CHAPTER 4

HOLOCENE SEDIMENT THICKNESS AND FACIES DISTRIBUTION, LOOE KEY NATIONAL MARINE SANCTUARY, FLORIDA

Barbara H. Lidz, Daniel M. Robbin and Eugene A. Shinn
US Geological Survey Center for Coastal Geology
St. Petersburg, FL

Introduction

The purpose of this report is to characterize sediment components, thickness, and depositional processes within the Looe Key National Marine Sanctuary and to map underlying pre-Holocene bedrock topography. The relatively small (3.6 x 5.2 km) sanctuary is located in the southernmost extension of the Florida reef tract approximately 13 km southwest of Big Pine Key and 8 km southwest of Newfound Harbor Keys (Figure 4.1). Focus of this work was on the entire sanctuary rather than Looe Key reef alone; the reef occupies a small (approximately 0.2-km-wide by 1-km-long) area within the sanctuary. For administrative purposes, the reef has been set aside like a sanctuary within a sanctuary for better concentration of enforcement; the reef area within the sanctuary is called the "core" area.

The first study to characterize and identify the distribution of constituent sedimentary particles in the Florida reef tract was by Ginsburg (1956). His work was centered in the upper Keys reef area off Key Largo, where prevailing southeasterly winds and waves are perpendicular to the platform margin and island chain. Swinchatt (1965) identified sediment composition in transects from the reefs shoreward in the lower Keys off Marathon, where prevailing winds and waves impinge on the platform margin at an acute angle. Our research concentrates on the area within the boundaries of the Looe Key Sanctuary, where winds and waves essentially parallel the platform margin and consequently have a different influence on the distribution and transport of carbonate sedimentary grains than in the middle and upper Keys. The most notable effect in the lower Keys is the piling up of sand on the seaward side of reefs (Shinn *et al.,* 1981). Shinn *et al.* (1981) have suggested that carbonate sand, which has covered part of the deep reef seaward of the main spur-and-groove zone at Looe Key, was transported parallel to and offshore from the platform margin during heavy weather, most likely during hurricanes, tropical storms, or winds associated with periodic winter cold fronts that blow offshore in the lower Keys. Ball *et al.* (1967) described the effects of Hurricane Donna in the upper Keys and pointed out that the major direction of transport was landward, away from the platform margin. Landward movement of sediment during a hurricane was also documented by Perkins and Enos (1968). Enos (1977) mapped the thickness and distribution of sediments and reefs through the entire Florida reef tract from Miami to Key West using high-resolution seismic sparker profiles and also documented predominantly landward transport of carbonate sediments.

This paper describes the bathymetry, sediment composition and thickness (of carbonate sediment and reefal debris overlying Pleistocene bedrock), as well as bedrock topography which has a major effect on subsequent depositional processes. The work is based on interpretation of 2380 cumulative data points along 114 km of high-resolution subsea seismic-reflection profiles and thin section analyses of 96 surface sediment samples throughout the sanctuary. Rotary cores drilled through the Looe Key reef by the US Geological Survey's Fisher Island staff (see Shinn *et al.*, 1981) were used to verify subsurface reflectors and sediment thickness interpreted from the seismic records. Whereas emphasis of this research was on the entire sanctuary, most of the other work presented in this volume was restricted to the Looe Key reef and central core area immediately surrounding the reef. Subsequent to compilation of reports for this volume in 1983, Lidz *et al*. (1985) condensed and published this chapter. That paper should be used as the formal literature citation.

Methods

Subbottom profiling

The 114 km of high-resolution seismic-reflection profiles were shot in July 1983 using an ORE Boomer* with a power output of 100J filtered at 1.0 - 1.5 kHz. The boomer plate trailed 20 m behind the boat along with a 12-element hydrophone streamer which provided input to an EPC 4100 recorder. In addition to direct paper chart readouts, upon which the majority of this study is based, all data were recorded on $^{1}/_{4}$-inch magnetic tape for later filtering and manipulation. Because of the high quality of the seismic records, data enhancing techniques were not necessary.

To interpret these profiles, the Pleistocene bedrock reflector was first identified and traced with a transparent-color marking pen. Selected examples showing major topographic features (of the bedrock and sediment geometry) are shown in Figure 4.2. Identification of the bedrock horizon and its depth along nearly all 114 km of the profiles provided 771 data points from which thickness of the overlying material could be calculated. All measurements were based on the average velocity of sound in sea water (1500 m/sec). A simple scale consisting of a clear plastic strip graduated in meters based on a sound velocity of 1500 m/sec was used to measure water depth and distance to subsurface reflectors.

Most data points were recorded at 5-min intervals. If the profiles showed unusual topography or sediment geometry, however, additional data points defining these particular features were taken from the records at more closely spaced intervals. Loran C coordinates from a Texas Instruments 9000A Loran C receiver were recorded simultaneously with each data point. Each data point was transferred to a Loran C grid chart/base map (constructed later), resulting in plots of track line location, interpreted water depth (uncorrected for tidal changes), sediment thickness and depth to Pleistocene bedrock. Data plotted on these respective base maps were then contoured (Figures 4.3 - 4.6).

Sediment sampling and preparation

Surface sediment samples, collected with an $11^{1}/_{2}$-oz Planters Peanut can with fitted plastic top, were taken during the same study period in transects (indicated on Figures 4.3 and 4.7) throughout the sanctuary principally by skin diving to a water depth of approximately 15 m. In closely spaced transects just seaward of the sanctuary core boundary, samples were collected using Scuba. In the deeper (>30 m) water seaward of Looe Key reef, samples were recovered with a 0.1 m^3 Peterson grab deployed by hand with 1-cm-diameter nylon line. In all cases, sediment collected was restricted to grains of very coarse sand size (2 mm) and smaller. Where possible (i.e., within the core area), sample sites were identified in conjunction with aerial photographs. Loran C coordinates, depth (except as noted in footnotes on Table 4.1) and a brief bottom description were recorded for the 96 sample stations.

Sediment samples were later oven-dried, mixed, and split into smaller subsamples that were placed in plastic ice cube trays and vacuum-impregnated with polyester resin. After hardening, the sediment/plastic cubes were cut in half vertically with a band saw, then mounted on glass slides and ground to a thickness of approximately 30 µm. The thin sections were placed under a petrographic microscope with mechanical stage and point counted. Counting was accomplished

* Use of brand names does not constitute endorsement by the USGS.

by making three transects across each thin section and petrographically identifying the grain under or closest to the crosshairs after each 250-µm advance of the mechanical stage. Point count transects were run from top to bottom across the cube-shaped thin section in order to account for any compositional changes that might be caused by sorting during sample preparation. Some sorting (i.e., coarse at the bottom and finer at the top of the cube) was noted in a few slides but did not occur often enough to influence counts or warrant further discussion. Three transects across the slides resulted in a total point count of 15,890 grains with an average count per slide of 166 grains (maximum 184, minimum 141).

Carbonate grains were identified based on previous experience and according to the carbonate petrography manual compiled by Scholle (1978). Six categories were tabulated (Table 4.1; Figure 4.8), three of which comprised the most common particles (coral, mollusc and *Halimeda*), and four of which comprised the least common (echinoid, bryozoa/red algae, benthic foraminifers, and "other"). The "other" category included pelagic foraminifers, worm tubes, spicules of sponges, tunicates and alcyonarians, ooids, mud, and "unknown." Since the percentages of the last four categories were too low to construct meaningful maps, only the percentages of the three major constituent particles were plotted on the grid base map and contoured (Figures 4.9 - 4.11). The purpose of contouring these data was to show facies distribution and to see if this distribution would identify the direction of sediment transport. Traditional sieving for grain-size distribution, a procedure normally done in siliciclastic sediment studies, was not attempted. Such analyses were considered of questionable value in studies of skeletal carbonate sands.

Navigation problems and water depth

No navigation chart with accurate Loran C Lines of Position (LOPs) was found to exist for the Looe Key Sanctuary. A recent Sanctuary Boundary Survey Plan, conducted by the Department of Army Corps of Engineers in 1983 and based on National Geodetic Survey data, gives latitude and longitude for sanctuary location. Regional Loran C LOPs overprinted on National Ocean Service (1983) nautical charts (cf. chart #11442, Sombrero Key to Sand Key, from which sanctuary location and Loran C grid for Stations 1 and 4, shown in Figure 4.1 inset, were reproduced) are not accurate, being off by more than 1 km in places. Precision of the Loran C receiver, however, is high. Once "true fixes" are taken at a particular place, it is usually possible to return to within at least 15 m of that site.

A Loran C grid chart (Figure 4.3) was therefore constructed using Loran C chain designation 7980 for the Gulf of Mexico (Time Differences or TDs = LOPs in microseconds for Loran C designation 7980, Stations 1 and 4). During the July 1983 study period, Loran C Stations 1 (13900 µsec) and 4 (62500 µsec) were used exclusively. Reception of Loran C Stations 2 and 3 was inconsistent; thus, Stations 1 and 4 provided the TDs or Lines of Position used for navigation, fixed-object location and construction of the Loran C grid chart/base map shown in Figure 4.3.

Comparison of the sanctuary position and Loran C TDs on the above National Ocean Service chart (Figure 4.1 inset) with those shown in Figure 4.3 indicates that the location of the sanctuary differs by as such as 750 m to the north (Figure 4.1) of its actual location (Figure 4.3). In other words, in this case the Loran C LOPs overprinted on the chart are off by 750 m to the north, and the sanctuary boundaries printed on the chart are not an accurate location of the sanctuary. Two Loran C receivers used simultaneously during the study period consistently received identical TDs and repeatedly provided the same coordinates for position of the boundary markers for the duration of the study period. They consistently showed that the boundary marker buoys are actually moored 750 m south of the position indicated on the nautical chart. This study has therefore resulted in construction of the only reliable Loran C grid chart (Figure 4.3) available for the Looe Key Sanctuary. Position of marker buoys and distinct bottom features, as well as the sample sites and seismic track lines described in this study, can only be reoccupied with reasonable accuracy using the chart shown in Figure 4.3 and a Loran C receiver tracking Stations 1 and 4.

Location of the inner core area shown on Figures 4.3 - 4.6 was defined by Loran C coordinates for the core area marker buoys (Table 4.2) and differs from that indicated by latitude and longitude on the Corps of Engineers Sanctuary Boundary Survey Plan (1983). Use of latitude and longitude alone can provide, at best, only a general location. The location shown on our charts is accurate in that the south markers for the inner core area are placed between Looe Key reef and the dropoff, instead of at the dropoff as indicated by the Boundary Survey, and the north markers are accordingly farther north on our charts. In addition, the Boundary Survey placed three of the four core area marker buoys in much deeper water (see Table 4.2) than depths actually occupied. The same Survey also described the sanctuary as being "located in the Straits of Florida."

Loran C fixes were recorded for each sediment sample location and at least every 5-min-interval mark on the seismic-reflection records. Readings were also taken at buoys (Table 4.2) marking the inner core area, the northwest and northeast corners and southeast boundary of the sanctuary (the southwest boundary marker was off station), at Coast Guard Marker 24 located within the southeast corner of the core area, and at prominent bottom features easily identified on aerial photographs. Using the Corps of Engineers Sanctuary Boundary Survey Plan (1983) as a guide from which to trace the sanctuary boundaries and based on Loran C coordinates for the sanctuary marker buoys and Marker 24, a Loran C grid chart was prepared by division of the area between the fixed points into precisely measured increments using 10-point dividers and a Gerber scale. The completed grid, upon which the core area Loran C coordinates were plotted, was then inked onto transparent Stabelene mylar drafting film.

