USGS
science for a changing world

Environmental Quality and Preservation—
Reefs, Corals, and Carbonate Sands: Guides to Reef-Ecosystem Health and Environments

A healthy reef ecosystem builds a protective offshore barrier to catastrophic wave action and storm surges generated by tropical storms and hurricanes.

Aerial photograph of spurs and grooves at Sand Key Reef, located southwest of Key West, Florida. Spurs and grooves are oriented perpendicular to incoming waves. Spurs are approximately 6 m (20 ft) wide.

Introduction

In recent years, the health of the entire coral reef ecosystem that lines the outer shelf off the Florida Keys has declined markedly. In particular, loss of those coral species that are the building blocks of 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 groundings, farmland runoff, nutrient influx, air-borne contaminants, groundwater pollutants) a contributing factor and if so, to what extent? At risk of loss are biologic resources of the reefs, including habitats for endangered species in shoreline mangroves, productive marine and wetland nurseries, and economic fisheries.

A healthy reef ecosystem builds a protective offshore barrier to catastrophic wave action and storm surges generated by tropical storms and hurricanes. In turn, a healthy reef protects the homes, marinas, and infrastructure on the Florida Keys that have been designed to capture a lucrative tourism industry. A healthy reef ecosystem also protects inland agricultural and livestock areas of South Florida whose produce and meat feed much of the United States and other parts of the world.

In cooperation with the National Oceanic and Atmospheric Administration's (NOAA) National Marine Sanctuary Program, the U.S. Geological Survey (USGS) continues long-term investigations of factors that may affect Florida's reefs. One of the first steps in distinguishing between natural change and the effects of human activities, however, is to determine how coral reefs have responded to past environmental change, before the advent of man. By so doing, accurate scientific information becomes available for Marine Sanctuary management to understand natural change and thus to assess and regulate potential human impact better. The USGS studies described here evaluate the distribution (location) and historic vitality (thickness) of Holocene reefs in South Florida, relative to type of underlying bedrock morphology, and their varied natural response to rising sea level. These studies also assess movement and accumulation of sands, relative to direction of prevailing energy, and origin of the component sand grains. Geophysical data collected with high-resolution sound-wave instruments that provide pictures of the sediment and bedrock are used to interpret sediment thickness. Reef thickness is determined by collecting limestone rock cores by drilling. Drill cores through reefs are used to identify the coral species that built them and to determine how reefs reacted to rising sea level. These data are supplemented by using isotope-dating techniques to derive the carbon-14 (C^{14}) age of the corals and mangrove peat in the cores. Mangrove peat forms in very shallow water and at the shoreline but is found today buried beneath offshore reefs.

Background Information

Geologic time is classified into various categories, one of which is an epoch. The Pleistocene Epoch spanned time from ~1.77 million (1.77 Ma) to 10,000 years ago (10 ka) and was a period of alternating glacial and interglacial stages with corresponding rapidly fluctuating high-amplitude sea levels. The last glacial interval, or Ice Age, occurred at the end of the Pleistocene when sea level is believed to have been more than 130 meters below present (1 m = 3.281 feet). The Holocene Epoch followed, beginning about 10 ka, and extends to the present. The first ~3,000 years of the Holocene were marked by a period of rapidly melting Ice Age glaciers and warming oceans. The rapidity at which these events occurred caused an initial rapid rise in the most recent sea-level fluctuation. Sea-level curves derived from isotope dating of corals and mangrove peat relative to their locations below present sea level indicate that the rapid rate of Holocene sea-level rise began to slow about 7 ka.

