USGS
science for a changing world

Environmental Quality and Preservation—Bedrock Beneath Reefs: the Importance of Geology in Understanding Biological Decline in a Modern Ecosystem

Introduction

At issue is the health of the entire coral reef ecosystem that lines the outer shelf off the Florida Keys. In recent years, nearly all biological components have declined markedly. In particular, loss of coral species that are the building blocks of a solid reef framework has significant negative implications for economic vitality of the region. What are the reasons for this decline? Is it due to natural change, or are human activities (recreational diving, ship grounding, farmland runoff, nutrient influx, air-borne contaminants, groundwater pollutants) a contributing factor and if so, to what extent? To answer these questions, one must be able to distinguish between natural change and human impact. Logically, then, the place to begin is to establish the geologic framework and evolutionary history of the ecosystem, before the advent of man. By so doing, accurate scientific information becomes available for proper authorities and Marine Sanctuary management to understand natural geologic and biologic change. Thus they are able to assess and lessen potential human impact more effectively.

The Importance of a Healthy Reef Ecosystem

The importance of a healthy reef ecosystem is essential to the quality of human life, whether in Florida or in areas worldwide where other reef systems are also deteriorating. The hard rock of reef framework serves as a protective offshore barrier to catastrophic wave action and storm surges generated by tropical storms and hurricanes. Without this protection, homes, marinas, and infrastructure on the Florida Keys that are designed to capture a lucrative tourism industry and inland agricultural areas of South Florida that feed much of the Nation are more susceptible to destruction by these forces. Moreover, biologic resources of the reefs and shoreline mangroves that include habitats for endangered species, productive marine and wetland nurseries, and economic fisheries are also at risk. The irony is that the very riches of this ecosystem attract the residential, recreational, and commercial activities that may be contributing to its decline.

By examining the geologic record, in this case the record of ancient reef growth, we can understand what controls where and why modern reefs grow. Corals require narrow conditions: relatively shallow depths and stable salinity, clear nutrient-poor water, and warm temperatures. In tropical areas, the primary control of these elements (in other words, reef growth) is sea level, whereas the primary control of reef distribution is bedrock topography, that is, the shape of the rock surface under the modern reefs (Plate 1). In Florida, ancient reefs form much of the bedrock surface. Mapping surface contours of the pre-existing reef rock is the first step toward reconstruction of the geologic history and processes at work. Geophysical data, collected on seismic profiles with high-resolution sound-wave instruments that see through the overlying sediments, provide the bedrock-surface depth (elevation) below sea level.