All data were taken within a 10-day study period, and to our knowledge the Loran C station signals used did not drift during this period. During an attempt to ground-truth fathometer readings six months later, however, we were unable to obtain true TDs from Loran C Stations 1 and 4 for the position of Marker 24 (a fixed tripod) or those of the on-station sanctuary boundary and core area marker buoys. The TDs had drifted considerably. Loran C signals are known to be affected by climatic conditions; fortunately, climatic conditions were calm, warm and stable during the July study period. Revisitation to the area in January 1984, however, immediately followed passage of a wind-driven cold front, and neither station's signal could be duplicated without first determining a (coincidental) correction factor of +10.0 for both LOPs.

Depth measurements throughout the sanctuary were based on interpretation of seismic-reflection records and use of weighted measuring tapes where possible (Figure 4.4; Tables 4.1, 4.3). Since tidal fluctuation in the lower Keys was less than 1 m during the study period (National Ocean Service, 1983, Key West tidal station), no correction factor was applied to the interpreted depths. Divers' depth gauges were used at two locations. A depth finder and Precision Depth Recorder were also employed during the study, but their values could not be incorporated into the bathymetric map due to inconsistent readings.

Results

Bathymetry

Contoured bathymetry of the area within the sanctuary and approximately 2.8 km landward of the north boundary, as interpreted from 838 data points along the seismic-reflection profiles, is shown in Figure 4.4. The most prominent topographic feature is a distinct east-west dropoff immediately seaward of the inner core area (also see Figures 4.2 and 4.5). The dropoff is sharp, and diving revealed a 30° - 40° slope extending from approximately 20 m down to 30 -

33 m, depending upon location. Two seismic-reflection profiles (see track line 1 in Figure 4.3) were run approximately 2 km seaward beyond the sanctuary and dropoff out to a depth of 80 m. Limited data from these nearly parallel tracks provided the basis for the contours which extend south of the boundary in Figures 4.4 - 4.6.

The dropoff extends from the east to west margin of the sanctuary and probably continues for several kilometers in either direction. Probably nowhere, however, is the degree of dropoff more spectacular than seaward of the southwest corner of the core area, where the slope is coral encrusted. Seaward of the southeast core area boundary, however, diving showed the slope to be less steep (Figure 4.2) and covered with carbonate sand.

Aside from the dropoff and Looe Key reef, parts of which are exposed at low tide, the third notable bathymetric/topographic feature is the broad depression which begins at a depth of 7 m near the north margin of the sanctuary. The depression deepens landward to a maximum of 14 m (Figures 4.4 and 4.5). This depression, called Hawk Channel on navigation charts, is part of the shelf lagoon that extends throughout the entire reef tract from Miami to Key West and beyond.

The bulk of the sanctuary therefore encompasses a 1- to 2-km-wide ridge between Hawk Channel and Looe Key reef. Throughout the reef tract, the seaward edge of the ridge (or outer margin of Enos, 1977) is ornamented with linear reefs composed principally of *Acropora palmata*. The top and landward parts of the ridge are generally ornamented with subcircular patch reefs composed of massive head corals and alcyonarians. Patch reefs also occur in Hawk Channel, but in the vicinity of Looe Key Sanctuary, they are sparse.

Bedrock topography

Given water quality favorable for coral growth, probably no single feature influences reef distribution more than the underlying bedrock topography. Previous core drilling studies (Shinn *et al.,* 1977; Shinn *et al.,* 1981) have confirmed that most major reefs in the Florida Keys overlie either small bedrock highs or the seaward side of large, broad topographic highs. Enos (1977) found that some patch reefs were located over topography formed by mudbanks during the early Holocene when sea level was lower.

With the exception of the spurs and grooves, bedrock topography clearly has controlled reef distribution in the study area. The subsurface Pleistocene horizon was identified in almost all 114 km of the seismic-reflection profiles, resulting in 771 data points that were used to illustrate bedrock configuration (Figure 4.5). Comparison of Figures 4.4 and 4.5 shows that the prominent sedimentary lobe south of the southeast corner of the core area is controlled by a Pleistocene bedrock feature. Reef growth has caused buildup along the seaward edge of this bedrock feature in the west half of the sanctuary. Reef growth effectively retards seismic returns and is responsible for the "no data" areas in Figures 4.5 and 4.6. East of the no data zones, seismic penetration was possible due to extensive carbonate sand cover. Figure 4.5 shows that one can confidently project the existence of a major change in slope beneath the southernmost no data zone.

It is also clear from Figure 4.5 that the bathymetric deepening of the sanctuary into Hawk Channel to the north is controlled by bedrock topography. Depth from water surface to bedrock in the axis of the channel ranges from 16 - 17 m, whereas beneath the east-west ridge underlying most of the sanctuary, depth to bedrock ranges from 12 - 14 m except for several localized depressions up to 18 m deep. Bedrock lows are usually filled with sediment, whereas bedrock highs are generally sites of modern reef growth. Reef growth apparently began on this ridge but transgressed landward with rising sea level so that today the major part of the reef overlies a sand-filled bedrock depression (Figure 4.12). This upward and landward transgression of coral reefs through time during a period of rising sea level has been documented by core drilling at several reefs along the Florida reef tract (Shinn *et al.,* 1977; Shinn, 1980; Robbin, 1981; Shinn *et al.,* 1981).

Sediment thickness

Isopachous variations in sediment cover (Figure 4.6) also reflect the relationship between sedimentary processes and underlying topography. Areas of thick sediment generally occur over localized bedrock lows, where sediment has simply filled depressions in the basement rock. A notable example is the 10- to 12-m-thick deposit filling the depression in the north half of the inner core area. Core drilling at sites LK-1, LK-9 and LK-10 (Shinn *et al.,* 1981; this paper, Figure 4.7) show that sediment thickness in this depression closer to the reef ranges from 13 - 15 m.

Only a thin sediment cover is generally maintained in the area of the steep dropoff with one localized exception: the thickest accumulation in the sanctuary lies southeast of Marker 24 (Figure 4.6) on the dropoff slope on the east side of a bedrock lobe that protrudes to the south (Figure 4.5). This lobe has apparently acted as a barrier to westward moving sediment, causing it to spill downslope in a southerly direction and accumulate behind the bedrock feature. Farther offshore, sediment thickness increases (with respect to the generally thin cover on the dropoff) below 30-m depths. In the most seaward area examined about 2 km south of the sanctuary, the deeper water deposits form accumulations as much as 9 m thick.

Rates of accumulation

Data concerning the recent Holocene relative rise in sea level (Scholl, 1964; Stockman *et al.,* 1967; Shinn, 1980; Robbin, 1984) indicate that the reefs and unconsolidated sediment deposits have formed and accumulated during the past 6,000 - 7,000 years. Prior to 7,000 years ago, the underlying Pleistocene bedrock within the sanctuary was dry land. Average sediment thickness within the sanctuary is 5.7 m, as determined from 410 measurements interpreted from the seismic-reflection records. Calculations based on the 5.7-m average and radiocarbon dates of Shinn *et al.* (1981) from material near the base of rock core LK-5 (Figure 4.12) infer an average rate of accumulation within the sanctuary of approximately 1 m/1,000 years since coral growth began. Within the bedrock depression immediately landward of Looe Key reef (north half of the core area) at the site of core LK-1, the average rate of sedimentation has been on the order of 2 m/1,000 years. Previous core drilling through the Looe Key reef (Shinn *et al.,* 1981, Figure 4.6) shows that initial coral growth began an the bedrock high just seaward of the reef. As sea level rose, the reef grew landward until it reached its present position overlying a thick deposit of carbonate sand (Figure 4.12).

Sediment composition

Thin sections of sediment samples were point counted for percent constituent particles, as described in the methods section. Results are tabulated in Table 4.1. In descending order of abundance are coral, molluscs and *Halimeda*, together comprising more than 72% of all samples regardless of grain size. The fact that these three components dominate the sediment is in accord with previous studies in the reef tract (Ginsburg, 1956; Swinchatt, 1965; Enos, 1977). The order of dominance in the sanctuary, however, differs from the generally accepted view that carbonate sands of the Florida reef tract usually contain more *Halimeda* than any other type of grain.

Percentages for particulate coral, mollusc and *Halimeda* grains were contoured on respective maps (Figures 4.9 - 4.11; cumulative 231 data points) to detect areas of high productivity, if possible, and to see if contours would suggest sediment transport direction. The latter was attempted because previous work and diver observations (Shinn *et al.,* 1981) had suggested east-to-west transport to such an extent that seaward parts of Looe Key reef had been smothered. Contoured east-west closures and "noses" in parts of Figures 4.9 and 4.11 are thought to support the east-to-west transport hypothesis. Alternatively, the contours may simply be reflecting underlying bedrock topography and/or sediment thickness which is more clearly related to bedrock topography.

Regardless of source area and direction of transport, sedimentary analyses produced surprising information concerning composition of reef tract sand in the Looe Key Sanctuary. As mentioned earlier, previous studies (Ginsburg, 1956; Swinchatt, 1965; Enos, 1977) have emphasized the prevalence of *Halimeda* within Florida reef tract sand, even in close proximity to coral reefs.

Coral

Coral was the single greatest component in 47 (49%) of the 96 sediment samples with an average grain count of 28% (range 3 - 53; Tables 4.1, 4.4; Figure 4.8). Coral sand distribution (Figure 4.9) shows that the presence of coral decreases markedly offshore, as one would expect, and comprises 10 - 15% of the finer grained sediment in the deep water seaward of the dropoff. Percent coral increases rapidly to more than 50 on and just above the dropoff due south and west of the core area. A closure with a high concentration (>55%) of coral occurs in an area of extensive coral growth in the west area of the sanctuary. High concentrations also occur near the northeast and north boundary, where a series of low-lying hardbottoms (also called live bottoms elsewhere in this volume) and patch reefs populated by hard and soft corals occurs. Although sediment samples were not taken in Hawk Channel north of the sanctuary, it is likely that coral percentage is low in those finer grained sediments. Coral patches and reefs are sparse in this part of the channel. Contours in the northwest corner of the sanctuary (Figure 4.9) support the relative absence of source areas by suggesting a decrease in coral particles to the north.

Sediment particles in the core area are typically dominated by coral. Data points within the core area were not contoured because of local irregularity of bottom depth and its effect on sediment content and transport. The core area contains zones of pebble- to boulder-size (4 to >256 mm) coral rubble (Figure 4.7, Plate 4.1) as well as the spur-and-groove system that forms Looe Key reef. This high- and low-relief seafloor topography influences sediment entrainment and creates pockets of trapped sands. Figure 4.7, illustrating Looe Key reef and the coral rubble zones that form behind the reef, shows distribution of the 19 uncontoured sample sites within the core area. Although only one of those samples (LKS-90) contained more than 50% coral, 10 others (LKS-52, 54, 59, 62 - 63, 91 - 95) were also coral-dominant (see Tables 4.1 and 4.4). The rubble "horns" are composed of nearly 100% coral, but because of the large size of the component blocks, they were not addressed by this study. Coral pebbles and boulders also occur sporadically within the reef in grooves separating the spurs.

The coral rubble has accumulated mainly behind or landward of Looe Key reef, as is the case for similar features worldwide [cf. the Great Barrier Reef of Australia (Davies, 1983)], yet much of the sand-size sediment southwest of the reef in depths of 10 - 20 m (Figure 4.4) contains up to 50% coral. Since Looe Key is the closest source of coral debris, this implies local offshore transport of sand-size coral in a southerly direction, whereas pebble- to boulder-size coral has been transported in a northerly (landward) direction.

