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State University of New York at Binghamton,
Ph.D., 1972
Geology

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BIOGENIC BUILDUPS AND CARBONATE SEDIMENTATION, DRY TORTUGAS REEF COMPLEX, FLORIDA

A Dissertation Presented

by

VLADIMIR JINDRICH

Submitted to the Graduate School of the
State University of New York at Binghamton
DOCTOR OF PHILOSOPHY
May 1972
Major Subject Geology

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BIOGENIC BUILDUPS AND CARBONATE SEDIMENTATION, DRY TORTUGAS REEF COMPLEX, FLORIDA

A Dissertation

by

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ABSTRACT

The Dry Tortugas, a horseshoe-shaped complex of carbonate banks and coral reefs, is located at the southern terminus of the Florida limestone shelf. The complex rises to the surface waters from a drowned Pleistocene surface that forms a circular platform having a general depth of 17-21 m.

Three basic biogenic buildups (facies) comprise the reef complex: 1) detrital lagoonal bank, 2) Montastrea reef bank and, 3) *Acropora palmata* reef. These facies lie adjacent to one another and are also present in vertical succession as individual growth stages of varying thickness and lateral extent. A zone of *Acropora cervicornis* is developed as a transition between the *Montastrea* and *A. palmata* growth stages.

The present organic assemblages and topography bear evidence of dominantly lateral progradation and cumulative storm effects that are linked to the slow eustatic sea-level rise for the past several millenia. Long-continued storm degradation is manifested by 1) continuous removal of *A. palmata* and its replacement by storm-resistant coralline algae and *Millepora* sp. to produce truncated rocky surfaces, 2) abundant reef rubble, 3) erosion of spur-grooves, and 4) development of intertidal rubbly reef flats.

Sediments ranging from cobble-sized rubble to medium silt are composed of *Halimeda*, coral and mollusc grains; coralline algae and foraminifers are present in minor amounts. Variations in texture and constituent particle composition are interpreted to be mainly a result of mode of sediment trans-

port and effect of grain shape. Broadly-defined grain size populations produced by three modes of transport have characteristic assemblages of constituent particles. The populations include a gravel-sized surface creep population, sand-sized saltation population, and very fine sand-to silt-sized suspension population. Strong mixing occurs between the gravel and sand population on the storm-degraded shoals, and between the sand and silt population on the lagoon bottom. Sands flanking the reefs and reef banks show minimum mixing hence good degree of sorting. Incongruous mixtures of the in-place fraction and varying proportions of the transported populations constitute detrital lagoonal banks as a substrate stabilized by seagrass and coral growth. The gravel-sand and sand-silt mixtures are related to deposition under highly variable energy conditions. Variability in energy conditions does not cause strong population intermixing on beaches. From the same reason, beach sediments show a high degree of sorting in all size grades from cobbles to fine sand.

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INTRODUCTION

The Dry Tortugas is an isolated cluster of low islets 65 miles west of Key West in the Gulf of Mexico. The islands rise to the surface from a submerged complex of carbonate banks and coral reefs situated on the shallow Florida limestone shelf.

The purposes of this study are to investigate the history and development of the Dry Tortugas complex, especially with respect to post-glacial sea-level rise, to ascertain the present-day distribution of biota and sediment types, and to relate these features to those of well-known West Indian reefs.

In the course of the field study it became apparent that the Dry Tortugas complex is affected much by past hurricanes and that recovery has proceeded at a slow rate. This provided an opportunity to study storm effects upon reef growth, surface morphology, and distribution of reef-derived sediments. Interpretations of long-term consequences of storms, as inferred from the Tortugas may be useful in developing a better understanding of the history of post-glacial reefs and their superficial features.

In analyzing the surface sediments associated with the Tortugas biogenic buildups special emphasis was placed on the problem of textural maturity in skeletal carbonates. Constituent particle analyses of different size grades of sediment were made in an attempt to ascertain factors that control the particle composition at different stages of textural maturity in skeletal mixtures produced and deposited on a coral reef complex.

Pioneering research in the Dry Tortugas was conducted early in this century at the Tortugas Marine Laboratory formerly on Loggerhead Key. These include the earliest studies of biochemical precipitation of calcium carbonate from sea water (Drew, 1914; Field, 1919; Lipman, 1924). From a large number of ecological reports only a few are related to those topics dealt with in this work. These include study on the role of alcyonarians in reef formation (Cary, 1918), and growth-rate measurements of some reef-building scleractinians made by Vaughan (1915). No thorough sedimentological work had been done in the Tortugas,except for a brief description of several lagoonal sediment samples (Thorp, 1936) and the reef development referred to as an atoll (Vaughan, 1914). Ginsburg (1953) provided a detailed analysis of beach-rock from Loggerhead Key. Brooks (1964) in a general geological account refuted the term "atoll" for the Tortugas, but instead related the circular distribution of biogenic build-ups to the action of prevailing seasonal storms.

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The author is thankful for logistical assistance from the U.S. Coast Guard at Key West and at the Dry Tortugas Lighthouse Station for providing the field camp with fresh water and for shipping fuel and provisions.

The study was supervised by Dr. Don L. Kissling of the Department of Geology, SUNY Binghamton. I would like to extend my gratitude to Dr. Kissling for his continuous interest in my work, stimulating discussions, and for reviewing the manuscript. Dr. Paul Enos made critical comments that considerably improved the manuscript in its final stage. Mrs. Olga Kurty and Mr. Jim Lyon of the Department of Geology, SUNY Binghamton, aided in drafting and photographing the illustrations.

METHODS OF STUDY

Field work in the Tortugas was carried out from a temporarily established camp on Loggerhead Key during June and July 1969. Equipment used included a small boat, simple diving gear, light-weight grab sampler, and a portable current meter.

87 marine sediment samples and 19 beach samples were collected. Sample stations, positioned along strategically placed traverse (Fig. 1), were selected subsequent to detailed underwater observations with respect to topography, substrate type, and local biota. Surface samples from depths less than 10 m were collected by diving. Deeper substrates, largely the lagoonal sediments, were sampled with a light-weight grab sampler. On beaches where the sediment is generally laminated, the uppermost bedding unit from the middle foreshore was scooped for examination or retained as a sample.

Laboratory routine included washing the finer sediment over a 230-mesh Tyler sieve to separate the sand and mud fractions. Sand samples were dry sieved through a 0.5 phi-spaced set of screens with a Ro-Tap shaker for 15 minutes each. Constituent percentages of individual samples were based on 100 grain counts identified by the binocular microscope. Rounded and polished grains of beach samples were identified from thin sections cut from blocks of sediment impregnated in plastic. For about one-third of the samples, 50 grains were counted from each size fraction to obtain modal concentrations of chief constituents. Constituent composition herein refers to those particles larger than 4.0 phi. Identification of particles smaller than 3.0 phi has proved difficult and in some samples up to 14% of the particles were indeterminant. Grain-size distribution of the mud fractions were determined by pipette analysis. Minerology of mud was determined by x-ray diffraction. Computation of textural parameters were by formulae of Folk (1965).

GENERAL SETTING

The Dry Tortugas, a horseshoe-shaped complex of carbonate banks and reefs measures about 20 kilometers in length along NE-SW axis. The complex is about 11 kilometers wide and has a broad crescentic shoal bulging toward the northeast. The bulk of the complex lies at shallow depths. The flat shoals support several low islets standing 1 to 2 meters above the high tides. Three passages (Southeast Channel, Southwest Channel, and Northwest Channel) divide the Dry Tortugas complex into three segments and provide free water circulation between the open sea and the central lagoon. For purpose of this report the segments are called the Garden Key, the Loggerhead Key, and the East Key segments. A number of biogenic buildups forming mounds or ridges up to 2 kilometers long occur in the lagoon. Many of the buildups join the Garden Key and East Key segments creating a honey-combed pattern characteristic of the lagoon side of these segments.

The bathymetric chart (U.S.C. & G.S. No. 585) reveals that the Dry Tortugas complex rises from a platform 17-21 meters deep. This is also the maximum depth of the lagoon and passages separating the segments. The complex is situated at the southeast margin of the submerged platform. Along the northwest perimeter, the platform forms a sea terrace 1-2 kilometers wide before it drops to the surrounding shelf at 35-40 m depth. (fig. 1)

The Dry Tortugas lies in the belt of east to southeast trade winds. The trades blow during spring to summer months and create a mild to moderate surf on the windward, nearly emergent, parts of the Tortugas. During winter months, intermittent northerly winds having velocities of 20-30 mph cause fairly heavy surf (records from the U.S. Coast Guard station on Loggerhead Key).

Seasonal storms and hurricanes are typical for the Gulf of Mexico. Occurring during the late summer and fall months, such storms cause extremely high tides and violent surge.

Tides at the Dry Tortugas are of mixed, dominant-diurnal type (fig. 2). The semidiurnal phase occurs typically only during several days at neaps. Spring tidal range averages about 95 cm and neap tides average about 25 cm.

The regional tidal crest progresses from the east through the Straits of Florida toward the Gulf of Mexico, then northward across the shelf in the vicinity of the Marquesas Keys and the Dry Tortugas, and finally eastward along the northern margin of the Florida Keys (Chew, 1954). Upon reaching the Dry

Tortugas from the east the tidal wave enters Southeast Channel and Southwest Channel. In these channels the constricted waters generate a swift, tidal flood current flowing to the north and northeast through Northwest Channel. During the ebb phase the tidal flow pattern is reversed. Measured values for near-surface flow are 40-60 cm/sec in Southwest Channel, 30-50 cm/sec in Southeast Channel and, 20-30 cm/sec in Northwest Channel. Maxim. current velocities in the central parts of lagoon range from imperceptible to about 20 cm/sec. Current flow is variable over the shoals where current directions and velocities are controlled by local bottom irregularities. Flow over the shoaling crests commonly attains velocities ranging from 50-80 cm/sec. during the ebb phase at spring tides. These velocities were measured at shoals surrounding Loggerhead Key and Garden Key, and parts of the reef flat on the Garden Key segment. The maximum current velocity of 110 cm/sec was recorded during the ebb tide on sandy shoals at the honeycombed lagoon side of Garden Key segment.

BIOGENIC BUILDUPS

The following principal types of biogenic buildups are recognized in the Dry Tortugas reef complex: reef, reef bank, and lagoonal bank.

The term reef is applied to those structures faced on their windward sides by rigid, wave-resistant walls against which the surface waters break in unprotected, open-shelf locations. Where it has reached the water surface the reef wall dissipates wave energy and modifies sedimentary environments to the leeward. The reef wall, formed at least partly by the *in situ* framework of reef corals, is characterized by the *A. palmata* community at its crest. In its capacity to raise a rigid framework into the surf zone the *A. palmata* community appears to be best adapted as a true reef community in the strictest sense and meets the requisites of the reef definition advanced by Lowenstam (1950).

The *reef bank* is a rigid structure surfaced by the low-energy *Montastrea* community, which, due perhaps to its location or incomplete development, generally does not raise its crest into the high-energy surf zone. In the Tortugas, the crests of reef banks built in leeward locations are at shallow depths of 1-2 m. Reef banks forming composite windward belts that face the open shelf frequently raise their crests into very shallow water also. There is evidence that some of these shoals are storm-degraded reefs, previously populated by *A. palmata*. However, evidence of past storm activity is less clear elsewhere and it is difficult to determine whether such crests represent original accretion surfaces, or surfaces resulting from storm erosion, or a combination of both. This problem is discussed further under storm effects.

