Mayer 1910) and contributed to research on temperature tolerance of corals and other marine organisms (Mayer 1914, 1918). Without the aid of drilling, T. Wayland Vaughan, a close friend of Mayer, correctly deduced that the Tortugas was an elliptical atoll-like structure built primarily of Pleistocene coral, which spurred his interest in reef geology, ecology, and coral growth

rates (Vaughan 1914a, b, 1915a, b, 1916). After Mayor's death in 1922 (Mayer changed the spelling of his name to Mayor in 1918), William H. Longley (who with Hildebrand 1941, pioneered the first underwater color photography of tropical Atlantic fishes), then David Tennent (sea-urchin embryology) directed the Carnegie Laboratory until its closure in 1939 for economic reasons. Today, little is left of the facility. A memorial plaque designed by Mayor's artist wife was erected near the site a year after Mayor died. The monument stands in lone testimony to the benchmark tropical marine-biology research that Mayor had envisioned and that he and his colleagues had achieved (Stephens and Calder 2006).

Prior to being designated a National Marine Sanctuary in 1990, reefs in the vicinity of the Florida Keys were drilled in the search for oil. Hydrocarbons are being produced from Lower Cretaceous limestone, anhydrite, and dolomite that compose the Sunniland Formation of Florida (Winston 1969, 1972). Seventeen exploratory wells were drilled in south and central Florida and in the keys beginning at about the time oil was discovered at the Sunniland Field in 1943 (Fig. 2.2; Dustan et al. 1991). All wells had oil shows, but no show was economically viable. All wells left magnetic signatures due to borehole casing. Most offshore well sites evolved into 'artificial reefs' as sessile organisms colonized discarded wires and casings, and great numbers of fish congregated in borehole cavities that formed havens in otherwise featureless seafloor sites (Shinn et al. 1989a, 1993). Conclusions drawn from the well-site studies were that none of the environments sustained permanent biological damage during the one-time perturbations of drilling, even to depths of several thousand meters, and that the biological impact was negligible. Conclusions could not be drawn from those studies for wells that would become producing wells with longer-term on-site perturbations.

2.2 Overview of Large-scale Geologic Parameters

South Florida is built of thousands of meters of Cenozoic limestone deposited on top of an igneous Mesozoic basement (e.g., Applin and Applin 1965;

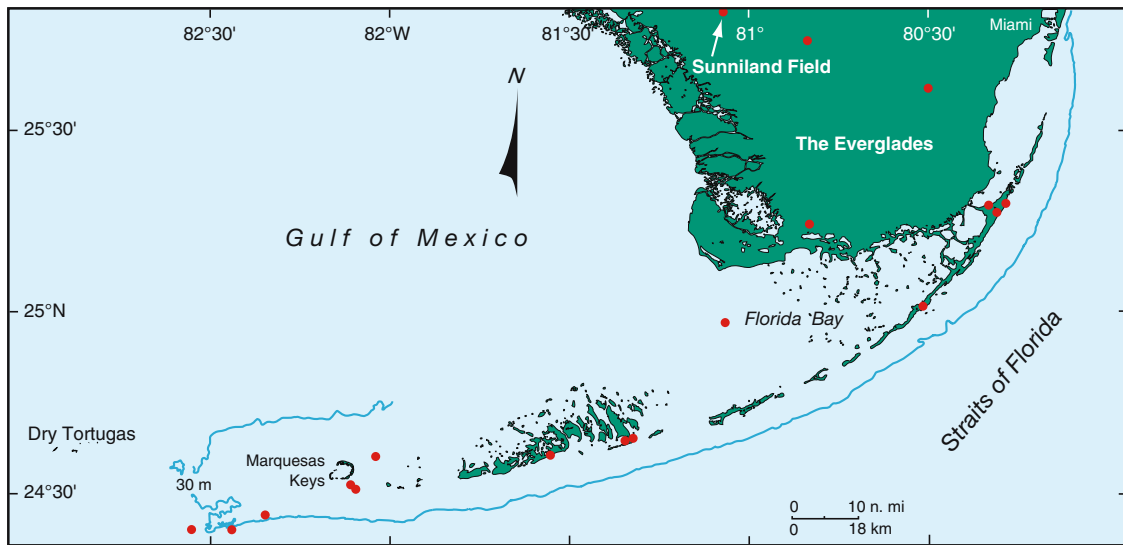


FIG. 2.2. Index map shows location of exploratory oil wells (red dots) drilled in South Florida between 1943 and 1962. The well at Sunniland Field is an oil producer

Milton and Grasty 1969; Winston 1969). The uppermost sections are stratigraphically successive late Pleistocene non-coralline marine sequences, later Pleistocene coral reefs and cemented-oid tidal bars, and Holocene corals. The exposed Florida Keys consist of an emergent coral reef (Key Largo Limestone; Multer et al. 2002) and tidal-bar oolite (Miami Limestone; Halley and Evans 1983) that accumulated during the eustatic highstand of ~125 ka. The climate today is subtropical, and the reef tract is regarded as being marginal for coral growth (Jaap 1984; Shinn 1988; Shinn et al. 1989b). Marginality is due in part to a high-latitude flooded shelf that allows tidally induced coastal, bay, and gulf waters to flow over many of the reefs. Variable salinity, nutrient content, temperature extremes, and turbidity unfavorable for coral growth characterize these waters.