Molluscs

The second surprise in the study was that molluscan fragments also exceed *Halimeda* in abundance. Excluding the 47 coral-dominant samples, 32 (or 33%) of the remaining samples were composed principally of mollusc particles. Molluscs also show a similar intermediate, with respect to coral and *Halimeda*, grain count average of 24% (range 7 - 50; Tables 4.1 and 4.4, Figure 4.8). Because the thin section pointcount method does not permit differentiation between fragments of pelecypods or gastropods, nor can they readily be identified as to species, it is difficult to determine the source areas. The contours of percentages in Figure 4.10, however, do give some clues. The broad areas containing 10 - 20% molluscs are mainly carbonate sand terraines (as observed on aerial photographs and by diving; see Table 4.1 for bottom description at sampling sites). In general, these desert-like areas, barren of coral and *Halimeda*, lack the productivity of grass-covered areas, which in turn are less productive than hardbottoms or coral areas. Note the broad areas north and west of the core area in Figure 4.10, where the bottom is either carpeted by *Thalassia* or contains coral patches. The molluscan content there ranges between 20 and 40%. In the highly diverse coral-rich area of the deep reef west and southwest of the southwest corner of the core area, molluscan particulates reach 50%. The best explanation for these percentages is that both grass-covered and coral-covered areas represent the living sites of molluscs and that upon breakdown into sand-size particles, both by biological and physical processes, transport has been relatively minor. The baffling and binding effect of sea grasses aids sediment stabilization and has probably prevented extensive transport beyond the source areas.

Of the 19 samples within the inner core area, mollusc fragments are dominant in seven (LKS-51, 53, 55-56, 58, 60, 64; Figure 4.7; Tables 4.1, 4.4). These seven samples are from sites within or proximal to areas of grooves between the spurs, high-energy habitats where molluscs are not normally endemic. Although the contours within the sanctuary suggest that offshore transport of a molluscan death assemblage is minimal, the high mollusc fragment concentration within the grooves at Looe Key reef appears to be a reflection of the constraints afforded by the irregular seafloor relief.

Halimeda

The calcified codiacian alga *Halimeda* is probably the dominant sediment producer throughout the Caribbean. One species, *H. incrassata*, forms small, widely scattered colonial "tufts" whereas another species, *H. opuntia*, grows as large (20- to 50-cm-diameter) colonial "cushions" that thrive in and around *Thalassia*-covered bottoms, on hard substrates within reefs, and especially on reef flats and boulder-covered areas. Storms periodically break up and disperse these living tufts and cushions as individual sand-size plates, but because of their proliferous growth rate, the plant recovers rapidly. Hudson (1985) has documented conspicuous growth demonstrated by *H. opuntia* in the Marquesas Keys off southwest Florida (Figure 4.1). His work has shown that this species produces as many as seven new plates along the upper edge of a single mature plate in a period of a few weeks.

It was thus interesting to note that this distinct and prolific alga was dominant in only 13 (14%) of the 96 samples with a grain count average of 20% (range 3 - 46; Tables 4.1 and 4.4, Figure 4.8). A possible (but thought to be negligible) influence on the generally low percentages may have resulted from a combination of two factors: the relatively large (some as much as 1500 µm wide) size of whole algal plates present in the sand-size material and the procedure used in the point-count method. Each grain of any component particle that appeared beneath the crosshairs was point counted only once. If a particularly large grain, for example one 1000 - 1500 µm in size, appeared under the crosshairs and was counted, as many as four or more additional 250-µm stops may have been required to advance the thin section beyond the large grain, depending upon its orientation at the time of count. When this occurred, therefore, as many as four or more other grains nearest the crosshairs were counted at the additional advance stops. Once past the original large grain, point count of grains falling directly beneath the crosshairs was resumed. Although first glance at many of the thin sections suggested an abundance of *Halimeda* grains, actual percentage may have been influenced slightly using this procedure. The same procedure, however, was also applied when counting large mollusc and coral grains, thus providing a similar bias and balance which would have uniformly affected the count of all large particles regardless of grain type. The fact remains, however, that percent coral sufficiently exceeded percent *Halimeda* so that even if the other four or more smaller grains (some coral, some molluscan) nearest the large algal plate under the crosshairs had not been counted, the percent of particulate coral would probably remain dominant in overall average as well as in total samples examined.

Figure 4.11 shows that in some cases the percentage of *Halimeda* is high in the same areas as that of molluscs. The area in the east and north parts of the sanctuary, however, where *Halimeda* content is high is also the same area where the percentage of molluscs is low, a non-grassy, desert-like area of rippled sand. This is not surprising because *Halimeda* plates are light in weight, being riddled with natural tubules and canals, and due to their disc-like shape as well, they are easily transported by tide and wave-driven currents. The high percentages of 40 - 45 near the east boundary are probably related to the extensive grass and hardbottom areas that begin just east of the east margin. The contours showing decreased percentages away from this source area supports the hypothesis of westward transport mentioned earlier.

Minor particles

Minor sediment components consisting of echinoid, bryozoa/red algae, benthic foraminifers and unknown particles (including mud) were identified in thin section (Table 4.1) but were not contoured as separate maps. Mud is particulate matter less than 62 µm across, whose origin usually cannot be determined using standard light microscopes. In most samples the mud became clotted during sample preparation, so what was identified as mud was usually a sand-size agglomerate of clots or lumps. Mud was most abundant in samples seaward of the major dropoff in water more than 30 m deep. In some samples sand-size particles have been highly micritized by boring algae and mud infill, as described by Bathurst (1967). In some cases such micritized grains are indistinguishable from clots of carbonate mud (see Figure 4.8).

Benthic foraminifers dominated all other particles in only one sample (LKS-77) and comprised more than 15% (range 1 - 22) of the point-counted particles in 4 (4%) of the samples (Tables 4.1, 4.4). Foraminifers were found to be concentrated in the muddy sands seaward of the dropoff (>30 m of water). No attempt was made to quantify the various foraminiferal families identified other than to note that among the most common tests were members of the miliolid, soritid, rotalid, discorbid and amphisteginid families. These families are characteristic of a carbonate platform margin environment [0 - 40 m depths (Rose and Lidz, 1977)], of which the Florida reef tract is an example.

Local current patterns and shallow-water features such as basins, mudbanks and patch reefs influence the distribution and abundance of benthic foraminifers. Benthic species generally prefer calm, protected living areas behind the area of agitated water at the shelf break, where tidal flushing also occurs. In general, miliolids dominate mudbanks and "lakes" of a carbonate platform and soritids prefer the seagrass areas. Abundance of live specimens across a platform generally decreases in an offshore direction, and in deeper water beyond the platform edge, abundance of individuals, albeit of different, deeper water species, again increases. The observation that the greatest concentration of platform foraminifers was found seaward of the dropoff does not imply a less favorable habitat landward of the reef but is more likely a reflection of offshore transport.

Neither bryozoa/red algae nor echinoid percentages showed any meaningful trend. Both comprised more than 10% of the sediment (Tables 4.1, 4.4) in a few samples scattered at random throughout the sanctuary regardless of type of bottom, water depth, or proximity to the reef. The bryozoa/red algae group dominated all other grain types in one sample (LKS-76) and formed more than 1.5% (range 2 - 23) of the point-counted particles in 4 of the samples. Echinoid fragments also composed greater than 15% (range 1 - 18) of the sediment in 4 samples, while more than 15% (range 2 - 22) of the particles counted could not be identified in 15 (16%) samples.

Discussion

Coral rubble and sand transport

Although bedrock topography has a shape similar to that of other areas in the Florida Keys, i.e., a broad ridge near the edge of the platform and a landward trough (Hawk Channel), the dropoff in the seaward part of the sanctuary is more pronounced than anywhere else of similar depth in the reef tract. In the upper Keys area, where the platform margin is essentially perpendicular to prevailing winds, both sediment and coral rubble are consistently transported landward (Ball *et al.,* 1967; Perkins and Enos, 1968). In the Looe Key area, however, where the platform margin is nearly parallel to wind direction, carbonate sand has accumulated both landward and seaward of the reef. Forereef accumulation has been so extensive that a deeper outer part of Looe Key reef has been smothered, and coral rubble (pebble- to boulder-size but mainly in the size range of cobbles, or 64 - 256 mm; Figure 4.7, Plate 4.1) has collected landward of the reef.

The large waves and swells produced by storms must come from the deep water seaward of the reef, whereas storm waves from the north and northeast must be smaller due to shallow water depth and lack of sufficient fetch. Seas moving in a landward direction in such storms apparently deposited the coral boulders behind the reef where they are not likely to be removed by the smaller waves and swells emanating from a landward direction. On the other hand, sand-size material can be transported by seas moving in any direction. This combination of depth, wave direction and fetch is thought to be the explanation for the distribution of coral boulders (Plate 4.1) landward of the reef and coral-rich sands (Figure 4.9) seaward of the reef. Rapid sediment transport and deposition (approximate rate 2 m/1,000 years) accounts for the 12- to 15-m-thick section of carbonate sands behind the reef in the north half of the core area (Figure 4.12).

As discussed above, sediment transport appears to be related to the east-west trend of the platform margin and the angle at which storms and hurricanes impinge on the platform. Historically, most hurricanes have approached Florida from the southeast. Because hurricane winds rotate counterclockwise, the first winds to obtain landfall will blow offshore from the northeast. In addition, the strongest winds in a Caribbean hurricane that is moving in a northwest direction are in the northwest quadrant. Therefore, the first and strongest winds to hit the lower Keys will be from the northeast, precisely the direction required to explain the sand accumulation seaward of Looe Key reef. In the upper Keys, where the trend of the platform margin is essentially north-south, strong northeast winds move sediment primarily in a landward direction (Ball *et al.,* 1967; Perkins and Enos, 1968), although Ball *et al.* (1967) also reported a lesser degree of offshore transport in a few passes between large reefs. This offshelf movement was thought to occur as the hurricane progressed northwestward and winds in its southeast quadrant blew mainly in an offshore direction. Such winds, combined with receding water that had been piled up on the shelf by onshore winds, would probably account for some seaward movement of the sand.

Sediment composition

One of the more surprising discoveries of the sediment analysis was that both coral and mollusc grains were more common than *Halimeda*. In the classic study by Ginsburg (1956) and later confirmed by Swinchatt (1965), *Halimeda*-derived grains were found to dominate reef tract sediment. Figure 9 of Ginsburg (1956) shows that, although *Halimeda* dominates all other sedimentary particles in his study area, its relative percentage was less in the middle Keys off Marathon than in transects in the upper Keys. This observation suggests a trend of decreasing *Halimeda* sand content from north to southwest along the reef tract, which is compatible with our discovery that *Halimeda* is subordinate to mollusc and coral fragments in the Looe Key Sanctuary.

Coral growth has been retarded in the middle and lower Keys due to rising sea level and consequent influx of estuarine and turbid, cold Gulf of Mexico water to the reef areas during winter (Ginsburg and Shinn, 1964; Shinn, 1976; Lighty, 1977; Roberts *et al.,* 1982). Living reefs are absent opposite major breaks in the Florida Keys. One such reef opposite a 1.0-km-wide breach in the island chain (Hudson, this volume) is Alligator reef in the middle Keys. Drilling at Alligator reef showed the reef to have been constructed by *Acropora palmata*, which is almost non-existent there today (Robbin, 1981). Core drilling of the spurs at Looe Key reef by Shinn *et al.* (1981) also showed *A. palmata* to have been the major reef builder, although today it is sparse on the spurs drilled. Both studies suggested that *A. palmata* growth began to diminish about 4,000 years ago. According to published sea-level curves (Scholl, 1964; Stockman *et al.,* 1967; Robbin, 1981), sea level 4,000 years ago was approximately 3 m lower than today. Under such conditions, Florida Bay and most of the tidal passes through the Florida Keys would not have existed, and water quality along the platform margin facing the Straits of Florida would have been more favorable for coral growth than it is today.