Lagoonal banks are elevations made up primarily of skeletal fragments accumulated by the trapping and stabilizing effects of marine organisms (Ginsburg and Lowenstam, 1958). The crests and upper flanks of many lagoonal banks acquire a veneer of coral that may add a certain degree of rigidity to these buildups. The degree of such rigidity can be extremely variable and reflects basically the ratio of coral framework to loose skeletal matrix in the bank. Lagoonal banks (carbonate banks or mounds on the Florida reef tract) are not always easy to define in terms of their internal rigidity and resistance to waves. The problem is illustrated in descriptions of banks in the Alacran lagoon, Yucatan. These structures, comparable to those of the Tortugas, were alternatively termed lagoonal patch reefs or micro-atolls by Kornicker and Boyd (1962), and cellular reefs or coral pinnacles by Hoskin (1963, 1966). Logan, defining these Alacran structures as seagrass banks, denies their ability to form even semi-rigid frames (Logan et al., 1969, p. 185).

Reef

Well-developed reef fronted by reef wall and backed by a reef flat is found only in the southern part of Tortugas complex where it comprises the bulk of the Garden Key segment.

Reef wall. - The reef wall, facing the windward side of the Garden Key segment (fig. 4) trends northeast for a length of 3.5 km. From the low water mark the reef wall dips gently about 5 degrees seaward to form a 200-250 m broad slope whose surface is slightly convex. At approximately the 10 m isobath the slope steepens rather abruptly to the base of the wall at about 25 m dept.

The entire crest of the reef wall is capped by a coral-rubble pavement (fig. 10A,B) that thins out leeward onto the reef flat, and also extends windward where the rubble partly conceals the upper wall slope. Toward the northeast, on approaching Southeast Channel, the rubble pavement thickens at the crest forming a narrow flat-topped barrier up to 30 m wide (fig. 4). The barrier runs parallel to the reef wall and forms an island (Long Key) 1 m above high water level. At its northern end the reef-rubble barrier projects several hundred meters leeward as a rubbly horn on Bush Key which is sandy elsewhere. Coral rubble paving the upper reef wall grades at depth into a hard, deeply pitted and cavernous dead reef-rock containing rippled sand in depressions. Living coral is scarce. Small heads of *Montastrea* sp., *Diploria* sp. and *Porites asteroides* are scattered over the hard bottom and increase in density with depth. *Acropora palmata* is absent, except for a few scattered living individuals observed upon the shallow rubble pavement (figs. 10A, B). The specimens of *A. palmata* are mostly small and developed in a "panshoal" growth form (Storr, 1964) or display a nonbranching form encrusting cobble-sized rubble.

The biota of the upper reef wall is dominated by abundance of soft algae (*Pocockiella variegata*, *Turbinaria turbinata*, *Padina* sp.) growing attached to the rubble in the surf zone (fig. 10A). With increasing depth soft algae are gradually replaced by a rich variety of alcyonarians and many *Millepora* sp. The rubble and dead reef-rock are encrusted by coralline algae and extensively bored (Pl. 2B, C). Species of the calcareous green alga *Halimeda* are ubiquitous (Pl. 1), either filling crevices on the hard bottom (*H. tuna*) or concentrated locally in dense thickets (*H. opuntia*).The sea urchin *Diadema* *antillarium* and the gastropods *Strombus gigas*, *Cyprea zebra* and *C. cervus* are characteristic elements of the upper reef wall biota.

At places on the upper reef wall a bed of dead *Acropora cervicornis* reef-rock stands up to 2.5 m above the surrounding bottom. The seaward edges of this elevated reef-rock are eroded into irregular flat-topped pedestals or seaward projecting spurs, 3-5 m wide and up to 15 m long. The spurs rise above the sand or rubble-paved floors of intervening grooves (fig. 11). The crests of spurs are truncated flat and the scoured surfaces, healed by algae encrustations, locally support incipient repopulation of non-branching corals as *Diploria* sp. and *Porites asteroides*. The algal-encrusted surfaces conceal the interlaced, mesh-like framework of *in situ A. cervicornis* branches, welded by coralline algae, but the framework is revealed in the steep erosional walls of the spurs.

Limited underwater observations at the steep lower reef scarp below 10 m depth showed scattered coral heads interspersed with alcyonarians.

Reef flat. - The reef flat occupies an area immediately leeward from the crest of the rubble barrier at the Garden Key segment. The reef flat, about 0.8 km in width, dips slightly to the leeward where it grades into the flat-topped, slightly submerged lagoonal banks (fig. 4). Parts of the reef flat adjacent to the reef wall are exposed or just at the surface during low tides, the distal parts are generally about 1 m below the low tide mark.

Sediments surfacing the reef flat are 1) skeletal sheet deposits derived largely from the windward reef wall, and 2) skeletal accumulations of organisms indigenous to the reef flat (off-reef drape and auxiliary deposits, respectively, of Logan *et al.*, 1969). Adjacent to Long Key and Bush Key the reef flat is practically sealed off from the open sea and sediments here have their source from abundant indigenous molluscs living within a soft substrate and various species of *Halimeda* growing upon it.

South of Long Key the reef flat is cut by a broad gap in the rubble barrier, which is swept by tidal currents. The gap is 2 m deep and 0.5 km wide. Here the reef flat is surfaced by coarse skeletal debris and thin sheets of *A. cervicornis* rubble with whole, little-worn bivalve shells. There is a dense population of *Diadema antillarium*. Thickets of living *A. cervicornis* give way to shallow sea-grass beds (*Thalassia testudinum*) farther leeward.

Farther to the south the rubble barrier gradually submerges as it thins and spreads onto the reef flat as a leeward reef apron. The agitated water flowing across the rubble pavement onto the adjacent reef flat promotes varied organic growth showing a lateral zonation in bands parallel to the reef wall. This zonation, developed in response to gradual decrease of energy conditions and increase in water depth, is as follows:

1) Algal zone. - The algal zone is confined to the rubble pavement and extends windward to where rubble overlies the upper

parts of the seaward-dipping reef wall. The width of algal zone on the reef flat measures about 50-80 m. An abundance of soft and coralline algae is characteristic. Coral pebbles and cobbles are frequently encased in crusts of coralline algae (Pl. 2B) and are extensively bored by organisms so as to conceal the character of coral fragments. Despite the relative abundance of coralline algae, no algal cementation of rubble was observed.

2) *Porites* zone. The *Porites* zone is characterized by abundant colonies of the coral *Porites porites* frequently concentrated in dense thickets just below the low water level. The colonies are commonly interspersed with sea-grass and clusters of *Halimeda* sp. The branching alga *Goniolithon* sp. was observed locally attached to dead corals. The width of the *Porites* zone ranges from several meters up to 150 m. The *Porites* zone, including the indigenous skeletal substrate rich in *Halimeda* fragments, is representative of the lagoonal bank facies.

3) *Thalassia* zone. - The *Thalassia* zone, measuring about 0.5 km in width and averaging 1 m below the low water level, comprises the remainder of reef flat. The zone is covered by extensive sea-grass meadows of *Thalassia testudinum* and less abundant *Cymadocea manatorum*, with numerous calcareous algae (*Halimeda incrassata*, *H. monile*, *H. opuntia*, *Udotea* sp., *Penicillus* sp. (Pl. 1). The corals, *Manicina areolata*, *Siderastrea radians*, *Porites porites*, and clumps of *A. cervicornis* are scattered over the whole zone. Several large heads of *Montastrea annularis* were observed also. Molluscs are

abundant, including numerous burrowing forms living in a substrate similar to that of the Porites zone. Conspicuous dwellers are the large gastropod (Cassis madagascarensis, the starfish Oreaster reticularis, and sponges Ircinia sp. and Spheciospongia sp.).

Reef Banks

Areally the reef banks constitute a substantial part of the Dry Tortugas complex forming the crescentic East Key segment, the Loggerhead Key segment, and the southern half of the Garden Key segment.

Reef banks average 2-3 km in width and reach a length of 17 kmkin the East Key segment. Crests of reef banks lie 1-5 m below the water surface, although portions of the leeward Loggerhead Key segment rise to the low water level.

The general topography is characterized by broad, flat median shoals and rugged, irregularly gullied windward flanks. Surfaces of the median shoals consist largely of indurated, hard rock encrusted by coralline algae. Several chip samples revealed dead massive coral beneath the thin algal crust, intensively bored by Lithophaga sp. and other organisms. (Pl. 2A)

Corals such as Montastrea sp., Diploria sp., A. cervicornis, and Porites asteroides provide rigidity to the reef banks. They are rather scarce upon the flat shoals but increase in density toward the rugged flanks. The leeward flanks, or more protected shoals, frequently support thick growths of A.

cervicornis characteristically associated with *Halimeda opuntia* growing in profusion on the lower branches of the corals.

Alcyonarians and *Millepora* sp. are probably the most abundant and typical organisms surfacing the rocky substrate of reef banks. Except for a veneer of coral rubble, flat shoals generally retain little sediment. More sediment occurs upon the rugged topography along the windward flanks where coarse skeletal sand and *A. cervicornis* rubble are trapped in depressions. Fine skeletal sand typically occurs at the lagoonal margins of the windward segments. The fine sand, locally forming extensive leeward aprons, grades into lagoonal banks bounded by steep lagoonal faces.

The median flat shoals adjacent to East Key and Pulaski Shoal in the crescentic East Key segment display hard rocky substrates populated by abundant alcyonarians and scattered coral heads. Local seagrass beds and thin sheets of coarse skeletal sand and rubble conceal the rocky bottom. Eroded and channeled *A. cervicornis* reef-rock on the windward slope at Pulaski Shoal (figs. 13, 14), locally veneered by coral rubble containing fragments of *A. palmata* is analogous to structures described above for the reef wall on Garden Key segment.

Remnants of *A. palmata* growths are also seen at the southern tip of Loggerhead Key segment. The southern end of this segment, extending into unprotected waters for a distance of about 1.5 km., has its crest and upper sides constructed of dead, truncated *A. cervicornis* thickets encrusted by coralline algae (fig. 12). On the windward edges the *A. cervicornis* thickets assume a deeply grooved, 2-3 m thick reef-rock topped by coralline algal-coated platform. Soft mats of the colonial zoanthinarian *Palythoa mammilatus* now cover large parts of the platform at depths of 2-4 m. Occasional clumps of dead, algal-encased *A. palmata* and eroded remnants of thicker proximal branches of this coral are found in growth position attached to the platform surface. The *A. cervicornis* reef-rock rises from a sandy substrate sloping south and southeast at the angle of repose as a reef apron.