In South Florida, the bedrock beneath the Florida Keys and reef tract is Pleistocene. Some Pleistocene reefs in Florida are as much as 30 m in height, 0.5 kilometer (1 km = 0.6214 mile) in breadth, and extend the length of the reef tract, indicating optimal environmental conditions for coral growth during that time. Pleistocene reefs are cumulative in that they alternately grew, died from exposure during lowstands of sea level, and were re-colonized by corals during the next rise in sea level. By contrast, Holocene reefs flourished continuously during the latest rise in sea level and attained a maximum of 16.8 m in thickness within 5,000 years, indicating that conditions for coral growth then were also excellent. C^{14} ages show that the reefs lived from about 7 to 2 ka. The fact that Holocene reefs are thinner than Pleistocene reefs may seem at first glance to be a reflection of comparatively less time for development. However, Holocene growth was constrained primarily by a slowing of the rate of sea-level rise that limited space for upward expansion and, in Florida, by flooding of the inner shelf at ~2 ka that created Florida and Biscayne Bays. Rising sea level altered water depth, which affected wave energy and circulation and changed water chemistry and temperature. Sea level at 2 ka was ~0.5 m lower than today, and tidal influx of deleterious murky, nutrient-rich bay water and cold Gulf of Mexico water to the clear warm waters surrounding the reefs had begun.

Environmental Signatures in Reefs, Corals, and Carbonate Sands

By examining the evolutionary geologic record of the reef-tract ecosystem, we can understand what controls where and why reefs grow. Because coral larvae generally settle on sites where the bottom is hard and free of sediment, reefs began growing on elevated bedrock. Sands, which prevent reef establishment, filled depressions. To grow, corals require narrow conditions: relatively shallow depths and normal salinity, clear nutrient-poor water, and warm temperatures. The primary control of these conditions, in other words, reef growth, is sea level. The primary control of reef distribution is the availability of a hard, elevated, sediment-free surface, in other words, the landscape or topography of the bedrock under the reefs. In Florida, the bedrock surface was dry land until about 7 to 6 ka when the sea began to flood what is now the reef tract.

Much can be learned about Holocene reefs, corals, sediments, and environments by core drilling through the reefs. Coral-rock cores show that, in general, the components of Holocene topography mimic those of the Pleistocene, i.e., Holocene reefs began growth on top of Pleistocene reefs, and uncemented Holocene sediments overlie cemented Pleistocene sediments. Some reef cores contain mangrove peat at the bottom that formed when the bedrock shelf surface was exposed in the early Holocene. Presence of peat offshore indicates an earlier shoreline position and a period of lower sea level. C^{14} dating of the peat tells us when the old shoreline existed, and location of the peat 'x' meters below present sea level tells us the depth of the previous shoreline relative to present sea level.

Reef Records

The Holocene coral species recovered in cores are framework builders. Many single cores from individual reefs contain species of head corals at the bottom and branching corals at the top, indicating a change in environmental conditions at that location through time. An analysis of a number of cores from transects across a reef shows the same coral zones through time and space, i.e., seaward head-coral zones shifted landward to branching-coral zones within the same reef. The shift occurred as the reef migrated or grew landward (called backstepping) over carbonate sands with rising sea level. In both examples, the massive head corals grew first, indicating that quiet-water conditions (> 5 m) prevailed first. Branching forms that prefer the surf zone (< 5 m) then replaced the head corals. C^{14} ages on both types of corals give us the times in the area where the cored reefs are located when sea conditions were quiet and then became high energy. The coral zones developed in response to flooding of Pleistocene-reef islands that once lined the edge of the margin during the early period of lower Holocene sea level. The reef islands had protected the head corals from

Healthy ecosystem components—head and branching reef-building corals in clear Florida water in 1971. Tiny coral polyps, soft-bodied animals living in colonies like bees, build coral reefs. Each polyp constructs an outer skeleton of hard limestone that adds a new layer to the reef. Diameter of head coral is approximately 0.7 m.

m = meters

high-energy waves. Their submergence removed that protection and allowed the surf zone to move landward, creating the high-energy environment required by the branching corals. Not all Holocene reefs were able to keep pace with sea-level rise, however. Those that did not survive died because sea level rose too quickly for them to maintain their ideal depth and they slipped below their threshold. Holocene corals also built magnificent spurs and grooves on windward sides of reefs. The spurs thrived until the corals became overcrowded. Constrained by position of overhead sea level and presence of sand-filled grooves at either side, the corals eventually succumbed for lack of space. Few coral spurs are actively accreting today.