The reef-rimmed Florida margin differs in morphology and depositional processes from the classic windward carbonate-margin model (James and Ginsburg 1979). The shelf is shallow, topographically asymmetrical at the shelf edge (reefs and reentrants), several meters deeper to the southwest than northeast, and has an average present gradient of ~0.8 m/km from the keys to the break in slope. Pleistocene gradients were generally less pronounced (Perkins 1977; Multer et al. 2002). Other typical

windward margins are steeply inclined (James and Ginsburg 1979; Hine et al. 1981; Hine and Mullins 1983). Though the modern shallow setting is marginal for coral growth, Pleistocene corals produced imposing structures in paleoenvironments that were optimal for cumulative coral accretion (Lidz et al. 1991; Multer et al. 2002; Lidz 2004). Processes associated with the present shelf involve complex, multidimensional, tidally induced exchanges of inimical inshore waters with the reefs. In comparison, processes associated with the late Pleistocene shelf were simple and were topographically controlled. The result was vigorous coral growth at the edge of an extensive, broad, protective landmass (Lidz 2006) vs. diminished vigor of later Holocene reef growth along a shallow, coastal, shelf.

The primary controls on late Quaternary shelf and reef-framework buildup were position of sea-level maxima relative to topographic elevation and effects of those maxima and antecedent topography on coral growth and reef location (Lidz 2006; Lidz et al. 2006). Secondary were surf-zone duration, oceanographic influences, and karstification during periods of subaerial exposure. The geologic record shows that reef growth varied locally through time – in location, dimension, structure, geometry, depth, age distribution, and accretionary direction. Yet the recurring regional theme is the replication

of antecedent facies and geomorphic landforms, and thus repetition of stratigraphic shelf-edge asymmetry.

2.2.1 The Pleistocene Key Largo Limestone Coral Reef

All of South Florida during the Pleistocene was submerged many times as a wide, shallow platform whose curving southernmost edge lay isolated, often 160 km from any mainland to the north. Sea level fluctuated periodically (Fig. 2.3a, b), and discontinuous arcuate chains of bank-barrier and patch reefs evolved, flourished, and died. These coral reefs often provided protection for the production of carbonate sediments that became widespread leeward mudstones, packstones, grainstones (Appendix 2.B, Plates 2.1, 2.2), and finally bryozoan- and ooid-rich sediments.

Sanford (1909, p. 214) first applied the name Key Largo Limestone to “the elevated reef that forms the backbone of the main chain of the Florida Keys from Soldier Key to Bahia Honda.” During Key Largo time, repeated fluctuations of sea level allowed karst features to form during periods of subaerial exposure, including precipitation of dark-brown laminated subaerial crusts or calcrete (Fig. 2.4a–e; Multer and Hoffmeister 1968). Positions of these crusts in cores (Appendix 2.B, Plate 2.3) serve as markers, indicating times of land emergence above the sea due to a lowered sea level. Presence of the crusts allowed division of the Pleistocene into distinctive marine sequences, termed the Q1–Q5 Units for Quaternary (Perkins 1977). Multer et al. (2002) compiled a schematic summary overview of the five units in the Key Largo Limestone (Appendix 2.B, Fig. 2.B-1).

Thick siliciclastic carbonates and the presence of topographic highs strongly influenced formation of Q1-Unit sediments at the south end of the platform (Ginsburg et al. 1989; Guertin et al. 1996; Cunningham et al. 1998). Quartz grainstones and mollusc-quartz wackestones characterize Q1 rocks.

Quartz became less common during the succeeding Q2-Unit period with red coralline algae more abundant. Deposition of an initial deep-water arenaceous facies was followed by accumulation of successive skeletal-grain beds, reducing water depths, and increasing water temperature.

Such factors encouraged skeletal-carbonate production by shallow-water organisms and corals (*Montastraea annularis*, *Porites* sp., and *Acropora cervicornis*), especially on the higher submarine topography.

Pleistocene carbonate production at the Florida Platform margins may have begun during the interval between 420 and 360 ka (marine oxygen-isotope Stage 11), which is regarded as the longest and warmest period during the past 500 ka (Droxler and Farrell 2000; Kroon et al. 2000). Maximum coral reef accretion, however, occurred during Q3 time with rigid and fused pillars and thickets forming bank-barrier and patch reefs. Non-rigid and stabilized thickets as well as rubble were also common (Appendix 2.B, Fig. 2.B-2). Perkins (1977) described the Q3 reef framework beneath Big Pine Key as being 29 m thick. Multer et al. (2002) found the same coralline framework in nine successive core holes from Grassy Key to north Key Largo (Fig. 2.1a). Lateral growth of patch reefs may have been responsible for the formation of many intermittent bank-barrier reefs along the shelf edge during Q3 and subsequent times. Coring occasionally revealed successive “vertical mimicking” in Q3–Q5 coral-rich frameworks superimposed on ancient topographic highs under both the emergent Florida Keys and Florida Bay (Multer et al. 2002).

Following Q3 time, prolonged subaerial exposure (Fig. 2.3a) of the Florida shelf produced widespread laminar subaerial crusts (Appendix 2.B, Plates 2.3-1, 2, 3, 7; 2.4-1, 3; 2.5-2). During Q4 time, abundances of coral and coralline algae decreased, and quartz appeared locally as a basal constituent in Q4 limestones (Harrison and Halley 1979; Harrison et al. 1984). Cores (Appendix 2.B, Plate 2.4-3) show wide distribution of quartzose grainstones that occasionally display inclined bedding. Field studies and SEM photomicrographs of the quartz point to possible former regolith and/or beachrock environments (Multer et al. 2002). Molluscan-peloid-bryozoan packstones and grainstones with patch reefs dominate the upper Q4-Unit sections with rapid facies changes and channels to backreef areas.

Rocks assigned to Q5e time (terminology of Multer et al. 2002) are exposed today along the Florida Keys and represent the high stand (~125 ka) of isotope-substage 5e (Fig. 2.3a). In the lower Keys, ooids precipitated from tidal currents passing

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