Farther down the island chain to west of the Marquesas Keys (Figure 4.1), however, *Halimeda* particles increase markedly to comprise at least 90% of the sediments, as shown by ongoing studies by the US Geological Survey Fisher Island staff in an area known as the Quicksands. Here, the algal sand forms accumulations as much as 12 m thick that cover a 13 km x 29 km area (Shinn *et al.,* 1982; Shinn *et al*., 1990). In this case, it was concluded that a combination of cold Gulf of Mexico water and prevailing poor water visibility have prevented coral reef establishment while concurrently permitting extensive *Halimeda* growth. Whether or not *Halimeda* growth rates are actually faster west of the Marquesas than in other areas of the Keys is not known, although Hudson (1985) has documented extremely rapid growth. Unfortunately, there have been no companion studies In the upper Keys for comparison.

The most plausible explanation for coral sand dominance at Looe Key Sanctuary, therefore, is not a reduced *Halimeda* growth but increased production of coral-derived grains. Except for Looe Key reef, whose corals are less prolific and diverse than those comprising reefs to the north (for example, in the Key Largo Coral Reef Marine Sanctuary), coral growth within the entire sanctuary is diminished with respect to other areas along the reef tract. In fact, reefs immediately to the east of the sanctuary are considered dead by Caribbean standards, and the patch reefs or hardbottoms that are scattered throughout the north half of the sanctuary are composed of dead coral. Relatively few living corals other than alcyonarians can be found on these patches.

Dead coral is more readily attacked by boring organisms, such as pholad clams, boring sponges and parrot fish, than is living coral. Thus, when a reef dies, incipient deterioration is immediate as boring sponges initiate the first stage of coral reduction into silt- and sand-size particles through erosive actions (Neumann, 1966; Rützler, 1975; Hudson, 1977; Moore and Shedd, 1977). Hudson (1977) found that corals at Hen and Chickens reef in the middle Keys, killed in 1969 by cold water, were attacked by *Cliona* (a boring sponge) and other organisms which destroyed dead *Montastraea annularis* heads at a rate of about 7 mm/year, a rate which is slightly less than the growth rate (8.5 mm/year) for the species. Prior to the 1969 kill, the sand between coral heads at Hen and Chickens consisted almost entirely of whole *Halimeda* plates. Post-1969 observations (J. H. Hudson and E. A. Shinn) revealed that sediment composition had been converted to silt-size coral-dominant sand. The sudden increase in silt-size coralline sediment was often cited as the cause of coral death, when in actuality it resulted from coral death and subsequent bioerosion (Hudson and Shinn, pers. observation). We conclude, therefore, that bioerosion of dead coral substrates rather than reduced *Halimeda* production is responsible for dominance of coral particles in sediments at Looe Key Sanctuary and probably in the lower Keys in general, because the ratio of dead to live corals is higher than in the Key Largo Coral Reef Sanctuary off the upper Keys.

Conclusions

Carbonate sedimentary particles, sediment thickness, depositional processes and mapping of underlying pre-Holocene bedrock topography have been described for the area in the lower Florida reef tract known as the Looe Key National Marine Sanctuary. This work has documented the dominance of particulate coral over *Halimeda* grains in the sanctuary. Although *Halimeda* is considered the principal sediment-producer in the Caribbean, it becomes increasingly subordinate to coral and mollusc particles in the sediment from north to southwest along the Florida reef tract. This trend complements a similar trend in live to dead reef corals that allows bioerosion of dead coral heads to contribute progressively greater percentages of particulate coral to the sediment than *Halimeda* grains. At the same time, *Halimeda* production is thought not to have been reduced.

Movement of sediment in the sanctuary occurs in a predominantly east-to-west direction, a direction that is supported by the contoured percentages of coral and *Halimeda* fragments. Sediment thickness indicates that rate of accumulation has been 1-2 m/1,000 years.

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References cited

Ball, M. M., Shinn, E. A., and Stockman, K. W., 1967, The geologic effects of Hurricane Donna in South Florida. J. Geol., 75(5):583-597.

Bathurst, R. G. C., 1967, Oolitic films on low energy carbonate sand grains, Bimini Lagoon, Bahamas. Mar. Geol., 5:89-109.

Corps of Engineers, 1983, Looe Key National Marine Sanctuary Boundary Survey Plan, surveyed by G. F. Young, Inc., St. Petersburg, for Department of Army Corps of Engineers, Jacksonville, 3-3-83.

Davies, P. J., 1983, Reef growth, in Barnes, D. J., ed., Prospectives on Coral Reefs, published for Australian Institute of Marine Science by Brian Clouston, Publisher, Manuka, Australia, p. 69-106.

Enos, P., 1977, Quaternary depositional framework of South Florida. Part I: Carbonate sediment accumulations of the South Florida shelf margin. Geological Society of America Memoir 147, p. 1-130.

Ginsburg, R. N., 1956, Environmental relationships of grain size and constituent particles in some South Florida carbonate sediments. Amer. Assoc. Petroleum Geologists Bull., 40(10):2384-2427.

Ginsburg, R. N., and Shinn, E. A., 1964, Distribution of the reef-building community in Florida and the Bahamas (abs.). Amer. Assoc. Petroleum Geologists Bull., 48:527.

Hudson, J. H., 1977, Long-term bioerosion rates on a Florida reef: a new method. Proceedings, Third International Coral Reef Symposium, Miami, v. 2, Geology, p. 491-497.

Hudson, J. H., 1985, Growth rate and carbonate production in *Halimeda opuntia*, Marquesas Keys, Florida, in Toomey, D. F., and Nitecki, M. H., eds., Paleoalgology: Contemporary Research and Applications: Berlin, Heidelberg, Springer-Verlag, p. 257-263.

Lidz, B. H., Robbin, D. M., and Shinn, E. A., 1985, Holocene carbonate sedimentary petrology and facies accumulation, Looe Key National Marine Sanctuary, Florida. Bull. Mar. Sci., 36(3):672-700.

Lighty, R. G., 1977, Relict shelf-edge Holocene coral reef: southeast coast of Florida. Proceedings, Third International Coral Reef Symposium, Miami, v. 2, Geology, p. 215-221.

Moore, C. H., Jr., and Shedd, W. W., 1977, Effective rates of sponge bioerosion as a function of carbonate production. Proceedings, Third International Coral Reef Symposium, Miami, v. 2, Geology, p. 499-505.

National Ocean Service, 1983, Nautical Chart #11442, 22nd ed., April 16, Florida Keys (Sombrero Key to Sand Key): published by NOS, National Oceanic and Atmospheric Administration, US Department of Commerce, Washington, D.C.

National Ocean Service, 1983, Tide tables: high and low water predictions for East Coast of North and South America including Greenland (issued 1982). Published by NOS, National Oceanic and Atmospheric Administration, US Department of Commerce, Washington, D.C.

Neumann, A. C., 1966, Observations on coastal erosion in Bermuda and measurements of the boring rate of the sponge, *Cliona lampa*. Limnol. Oceanogr., 11:92-108.

Perkins, R. D., and Enos, P., 1968, Hurricane Betsy in the Florida-Bahamas area: geologic effects and comparison with Hurricane Donna. J. Geol., 76:710-717.

Robbin, D. M., 1981, Subaerial $CaCO_3$ crust: a tool for timing reef initiation and defining sea level changes. Proceedings, Fourth International Coral Reef Symposium, Manila, v. 1, p. 575-579.

Robbin, D. M., 1984, A new Holocene sea level curve for the upper Florida Keys and Florida reef tract, in Gleason, P. J., ed., Environments of South Florida, Present and Past, II: Miami Geological Society, p. 437-458.

Roberts, H. H., Rouse, L. J., Jr., Walker, N. D., and Hudson, J. H., 1982, Cold-water stress in Florida Bay and northern Bahamas: a product of winter cold-air outbreaks. J. Sedimentary Petrology, 52(1):145-155.

Rose, P. R., and Lidz, B., 1977, Diagnostic foraminiferal assemblages of shallow-water modern environments: South Florida and the Bahamas, in Lidz, B., ed., Sedimenta VI: Comparative Sedimentology Laboratory, University of Miami, 55 pp.

Rützler, K., 1975, The role of burrowing sponges in bioerosion: Oecologia (Berl.), 19:203-216.

Scholl, D. W., 1964, Recent sedimentary record in mangrove swamps and rise in sea level over the southwestern coast of Florida, Part I and II. Mar. Geol., 1:344-366, 2:343-364.

Scholle, P. A., 1978, A Color Illustrated Guide to Carbonate Rock Constituents, Textures, Cements and Porosities. American Assoc. Petroleum Geologists Memoir 27, 241 p.

Shinn, E. A., 1976, Coral reef recovery in Florida and the Persian Gulf. Environ. Geol., 1:241-254.

Shinn, E. A., 1980, Geologic history of Grecian Rocks, Key Largo Coral Reef Marine Sanctuary: Bull. Mar. Sci., 30(3):646-656.

Shinn, E. A., Holmes, C. W., Hudson, J. H., Robbin, D. M., and Lidz, B. H., 1982, Nonoolitic, high-energy carbonate sand accumulation: the Quicksands, southwest Florida Keys (abs.). Book of Abstracts, American Association of Petroleum Geologists Annual Meeting, Calgary, p. 110-111.

Shinn, E. A., Hudson, J. H., Halley, R. B., and Lidz, B., 1977, Topographic control and accumulation rate of some Holocene coral reefs: South Florida and Dry Tortugas. Proceedings, Third International Coral Reef Symposium, Miami, v. 2, Geology, p. 1-7.

Shinn, E. A., Hudson, J. H., Robbin, D. M., and Lidz, B., 1981, Spurs and grooves revisited: construction versus erosion, Looe Key reef, Florida. Proceedings, Fourth International Coral Reef Symposium, Manila, v. 1, p. 475-483.

Shinn, E. A., Lidz, B. H., and Holmes, C. W., 1990, High energy carbonate sand accumulation, the Quicksands, southwest Florida Keys. J. Sedimentary Petrology, 60(6):952-967.

Stockman, K. W., Ginsburg, R. N., and Shinn, E. A., 1967, The production of lime mud by algae in South Florida. J. Sedimentary Petrology, 37(2):633-648.

Swinchatt, J. P., 1965, Significance of constituent composition, texture, and skeletal breakdown in some Recent carbonate sediments. J. Sedimentary Petrology, 35(1):71-90.

Table 4.1. Brief bottom description of each surface sediment sample location, total grain count per thin section, and percentage for each of seven constituent particles. "Other" category includes mud and unidentifiable grains. Location of samples is shown in Figures 4.3 and 4.7.