C^{14} age dates from corals at the outer-shelf margin show that Holocene reefs began growing sooner off the lower Keys than off the upper Keys, a result of earlier shelf flooding because of lower bedrock elevation to the southwest. However, Holocene reefs lived longer off the upper Keys than off the lower Keys, a result of later flooding and protection from adverse oceanic elements by the Pleistocene-reef islands at the margin. Today, outer-shelf reefs off the upper Keys are protected by the linear island of Key Largo not from high wave energies but from the turbid nutrient-laden water of Florida Bay (Plate 1). Reefs less than 2 ka are very thin, indicating that conditions for coral growth in more recent times were not as good as those in the earlier Holocene. In modern times as recently as in the 1960s, Holocene reefs supported actively accreting corals to some degree. Very few such reefs are alive today and those that are, are in very poor condition.

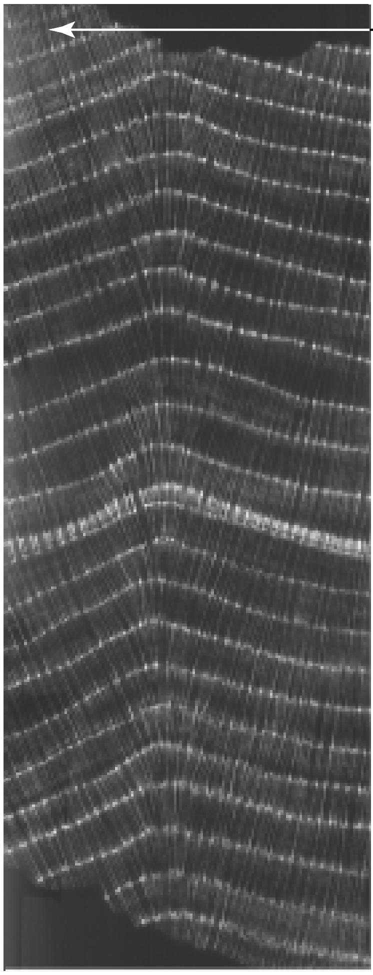
One of the best places to see inside a fossil reef is at the old quarry at Windley Key Fossil Reef State Park on Windley Key in the middle Keys (Plate 1). The coral species comprising the emergent Pleistocene reef are the massive framework-building head corals that live in low-energy conditions. The corals in this reef 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, 125 ka, was 7.6 m higher than at present, and it is known that sea level has not been as high since then.