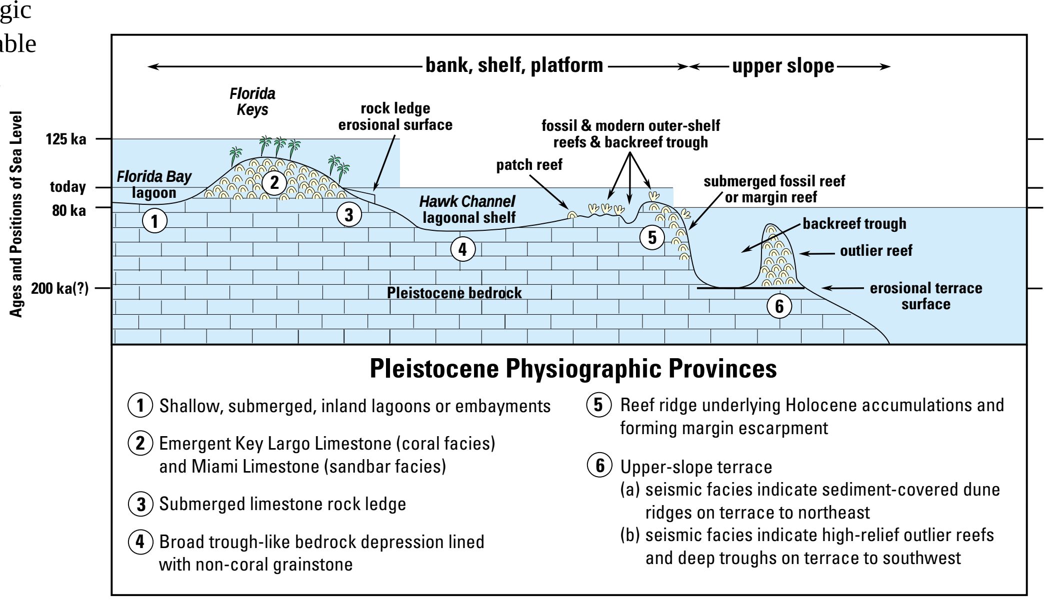


Figure 1. Schematic cross section (not to scale) showing the six general bedrock provinces along the South Florida shelf and terminology used in text. The Pleistocene ranges from ~1.77 Ma to 10 ka. The Holocene ranges from 10 ka to the present. Sea-level positions and timing shown in years before present. If sea level were to rise from its present position by 5 to 7 m, it is very likely that framework-building corals would once again become established on those areas of the Florida Keys that are basically sediment free.

Ma = million years
ka = thousand years
m = meters

Figure 2. Seismic profile showing a "slice" or cross section through geologic features. This cross section displays the shelf margin at left and multiple prominent, parallel outlier reefs off Sand Key Reef, located at the edge of the shelf margin southwest of Key West (Plate 1, insert). The deep 'V'-shaped line called a multiple, at the bottom of the profile, mimics the sediment surface between the two largest outlier reefs. Outlier reefs are so called because they are disconnected from the adjacent shelf margin.

The U.S. Geological Survey (USGS) Coastal and Marine Geology Program, in cooperation with the National Oceanic and Atmospheric Administration's (NOAA) National Marine Sanctuary Program, continues investigations of factors that may be affecting Florida's reefs. The USGS studies described here identify location and degree of development of major geologic features during the last 125,000 years (125 ka) and are based primarily on seismic geophysical data.

Environmental Signatures in the Geologic Record

Bedrock Surface

Analysis of the bedrock surface reveals facts on natural processes of past reef growth and demise, rising and falling sea level, flooding of the bedrock surfaces, sediment movement and accumulation, and changing water depth, circulation, water chemistry, and wave energy. Supplemental knowledge obtained from samples taken by coring through reefs documents various responses by corals and reefs to rising sea level, such as coral species zonation and landward reef and mangrove-shoreline migration. Uranium-thorium and carbon-14 (C^{14}) dating of corals tells us when they began to grow, how long they lived, and when they died. C^{14} dating of mangrove peat, which forms at the shoreline and is known to exist beneath offshore reefs, reveals when shorelines existed farther seaward. The mapped bedrock surface delineates areas of different elevations (Plate 1) and shows where new coral growth would have first become established. Because coral larvae generally settle on sites where the bottom is hard and free of sediment, reefs began growing on elevated bedrock. Sand, which prevents reef establishment, filled the depressions. The mapped surface also shows pathways the water would have taken inland as the sea flooded the shelf and thus positions and configurations of ancient shorelines.

The Florida Keys

The upper and middle Florida Keys are themselves composed of the emergent skeletal remains of a discontinuous coral reef, called the Key Largo Limestone, that grew long before the patch reefs and outer-shelf reefs one sees today (Fig. 1). The lower Keys were once sandbars actively moving back and forth with the tides. Uranium-thorium dates from corals in the fossil reef give an age of ~125 ka, identifying a time when sea level was higher than today. The dominant coral species comprising the emergent reef are massive framework-building head corals that live in low-energy (deeper than 5 m) conditions (m = meters). They indicate that sea level was too high for a surf zone to have existed where they grew. It is commonly believed that sea level at that time was 7.6 m higher than at present. It has not been as high since then.

The Shelf Margin

The same species of massive head corals that constructed the Key Largo Limestone also built an immense, younger reef that is now the submerged shelf margin (Figs. 1-3). Uranium-thorium dates from these corals yield an age of 80 ka, marking yet another period when sea level was high but not as high as when the Keys were formed. The massiveness (up to 30 m of relief) and regional extent of the margin reef indicate that conditions were once optimal for coral growth nearly everywhere in the area. No younger reefs can compare in either relief or extent with the 80 ka shelf-margin reef, denoting that environmental factors for reef growth since then have never been as good.