Sample no.*	Bottom description	Grain count	Percent Constituent particles: *Halimeda*	Mollusc	Coral	Echinoid	Bryozoa + Red algae	Benthic foraminifers	Other
LKS-1	*Thalassia*, *Penicillus*, *Syringodium*	174	40.2	17.2	20.1	8.6	3.5	2.9	7.5
LKS-2	Sparse grasses	165	28.0	18.8	17.6	4.8	3.6	4.8	22.4
LKS-3	Grassy	147	46.2	15.7	21.1	2.7	5.4	1.4	7.5
LKS-4	Sandy, rocky, patchy *Sargassum*, *Thalassia*	145	41.7	25.7	11.1	3.4	3.5	1.4	13.2
LKS-5	Patchy *Thalassia*, sponges, sand, alcyonarians	175	33.7	13.0	31.4	2.9	5.8	4.0	9.2
LKS-6	Barren, rocky outcrops, rare alcyonarians	154	43.5	16.9	24.0	2.6	5.9	3.9	3.2
LKS-7	Barren	154	37.0	10.4	31.8	1.9	9.8	3.9	5.2
LKS-8	*Thalassia*-covered, rare *Udotia* (?)	154	40.9	7.8	27.9	5.8	11.0	1.3	5.3
LKS-9	Barren, wide sand waves ~5 cm high x 15 cm wide	166	36.2	16.3	30.1	3.0	7.2	2.4	4.8
LKS-10	Dense grass (*Thalassia*, *Syringodium)*, patchy sand	163	21.5	12.9	28.8	6.8	3.6	4.9	21.5
LKS-11	Little sand, 50% *Thalassia,* 50% *Syringodium*	162	24.7	20.4	25.9	3.1	3.8	6.7	15.4
LKS-12	Reef rubble, *Millepora*, *Diadema*, light cover alcyonarians, no grass	166	25.9	13.9	39.8	5.4	3.0	3.6	8.4
LKS-13	Typical backreef community, small head corals, no grass, no buildup, some large alcyonarians, *Diadema*	171	15.8	7.0	52.6	6.4	2.4	2.9	12.9
LKS-14	Uniform 30 cm long x 1 cm high sand waves, bare except for sparse *Penicillus* and *Udotia*	165	33.9	22.4	15.8	6.1	2.4	4.2	15.2
LKS-15	Sandy, sparse *Thalassia* and red algae	166	27.1	16.9	29.5	4.2	6.6	1.8	13.9
LKS-16	Moderate *Thalassia,* sparse *Udotia* and alcyonarians, large loggerhead sponge	162	37.7	22.8	25.3	3.7	4.3	1.2	4.9^{Δ}
LKS-17	Barren, sandy, sparse red algae and *Udotia*, irregular sand waves 10 - 15 cm long x 1 cm high	174	17.2	13.8	33.3	4.0	12.2	4.0	15.5
LKS-18	Barren, small community of large loggerhead sponges + alcyonarians, single *Halimeda incrassata*	151	21.2	18.6	34.4	4.6	5.3	3.3	12.6
LKS-19	Barren	175	19.4	18.3	36.0	5.1	6.3	4.6	10.3
LKS-20	Barren, sparse red algae	178	18.0	20.8	37.6	3.9	9.0	2.3	8.4

Table 4.1. Brief bottom description of each surface sediment sample location, total grain count per thin section, and percentage for each of seven constituent particles. "Other" category includes mud and unidentifiable grains. Location of samples is shown in Figures 4.3 and 4.7 (cont.)

			Percent Constituent particles						
Sample no.*	Bottom description	Grain count	*Halimeda*	Mollusc	Coral	Echinoid	Bryozoa + Red algae	Benthic foraminifers	Other
LKS-21	Begin spur and groove with typical reef community, low amplitude 5 cm high x 10 cm long sand waves, peaks 30 - 40 cm apart	178	21.4	25.8	23.0	5.1	8.4	5.6	10.7
LKS-22	Barren, sandy, 1 sponge, regular sinuous peaked sand waves 5 cm high, peaks 30 - 40 cm apart	175	26.3	24.6	27.4	2.3	10.3	2.3	6.8
LKS-23A	Moderate grass cover (*Batophora, Syringodium*, *Thalassia)*, *Halimeda* on rubble, feather-like green alga	143	14.7	19.6	31.4	4.2	6.3	7.0	16.8
LKS-23B	Sand waves, some red algae and *Udotia*	176	21.0	30.7	22.7	1.1	8.0	8.5	8.0
LKS-24	Dense *Thalassia, Syringodium*	160	23.0	31.9	15.0	11.9	6.9	3.8	7.5
LKS-25	Barren, small patches light *Thalassia*	165	26.7	24.2	19.4	7.2	6.1	5.5	10.9
LKS-26	Moderate *Thalassia*, some sand patches, alcyonarians	155	23.9	16.1	34.8	6.5	5.8	4.5	8.4
LKS-27	Dense *Thalassia*, light *Syringodium,* sparse *Penicillus*, some red or brown algae	158	29.1	31.0	22.1	9.5	3.2	1.3	3.8
LKS-28	Typical low relief backreef with small head corals, alcyonarians	177	16.4	25.4	37.3	5.1	4.5	3.4	7.9
LKS-29	Patchy sand, moderate *Thalassia*, sparse *Penicillus* and large red-stalked alga	153	32.0	20.2	26.8	3.9	4.0	2.0	11.1
LKS-30	Barren, sparse red algae, *Udotia*	155	22.6	24.5	23.9	5.8	12.3	4.5	8.4
LKS-31	Dense *Thalassia*, some *Syringodium*	175	16.0	18.3	29.7	10.3	2.3	4.0	19.4
LKS-32	Barren, very sparse *Udotia*, *Thalassia*	167	24.0	12.0	34.7	3.6	6.0	2.4	17.3
LKS-33	Patchy sand and grass, moderate *Thalassia* in grassy area, sparse *Udotia* in sand	161	23.6	14.3	33.5	3.7	6.2	3.1	15.5^{Δ}
LKS-34	Loggerhead sponges, dense *Thalassia*, *Syringodium*	156	14.7	12.2	34.0	10.9	7.0	2.6	18.6
LKS-35	Live hardbottom	163	13.5	20.3	42.3	1.8	8.0	1.2	12.9

Table 4.1. Brief bottom description of each surface sediment sample location, total grain count per thin section, and percentage for each of seven constituent particles. "Other" category includes mud and unidentifiable grains. Location of samples is shown in Figures 4.3 and 4.7 (cont.)

			Percent Constituent particles						
Sample no.*	Bottom description	Grain count	*Halimeda*	Mollusc	Coral	Echinoid	Bryozoa + Red algae	Benthic foraminifers	Other
LKS-36	Patchy sand, alcyonarians, some exposed rock	152	11.8	45.4	19.7	0.7	5.9	4.6	11.8^{Δ}
LKS-37	Live hardbottom, moderate *Acropora cervicornis*	161	6.8	50.3	17.4	4.4	9.9	3.7	7.5
LKS-38	Barren, isolated red algae and *Udotia*	167	19.1	32.9	24.0	4.8	4.2	3.0	12.0
LKS-39	Barren, some small, sparse patches *Thalassia*, *Syringodium*	170	24.7	41.2	8.8	3.5	4.7	5.3	11.8
LKS-40	Light cover *Thalassia* and *Syringodium*	141	14.9	38.3	13.5	7.8	4.2	2.1	19.2
LKS-41	*Halimeda*, red and green algae, no grasses	168	31.5	31.5	6.6	13.1	4.2	5.4	7.7
LKS-42	Light *Halimeda*, *Thalassia*, some *Udotia*	181	28.2	35.4	9.4	17.7	2.7	3.3	3.3
LKS-43	Hardbottom, several good-size colonies *Oculina*, some coral, rest barren	165	13.9	27.3	26.7	7.3	4.2	3.6	17.0
LKS-44	Live hardbottom	172	4.1	39.4	43.0	4.1	4.7	0.6	4.1
LKS-45	"Scruffy" live hardbottom	166	13.3	24.1	36.2	5.4	9.0	4.2	7.8
LKS-46	Good live hardbottom, dead clump *Acropora cervicornis*	178	3.4	16.8	57.9	1.7	9.0	1.7	9.5
LKS-47	Reefal, 0.5 m high buildup, live corals on top, patchy	177	7.9	29.9	37.9	4.5	7.3	2.3	10.2
LKS-48	Barren, very sparse small pieces live red algae	179	14.0	31.3	32.4	3.3	2.3	3.9	12.8
LKS-49	Live hardbottom, fewer head corals and more alcyonarians than earlier live hardbottom sites	184	8.7	23.4	49.5	0.5	7.6	2.2	8.1
LKS-50	Barren except for abundant baby conch on sticky fine-grained bottom	173	15.0	37.6	2.9	13.3	4.6	7.5	19.1
LKS-51	Depth 8.0 m, sand in groove next to core LK-1 (1980) and LK-9 (1983), first groove west of pot wreck sandhole	167	15.6	26.9	25.1	3.0	8.4	5.4	15.6
LKS-52	Depth 1.0 m, coral rubble in coarse sand matrix, $^{1}/_{2}$ sand halo west of grass	183	8.7	21.3	39.9	2.7	9.9	3.8	13.7
LKS-53	Depth 2.0 m, coral rubble in coarse sand matrix	180	13.3	35.6	25.6	2.8	13.3	3.9	5.5
LKS-54	Depth 5.3 m, coarse sand	171	14.0	27.5	36.3	5.3	7.6	3.5	5.8
LKS-55	Depth 7.3 m, coarse sand	177	16.4	33.9	27.7	5.6	5.6	2.8	7.9^{Δ}
LKS-56	Depth 8.3 m, coarse sand	168	21.4	36.9	25.0	1.8	5.4	3.0	6.5

Table 4.1. Brief bottom description of each surface sediment sample location, total grain count per thin section, and percentage for each of seven constituent particles. "Other" category includes mud and unidentifiable grains. Location of samples is shown in Figures 4.3 and 4.7 (cont.)

			Percent Constituent particles						
Sample no.*	Bottom description	Grain count	*Halimeda*	Mollusc	Coral	Echinoid	Bryozoa + Red algae	Benthic foraminifers	Other
LKS-57	Depth 10.7 m, rippled, stabilized by algal scum	167	22.2	31.7	28.1	1.8	10.8	0.6	4.8
LKS-58	Depth 4.5 m, seaward edge of rubble zone, coarse sand	160	23.1	34.4	20.0	0.6	13.1	3.1	5.6^{Δ}
LKS-59	Depth 5.5 m, east edge of Marker 24, fine sand	182	23.1	20.3	32.4	4.4	5.0	6.0	8.8
LKS-60	Depth 8.6 m, coarse sand	163	30.7	31.3	20.2	4.9	7.4	3.7	1.8
LKS-61	Depth 9.9 m, coarse sand	157	12.7	26.8	38.2	1.3	11.4	3.8	5.7^{Δ}
LKS-62	Depth 5.4 m, coarse sand	173	17.3	27.2	33.0	2.9	9.8	4.6	5.2
LKS-63	Depth 7.0 m, coarse sand	159	20.8	25.2	40.2	2.5	5.0	2.5	3.8
LKS-64	Depth 8.0 m, coarse sand	161	29.2	31.7	21.1	1.2	8.1	3.1	5.6
LKS-65	Depth 8.9 m, coarse sand	165	20.6	27.3	29.1	5.4	7.3	4.2	6.1
LKS-66	Depth 17.7 m, top of slope	168	24.4	16.0	30.4	4.8	8.9	10.1	5.4
LKS-67	Depth 30 m, near toe of slope, coarse sand	159	21.4	24.5	24.5	6.9	8.2	6.3	8.2
LKS-68	Coarse sand	166	18.1	19.3	39.8,	1.8	12.0	3.6	5.4
LKS-69	Silt and mud in coarse sand, abundant large ($^1/_2$ cm) dead *Sorites* tests	154	22.1	19.5	32.5	3.9	8.4	9.1	4.5
LKS-70	Silt and mud, no coarse sand	142	10.6	20.4	26.1	9.2	6.3	21.8	5.6
LKS-71	Coarse sand in fine matrix	155	9.7	31.6	7.1	16.1	7.7	12.9	14.8^{Δ}
LKS-72	Coarse and fine sediment	167	17.4	29.3	32.3	2.4	6.6	9.0	3.0
LKS-73	Coarse and fine sediment	173	27.2	36.4	15.6	1.7	8.7	6.9	3.5
LKS-74	Coarse and fine sediment	164	17.1	15.9	38.4	6.1	9.1	6.7	6.7
LKS-75	Coarse and muddy sediment	164	9.8	30.5	21.3	7.3	6.1	9.1	15.9
LKS-76	Fine-grained, *Manicina*	148	9.5	21.6	8.8	12.8	23.0	15.5	8.8
LKS-77	Mud	171	11.1	19.3	12.9	15.2	13.5	19.9	8.1
LKS-78	Live *Halimeda*, *Udotia* in mud, allochthonous ooids	156	12.8	18.6	22.4	10.9	10.9	11.5	$12.7^{\Diamond}$
LKS-79	Mud	157	13.4	29.3	18.5	8.3	11.4	13.4	5.7
LKS-80	Mud	161	16.1	24.2	8.1	14.3	15.5	13.7	8.1
LKS-81	Mud	175	8.6	12.0	52.0	8.6	13.7	2.9	2.2
LKS-82	Mud	184	21.2	26.6	24.5	6.0	7.0	8.2	6.5
LKS-83	Mud, dead *Thalassia* with roots	164	9.8	31.1	22.6	9.1	11.0	9.1	7.3
LKS-84	Mud	179	12.3	26.8	16.2	11.7	15.6	11.2	6.1^{Δ}
LKS-85	Mud	170	16.5	20.0	14.7	10.6	14.7	8.8	14.7
LKS-86	Mud, a few large ($^1/_2$ cm) *Sorites*	172	13.3	19.8	20.9	15.7	11.1	11.6	7.6
LKS-87	Mud	159	19.5	31.4	14.5	11.3	8.8	10.1	4.4
LKS-88	Mud	161	19.2	21.1	8.7	11.8	17.4	17.4	4.4
LKS-89	Fine sand on north edge of rubble horn, regular sinuous sand waves	166	22.9	20.5	39.2	3.6	8.4	1.8	3.6
LKS-90	Coarse rubble behind reef	148	9.5	22.3	52.0	0.7	8.8	2.7	4.0
LKS-91	*Thalassia*, *Syringodium*	168	23.2	18.4	40.4	5.4	4.2	4.2	4.2