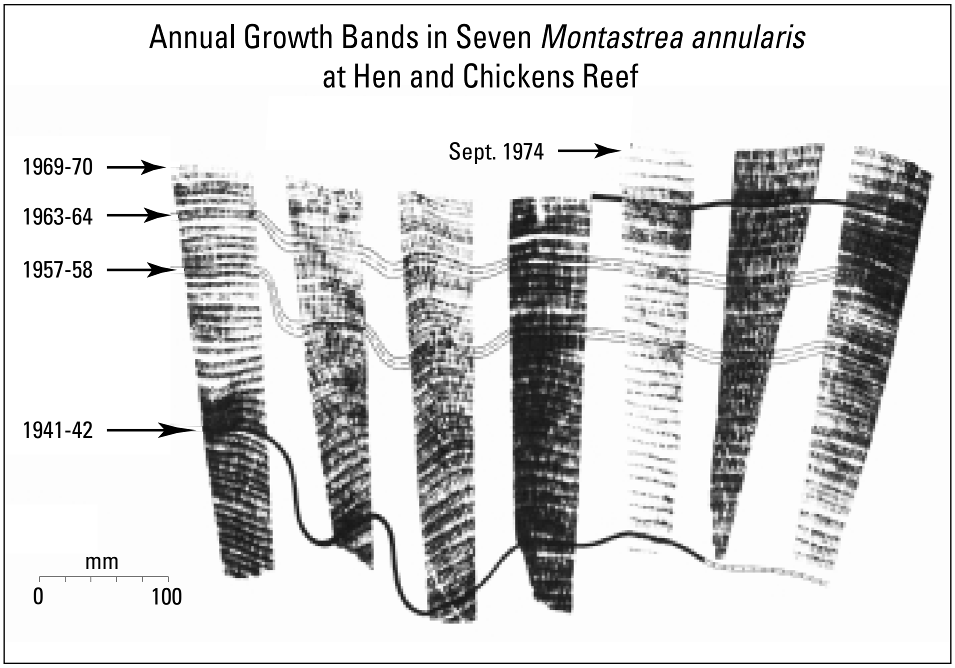
Coral Records

Individual corals also contain environmental signatures—within annual growth bands. Coral growth bands are like tree rings and are visible, just like bone structures in dental or medical x-rays, when the coral core is cut into slabs and x-rayed. In a core from a live coral, growth bands can be counted back from the surface beginning with the year of coring to obtain the age at the bottom. Some growth bands are wider than others and are called stress bands. They indicate a period during deposition of the annual band when water temperatures were unusually warm or cold. Some bands fluoresce under ultraviolet light in response to an infusion of humic acids that became bonded to the skeleton. Fluorescent humic acids are a component of fresh water. Thus, presence of a fluorescent coral band indicates a period of high freshwater influx onto the reef during deposition of the band. The study of annual coral growth bands is called sclerochronology.

Records in Carbonate Sands

Finally, even the coarse- and fine-grained carbonate sands that line the reef tract contain environmental signatures. Sands record geologic pro-





Left: X-radiograph of slabbed core from a species of head coral (*Montastrea annularis*) at Hen and Chickens Reef showing white annual growth bands. Note wide abnormal stress band deposited in the coral skeleton as a response to unusually cold water temperatures during the winter of 1941-42. The live head coral was sampled in the spring after deposition of the 1955-56 annual band. See Plate 1 for location of Hen and Chickens Reef. Approximate vertical distance between annual bands is 1 cm.

cm = centimeters
2.54 cm = 1 inch

Above: X-radiographs showing correlation of banding in seven different *Montastrea annularis* coral heads at Hen and Chickens Reef. Four at left are from heads killed by cold in the winter of 1969-70. Three at right are from corals that were alive and healthy when sampled in September 1974. Topmost right-hand stress bands joined by bold line correlate with time of demise of corals in left x-radiographs. Stress band for 1941-42 in five left x-radiographs indicates that conditions were equally severe for those five corals. Other minor stress bands occur that are very faint or that do not correlate from coral to coral. Normal annual bands are correlative among all corals.

cesses. For example, seismic profiles across a submerged terrace off the northeastern part of the shelf margin show linear low-elevation features believed to be incipient reefs that have been buried by sediment. Their burial indicates that prevailing energy there during the Pleistocene was onshore as it is today and that during a low-stand in sea level, winds and waves along that part of the terrace washed sands landward. Along the southwestern part of the terrace, however, essentially sediment-free backreef troughs behind immense linear reefs indicate longshore energy and sand transport. It is just this longshore sand-transport direction, parallel to the reefs and arc-shaped margin, that kept young incipient reefs there sediment free and allowed corals to re-colonize the hard reef surfaces and to build extensive reef ridges during the repeated rises in Pleistocene sea level. Other types of sedimentary processes are observed on the roughly rectangular sand-covered Marquesas-Quicksands ridge farther west in the Gulf of Mexico. The ridge is ~10 m higher in elevation than the surrounding shelf and is thus isolated from sand importation. Five processes occur on the ridge. (1) Sands are produced in place (geological source) by the dominant organisms, several species of a calcareous green alga (biological origin). (2) The sands are molded into prominent tidal bars and sand waves that lie directly on bedrock, which are evidence of the strength and direction of current flow across the ridge. (3) The sands fill shallow (~3 m) bedrock lows on the ridge and (4) accrete behind bedrock highs such as at Halfmoon Shoal, a response to underlying bedrock topography. In time, (5) they are swept westward and off the ridge by the currents, as shown in seismic profiles of westward-dipping bedforms at the west edge of the ridge. The Quicksands are so named, even on navigational charts, because the sands are always in motion.