Outlier Reefs

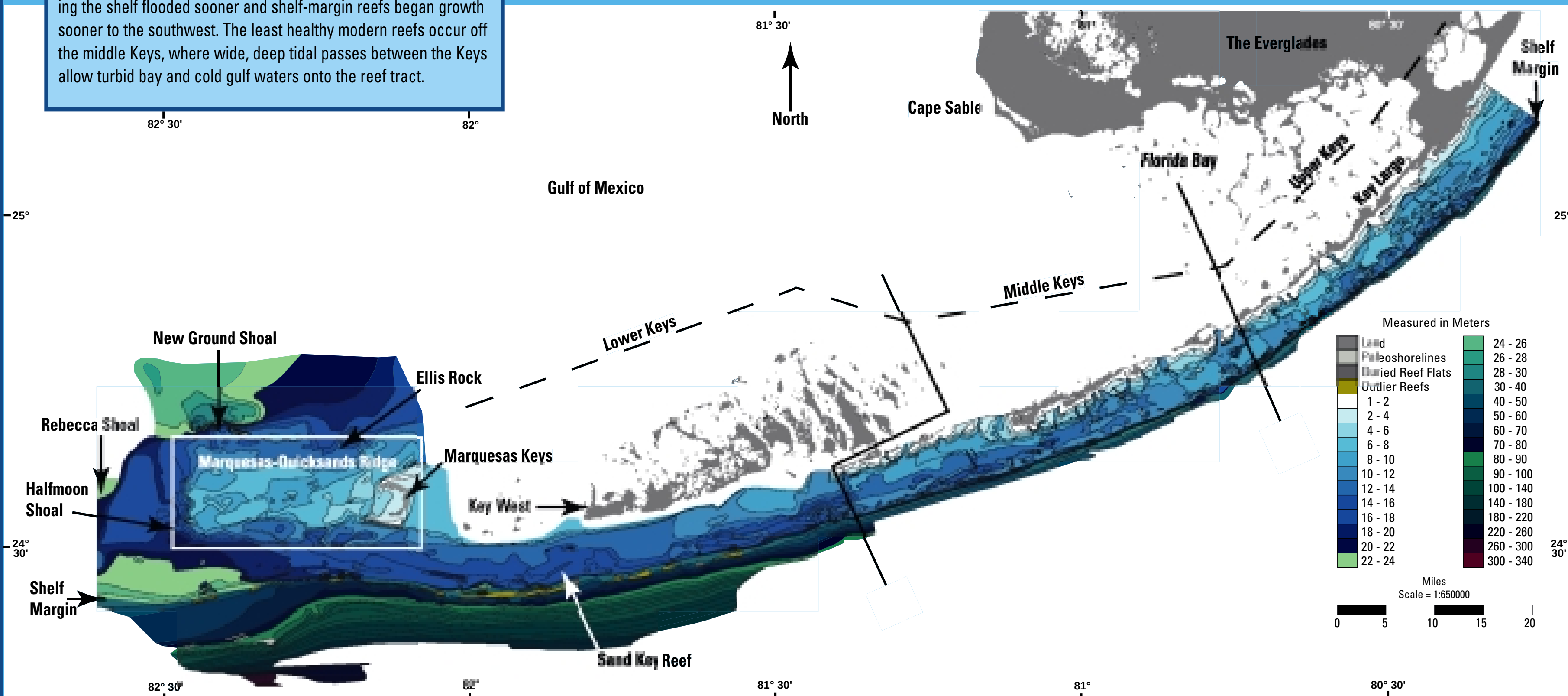
Because of the optimal environment for reef growth at 80 ka, of particular interest is the evolution of massive linear reefs that lie seaward of the margin reef off the lower and middle Keys. Called outlier reefs, these reefs are located on an eroded upper-slope surface (terrace) thought to have formed ~200 ka (Figs. 2, 3). Although the outlier reefs contain the same massive head-coral species and are the same age as the reef at the shelf

Plate 1. Index map showing tip of South Florida and Cape Sable, the Florida Keys, the Marquesas Keys in the Gulf of Mexico, and the bedrock surface along the shelf and margin. The upper and middle Keys are formed of the 125-ka coral reef; the lower Keys are formed of cemented tidal bars of the same age. Colors on the map represent different bedrock elevations ranging from highest (pale blues) to lower (dark blues) to lowest (shades of green). Contacts between colors can be interpreted as representing positions and configurations of ancient shorelines as sea level rose. Outlier reefs are in shades of brown (light=high relief, dark=low relief or buried). The 80-ka shelf-margin reef coincides with a dark blue line just landward of the outlier reefs. Note elevated rectangular platform on which the Marquesas Keys are located. Deep water on three sides and a current-swept, sediment-free channel on the east indicate that sediments on the platform are formed in place. In general, the map shows bedrock elevations are several meters higher to the northeast than southwest, meaning the shelf flooded sooner and shelf-margin reefs began growth sooner to the southwest. The least healthy modern reefs occur off the middle Keys, where wide, deep tidal passes between the Keys allow turbid bay and cold gulf waters onto the reef tract.