Table 4.1. Brief bottom description of each surface sediment sample location, total grain count per thin section, and percentage for each of seven constituent particles. "Other" category includes mud and unidentifiable grains. Location of samples is shown in Figures 4.3 and 4.7 (cont.)

			Percent Constituent particles						
Sample no.*	Bottom description	Grain count	*Halimeda*	Mollusc	Coral	Echinoid	Bryozoa + Red algae	Benthic foraminifers	Other
LKS-92	Small (2 m) fine-grained sand patch in grassy area	164	15.9	22.5	40.9	1.8	8.5	3.7	6.7
LKS-93	Sandy blowout, closely spaced sand waves 4 - 5 cm high, ~10 cm between peaks	171	15.2	19.3	45.6	0.6	9.9	4.1	5.3
LKS-94	Sandy blowout, sand waves similar to those at LKS-93	174	22.4	23.0	36.2	2.9	6.3	4.6	4.6
LKS-95	*Thalassia*, *Syringodium*	180	18.9	17.8	28.3	8.3	7.8	8.9	10.0

Total grain count - 15,890; maximum 184; minimum 141; mean 166.

* See Figure 4.4 for bathymetry as interpreted from the seismic profiles. Depths taken with weighted tape measure are given for samples LKS-51 through LKS-65. Depths for LKS-66 and LKS-67 were read from diver's depth gauge.
∆ Total percent - 99.9.
◊ Total percent - 99.8.

Table 4.2. Comparative data for boundary marker buoys. Loran C coordinates defining accurate locations of Coast Guard Marker 24 and sanctuary and core area boundary buoys (described by Corps of Engineers as tie down anchors). Coordinates were obtained from Loran C receivers tracking Loran C TDs for Stations 1 and 4 at 13900 and 62500 µsec, respectively. Note that the SE and SW sanctuary buoys are located in the middle of the east and west boundaries and not at the south corners; both south corners lie in approximately 40 - 45 m of water (Figure 4.4) at the edge of the Gulf Stream. Also note that the SW buoy marking the west sanctuary boundary and buoy at the SW corner of the core area are described as being "off station." Both marker buoys were actually missing at the time of study.

	Location			Water depths	
	This Paper Loran C	Corps of Engineers Boundary Survey Plan Latitude	Corps of Engineers Boundary Survey Plan Longitude	This Paper m (ft)	Corps of Engineers Boundary Survey Plan m (ft)
Looe Key Sanctuary Boundary Markers					
NE buoy (corner)	13979.4, 62547.3	24°34'91"	81°23'00"	9 (30)	9 (30)
SE buoy (due east of Marker 24)	13977.4, 62547.8	24°32'12"	81°22'59"	15 (49)	12 (40)
NW buoy (corner)	13972.8, 62560.1	24°33'34"	81°25'59"	11(36)	9 (30)
SW buoy (due west of Marker 24)	Off Station	24°31'37"	81°26'00"	12 (40)	12 (40)
Core Area Boundary Markers					
NE buoy (corner)	13975.3, 62553.0	24°33'04"	81°24'16"	4 (13)	9 (30)
SE buoy (corner)	13975.2, 62552.4	24°32'45"	81°24'05"	4 (13)	11 (35)
NW buoy (corner)	13974.2, 62554.7	24°32'50"	81°24'41"	7 (23)	9 (30)
SW buoy (corner)	Off Station	24°32'37"	81°24'38"	11(36)	9 (30)
Coast Guard Marker 24	13975.1, 62552.6	Not given		3 (11)	Not given

Table 4.3. Water depths within inner core area taken by weighted tape measure at sites of 19 sediment samples, locations of 11 reef rock core holes and nine coral core stations.

Sediment Samples			Reef Core Samples			Coral Core Samples		
Sample No.	Depth (m)	(ft)	Sample No.	Depth (m)	(ft)	Station No.	Depth* (m)	(ft)
LKS-51	8.0	26.2	LK-1	3.2	10.0	A	4.1	1.2
LKS-52	1.0	3.3	LK-2	2.0	6.6	B	5.3-6.5	17.4-21.3
LKS-53	2.0	6.6	LK-3	4.9	16.0	C	5.3-6.2	17.4-20.3
LKS-54	5.3	17.9	LK-4	5.8	19.0	D	3.8-4.1	12.5-13.4
LKS-55	7.3	29.9	LK-5	6.0	19.7	E	6.4	21.0
LKS-56	8.3	27.2	LK-6	8.0	26.2	F	3.8	12.5
LKS-58	4.5	14.8	LK-7	8.0	26.2	G	5.8	19.0
LKS-59	5.5	18.0	LK-8	9.4	31.0	H	4.7-5.5	15.4-18.0
LKS-60	8.6	28.2	LK-9	1.0	3.3	I	4.3	14.1
LKS-62	9.9	32.5	LK-10	awash				
LKS-63	7.0	23.0	LK-11	4.6	15.0			
LKS-64	8.0	26.0						
LKS-89	2.5	8.2						
LKS-90	<1.0	<3.3						
LKS-91	1.0	3.3						
LKS-92	1.3	4.3						
LKS-93	2.0	6.6						
LKS-94	2.5	8.2						
LKS-95	3.2	10.0						

*Depths were measured from water surface to top of coral head cored. Water depths at Stations B, C, D and H are given as ranges due to coring of two or more head corals.

Table 4.4. Summary of dominant-grain percentages of all samples analyzed, their percent average and range of total grains counted, and their percent dominance within inner core area.

Grain	% of 96 Samples in which grain is dominant	% Average grain count	% Range grain count	% of 19 Samples within core area in which grain is dominant	Minor particles >10% of grain count
Coral	49.0	27.7	3-53	63.2	NA
Mollusc	33.3	24.1	7-50	36.8	NA
Halimeda	13.5	20.3	3-46	0.0	NA
Bryozoa/red algae	1.0	7.7	2-23	0.0	20.8
Benthic foraminifers	1.0	5.4	1-22	0.0	12.5
Echinoid	0.0	5.7	1-18	0.0	15.6
Other	0.0	9.1	2-22	0.0	35.4
Total	97.8*	100.0		100.0	

* Two samples (LKS-41 and LKS-67) were not figured in percent of 96 samples because they had equal percentage concentrations of *Halimeda* and molluscs, and coral and molluscs, respectively. Together, their percent value is 2.1, bringing the total to 100.0.

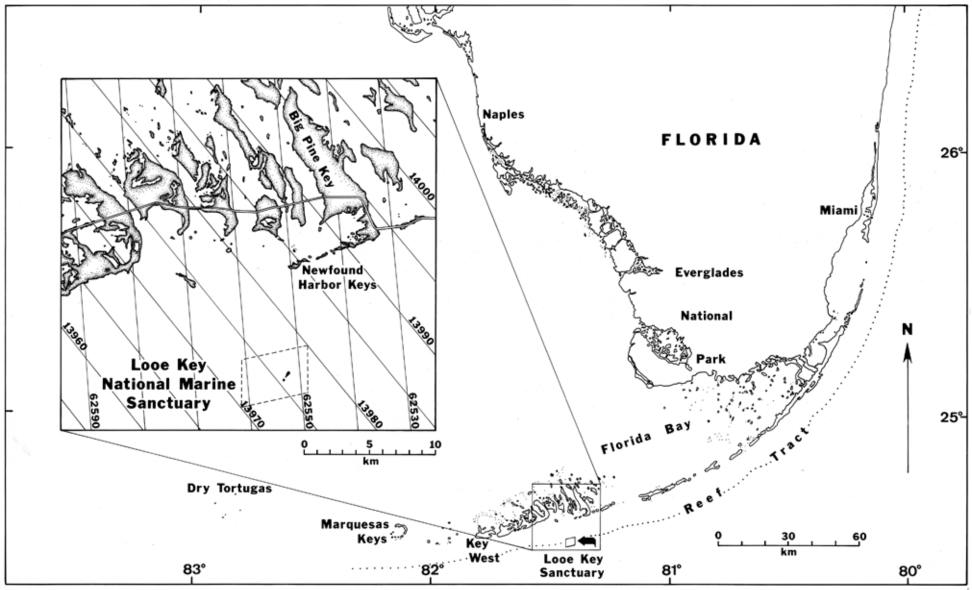


Figure 4.1. Index map for Looe Key National Marine Sanctuary. Loran C TDs for Stations 1 (13900 µsec) and 4 (62500 µsec) for the Gulf of Mexico were reproduced from National Ocean Service chart #11442. Coast Guard Marker 24 within sanctuary (dashed lines on inset) indicated by standard nautical chart symbol for position of lighted fixed marker.