Toward the northeast the Loggerhead Key segment gradually assumes a leeward location. Here the rocky median flat shoal gives way to sandy shoals with seagrass beds. At surf-protected locations adjacent to Loggerhead Key the seagrass beds support dense growth of *A. cervicornis*, *Halimeda* spp. and some of the largest colonies of *Montastrea annularis* and *Diploria* sp. in the Tortugas. Irregular, broad spurs of coral rock encrusted by coralline algae and repopulated by small coral heads are prominent on parts of the segment flanks bordering on Southwest Channel. Although irregular in detail, these spurs project southward forming an angle of about 60 degrees with the long axis of the segment. The spurs, several tens of meters long, generally do not join the median rocky flat shoal but are separated from it by sandy floor strewn with coral rubble. A similar substrate also separates the spurs. However, a substantial part of the flank, 10 km in length, is surfaced by sandy floor that dips at the angle of repose toward Southwest Channel and the lagoon. This sloping flank is populated locally by thickets of living A. cervicornis and seagrass. The leeward flank of the Loggerhead Key segment is a gently dipping, dominantly rocky surface (fig. 4) populated by abundant alcyonarians and scattered coral heads. Large parts of the rocky substrate are blanketed by skeletal sands and seagrass.

Lagoonal banks

Lagoonal banks rise as isolated mounds from the flat lagoon bottom or join the lee side of reef banks. Best developed are the rounded and elongated lagoonal banks in the lee of the Garden Key segment. These banks form an anastomosing network grading into adjacent reef flat and constitute an integral part of the sediment mass fronted by reef wall (fig. 4). The size of lagoonal banks ranges from several tens of meters across and several meters in elevation to large, sea-level bodies up to 2 km in length and rising up 20m from the lagoon bottom to the low water level. The characteristically steep sides of lagoonal banks reveal soft substrate of poorly washed skeletal detritus stabilized by seagrass and several species of green calcareous algae. There are widely scattered small coral heads on the upper flanks. Dense growths of A. cervicornis and Halimeda opuntia are most typical upon the flat-topped crests of sea-level lagoonal banks. Many large, isolated lagoonal banks in the Tortugas lagoon reveal bare convex surfaces veneered by sand and sheets of A. cervicornis rubble populated by abundant alcyonarians. These include banks supporting Hospital

Key and Middle Key (fig. 1).

GEOLOGICAL EFFECTS OF STORMS

The present surficial features of the Tortugas reef complex bear imprints of several hurricanes that modified the physiography significantly. However, because of the lack of any previous systematic geological survey that might have provided comparative standards, the assignment of cumulative storm effects to any one of a succession of hurricanes is difficult. Analyses of the geological work of hurricanes shortly after they occurred at previously investigated reefs of Florida and Bahamas (Ball _et_ _al_., 1967; Perkins and Enos, 1968) and British Honduras (Stoddart, 1963) have provided valuable guides in the evaluation of storm action as an important geological agent in coral reef formation.

Historical records of Fort Jefferson, Dry Tortugas, mention hurricanes in 1900, 1904, 1910 and 1935 that have done extensive damage to buildings at Garden Key and on the Fort itself. Data from the National Weather Service (Sugg _et_ _al_,, 1971) indicate that at least four hurricanes at recorded wind velocities 120-125 mph, passed directly over the Dry Tortugas since 1935. Tracks of major hurricanes that passed over the Dry Tortugas since 1873 are illustrated in Figure 3. These data, although probably incomplete, suggest the occurrence of one hurricane approximately every 5-6 years, compared to the 6-7 years estimate for south Florida (Ball _et_ _al_., 1967) and less than 10 years for British Honduras (Stoddart, 1963).

Effects on reef communities

It has been noted that biological recovery of reefs following the destructive storms are long-delayed and a matter of at least several decades (Stephenson, *et al.*, 1958; Stoddart, 1965). Reef crests and shoals are loci of the most pronounced storm destruction and the branching corals *A. palmata* and *A. cervicornis* are generally the first to succumb. The actual destruction may range from the removal and fragmentation of unfavorably oriented coral branches, through uprooting and overturning the colonies, to a complete stripping of coral thickets down to the dead reef-rock.

Despite the randomness of storm occurrence in place and time, it is nevertheless apparent that any slowly progressing biological recovery would be retarded continuously by periodic interference of storms. Biological recovery, viewed as a reef community succession, is essentially a process of competition for space among organisms with various resistance to storms and various growth rates. Thus it appears that the *A. palmata* community constantly develops through successional stages, which, although essentially ephemeral, may actually persist a long time if repopulation of *A. palmata* is inhibited or periodically removed by storms.

In the Dry Tortugas dense populations of brown algae and coralline algae, locally encrusting *Millepora* sp., and mats of *Palythoa mammilatus* may be considered as members of a successional stage of the *A. palmata* community. They apparently remain long after the storm damage, prevent coral attachment, and inhibit A. palmata recolonization (fig. 10A, B). The widespread occurrence of coralline algae, Millepora sp., and alcyonarians, colonizing extensive rocky shoals and rubble pavements, is thought to be the most conspicuous biological consequence of storm activity in the Tortugas. Furthermore, the storm-produced shallow rocky substrates are areas of intensive biological weakening by boring and grazing organisms.

Submarine erosion

Erosion induced by storm-driven waves is considered to have been responsible for the large-scale stripping of the shallow reef biota exposing the reef-rock beneath. Such degradation has brought sizable parts of the Dry Tortugas complex to the status of reef banks with crests and upper flanks marked by erosional surfaces. Upon subsequent encrustation by coralline algae the erosional surfaces become indurated hard bottoms furnishing a new substrate for coral repopulation.

The gradual deepening southward of the rubble barrier and reef flat in the Garden Key segment points to more severe storm erosion to the south. Probably the entire windward margin of the Garden Key segment originally had true reef status.

The shoals adjacent to East Key and Pulaski Shoal in the East Key segment may represent remnants of a degraded reef flat. Eroded A. cervicornis reef-rock associated with coral rubble containing fragments of A. palmata on the windward reef wall. The reef may have rimmed at one time the southern one third of the East Key segment between Southeast Channel and the East Key shoal, and the area around Pulaski Shoal to the north. Similar evidence points to a storm-degraded reef at the southern tip of Loggerhead Key segment.

The windward fronts, sites of well developed radial spurs and grooves on other West Indian reefs, are mantled in the Tortugas by rubble pavements or display a rugged relief revealing cavernous reef-rock dissected locally to ill-defined grooves. The magnitude of storm erosion documented from British Hunduras demonstrates that spurs were completely planned off by a single hurricane over a zone 40 km wide (Stoddart, 1963). The character of submarine topography and amount of coral rubble in the Tortugas indicate similar large-scale destruction. Resulting flat-topped, steep-sided and undercut ridges and stacks, largely of the A. cervicornis reef-rock, are clearly bounded by erosional surfaces. These ridges and stacks are separated by irregular, elongated rubbly or sandy grooves, and are considered to serve as initial cores in the development of spur-and-groove formation. Earlier storms apparently planed off the living layer of A. cervicornis thicket down to the dead framework furnishing a truncated surface for algal and coral growth. The scarcity of biologic repair and the relative freshness of erosional surfaces that bound the spur faces demonstrate effects of subsequent storms. Faces of some spurs display erosion of a very recent date attesting to the continuing mechanical destruction that appears to exceed the rate of organic accretion.

Inasmuch as grooves on reefs are invariably floored by moving sand and rubble, generally preventing coral attachment, the sides and tops of spurs are the only sites of active organic growth on reef fronts. Thus, the irregular geometry and discontinuity of elevated erosional cores in the Dry Tortugas can be modified by subsequent organic accretion. Such modification toward mature, continuous reef spurs is improved by oriented coral growth as detailed by Shinn (1963). However, I find it difficult to conceive that oriented coral growth alone could be capable of constructing parallel reef spurs, as maintained by Shinn (1963, p. 301). If spurs are regarded as ephemeral features originating and shifting in time and space through the dynamic process of storm erosion, the observation that surface biota of spurs masks the internal framework of different compostion (Shinn, 1963, p. 301) should be the rule rather than the exception. Furthermore, the admitted difficulty in finding various growth stages, suggesting rapid development of spurs (Shinn, 1963, p. 303), points to a major role of storm erosion in origin of spurs.

Deposition of rubble

Typical rubble is pebble-to-cobble-sized *A. cervicornis* sticks which form irregular thin sheets on all three segments of the Dry Tortugas and crests of some larger lagoonal banks. The largest continuous accumulation forms the rubble barrier capping the windward reef wall in the Garden Key segment. The highest elevations of the rubble barrier emerging as islands display crude bedding with a coarse rubble of massive corals and larger slabs of A. palmata at the base topped by ramparts of A. cervicornis sticks (fig. 16).

The fact that most rubble fragments are thoroughly perforated by boring organisms and/or encrusted by coralline algae indicates that no appreciable amount of rubble has been produced in the recent past. Hurricanes Alma and Inez that passed consecutively over the Dry Tortugas in 1966 with wind velocities of 125 mph and 120 mph, apparently did not liberate much fresh reef rubble except, perhaps, sheets of A. cervicornis sticks with relatively fresh appearance observed in protected locations. The bulk of the rubble barrier, consisting largely of heavily algal-coated and bored cobble-sized fragments, must have resulted from storms that occurred a considerable time ago when the reef front was more heavily populated by living coral, hence more rubble became available for storm erosion.

All significant rubble deposits point to leeward transport. No rubble accumulations were encountered seaward from the windward fronts.

Effects on islands

Field observations and comparison with theold bathymetric chart U.S.C. & G.S. 471a, issued in February 1917, show drastic changes in the physiography of the Tortugas islands over the past 55 years. At present there are seven islands. Another two, named Bird Key and North Key, were swept away by hurricane seas leaving only sandy shoals on top of lagoonal banks (Bird Key Bank at the Garden Key segment, banks adjacent to North

Key Harbor at the lee of East Key segment, fig. 1). Bird Key which measured about 200 m across is still shown on the chart issued in 1971.

Devastation by earlier hurricanes must have considerably reduced the size of Hospital Key that once supported the brick - constructed hospital serving Fort Jefferson. Brick fragments can still be found on a sandy shoal where large, disrupted blocks of beachrock now encroach a mere sand pile 1.5 m above sea level and some 50 m across. A significant size reduction of Middle Key and particularly of East Key has occurred since 1917. The sandy Bush Key has accumulated by wave refraction in the lee of its rubbly spit and the rubbly Long Key. Both Keys, the youngest of the Tortugas islands, formed since the year 1917. In contrast to East Key, Middle Key and Hospital Key, the more sheltered Bush Key shows a continuous increase in size by sand accretion. The leeward Loggerhead Key and Garden Key have not undergone any major physiographic changes over the past 55 years and appear to be in equilibrium with present conditions.

DEVELOPMENT OF THE DRY TORTUGAS REEF COMPLEX

Growth Patterns and Inferred Structure

Although coral distribution in the Dry Tortugas follows the vertical zonation scheme typical of West Indian reefs, individual segments exhibit variations in their development. Biogenic buildups defined earlier as the lagoonal bank, reef bank, and reef may be regarded as stratigraphically unconfined facies to which Walther's Law may be applied. Accordingly, these facies not only occur in lateral juxtaposition, but also exist in vertical successions as individual growth stages. In each of the major segments comprising the Tortugas reef complex, the vertical succession appears to differ in completeness, thickness, and lateral extent.

It was noted that major variations exist in the development and interrelationship between the *Montastrea* reef-bank facies and detrital lagoonal-bank facies that provide a shallow foundation for the *Acropora palmata* reef facies. Characteristically, *A. cervicornis* forms a bed several meters thick as a transition zone between the shallow foundation and *Acropora palmata* reef facies. Such vertical zonation is similar to that of Jamaican reefs (Goreau, 1959) and the Pleistocene reefs of Barbados (Mesollela *et al.*, 1970).