In Florida, vitality of the fragile coral reef ecosystem depends on a critical equilibrium between physical processes and landforms. The primary process is rising sea level. The landform is the bedrock surface and its shape and elevation above and beneath the sediments. Coral reefs and associated organisms flourished along the outer shelf until the sea flooded shallow inland bedrock depressions. As bay waters circulated seaward, water quality and chemistry around the reefs changed, forcing a shift in biotic communities. Reef-building corals are no longer alive. Understanding the natural connection between geologic parameters and the well being of biologic resources is an imperative first step toward resource-wise restoration, preservation and management of the ecosystem.

USGS
science for a changing world

The USGS serves the nation by providing basic, objective, and informative scientific knowledge on Earth history and processes, and on human impact on resources. Two of the most effective ways are through descriptive and interpretive maps and through the USGS marine homepage on the world wide web at:
http://marine.usgs.gov.



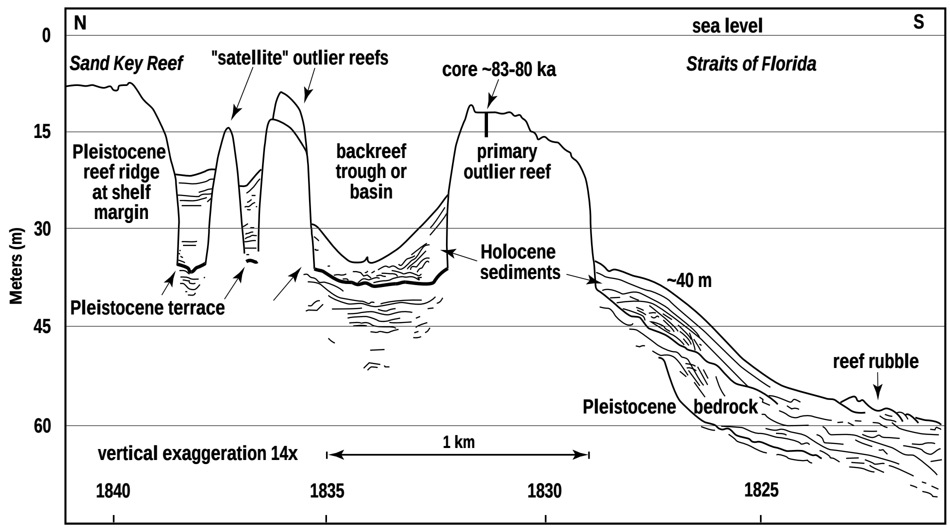


Figure 3. Interpreted seismic profile shown in Figure 2. Largest outlier reef developed at seaward edge of broad erosional surface (Pleistocene terrace). Note terrace surface is not visible beneath the reefs. Coral reefs and reef rubble or debris characteristically obscure sound-wave reflectivity of rock surfaces beneath them. A core drilled into the top of the main outlier recovered 6.09 m of coral rock. Uranium-thorium dating yielded ages of 83 to 80 ka for corals in the core. Tick marks at bottom of interpreted profile indicate time (24-hr scale).

ka = thousand years
km = kilometers
m = meters

margin, they differ from the shelf-margin reef in regional extent, and they exhibit varied stages of evolution. The outliers are mature off the lower Keys (28 m of relief), moderately well developed off the middle Keys (less relief), and appear in seismic profiles off the upper Keys as low-evolution beach-dune features buried by lime sand. The diverse evolution of the outlier reefs is believed to have resulted in part from differences in sand-dune development and the angle at which prevailing east southeasterly winds and waves impinged upon the arc-shaped shelf margin (Plate 1). Off the upper Keys, onshore tides during a period of lower sea level washed sands over the dunes, burying them. Off the lower Keys, longshore wind and wave energy moved sand parallel to the margin, keeping the higher-elevation incipient reefs sediment free (Fig. 4A-E). Through time and with recurring rises and falls in sea level, the outlier reefs off the lower Keys were repeatedly colonized by corals that eventually constructed tall rock ridges as wide as 0.5 km. Today, the outlier reefs remain separated from the margin by comparatively sediment-free backreef troughs (Figs. 2, 3). Only the top 6 m of the largest outlier have been cored and dated. The corals are 80 ka. Although the age of the base of the outliers is not known, it is likely that it is many tens of thousands of years older.