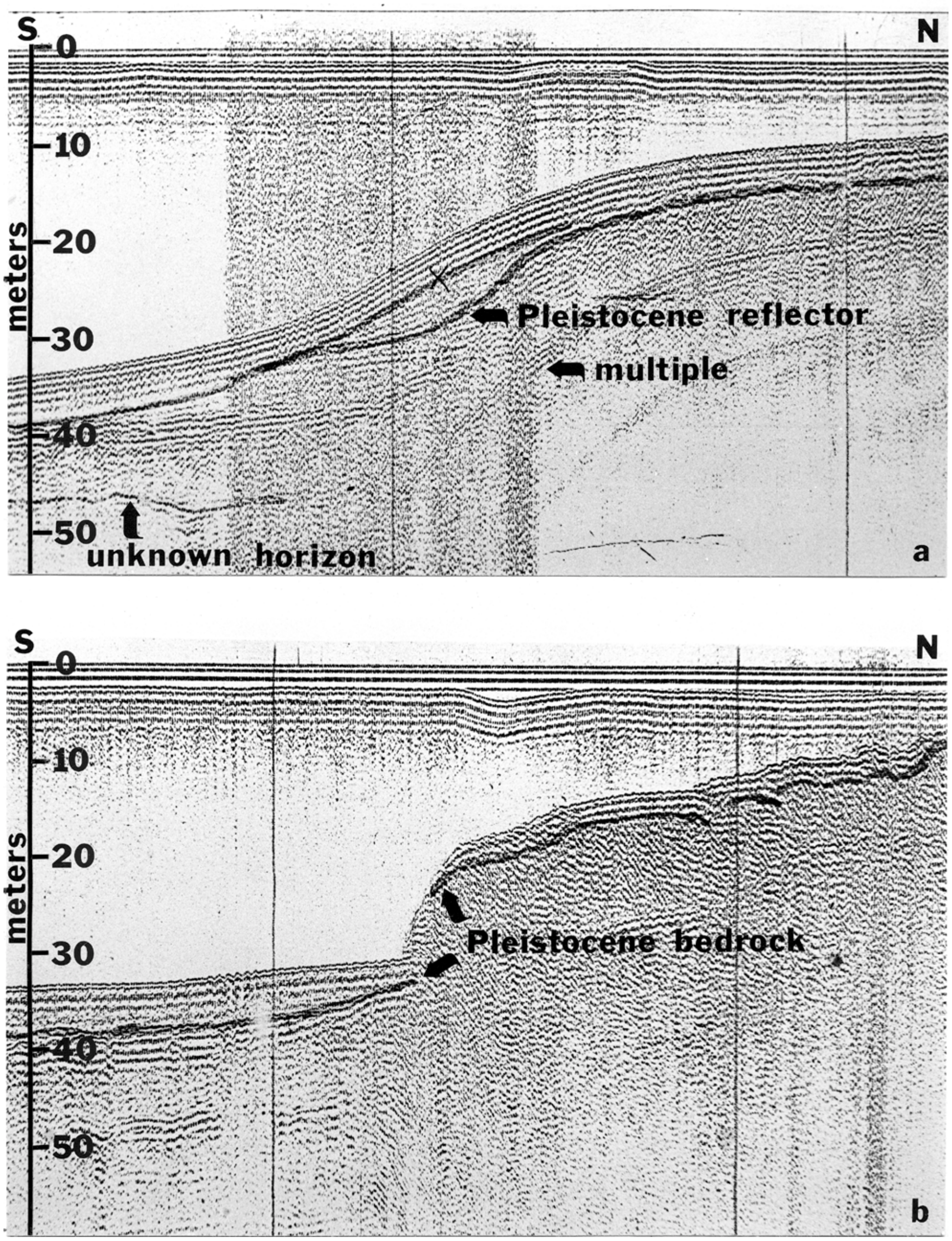


Figure 4.2. Two examples of seismic-reflection profiles (from track line 1, Figure 4.3) showing dropoff south of core area. (a) shows dropoff south of Marker 24 (east end of core area) where migrating sand has blanketed and smoothed slope. (b) shows crossing south of west edge of core area where slope has not been covered with sand. Pleistocene bedrock reflector was outlined with colored marking pen. In (a) the 'X' indicates false interpretation of Pleistocene bedrock.

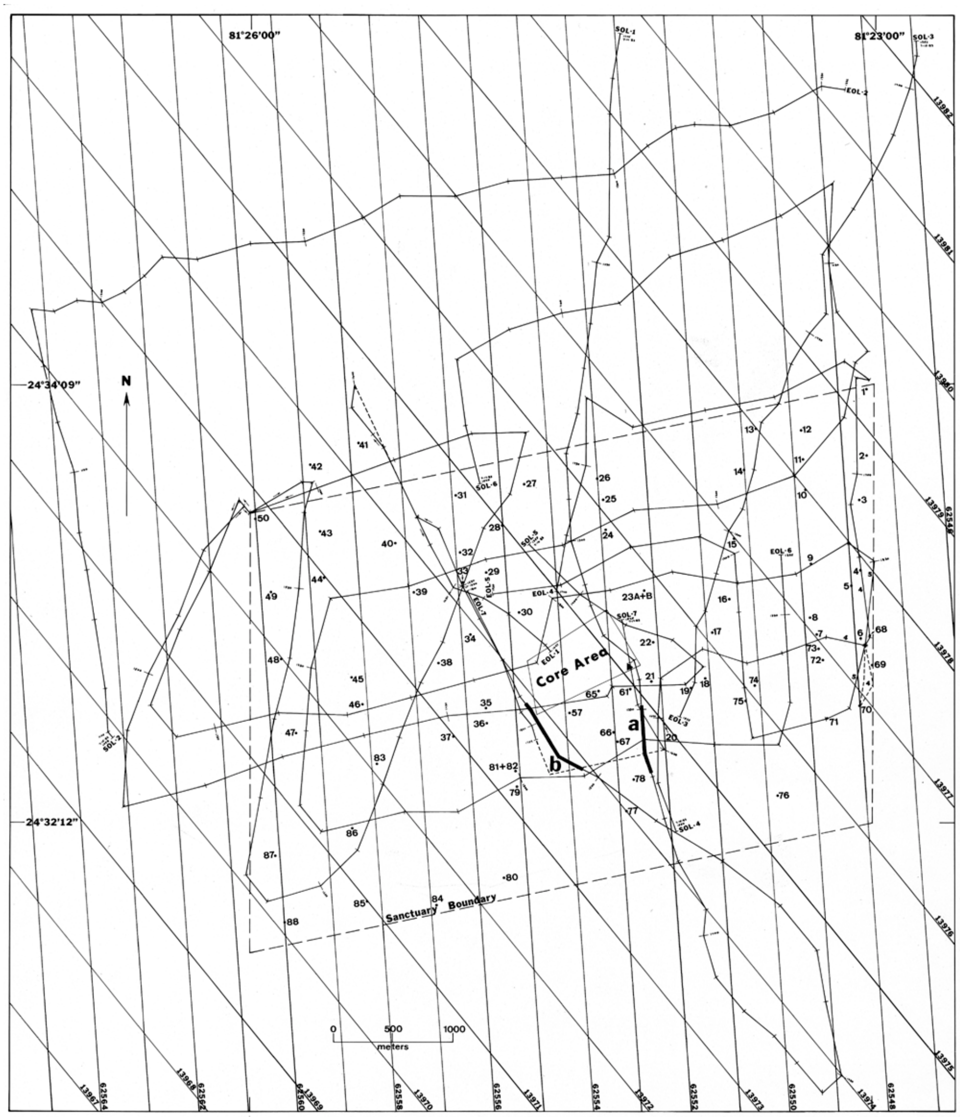


Figure 4.3. Loran C grid chart/base map showing seismic track lines (SOL - Start of Line; EOL - End of Line) and sediment sample locations. Additional 19 sample sites in core area are shown in Figure 4.7. Tick marks on track lines indicate 5-min-interval data points used to construct Figures 4.4 - 4.6. Short dashed lines on tracks 1, 4 and 7 indicate sections of seismic records rendered invalid by sharp course changes.

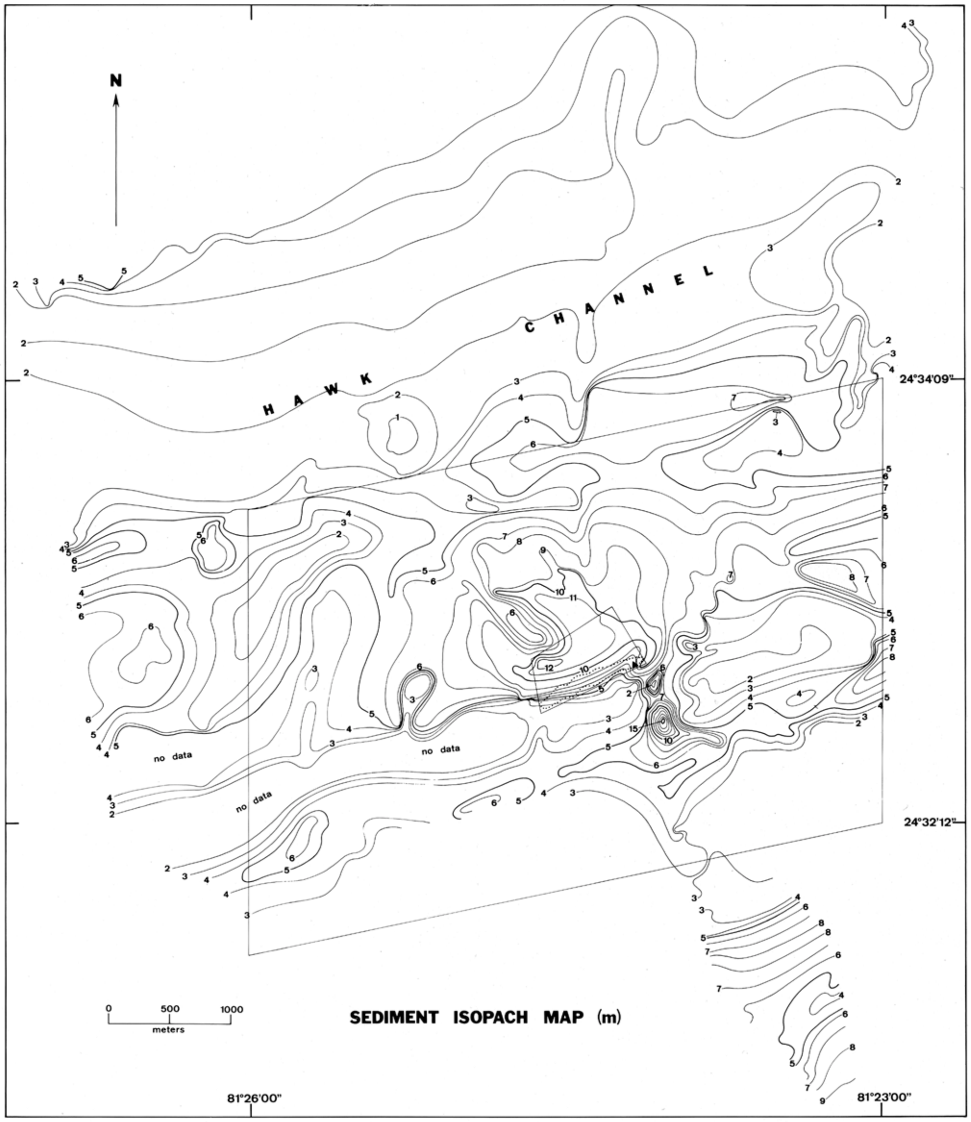


Figure 4.4. Bathymetric map based an 838 seismic data points. Core area not covered due to shallow water. Note prominent east-west dropoff south of core area.