Sands also record the types of organisms in the reef tract, and in the case of corals, sand analysis reveals whether they are healthy. Carbonate sediments in reef ecosystems consist of skeletal remains of the biota that inhabit the reef. Thus, they contain a record of change in biota through space (laterally) and time (vertically, through sediment cores), and through these biotic changes the sands reflect corresponding changes in the environment. Hence, sands in a reef ecosys-

Plate 1. Index map showing tip of South Florida and Cape Sable, the Florida Keys, the Marquesas Keys in the Gulf of Mexico, and a map of the thickness of Holocene reefs and sediments that overlie Pleistocene bedrock along the shelf and margin. Colors on the map represent different thicknesses ranging from bare rock (white) to thinnest (pale pinks) to thicker (dark reds) to thickest (rust). Linear white area in seaward part of map denotes bare rock on seaward side of a Pleistocene reef that forms the shelf margin. A submerged terrace lies at the toe of this reef. In general, the map shows that most of the sediments on the shelf and on the submerged terrace are ~3 m thick. Areas of thinnest coverage occur along the inner shelf, on the landward side of Hawk Channel (major bedrock depression between the Keys and shelf margin), and on the Marquesas-Quicksands ridge. Deep water on three sides of the ridge and a current-swept, sediment-free channel on the east side indicate that ridge sediments are formed in place. Note the Marquesas Keys formed in a shallow, nearly circular bedrock depression that also contains ~3 m of sediment, determined by probing to bedrock with a rod. The thickest shelf accumulations occur in backreef troughs behind the Pleistocene margin reef. Sediment is virtually nonexistent along a submerged rock ledge bordering the south-southeast sides of the Keys and at the seaward edge of the Pleistocene margin reef. The terrace outlier reefs are also sediment free. The thickest (40+ m) sediment accumulation in the study area occurs on the upper slope south of the Marquesas Keys in 80 to 190 m of water.

The Florida Keys are divided naturally by shape and composition. The upper and middle Keys are composed of a long arc- shaped coral reef. Known as the Key Largo Limestone, the reef parallels the shelf margin. The lower Keys consist of cemented sandbars. Called the Miami Limestone, the bars formed more or less perpendicular to the reef and margin. Both rock formations accumulated approximately 125 ka when sea level was about 7.6 m higher than present.

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.

Any loss of the economically viable and physically essential coral reef ecosystem would have significant, potentially very dangerous economic, health, and safety impacts on the densely populated Florida Keys and South Florida mainland.