Outer-Shelf Reefs

The most recent rise in sea level began at ~10 ka as a result of warming temperatures and melting glaciers. C^{14} dates on corals from fossil outer-shelf reefs landward of the margin reef indicate that they first began growing at about 7 to 6 ka. Thus, what is now the modern reef tract was land until flooding of the shelf began about that time. The coral species in the outer-shelf reefs (Fig. 1) are different from the massive head corals that built the older reefs. Framework-building branching corals that prefer high-energy conditions constructed the outer-shelf reefs and thus verify presence of the surf zone when the reefs were alive. Branching corals are known to grow only in water depths of up to 5 m, which indicates another relative position of sea level. The extent and ages of the outer-shelf reefs show they too thrived and lived from about 7 to 2 ka. Although discontinuous and not as massive as the older Key Largo Limestone reef, the shelf-margin reef, and the outlier reefs, thickness of the outer-shelf reefs relative to thickness of modern reefs indicates that conditions for coral growth from 7 to 2 ka were nonetheless considerably better than they are today. Much of what is now under water was still land until about 2 ka, when flooding of the large shallow bedrock depressions that became Florida and Biscayne Bays occurred. Creation of the bays contributed to demise of the reefs by allowing tidal exchange of turbid lagoonal waters onto the reef tract. The lagoonal bays were filled when sea level was about 0.5 m lower than today. Prior to about 40 years ago, modern reefs consisted of healthy branching corals. Today, very few of these corals are alive and those that are, are in very poor condition.

Cores taken from various locations through the outer-shelf reefs give us insights into reef growth during rising sea level. Location of reefs (distribution), types of corals (head or branching), landward reef migration (known as backstepping), and zones of changing coral species are some of the corals' responses to suitable site (elevated-bedrock availability), environmental conditions (protected or open to surf), and rising sea level. An increase in water depth alters circulation and wave energy, which are also controlled by local bedrock topography. Increasing water depth changes water chemistry and temperature through tidal flow of murky, nutrient-rich bay water and cold Gulf of Mexico water into the clear warm water surrounding the reefs. Human influence on these deleterious elements can severely impact an already naturally weakened reef ecosystem.