The variability of the lagoonal-bank facies and reef- bank facies in vertical succession appears to result from differential growth rates of corals relative to the accumulation rate of unconsolidated sediments comprising the lagoonal bank facies. *A. cervicornis*, with its branch-tip growth rate up to about 10 cm/year (Shinn, 1966), appears to be the only coral able to compete with and outgrow the relatively rapid accumulation of lagoonal-bank sediments. Annual deposition increment of 1.8 - 6.2 cm in some mud-bank areas of Florida is reported by Howard *et al.*, (1970, p. 1931-32). The sedimentation rate in turn is too great and prevents development of the slowly growing massive corals as *Montastrea* sp. having annual growth increments of 0.25-0.75 cm (Vaughan, 1915). This may explain why most sea-level lagoonal banks in the Dry Tortugas are populated preferentially by A. cervicornis and, why in some vertical successions terminated by the A. palmata reef facies the Montastrea reef-bank facies is considerably reduced or missing. On the other hand, lagoonal banks which accumulate at a slow rate or whose sediment-trapping and sediment-stabilizing ability ceases to function before they reach the effective wave base, become overgrown by massive corals and their continued growth upward may proceed as rigid reef banks. However, because the development of lagoonal banks is limited to protected locations, upward growth on open windward sides of the Dry Tortugas appears to be initiated by the Montastrea reef-bank facies as a rigid reef wall.

There seems to be correlation between the growth rate of lagoonal banks and the nature of water movements over the banks. The sediment-trapping and stabilizing capacity of marine organisms responsible for the bank buildup appears most effective in locations with optimum laminar flow generated by tides. Under these conditions lagoonal banks accumulate at a faster rate compared to either quiet or turbulent locations where the effective transport of suspension and saltation loads and nutrients is rather reduced. This is demonstrated by the concentration of larger, mature banks in Southwest Channel where tidal currents attain maximum velocities of 40-60 cm/sec, values which are below the 70 cm/sec critical velocity for the erodability of Thalassia-stabilized substrates as reported by

Scoffin (1970). Other prominent lagoonal banks are found across Northwast Channel and inside Southeast Channel where tidal velocities are 30-50 cm/sec. In the central parts of the lagoon, where tidal currents range from imperceptible to about 20 cm/sec, banks are few and smaller. Probably due to decreased current velocities, suspended sediment in the center of the lagoon settles out rather evenly without forming differential buildups.

The flat-topped, sea-level lagoonal banks in the lee of Garden Key segment have grown by lateral accretion and have joined the lee side of the reef flat as a network of coalescing banks separated by a system of meandering passages with lobate embayments (fig. 1). Upon further lateral expansion the inter-bank spaces become narrow and many embayments become stranded as local ponds. Lateral growth forces tidal currents to flow through the gradually constricting passages with increased velocities until the passages become modified into tidal channels by subsequent lateral erosion. This evolution suggests that some tidal channels on carbonate tidal flats may not originate by erosional cutting, but develop in a manner similar to the inter-bank passages in the Tortugas. This may also explain the observed tendency for straightening of some meandering tidal channels accompanied by a change from the lower flow regime to the upper flow regime during their history (Jindrich, 1969).

The surface morphology of the Loggerhead Key segment suggests that the bulk of this reef bank consists of unconsolidated skeletal debris irregularly veneered by storm-degraded reef-rock repopulated by corals. This hypothesis is supported by a drillhole on Loggerhead Key (U.S. Coast Guard water well drilled in July, 1969) which penetrated unconsolidated sediment to the depth of 18.5 m below the sea level, bottoming there on the hard Pleistocene platform from which the Tortugas rise (fig. 4). A sample comprising the whole drillhole column is a poorly washed detritus of essentially unabraded _Halimeda_ flakes and minute mollusc shells with preserved filaments of sea-grass tissue. The character of the sediment clearly indicates its accumulation as a lagoonal-bank facies. In addition, the Loggerhead Key segment is an example of _A. palmata_ reef that has evolved from the lagoonal-bank facies. Upon southeastward lateral progradation aided especially by accumulation of flanking detrital aprons, the segment expanded from a wholly leeward to a partly unprotected windward location. The lateral expansion was accompanied by replacement of massive corals by _A. cervicornis_, forming a zone which seems to directly overlie the flanking aprons and provides a foundation for the incipient _A. palmata_ reef facies.

The Garden Key segment and the crescentic East Key segment, which together form the windward perimeter of Dry Tortugas, are complex. The reef-bank facies, overlain locally by the reef facies, constitutes a relatively thin, rigid reef wall along the windward faces of these segments. The facies development in the lee of reef wall (the back-reef facies of some authors) undoubtedly reflects recurrent storm activity expressed as frequent changes of depositional and erosional events that shifted from place to place. Such environmental changes would be primarily a measure of the resistance of the windward wall to periodical storms. These considerations, corroborated from field observations on lateral scale, have important bearing upon the character of reef flat. As inferred from the present surface morphology, the internal structure of sediments beneath the reef flat very likely displays a complex overlap relationships between the lagoonal-bank facies and reef-bank facies, including the reef-wall-derived detritus and rubble beds (fig. 4).

The development of the oval-shaped Dry Tortugas complex was not established simultaneously along its whole perimeter as in the case of oceanic atolls controlled in their growth by the relative subsidence of the foundation. Organic growth at the Dry Tortugas seems to have been initiated, first, as the rigid reef wall along the windward perimeter. Upon reaching surface waters the reef wall exercised substantial influence upon those environmental conditions controlling subsequent development of reefs and banks at leeward locations. Based upon the surface observations supplemented by the drill-hole results from Loggerhead Key it is estimated that about three quarters of the total volume of Dry Tortugas reef complex consists of unconsolidated skeletal detritus concealed beneath a crust of rigid reef and reef-bank framework. The circular shape of the complex may be related to the direction of prevailing winds and seasonal storms (see also Brooks, 1964) and to the tidal-flow pattern upon the surrounding shelf.

At present, growth of the Dry Tortugas reef complex is being accomplished largely by lagoonward progradation of the windward segments and by expansion of sea-level lagoonal banks. Periodical storms hastening mechanical and biological destruction and thus promoting the supply of skeletal detritus, substantially augment the rate of lateral growth.

In morphology and overall geological setting the Dry Tortugas closely resemble the Alacran reef complex. At Alacran, skeletal detritus accumulated into differential buildups of the lagoonal-bank type, which occupy a vast part of the relatively closed lagoon (Logan _et_ _al_., 1969). The Dry Tortugas lagoon could have a similar appearance in a well-advanced stage of lateral progradation.

Effects of Holocene sea-level changes

The submarine platform which forms a broad terrace around the leeward side of Dry Tortugas at 17-21 m and was encountered at 18.5 m by the drillhole at Loggerhead Key forms a shallow foundation of the windward Garden Key segment (fig. 4). A drillhole at the Garden Key encountered Pleistocene coral reef, the Key Largo Limestone, at a depth of 10 m (Hoffmeister and Multer, 1968). This indicates that the platform may be a drowned, Pleistocene erosional surface with an elevated southeastern margin on which the post-glacial coral growth was renewed. With reference to the sea-level/time curves of Milliman and Emery (1968) and of Curray (1965) the post-glacial coral growth upon the platform should not be older than about 7000 B.P. and about 8500 B.P., respectively. Considering the age of Key Largo Limestone at 95,000 ± 9000 B.P. (Broecker and Thurber, 1965) the Tortugas submarine platform should represent a discontinuity between Holocene and older limestones (Thurber et al., 1965; Broecker and Thurber, 1965). The depth of Tortugas platform correlates well with the depth of drowned Key Largo Limestone surface encountered by drillholes beneath the Holocene Florida reef tract at 17 m (Hoffmeister and Multer, 1968).

Published Holocene sea-level curves (for example Shepard, 1961; Curray, 1965; Jelgersma, 1966; Milliman and Emery, 1968) indicate a post-glacial sea-level rise at a rate of about 1 m/100 years up to approximately 7000 B.P. From that time to the present there is some divergence of view on sea level behavior as summarized, for example, by Curray et al., (1970). However, many radiocarbon data are being accumulated which support the view of general slowing of eustatic rates from about 7000 B.P. with an abrupt decrease of sea-level rise at about 4000 B.P. This view, accepted here, is based on recently compiled curves by Scholl et al. (1969) from South Florida, by Redfield (1967) from North Carolina and Bermuda, and by Bloom (1970) from the Caroline Islands. These curves are closely related and indicate a eustatic rate in a range of about 8.3-33.0 cm/100 years prior to 4000 B.P., and 3.5-7.6 cm/100 years for the last 4000 years (fig. 5). While oceanic islands such as the Carolines are considered to be relatively free from isostatic warping (Bloom, 1967), slight subsidence of the Florida shelf at a rate of about 1.5-3.0 cm/100 years is admitted by Scholl <u>et al</u>. (1969).

Because coral growth is sensitive to sea-level changes the pronounced slowing of eustatic sea-level rates for the past several millenia should affect considerably the development of reefs. The slowly rising sea level on the order of several centimeters per century can be greatly exceeded by organic growth rates variously estimated at 70 cm/100 years (Vaughan, 1915) or 42-85 cm/100 years (Hoffmeister and Multer, 1964) for reefs composed of massive coral heads. The growth rate of 250 cm/100 years calculated for reefs constructed by branching <u>A. palmata</u> (Vaughan, 1915) stands particularly in sharp contrast with the present eustatic rate of sea-level rise.

In general, existing West Indian reefs must have caught up with the slowly rising sea level, which could not have been far below the present level several millenia ago. Under these circumstances coral growth must have responded by lateral expansion instead of vertical growth. However, the long-term cumulative effects of periodic storms have not been evaluated. Since the time of abrupt slowing of sea-level rise the crests of laterally growing reefs near to sea level must have been exposed continuously to destructive storm activity. Considering the decades required for biological recovery of reefs following destructive storms having recurrences measured in years, the complete recovery of many reefs for the past several millenia probably never took place. Observations from the Dry Tortugas, supported by comparative studies of the Florida reef tract and various Pacific reefs suggest that, the organic growth and the superficial features on modern reefs in storm belts developed in direct response to the present conditions of continuing storm "overexposure" linked with the low eustatic rates of sea-level rise.

From strictly surface observations it is difficult to assess accurately the budget of cumulative storm work on reefs for an extended period of time. Storm effects undoubtedly vary from one reef to another and much depends on local conditions such as the length of effective wave fetch and the size of the reef complex. In the Dry Tortugas the important long-term storm effects can be summarized as follows:

1. Almost complete removal of _A. palmata_ and its replacement by coralline algae, _Millepora_ sp., brown algae, and alcyonarians.
2. Plan~~t~~ation of reef crests and shoals resulting in widespread occurrence of hard, truncated surfaces upon the reef-rock.
3. Erosion of radial spur-grooves along the reef front.
4. Extensive accumulation of rubble beds and ramparts and development of intertidal rubble pavement as an essential part of the reef flat.