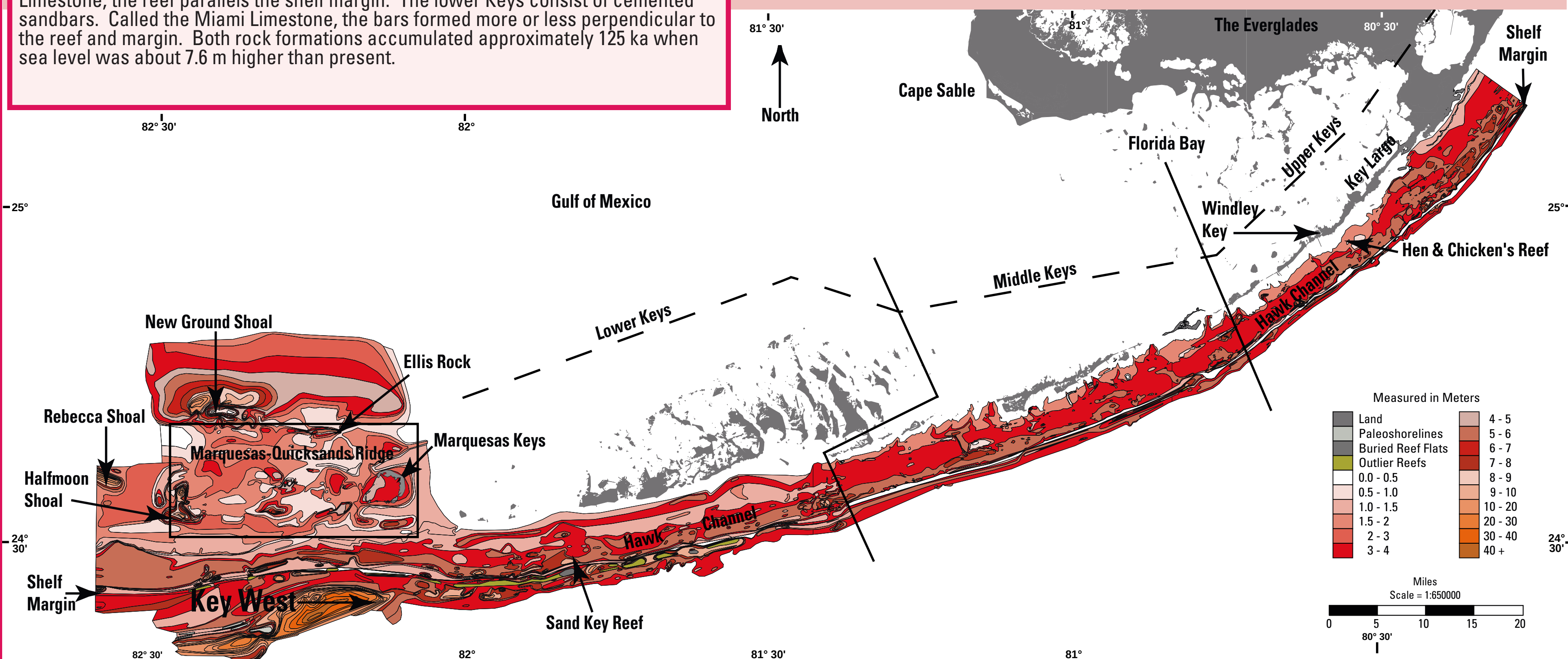
USGS
science for a changing world

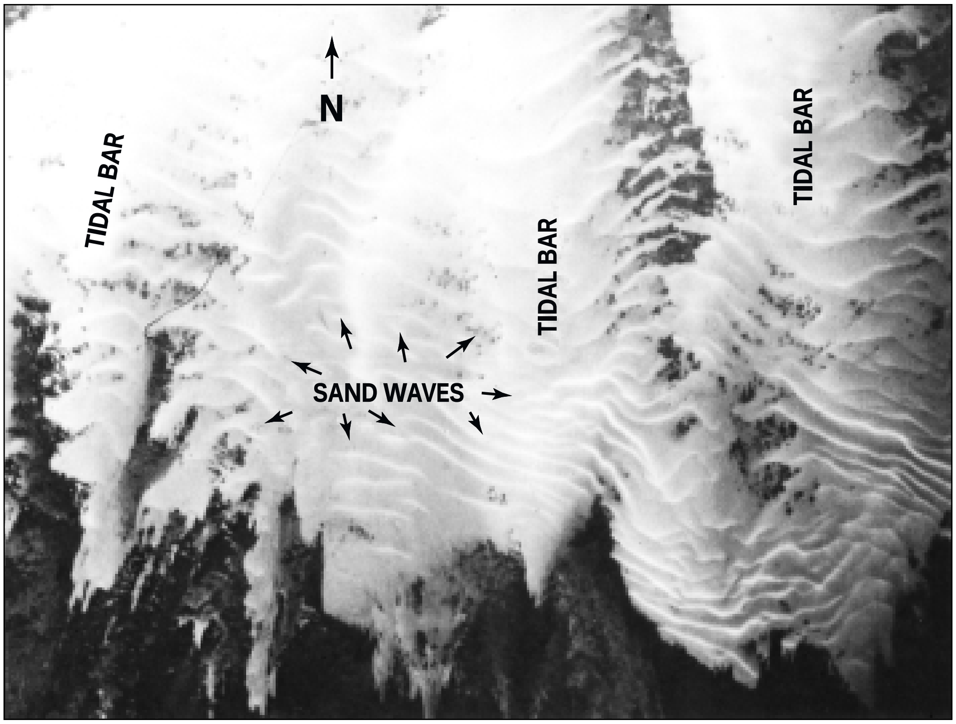
References Cited in Text:

Lidz, B.H., 1997, *Fragile Coral Reefs of the Florida Keys: Preserving the Largest Reef Ecosystem in the Continental U.S.* U.S. Geological Survey Open-File Report 97-453, 4 p., 1 Plate.