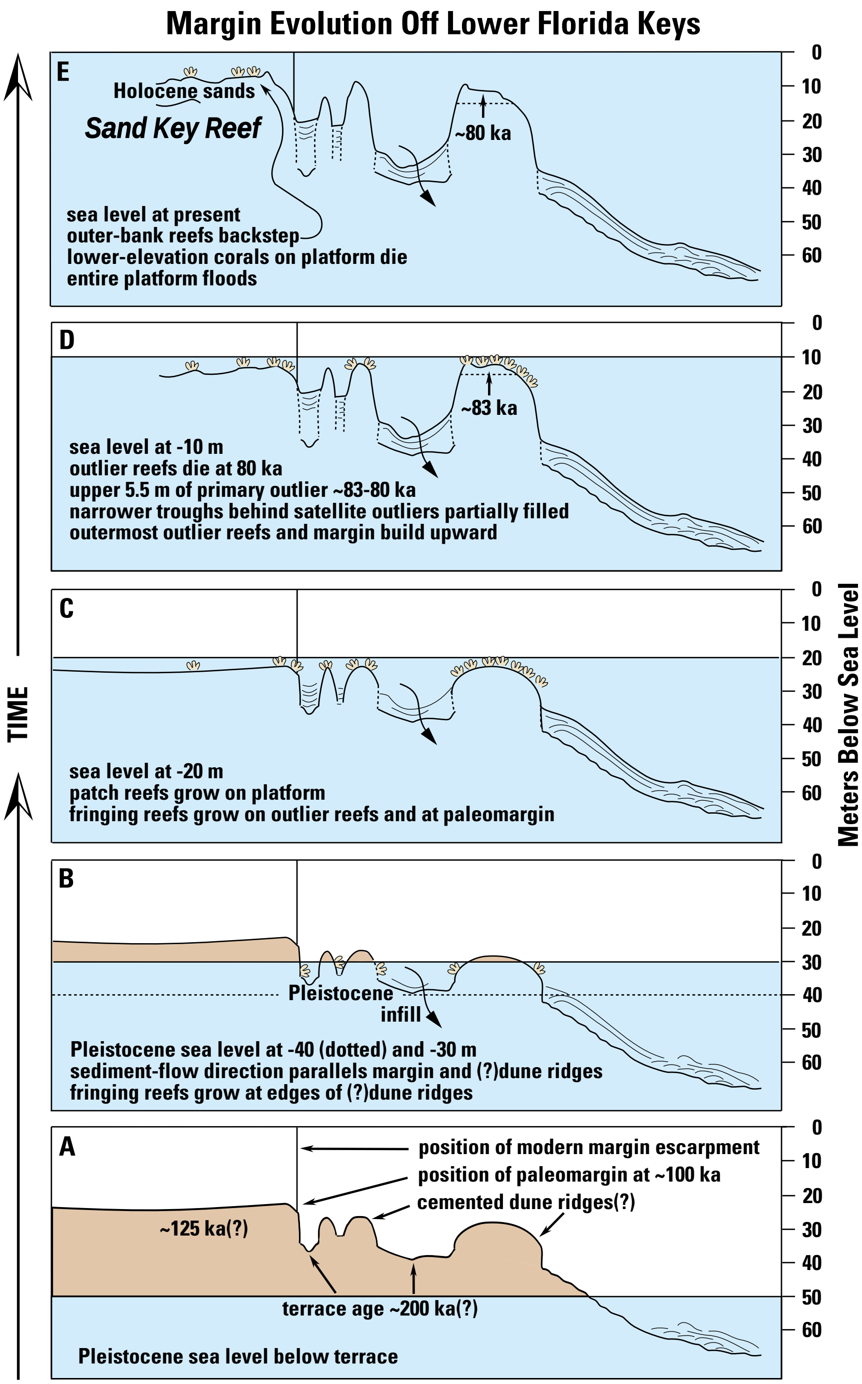


Figure 4. Proposed model for evolution of lower Keys shelf margin (sea level fluctuated many times but positions correspond to events shown). (A) Formation and cementation of sand dunes on the erosional terrace surface during a sea-level lowstand. (B) Colonization of sediment-free shelf-margin reef and dune ridges by corals. (C,D) Upward building of margin reef and outlier reefs over time and through numerous rises and falls of sea level. (E) Final demise of Pleistocene corals on outliers at ~80 ka and later migration of younger (~7- to 2-ka) outer-shelf reefs with shelf-wide flooding. Essentially no corals are alive on the outliers today. However, if sea level were to fall by some 10 m or so, it is very likely that framework-building corals would once again become established on the hard rock surface of the outlier reefs.

ka = thousand years
Holocene = <10 ka
Pleistocene:
- outlier-reef age = ~83-80 ka
- terrace age = ~200 ka(?)

m = meters

Summary

The corals that form the middle and upper Florida Keys verify the previous existence of an inshore reef ecosystem. Mangrove peats found beneath offshore reefs record the locations of earlier, seaward, shorelines. Zonation of coral species within a reef is evidence of increasing water depth and thus changing conditions, from quiet water protected from waves to high-energy surf to water too deep for a surf zone. Sea level has risen and fallen many times before, and the massive limestone outlier reefs were accordingly colonized, killed during exposure, and re-colonized. These signatures in the geologic record indicate that reefs and shorelines have come and gone in the past. Could the fragile modern ecosystem be undergoing yet another natural decline, or are human activities responsible or, at the very least, an added component? We cannot know without first knowing what controlled evolution and development of the ancient reefs, i.e., the bedrock characteristics, the processes that produced them, and the responses the ancient reefs had to environmental change. The bedrock is far more important than simply being the surface beneath modern reefs. The environmental signatures it contains provide the baseline information from which understanding decline of the modern reef ecosystem must be derived.

For more information, please contact:

Barbara H. Lidz
600 4th Street South
St. Petersburg, FL 33701
phone: 727-803-8747 x3031
fax: 727-803-2030
blidz@usgs.gov