Newell and Rigby (1957, p. 47), compared reefs of the West Indian Province with mature Pacific reefs having intertidal rocky reef flats fronted by algal rims. They ascribed the general immaturity and weak, patchy development of the West Indian reefs to temperatures below the reef growth optimum as Smith (1948) did earlier. If the north Jamaican reefs serve as a type locality for the best developed _A. palmata_ community characterized by an almost pure, dense population of huge, tree-like colonies (Goreau, 1959, p. 75), then these reefs indeed contrast in varying degrees with the comparatively poor development of this zone in much of the West Indian Province. Published descriptions of modern reef tracts from the Bahamas (Newell and Rigby, 1957), Florida (see Multer, 1969), p. 100-102) and from other areas indicate only patchy occurrence of *A. palmata* on broad rocky shoals or its replacement as at the Dry Tortugas.

It seems likely that modern West Indian reefs owe their immature appearance not so much to low temperatures, but to constant degradation by storms as outlined above. The world's southernmost coral reef is found at Lord Howe Island in the Tasman Sea. Here the coral assemblage is reduced to several genera due to low water temperatures (annual average 21°C winter average 18.5°C) that are similar to temperatures of south Florida waters. Yet the Lord Howe reef is continuous in linear extension and has a well developed, broad intertidal reef platform cut in algal-cemented reef rubble (Jindrich, 1971). The binding capacity of abundant coralline algae on Indo-Pacific reefs is believed to be more responsible in building wave-resistant structures than the corals themselves as has been pointed out by Setchell (1926). This emphasis has led others to propose the term "algal reef" instead of coral reef (Womersley and Bailey, 1969). Had the storm-generated reef rubble of West Indian reefs been effectively cemented by coralline algae or by other means to prevent its removal by recurrent storms from reef crests, many of these reefs would resemble their Pacific counterparts. This is indicated by the intertidal rubble pavement fronted by windward rubble barrier at the Dry Tortugas. Were this pavement and the adjacent rubble barrier cemented it would match perfectly the typical Pacific reef flat and algal rim.

The generally lower proportion of coralline algae on West Indian reefs than on Indo-Pacific reefs can be explained by differing wave-energy conditions between the two reef provinces. The West Indian reefs occur in landlocked seas having limited fetch for wave generation, whereas most Indo-Pacific reefs are fronted by vast expanses of open ocean with no fetch limitation. On the windward fronts of Pacific oceanic reefs where wave energy is greatest, organic growth is being accomplished chiefly by coralline algae rather than corals (see Ladd et al., 1950).

Mesollela et al., (1969, 1970) noted a correlation between the coralline algae content and overall extensiveness of reef tracts in a series of uplifted Pleistocene reefs at Barbados. They suggested that the high proportion of algae in the extensive reefs and the low algal content in smaller, discontinuous reefs might have reflected the degree of climatic warmth during the individual Pleistocene high sea stands. Inasmuch as encrusting coralline algae thrive today in the tropics as well as in the cold waters of sub-Arctic regions (Johnson, 1961), the relationship between the coralline algae content and the degree of climatic warmth may be questioned. High content of coralline algae may well result, as indicated earlier, from too high energy conditions that are less tolerant for luxuriant coral growth, but evidently stimulate algal encrustation. These conditions appear to be best met during periods of near stability of relative sea level implying lateral progradation of reef crests and their prolonged exposure to storms.

Shallow drilling on the reef flats of Bikini (Emery _et al_., 1954) and Eniwetok (Ladd and Schlanger, 1960) has demonstrated that the rocky reef flat is generally thin, only 2-3 m of reef-rock crust (algae-cemented coral boulders in borehole No. 3 on Bikini, Emery _et al_., 1954) overlying unconsolidated skeletal detritus. Similarly, Hoffmeister and Multer (1968) report unconsolidated sediments down to Pleistocene bedrock from holes drilled on top of the rocky platform at the seaward margin of the Florida reef tract. Radiocarbonate dates of cemented coral rubble on intertidal reef flats in the Carolines and Marshalls yield ages from about 4400 to 2500 B.P. (Curray _et al_., 1970). These dates cluster around the inflection points on eustatic curves that mark the decrease of sea-level rise several millenia ago. The infrequency of age dates younger than 2500 B.P. from the sampled rubble may be attributable to general decrease of rubble supply due to cumulative storm effects. These effects were demonstrated for short periods by Perkins and Enos (1968) from observed decrease of reef rubble generated in the Florida reef tract by the second of two successive hurricanes of the same vigor. A lack of an appreciable amount of fresh reef rubble is apparent on windward reef fronts in the Dry Tortugas.

The age dates and drilling results from reef flats are in agreement with the thesis, made earlier, that since the abrupt decrease of eustatic sea-level rise, surface morphology of the laterally expanding reefs primarily reflects storm activity over an extended period of time. Thus reef flats and spur-groove systems, developed in response to these conditions appear to be relatively young features. They probably began to form on most modern reefs some 4000 to 3000 years B.P. when sea level was very close to its present position. Laterally expanding organic growths, constantly degraded by storm erosion and healed chiefly by algal and Millepora encrustation between storms, form a reef-rock crust having a truncated, hard surface. These surfaces frequently occur as reef-flat pavements up to the potential organic growth ceiling at the low tide level. An increased supply of rubble, available at the onset of slow relative submergence inducing dominantly lateral growth, may be swept onto reef flats and cemented to extend the height of reef flats above low tide level. Such is the situation on many Pacific reefs. Subsequently truncated surfaces or erosional remnants of these cemented rubble beds, standing up to 2 m above the present reef flat, were often interpreted as the in-situ coral reef-rock and misconstrued as evidence for post-glacial high sea-level stands (Newell and Bloom, 1970).

The unconsolidated sediments underlying the 2-3 m thick lithified crust of reef flats are probably detrital aprons derived from reef fronts during the earlier Holocene periods of higher eustatic sea-level rates when reefs tended to grow dominantly upward. The higher eustatic rates probably offset somewhat the exposure of reefs to storm erosion, hence less detritus was available for reef-flanking aprons. Flanking deposits should have lagged behind the upward growing reef wall in vertical accretion and typical reef flats were probably absent.

CARBONATE SEDIMENTS

Constituent particle composition

All sediments studied are composed of skeletal fragments in the fraction coarser than 4.0 phi. Constituent percentages of individual samples are shown in Table I. Three major constituent groups form the bulk of sediments: corals, Halimeda, and molluscs. Next in importance are coralline algae and foraminifers. Minor constituents, grouped under miscellaneous, are represented by alcyonarian spicules, echinoid spines, crustaceans, ostracods, sponge spicules, and traces of bryozoans. These constituents, especially alcyonarian spicules, may constitute a significant portion (up to 11%) in some fine sediments. Mud pellets and ooliths, reported by Thorp (1936) from some lagoonal samples in amounts of 2.8% and 1.0% respectively, were not detected.

Bottom types and related sediments

Sediments of the Dry Tortugas are represented in a variety of size classes ranging from cobble gravel to medium silt.

In general, the sediment grain size decreases as the depth of sedimentary environment increases. Several bottom types are recognized: 1) rocky bottom, 2) detrital substrate stabilized by seagrass and branching corals, 3) sandy bottom, and 4) beach. Textural and compositional characteristics of the bottom sediments and their relationship to various environments are summarized in Table 2. Size-frequency distribution of representative sediments for individual bottom types are shown in Figs. 7, 8.

Rocky Bottom. - Rocky bottom includes indurated surfaces of the storm-degraded shoals on reefs and reef banks and the rubbly pavement at the windward side of Garden Key segment. Rocky bottom also occur at the entrance of Southeast Channel and Southeast Channel. Prevailing very high energy conditions prevent substantial sand accumulation, except of cobble and pebble gravel. Well-worn poorly sorted sandy gravel - gravelly sand (fig. 18) occurs in localized veneers several centimeters thick. This sediment has the highest amount of fragments of coralline algae (8-15%)observed in the Dry Tortugas. _Halimeda_ fragments are characteristically low in number or entirely absent, although living _H. tuna_ and _H. opuntia_ are common upon the rocky bottom.

Detrital substrate stabilized by seagrass and branching corals. - This type of bottom includes seagrass beds, and dense growths of _Acropora cervicornis_ and _Porites porites._ Species of _Halimeda_ that grow in abundance interspersed with seagrass and colonies of _P. porites_ further stabilize the detrital substrate. The

TABLE 1. - Constituent composition and grain size parameters

Sample station	Halimeda	Corals	Molluscs	Coralline algae	Forams	Miscell.	Unknown	Mean size (Mz)	Sorting (σ_I)	Mud %
				Marine samples						
A 1	9	42	24	14	5	3	3	1.08	0.42	
A 2	12	41	26	9	7	3	2	1.10	0.52	
A 3	12	22	37	6	9	7	7	1.28	0.78	
A 4	7	28	39	7	4	4	11	0.79	0.64	
A 5	28	9	36	3	13	8	3	2.23	0.57	
A 6	27	12	34	4	12	8	3	1.93	0.64	
A 7	6	45	31	8	4	3	3	0.86	0.75	
B 1	46	8	25	1	7	9	4	3.42	1.63	16.30
B 2	12	49	24	9	2	2	2	0.22	0.39	
B 3	8	50	25	11	1	2	3	0.08	0.38	
B 4	27	35	20	8	6	2	2	0.98	0.80	
C 1	55	12	14	1	7	3	4	2.38	0.69	
C 2	89	2	4		2	2	1	-1.05	1.19	
C 3	4	54	23	12	4	2	1	0.31	0.79	
C 4	3	54	22	9	5	3	4	0.48	0.78	
C 5	48	8	23	1	6	8	6	2.60	1.17	9.20
C 6	38	13	34	4	6	2	3	0.54	0.79	
C 7	49	3	23		4	10	11	3.73	1.27	33.20
D 1	62	15	16	3	2	2		-0.69	1.04	
D 2	57	3	21	1	4	4	10	2.89	1.46	24.18
D 3	58	2	30		2	6	2	2.71	1.48	11.05
D 4	9	46	31	9	1	1	3	0.55	0.52	
D 5	43	4	38	1	4	5	5	2.80	1.78	18.40
D 6	32	5	48	1	5	5	4	3.38	1.64	27.20
D 7	47	24	19	4	3	1	3	-0.59	1.12	
E 1	44	28	13	6	7	1	1	0.51	0.69	
E 2	20	47	18	5	6	3	1	0.86	0.48	
E 3	50	14	19	6	6	3	2	-0.63	1.20	
E 4	41	32	32	1	6	3	3	2.13	0.41	
E 5	58	22	10	4	2	1	3	-0.68	0.98	
F 1	8	51	21	12	4	3	1	0.53	0.58	
F 2	52	15	15	7	5	4	2	-0.78	1.03	
F 3	39	25	21	5	4	4	2	0.07	0.79	
F 4	43	21	23	2	7	3	5	2.15	0.76	
F 5	50	4	17	1	11	12	5	3.55	1.23	36.80
F 6	47	6	28		7	3	9	3.19	1.52	28.70
F 7	26	25	23	2	8	11	5	1.97	0.45	
F 8	54	15	22	6	1	1	1	-0.41	0.86	
F 9	29	42	19	6	2	1	1	-0.05	0.65	
F 10	36	28	21	5	5	2	3	1.17	0.54	
G 1	67	4	22	2	4	1		0.30	1.27	6.36
G 2	6	54	20	15	3	2		-0.72	0.80	
G 3	7	51	22	13	4	2	1	0.62	0.58	
G 4	16	2	52		12	8	10	3.84	2.06	44.70
G 5	62	12	19	3	3	1		-0.38	1.05	
G 6	64	6	23	2	5	4	6	0.41	1.27	4.48
G 7	49	20	16	3	5	4	3	1.66	0.68	
G 8	29	27	23	2	7	5	7	2.19	0.46	
H 1	26	5	45	2	6	7	9	3.26	1.56	12.68
H 2	14	50	19	8	5	2	2	0.18	0.51	
H 3	72	4	16	3	3	1	1	0.54	1.28	2.60
H 4	47	24	18	3	2	4	2	1.23	1.33	
H 5	57	8	14		4	4	13	2.88	1.82	35.85
H 6	41	28	22	2	2	1	4	0.71	0.55	
J 1	13	49	19	11	5	2	1	0.64	0.47	
J 2	31	29	22	2	7	6	3	1.37	0.86	
J 3	11	48	24	9	5	1	2	0.55	1.08	
J 4	41	24	22	1	7	2	3	2.15	0.48	
J 5	12	49	23	10	4	2		-0.42	1.10	
J 6	6	54	20	11	5	2	2	0.51	0.67	
J 7	1	61	29	9				-1.62	1.21	
J 8	39	28	21	4	6	2		1.48	0.72	