Lidz, B.H., 2000, *Bedrock Beneath Reefs: the Importance of Geology in Understanding Biological Decline in a Modern Reef Ecosystem.* U.S. Geological Survey Open-File Report 00-046, 4 p., 1 Plate.

Lidz, B.H., (in prep.), *Surface Features of the Florida Keys and Reef Tract:*
(1) North Key Largo to Vaca Key and The Elbow Reef to Sombrero Reef,
(2) Vaca Key to Key West and Sombrero Reef to Eastern Dry Docks,
(3) Key West to the Marquesas-Quicksands Ridge and Eastern Dry Docks to Rebecca Shoal.





Aerial photograph showing tidal bars and sand waves near the west side of the Marquesas Keys. Tidal bars are 1 m high and are oriented north/south in response to strong north/south currents. Sand waves on top of tidal bars are oriented perpendicular to the bars and many sand waves are awash at spring low tide. Dark areas are grass and various species of a calcareous green alga. Distance across photo is approximately 2.5 km.

km = kilometers
m = meters

tem are bioindicators of the health of the reef community and the quality of environmental conditions. Plastic-impregnated thin sections of sediment samples are used to identify and count grains under a microscope.

Sand-grain analyses conducted in 1963 and in 1989 showed that a significant increase in coral grains occurred in surface sands in areas off the middle and lower Keys over those 26 years. The increase correlates with an observed increase in nutrient influx and decline in coral reef health in the same areas and time. In other words, much higher percentages of coral fragments occur in areas where there are diseased and dead corals than in areas where corals are healthy. The reason is twofold: algae grow on dead coral surfaces, attracting grazers, and bioerosion of dead skeletal material—yet two more processes indicated by the sands, these biologic—is associated with organisms that break down dead coral. Fish bite off attached algae along with bits of skeletal coral, herbivorous sea urchins graze, and sponges, algae, fungi, barnacles, and bivalves bore into the coralline rock. Parrotfish and boring sponges are the major bioeroders. The same studies showed an increase in grains of a calcareous green alga in areas off the upper Keys. Proliferation of calcareous algae (preservable as sand grains) and fleshy red, blue, green, and brown algae (non-preservable) is also commensurate with increased nutrient supply and a declining ecosystem. Increases in both coral and algal sand grains and in observed growth of fleshy algae correlate with a conceptual model that shows the effects of increasing nutrients on organisms that comprise the bottom-dwelling population in a reef ecosystem and how that population will change. Is the nutrient influx natural, or is it the result of human activities? The USGS studies described here provide part of the scientific background needed before these questions can be answered—an understanding of natural changes within past ecosystems.

Summary

The geologic record of the Florida Keys reef tract is a rich archive of evidence for numerous significant past environmental changes. (1) Thick cumulative Pleistocene and continuous Holocene coral-growth records verify previous existences of healthy reef ecosystems and thus the optimal conditions under which they grew. (2) Dated mangrove peat found beneath offshore reefs documents the times and locations of earlier, seaward, shorelines. (3) Landward reef migration is evidence of rising sea level. (4) Shifts from head-coral zones to branching-coral zones within a reef are signs of changing conditions from quiet water to presence of surf and are thus evidence for flooding of once protective offshore reef islands. (5) Annual stress bands in corals indicate periods of severe water-temperature changes, and fluorescent bands verify weather variations that produced high freshwater influx to the reef. (6) Sands record geologic processes of transport direction, scouring of back-reef troughs, in-place formation, strength and direction of currents, infilling of bedrock depressions, and accretion behind bedrock highs, as well as biologic processes of grazing