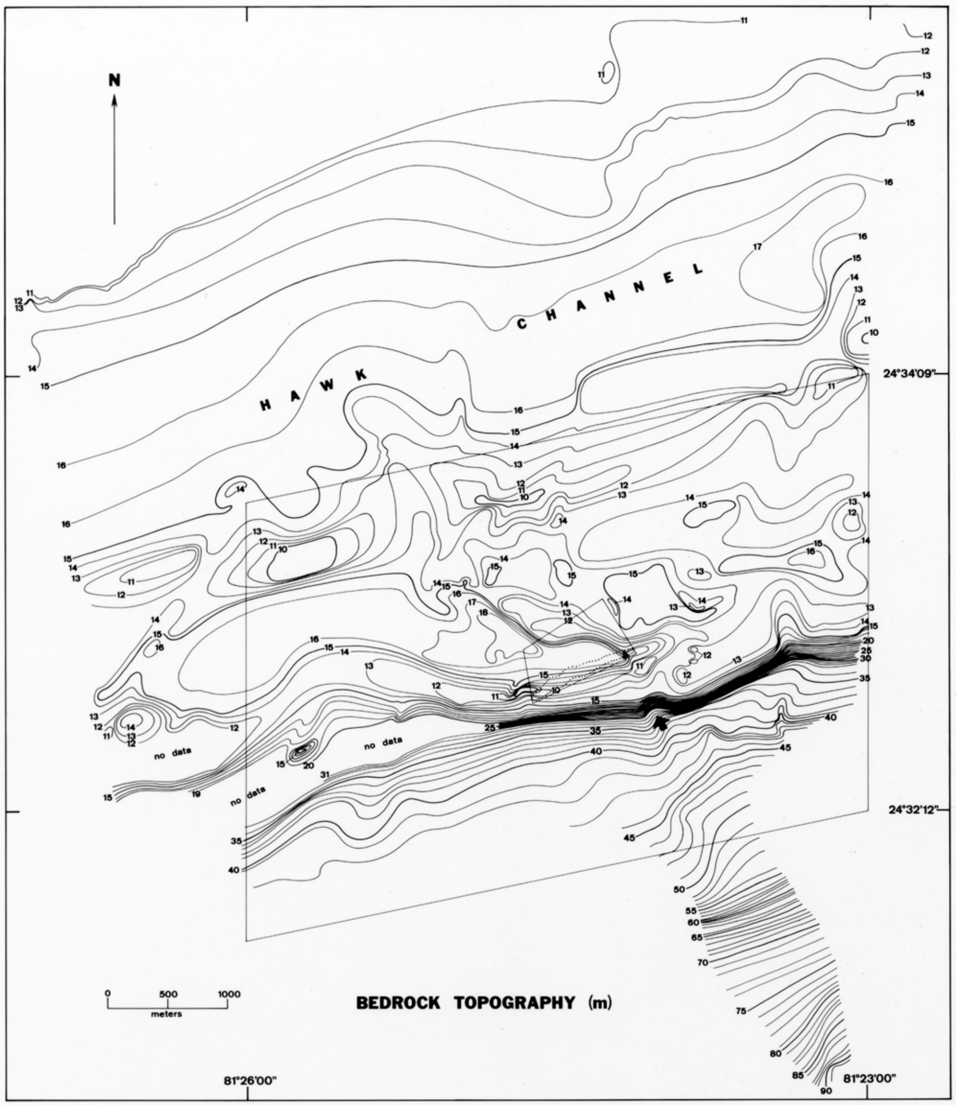


Figure 4.5. Subsurface Pleistocene bedrock topography. Note no data zones where overlying Holocene reef growth prevented penetration of seismic signals. Contours in core area inferred except where depth to bedrock is known from rock cores (see Figure 4.7).

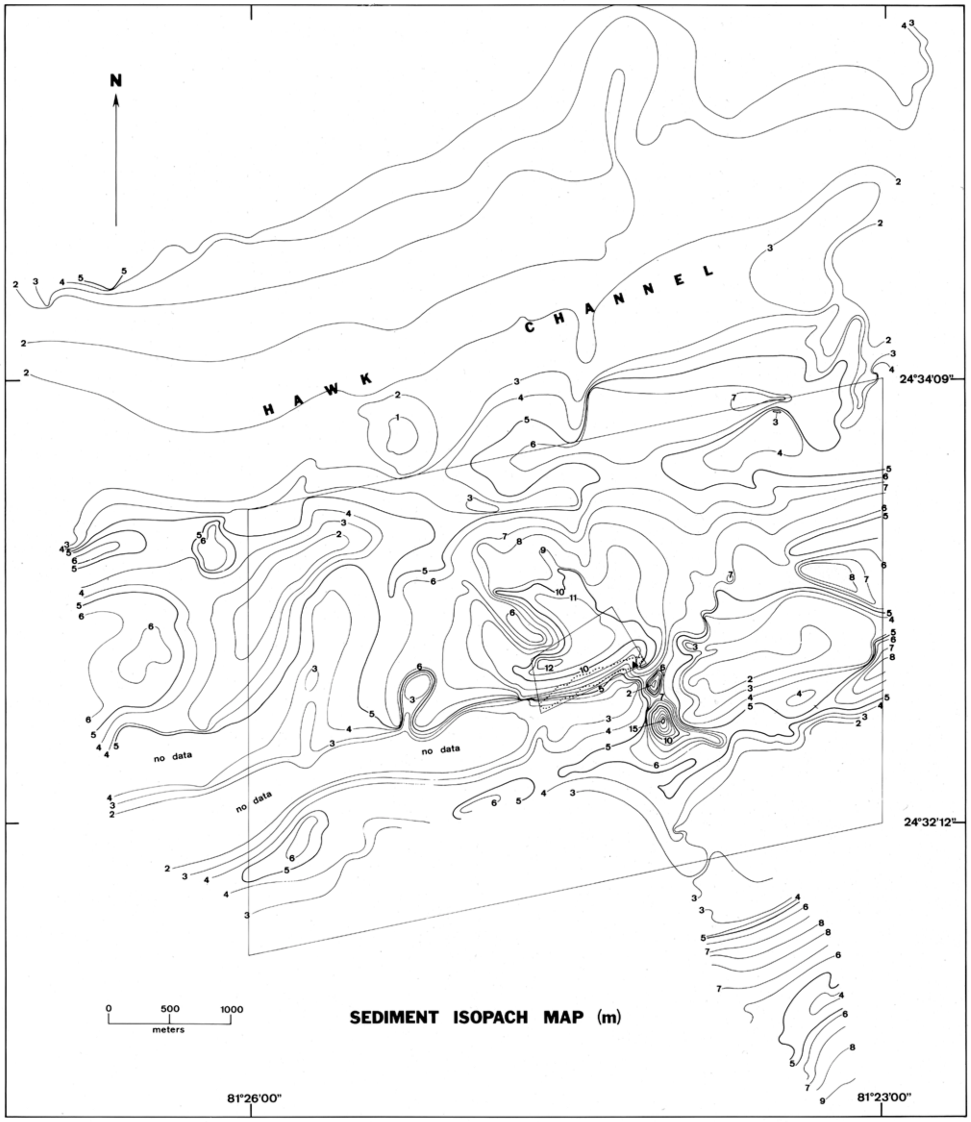


Figure 4.6. Isopachous map of unconsolidated carbonate sands and reef material based on difference between depth to seafloor and depth to bedrock. Contours in core area inferred from projection of data points outside core area. Note thickest accumulations in core area are north of 10-m contour.

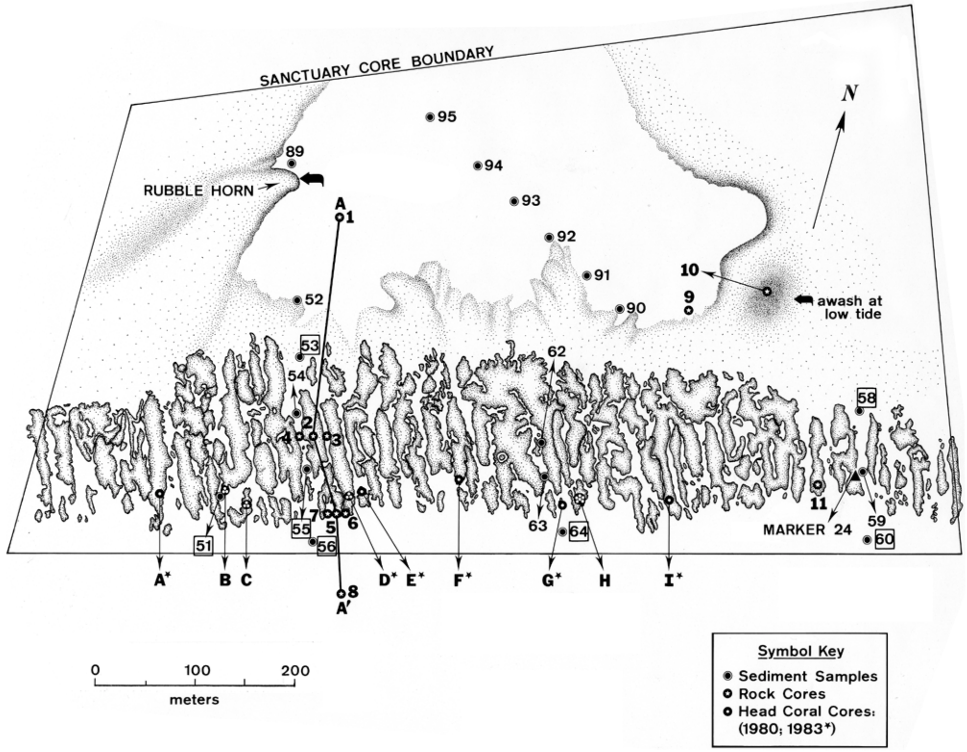
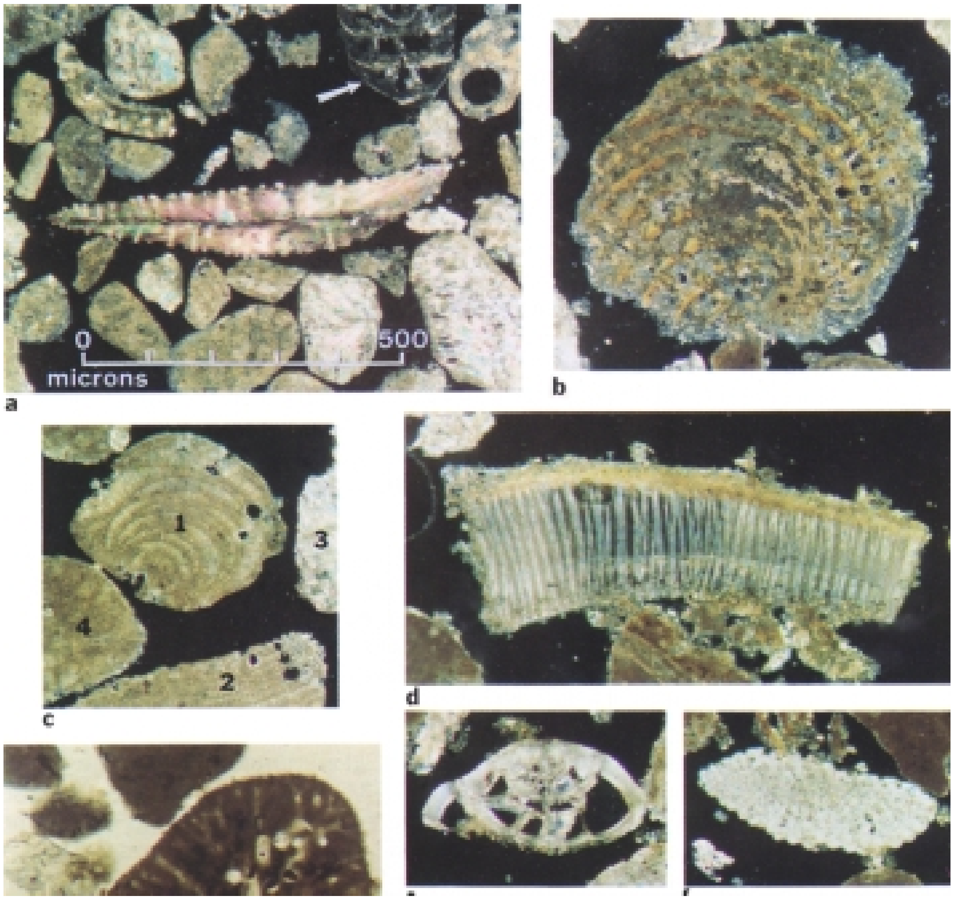


Figure 4.7. Sanctuary inner core area traced from aerial photomosaic and showing location of 19 sediment sample sites along with core holes drilled in earlier study (Shinn *et al.,* 1981). Stippled area behind reef is coral rubble zone. Cross section A-A' based an rock core drilling is shown in Figure 4.12. Also shown are locations of *Montastraea annularis* coral cores described by Hudson (this volume). Small white dots within each large black dot indicate number of head corals drilled per site. Rubble horn shown by arrow formed after 1981, probably during Tropical Storm Dennis (September 1982).


0
500
microns
a
b
1
3
4
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