TABLE 1.(Cont.) - Constituent composition and grain size parameters

Sample station	Halimeda	Corals	Molluscs	Coralline algae	Forams	Miscell.	Unknown	Mean size (M_z)	Sorting (σ_I)	Mud %
					Marine samples					
K 1	58	7	16	2	6	5	6	3.53	1.14	28.24
K 2	56	13	27	2	1		1	-0.15	0.68	
K 3	42	19	22	3	6	3	5	2.18	0.81	
K 4	2	58	27	9	1	1	2	-0.18	0.45	
L 1	44	12	24	2	8	5	5	2.86	1.51	16.77
L 2	39	8	31	2	7	6	7	2.79	1.40	18.24
L 3	37	28	18	8	4	3	2	0.58	0.92	
L 4	39	30	15	6	6	4		0.78	0.86	
L 5	16	41	27	5	5	3	3	0.58	0.69	
L 6	13	39	32	4	7	3	2	1.73	0.65	
M 1	44	7	31	2	8	4	4	2.91	2.03	28.66
M 2	32	38	16	5	4	3	2	1.46	0.91	
M 3	43	28	19	5	2	2	1	0.28	1.13	
M 4	13	46	28	7	3	1	2	-0.05	1.09	
M 5	47	6	29		6	4	8	3.57	1.58	39.40
M 6	46	5	27		8	5	9	3.62	1.37	36.55
M 7	6	58	21	7	4	2	2	0.58	1.21	
M 8	42	5	21		11	9	12	3.49	1.16	30.42
M 9	35	6	22	1	9	10	6	3.32	1.41	25.35
M 10	3	56	29	9		1	2	0.04	0.67	
M 11	14	52	25	8		1		-0.72	1.08	
M 12	4	55	25	10	3	3		0.42	0.75	
N 1		51	33	14	2			-2.04	1.82	
N 2	37	29	19	5	6	3	1	1.48	0.98	
Drill hole	56	1	38		3	2		-0.18		
					Beach samples					
EK	42	34	16	4	1		3	0.98	0.15	
GK 1	11	7	31	49	2			-1.37	0.53	
GK 2	30	24	17	26	1	2		-0.83	0.42	
GK 3	62	7	18	10	1	2		-0.92	0.50	
HK	26	35	23	5	2	1	6	0.66	0.26	
MK	38	28	23	1	4	1	5	1.13	0.39	
X 1	51	18	25	4	2			0.65	0.36	
X 2	60	14	21	2		1	2	-0.70	0.98	
X 3	58	18	19	3	1	1		0.88	0.76	
X 4	66	10	15	2	3	1	3	0.20	0.39	
X 5	54	19	20	2	4		1	0.68	0.54	
X 6	34	37	22		4	1	2	1.21	0.37	
X 7	55	24	18	1			2	0.27	0.46	
X 8	49	16	24	1	5	2	3	0.98	0.45	
X 9	64	16	17	2	1			-0.04	0.65	
X 10	62	13	21	1	2		1	-0.26	0.53	
Y 1	68	9	20	2	1			-0.39	0.54	
Y 2	55	15	24	1	3	2		0.60	0.41	
Y 3	26	67	5	1	1			2.10	0.33	

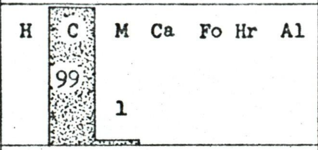
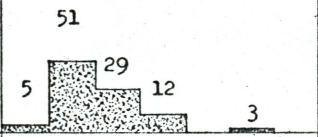
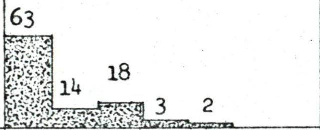
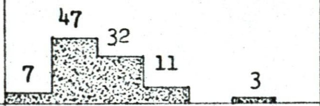
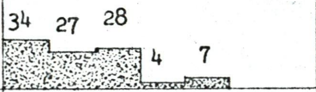
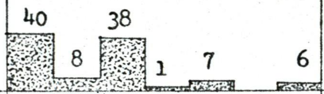
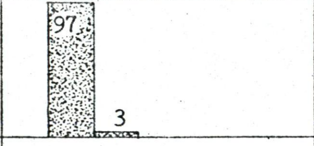
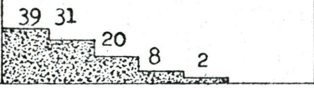
Table 2 - Bottom types and characteristics of related sediments in the Dry Tortugas

BOTTOM TYPE	ENVIRONMENT	SEDIMENT	
		Type	Phi mean (Mz) size range
Rocky bottom	reef front, reef flat	cobble-pebble gravel	data not available
	storm-degraded shoals	gravelly sand-sandy gravel	-2.04 to 0.55
Substrate stabilized by seagrass & coral	lagoonal banks, reef flat, surf-protected shoals	gravelly silty sand-sandy gravel	-1.05 to 2.48
Sandy bottom	windward slopes, storm-degraded shoals, channel entrances	very coarse-coarse sand	-0.72 to 0.79
	lagoon margins, leeward slopes	medium-fine sand	1.23 to 2.48
	lagoon bottom, shelf	silty fine-very fine sand	2.58 to 3.84
Beach	surf-exposed beach	cobble-pebble gravel	-7.50 to -4.80
	surf-protected beach	granule gravel-fine sand	-1.37 to 2.10

* H - *Halimeda*
C - coral
M - molluscs

Ca - coralline algae
Fo - foraminifers
Hr - *Homotrema rubrum*

Al - alcyonarian spicules

SEDIMENT			Energy conditions
Phi sorting (σ_1) range	Aver. % constituents *	Remarks	
data not available		biological breakedown effective	waves - very high
1.08 to 1.82		subround grains	waves & currents - very high
0.81 to 1.33		biological breakdown effective, unworn grains, int. burrowing	currents - low to moderate
0.38 to 0.80		subround (frosted) grains	currents (waves) - high
0.41 to 0.68		local burrowing	currents - moderate
1.14 to 2.06		burrowing	current & gravity - low to moderate
0.53 to 0.78		subround grains	waves - very high
0.15 to 0.98		subround-rounded (polished) grains, local burrowing	waves - moderate to high

substrate consists of varying proportions of pebble-granule gravel and sand-sized fragments. Silt-sized particles are locally present in amounts not exceeding 10% of the total sample weight. The sediment consists of fragmented skeletons, whole unworn shells of infaunal molluscs, Halimeda segments, and coral sticks (fig. 20). Constituent percentages are variable but Halimeda predominates. Some substrates stabilized by A. cervicornis are almost pure accumulations of the whole Halimeda segments concentrating beneath the interlocking coral branches overgrown by H. opuntia (fig. 10). The Halimeda-rich substrate stabilized by seagrass and branching corals surfaces isolated lagoonal banks and those adjoined to the lee sides of Garden Key and East Key segments. On the Garden Key segment the substrate extends to the windward as a substantial part of the reef flat (Thalassia and Porites zones). Consequently, this substrate is a fundamental lithosome of lagoonal banks and constitutes the unconsolidated core of some reef banks and beds underlying the reef flat (fig. 4).

Sandy bottom. - Of all bottom types sandy bottom occupies the largest area of the Dry Tortugas. The sandy bottom ranges from barren areas to those where seagrass, Halimeda, and coral growths do not exceed densities required for stabilizing effect and immobility of substrate. Very coarse to coarse sand, commonly displaying rippled surfaces, occurs in the high-energy zone along the margins of wave and current-swept rocky bottoms. The sand fills depressions on the shallow rugged relief and surfaces the windward slopes of reefs and reef banks as detrital aprons. Coarse sand also occurs as local veneers surfacing the entrance of Southwest Channel (fig. 21) and the storm-degraded shoals on some lagoonal banks (sample D4, M 10). Good sorting of grains that are commonly subround and frosted, high content of coralline algae, and low content of Halimeda, are diagnostic properties of the very coarse-coarse sand.

Medium-fine sand, locally overgrown by scattered patches of seagrass, forms substrates below the effective wave base or on surf-protected shoals. Widespread aprons of this sand occur on shoals marginal to the lagoon and on lagoon slopes and grade into the substrate stabilized by seagrass and/or A. cervicornis. Surfaces of the aprons are ornamented by sand piles of Callianassa burrows and by shallow trails of plowing echinoids (Encope sp.). Medium-fine sand from bare areas is well sorted and consists of subround fragments of Halimeda, coral, and molluscs. (fig. 22). Occurrence of seagrass on the substrate is reflected by decreased degree of sorting and grain coarsening caused by presence of coarse Halimeda fragments.

Silty fine to very fine sand veneers the generally flat lagoon bottom. Bathymetry of the Dry Tortugas suggests that the silty sand overlies the Pleistocene foundation in a thickness probably not exceeding several meters (fig. 4). Toward channel entrances the silty sand thins and grades into the medium and coarse sand that ultimately wedges out on the current-swept rocky bottom. Grab samples indicate that the silty-sand substrate supports various species of green calcereous algae, including Halimeda; scattered seagrass; and molluscan infauna. Seagrass is locally concentrated on mounds projecting several meters above the flat bottom. Similar substrate was obtained from shelf off the Garden Key segment at a depth of 26 m (sample G4, H1). The silty sand contains 11 - 45% of coarse-medium silt. All samples (19) are deficient in particles finer than 6.0 phi. Fragments and whole small shells of Halimeda and molluscs form the bulk of the sand-sized fraction. Characteristic is the high content of alcyonarian spicules (4-11%) and low content of coral fragments (2-12%). Fragments of Halimeda and alcyonarian spicules can be still recognized in the coarse-silt fraction.

Beach. - Coral cobble and pebble gravel form the surf-exposed Long Key and the windward spit of Bush Key as subaerial extensions of the rubble barrier at the Garden Key segment. In contrast to submerged rubble, beach fragments above the high tide level are free of algal coatings and organic boring. All other beaches, protected from direct surf during the prevailing conditions, include a variety of sediments ranging from granule gravel to fine sand. Very coarse to coarse sand is by far the most frequently occurring size class on the Dry Tortugas beaches.