WAYS IN WHICH MAPPED BEDROCK, SEDIMENT, AND SEAFLOOR INFORMATION BENEFIT THE ECOSYSTEM

Management Issues

1. Understanding the direct relation between geologic framework and biologic resources, such as localization of biotic communities.
2. Understanding the direct relation between geologic framework and physical processes, such as direction and rate of groundwater flow.
3. Understanding the direct relation between protective islands, open tidal passes, and sources and effects of deleterious waters on reef vitality.
4. Understanding the direct relation between, and variety in, localized physical environments and biological communities.
5. Understanding the relation between dominant organisms and dominant sediment components and how changes in dominant sediment components indicate changes in the biotic community.
6. Integrating scientific knowledge with resource-stewardship practices to attain sustainable archeological, ecologic, and socioeconomic (tourism, commercial fisheries) systems
7. Improving capabilities for restoration and preservation of each ecosystem component
8. Predicting variability and evaluating effects of coastal processes and ecosystem response to natural (rise/fall of sea level) and anthropogenic (pollutants) influences
9. Educating the visiting public with accurate scientific knowledge of:
   - how and why the many varieties of reef-tract resources exist
   - how and why each type is an integral part of the ecosystem and must be preserved
   - how and why each can be damaged or destroyed and if destroyed, how an out-of-balance ecosystem will respond
10. Assessing impacts on the ecosystem before issuing treasure-hunting permits
11. Informing politicians, the media and public visually and descriptively of locations and types of various habitats and environments prior to on-site visits

Ecosystem Issues

1. Mitigation of physical damages due to boat anchors, divers, or ship groundings and choice of the best and most effective type of restoration—by transplanting live corals directly onto elevated bare rock or onto prefabricated cement substrates placed in sandy areas.
2. Mitigation of sewage-disposal practices—by changing cesspools and shallow injection wells that empty into porous rock to wastewater-treatment plants and requiring holding tanks on boats
3. Mitigation of abnormal Everglades drainage—by removing levees and canals to restore natural water flow
4. Mitigation of runoff pollution—by reducing use of fertilizers and chemicals in inland farmlands
5. Siting and choice of equipment for installing fixed navigational structures and lighthouses (i.e., in barren sand holes or on bare bedrock)
6. Siting of mooring-buoy anchorages (i.e., in barren sand holes surrounded by live-rock habitats)
7. Siting and choice of equipment for maintaining dredged channels and digging trenches for stormwater drainage pipes (i.e., sand removal with minimal siltation and turbidity)
8. Siting of areas least susceptible to pollution and turbidity for transplanting corals and sea grasses, such as areas where sediment is thick or thin, sand or mud, or where the porous limestone is coated with caprock (i.e., thin sand or bare rock allow potentially contaminated ground waters to reach surface waters and reefs; areas of thick sand or mud or caprock form impervious aquicludes)

Systematic shelf-wide USGS mapping of sediment-constituent grains (Lidz, 1997), bedrock topography (Lidz, 2000), reef and sediment thickness (this report), and seabed features and bottom environments (three reports, in prep.) aids both Sanctuary management-policy and ecosystem issues.

for algae and resultant bioerosion of coral skeletons. (7) Sands are bio-indicators of the types of reef organisms and the general health of corals through space and time.

These geologic signatures are guides to reef-ecosystem health and environment and prove that conditions have been both good and bad for reef ecosystems in the past. Is the fragile modern ecosystem undergoing yet another natural decline, or are human activities responsible or, at the very least, an added component? We cannot know without first understanding the evolutionary history and characteristics of ancient reefs, the processes that produced or destroyed them, and the responses they had to environmental change. The reefs, corals, and carbonate sands are far more important than simply being major components in a reef ecosystem. Their history and what they can tell us about past environmental conditions comprise one of the baselines from which understanding the decline of the modern reef system must be derived.

For more information, please contact:

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