The beaches of Loggerhead Key, Garden Key and Bush Key have a continuous, high rate of supply of fresh skeletal detritus from adjacent shoals. Waves on these beaches tend to sort out the diverse skeletal material selectively into texturally and compositionally distinct units. Individual sand-sized grades are sorted in successive laminae or beds, several millimeters to several centimeters thick (fig. 15). Gravel segregates as parallel ramparts or ridges ranging in height from several centimeters up to 1.5 meters (fig. 16). Apart from coral cobbles and A. cervicornis pebbles (fig. 17), low granule ramparts, 2-5 cm high, formed by a concentrate of fragmented coralline alga, Goniolithon sp., locally occur on the Garden Key beach (sample GK1). Halimeda fragments concentrate in the very coarse to coarse sand that forms extensive bedded successions on the Loggerhead Key beach (fig. 15). Coral fragments are concentrated also in the medium-fine sand deposited as laminae at the leeward tip of Bush Key (sample Y3). Burrowing sand crabs, in addition to sea turtles excavating deep holes to lay eggs, locally destroy the original beach bedding. Sand-sized fragments display a considerable range of roundness. Best rounded grains occurring at the coarse sand-sized grade are still subround with frosted or low-polish surface.

Hospital Key, Middle Key and East Key, considerably reduced in size by the past hurricanes, are surrounded by barren, coarse-sand substrate of moderately well sorted and subround fragments. Beach sediments of these small islands are uniform in grain size ranging from coarse to medium sands. Distribution of Halimeda, coral, or mollusc fragments is likewise uniform with local slight predominance of coral or Halimeda. Sediment bedding is poorly developed or lacking. The coarse sand from East Key (sample EK) and the highly rounded and polished coarse sand from Hospital Key (sample HK) are the best sorted sediments of the Dry Tortugas (figs. 23, 24.)

Depositional processes and grain size populations

Biological and mechanical breakdown are the principal size-reduction mechanisms of carbonate skeletons in the Dry Tortugas. On substrates where dense seagrass and coral growths prevent significant sediment movement, biological breakdown, as described by Swinchatt (1965), is an important process. In other substrates fragments show varying degrees of grain wear resulting from the mechanical breakdown accomplished through the energy of currents and waves.

Distribution of grain size and constituents in transported bioclastic sediments are commonly related to factors that include: 1) differential resistance of skeletons to abrasion, 2) internal skeletal structure and size of parent organism, 3) hydraulic properties of skeletal particles and, 4) mode of transport. Although documented experimentally, evaluation of the relative importance of these factors in natural environments is generally difficult. Differing abrasion rates of various skeletal constituents were shown by Chave (1960, 1964) and Moberly (1968). Maxwell _et al._, (1964) found fragments of coralline algae concentrated in the coarse-grained fractions on a reef flat and attributed this to a high resistance of coralline algae to destruction. Folk and Robbles (1964) in a beach study argued for the control of skeletal structure (Sorby Principle) upon fragmentation of _Halimeda_ and coral reflecting an inbuilt bimodality in grain size distributions. Force (1969) observed in a tumbling mill discontinuous breakup of certain mollusc shells due to their specific microarchitecture. He could not, however, confirm the experimentally produced grain size populations in natural environment due to selective dispersal by waves and currents (Force, 1969, p. 902).

Moss (1962, 1963) provides a detailed insight into the means of depositional processes. He distinguished log-normal grain size populations produced by three means of sediment transport. Moss showed that the best-sorted particles are the ones transported by saltation involving characteristically the sand-sized material. The coarser-grained particles transported by rolling and sliding represent surface creep; the finer particles are transported in suspension. Critical sizes for these populations vary considerably due to variations in grain shape, competence of currents and nature of the bed (Moss, 1963, p. 306). Characteristics of individual populations, represented as straight line segments on the log-probability plots were used by Visher (1969) as environmental indicators for non-skeletal sediments.

Log-probability plots based on sieving data for skeletal sediments do not produce meaningful results. Disparities between the sieving and hydraulic sizes are apparent from settling velocity curves presented by Maiklem (1968) for different skeletal grain shapes. Plates, the slowest settling particles, settle about 50% slower than equidimensional blocks at the medium sand size. This difference increases to about 100% at the very coarse sand size and to over 300% at the pebble-sized material (Maiklem, 1968, p. 108). Differing grain size distribution curves computed from sieving and hydraulic data for the same samples are demonstrated in Fig. 9. Strong departures between the lower part of curves caused by abundance of irregularly shaped grains in the very coarse sand fraction is indicated in Fig. 9 A, B. Considerable deviation in the mean grain sizes in Fig. 9 C is related to the low effective density of porous, spherical foraminifer, Baculogypsina, a dominant constituent in the sample.

Variations in texture and constituent particle composition in sediments of the Dry Tortugas show correlations suggesting that these variations resulted primarily from different modes of transport and effects of grain shape. Grain size populations recognized here are based on the concept of Moss (1962, 1963). Critical sizes of these populations are inferred from observations of movement type of grains under various environmental conditions, supplemented by data from grain size distributions. In interpretations of these data the increasing diversity between sieving size and hydraulic size toward coarser size grades is taken into consideration. Grain size distributions at the medium-fine sand grade were observed to reflect more objectively the process of sedimentation. In the high-energy environment free of seagrass and coral growths, block-shaped grains up to -0.5 phi in diameter were sampled saltating within several centimeters of the bottom. Particles up to about 3.0 phi in size were commonly seen in suspension carried by currents on shoals during spring tides. These values are tentatively set for a size range of particles transported dominantly by saltation during the prevailing conditions. The settling velocity of - 0.5 phi block-shaped grains is equal to plates of about - 3.0 phi in diameter (see Maiklem, 1968, p. 105). This suggests that the size range of saltation population for platy fragments of <u>Halimeda</u> and molluscs probably extends into coarser size grades. The 3.0 phi value representing a critical size between the saltation and suspension population is a significant measure in grain size distributions in the Dry Tortugas. All sediments, except of the lagoonal silty sand and the substrate stabilized by seagrass, are free of size fractions finer than 3.0 phi. The significance of 3.0 phi diameter in grain size distributions was noted by Ginsburg (1956) in the Florida reef tract and by Folk and Robles (1964) who used 3.0 phi as an upper size limit for carbonate "mud" on beaches of Alacran.

Following are the characteristics of grain size populations in the Dry Tortugas:

1) Surface creep population is represented basically by the gravel-sized material controlled by source. Coral fragments form the coarsest size grades. Fragments of corals and coralline algae and whole or fragmented mollusc shells occur in varying amounts of finer grades. Fragments of <u>Halimeda</u> are winnowed away from this assemblage. On substrates where seagrass and coral growths reduce competence of currents, winnowing is less effective and coarse <u>Halimeda</u> fragments were observed moving intermittently as a surface creep.

2) Saltation population includes the sand-sized material coarser than very fine sand. Sorting is good in this size range.

In subaqueous environments the very coarse to coarse sand grade consists of coral and mollusc fragments. The medium-fine sand grade reveals a tendency for subequal amounts of *Halimeda*, coral, and mollusc fragments. At this size abrasion substantially reduces the shape diversity of grains and the settling velocities are near uniform. Furthermore, grains at this size grade appear to be the easiest to move long distances by saltation, thus having a potential for constituent intermixing. A similar tendency for subequal constituent representation was observed elsewhere in Florida in well sorted medium sands which had undergone considerable transportation from source (Jindrich, 1969). Constituent representation in most beach sands in the Dry Tortugas reflects a strong influence of source proximity and differs from the pattern of constituent distribution in marine sands.

3) Suspension population includes very fine sand and coarse-medium silt. Deficiency of particles smaller than 6.0 phi is attributed to their removal by tidal currents. The sand-sized fraction consists of fragmented *Halimeda* and molluscs in addition to whole minute shells of bivalves and gastropods. Alcyonarian spicules constitute 10-16% of the suspension population. The coarse texture of the silt fraction, showing a predominance of coarse silt, suggests that the material resulted from mechanical and biomechanical attrition of skeletal grains.

Distribution of constituent particles

In general, all major constituents occur most frequently in the coarse size grades. Mollusc and Halimeda fragments are also frequent in the fine sediments transported by suspension. Grain-size concentration intervals for major constituents are shown in Table 3. Increased frequencies of constituent particles are mutually exclusive in the same size fraction. This is apparent particularly at the medium-fine sand grade where constituents are present in subequal amounts. Table 3 also shows that concentration size intervals for constituents in beach samples are more narrowly confined than the intervals for marine samples.

	Marine Samples	Beach samples
Halimeda	-1.5 to 0.5, 2.5 to 4.0	-0.5 to 0.0
Molluscs	-2.0 to 1.0, 2.5 to 4.0	-2.0 to -1.0
Coral	-1.0 to 0.0	1.5 to 2.0

Table 3 - Phi grain-size intervals of maximum concentration for constituents in sediments of the Dry Tortugas (accumulations of coral rubble omitted.)

Folk and Robles (1964) found Halimeda fragments occurring most frequently on a beach in the granule to coarse sand grade and related this occurrence to the control of skeletal structure upon fragmentation. In the Dry Tortugas Halimeda fragments occur in coarse size grades that ~~and~~ undergo little transportation. These environments include 1) in place-formed substrate, 2) areas where patchy seagrass or coral growths reduce competence of currents and Halimeda fragments move as surface creep, and 3) beaches where waves are inadequate to abrade fresh supplies of coarse Halimeda material derived from adjacent shoals. However, where Halimeda fragments are subject to fragmentation on a long transport, finer fragments are sorted and deposited in other environments. In Table 4 grain-size concentrations of Halimeda fragments from the Dry Tortugas are compared with a variety of environments in other areas. The list shows a considerable range and overlap of size grades from the whole Halimeda segments to the very fine sand. Size fractions of Halimeda that are less frequent or deficient in some environments may be characteristic of others where depositional processes operate under different environmental conditions.

Distribution of coral fragments in the Dry Tortugas shows an overall deficiency of fragments in the size range from about -4.0 to -1.0 phi. Coral cobbles and large pebbles, which are moved only during storms, decrease their size mainly through biological weakening. Upon intensive organic boring the thoroughly perforated cobbles tend to liberate particles most frequently approaching the size of very coarse to coarse sand that are more readily transported. Observed concentrations of generally equidimensional fragments in the very coarse sand grade necessitates winnowing of platy Halimeda fragments and molluscs. In sediment fractions smaller than 2.5 phi coral fragments are rare. This is attributed to their dilution by fragments of Halimeda and molluscs in the suspension population.

Halimeda concentrations in phi units	Environment	Locality
-3.0 to -2.0	beach	Marshall Is. Fosberg & Carroll, 1965)
-2.0 to -1.0	intertidal bank	Florida Keys (Jindrich, 1969)
-2.0 to 1.0	beach	Alacran (Folk & Cotera, 1971)
-2.0 to 0.0	beach	British Honduras (Stoddart, 1964)
-1.5 to 0.5	grassy shoals	Dry Tortugas
-1.0 to 1.0	beach	Alacran Folk & Robles, 1964)
-1.0	lagoon	Kapingamarangi Atoll (McKee *et al.*, 1959)
-1.0	lagoonal pinnacle	Alacran (Hoskin, 1966)
-0.5 to 0.0	beach	Dry Tortugas
1.0 to 2.5	reef flat, lagoon	Heron Is. (Maxwell *et al.*, 1964)
2.5 to 3.5	lagoon	Dry Tortugas
3.0	tidal delta	Florida Keys (Jindrich, 1969)
3.5	intertidal bank	Florida Keys (Basan, 1970)

Table 4 - Grain-size concentrations of *Halimeda* from the Dry Tortugas and other modern carbonate environments.

Coral fragments are markedly concentrated in the medium-fine sand grade on the Bush Key beach. On a beach where grain transport by saltation is related to swash and backwash (Visher, 1969, p. 1083), the effective transport is limited when compared to current transportation in marine environment. Influx of fresh skeletal material and the absence of effective transport length on the Bush Key beach are conditions comparable to the tumbling mill experiments. Under such conditions modal occurrence of constituent particles at certain sizes may reflect differential abrasion rates, manner of fragmentation, or effect of skeletal structure.

Mollusc fragments, compared to other constituents, show least variation in occurrence at different sizes. Fragments of molluscs are derived from a wide variety of forms ranging from large massive epifauna such as Strombus gigas to minute thin-shelled infauna. Besides the fragmented material, molluscs commonly occur as whole shells. Therefore, mollusc grains display a variety of shapes; blocks, plates or other irregularly-shaped grains may occur at all sizes. The shape variability of mollusc grains is in contrast to coral, that tend to produce blocks at all sand size grades, and to Halimeda occurring almost exclusively as plates at the coarse size. In general, there is a slight increase of mollusc content at the granule to coarse sand grade and at the fine to very fine sand grade. This distribution is caused by the winnowing of Halimeda fragments from the coarse size grades and by very low content of coral fragments at the fine size grades.

Fragments of coralline algae concentrate at -1.5 to 0.0 phi and encrusting foraminifer Homotrema rubrum at about 0.0 phi. These constituents occur commonly at the coarse end in grain size distribution of some sands suggesting their transport by the surface creep and proximity to source.

Mixing of grain size populations

Spencer (1963) concluded from analysis of grain size distributions that all clastic sediments are mixtures of three or less log-normally distributed populations - gravel, sand and clay, - and that sorting is a measure of the mixing of these populations. Spencer's populations correspond closely to those produced by three means of sediment transport as Moss (1962, 1963) described. In view of this thesis, the plot of mean grain size and sorting for sediments of the Dry Tortugas (fig. 6) should illustrate the degree of mixing of the populations defined in foregoing pages. Despite considerable scatter of data the size-sorting diagram shows that very coarse to fine sands in the size range of -1.0 to 2.5 phi attain the highest degree of sorting. Coarser and finer sediments are increasingly more poorly sorted indicating a strong mixing between two basic populations so that a broadly U-shaped trend reveals.

Some grain size distributions in the Dry Tortugas exhibit poorly sorted fraction forming a coarse tail added to the well-sorted saltation population (fig. 8, sample C4, C5, E4, J2). These coarse fractions consist of platy grains of *Halimeda* and molluscs and contrast with the more equidimensional grains of the saltation population. Considering the slow settling velocity of plates, many grains in the coarse fraction probably belong to the saltation population and such distributions might be, in reality, better sorted. Some beach samples from Loggerhead Key show distinctly bimodal distributions, thus poor sorting (fig. 7, sample X2, X9). Because of selective beach sorting that produces thinly bedded Halimeda sands on Loggerhead Key, these abnormal distributions are thought to reflect sampling of two bedding units.

Based on the degree of mixing between the surface creep population, saltation population and suspension population, sediments of the Dry Tortugas fall in four textural groups, exclusive of cobble-sized rubble:

1) Very coarse - fine sand, very well to moderately well sorted. These sands are regarded as having the bulk of the size distribution represented by the saltation population with minimum admixture of the surface creep and suspension population. The sands of bare bottoms and most beach sediments constitute this group. Although the beach sands are on average better sorted than the marine sands there is a considerable overlap in the well-sorted class over an entire size range of this group (fig. 6). Best sorted samples are the coarse sands from Hospital Key and East Key. The very high degree of sorting on beaches of these islands is related to a low influx of moderately well sorted sands from adjacent shoals. The highly rounded and polished sand from Hospital Key may have been recycled. Grain size distributions of beach samples are shown in Fig. 7. Distributions of sands from subaqueous barren areas are shown in Fig. 8, sample E4, F4, J1.

2) Gravelly sand - sandy gravel. Most of these poorly sorted sediments fall in the size range of very coarse-coarse sands. Strong mixing in this group occurs between the pebble-sized surface creep population formed by A. cervicornis sticks and the very coarse-coarse sand saltation population formed by coral and mollusc fragments. The mixtures of gravel and sand veneer the storm-degraded shoals where both intermixed components exist separately as local veneers. Grain size distribution of sandy gravel is shown in Fig. 8, sample N1.

3) Silty sand of the lagoon. Samples of the poorly sorted silty sand cluster around 3.0 phi in Fig. 6. Individual samples are mixtures of the medium-fine sand saltation population having subequal amounts of Halimeda, coral and molluscs fragments, and the suspension population formed by Halimeda and molluscs fragments. The intermixed saltation population is a dominant component of the well to moderately sorted sands clustered around 2.0 phi in Fig. 6 which occur on shoals bordering the lagoon. Size-frequency curves show the saltation population with fixed mode at 2.5 phi to which an increasing amount of the suspension population is intermixed on approaching the lagoon bottom (fig. 8, sample E4, F4, C5, C7). This pattern of mixing and the high content of alcyonarian spicules in the suspension population strongly points to the non-indigenous origin of the lagoonal silty sand.

4) Gravelly silty sand - sandy gravel forming the substrate stabilized by seagrass and coral. These sediments are interpre-

ted as incongruous mixtures of the unsorted coarse-grained fraction formed in place, and the transport-produced populations trapped by the current-reducing ability of stabilizing organisms. Although all three means of grain transport were observed upon the stabilized substrate, recognition of intermixed components in the grain size distribution are obliterated by the effects resulting from biological breakdown and sediment bioturbation. Furthermore, there is an intimate relationship between the in place-formed fraction and the surface creep population. Decreased density of seagrass or coral growth facilitates mobility of the in place-formed fraction and aids in its fractionation by transport. The poorly sorted sediments of this group parallel on the size-sorting diagram the sorted sands from barren areas. Transitional are the moderately sorted sands from areas with scattered growths of seagrass or coral. Grain size distributions of sediments from areas with variable density of seagrass and coral growths are shown in Fig. 8, sample C2, F2, G5, M3. In the size range of about -1.0 to 0.5 phi on the size-sorting diagram the coarsest-grained samples of this group overlap with mixed sediments from the storm-degraded shoals. However, the material of stabilized substrates is unworn or angular and rich in Halimeda which is in strong contrast to the worn or rounded material from storm-degraded shoals deficient in Halimeda.

Strong mixing between grain size populations in the textural group 2 and 3 is related to highly variable energy conditions. Mixing between the surface creep population and saltation population on the storm-degraded shoals is thought to reflect interference of tidal currents with surf created by stormy seas. Mixing between the saltation population and suspension population may reflect fluctuations of tidal currents accentuated by alterations during seasonal storms. Variability of current energy as a mechanism causing mixing between the saltation population and suspension population is suggested also by Visher (1969, p. 1103). Fluctuation of energy conditions has relatively little effect on beach sorting. On a beach where different size grades are either selectively sorted or winnowed away strong mixing between grain size populations was not observed.

SUMMARY AND CONCLUSIONS

The Dry Tortugas reef complex is situated on an oval-shaped submarine platform 17-21 m deep. The platform, interpreted as an erosional discontinuity between Holocene and Pleistocene limestones, correlates well with the depth of Pleistocene foundation of the Florida reef tract.

Three types of biogenic buildups (facies) are recognized in constructing the Dry Tortugas segments: 1) Detrital lagoonal bank accumulated by means of the trapping and binding capacity of marine organisms, 2) reef bank, and 3) reef. These facies occur both laterally and, as growth stages of varying thickness and lateral extent, in vertical succession. A characteristic feature is the occurrence of an *Acropora cervicornis* zone developed as a transition between the reef-bank growth stage and the reef growth stage.

Volumetrically, the bulk of the Dry Tortugas reef complex is formed by unconsolidated sediments consisting of poorly sorted detritus of lagoonal banks and sorted detritus of reef-flanking aprons. These accumulations are only veneered by a reef-rock crust of *Montastrea* reef-bank facies, *A. cervicornis* zone and locally by *A. palmata* reef facies.

Organic growth, sedimentation, and morphology of the reef complex primarily reflect long-continued destructive activity of periodical storms having cumulative effects. Lateral growth has been dominant since the marked decrease of sea-level rise several millenia ago, resulting in overexposure to storm degradation of shallow reef crests. Observations made at the Dry Tortugas, Florida reef tract, and at several Pacific reefs suggest that, the geologically most significant consequences of the continuing storm overexposure on many modern reefs may be summarized as follows: 1) general proliferation of encrusting coralline algae at the expense of corals, 2) formation of spur-groove systems by erosion, 3) development of extensive rocky pavements along reef crests at intertidal level (reef flats) or at shallow depths, largely by marine plantation, and 4) general decrease in rate of reef rubble supply due to cumulative storm effects since the decrease of sea-level rise.

Due to the continuous storm degradation, reefs at the Dry Tortugas are conspicuous by the extreme paucity of living *A. palmata*. This branching coral is being replaced by species more resistant to storms (coralline algae, *Millepora* sp.) or possessing rapid growth rates (alcyonarians, brown algae, *Palythoa* mats) which further inhibit coral attachment.

The weak and patchy development of the Dry Tortugas reef complex, and of other West Indian reefs as well, can be explained by the volumetrically lower content of encrusting coralline algae in the reef framework, when compared to reefs of the Indo-Pacific Province. The apparent maturity of many Indo-Pacific reefs appears to be achieved mainly through the capacity of coralline algae to bind and stabilize coral rubble along reef crests.

Sediments in the Dry Tortugas are composed of skeletal grains of Halimeda, coral, and molluscs. Coralline algae and foraminifers are present in minor amounts. Sediment size ranges from cobbles to medium silt; absence of particles smaller than 6.0 phi is attributed to their removal by tidal currents. The mode of sediment transport and grain shape appear to be the most important factors controlling the relationship between texture and constituent particle composition. The grain size populations produced by different mode of transport include 1) gravel, transported by surface creep, 2) sand, transported by saltation, and 3) very fine sand-silt, transported in suspension. Grain shape significantly influences hydraulic behavior of skeletal grains at coarse size grades where difference between sieve sizing and hydraulic sizing are largest. Slowly settling platy grains are winnowed from most coarse-sized sediments formed by more equidimensional grains. The tendency of coral to occur as equidimensional grains, Halimeda as platy grains, and molluscs as variously shaped grains, has important impact in distribution of these constituent particles by transport. Hydraulic behavior of skeletal grains at about 1.5 to 2.5 phi size grade become more uniform. This is reflected in proportional distribution of Halimeda, coral and mollusc grains in well sorted medium-fine sands transported by currents.

Based on the degree of mixing between the grain size populations four textural groups are recognized:

1) Sorted sands forming detrital aprons flanking reefs and reef banks. This group includes most beach sediments.

2) Poorly sorted mixtures of gravel and sand forming veneers on the storm-degraded crests of reefs and reef banks.

3) Poorly sorted mixtures of sand and silt veneering the lagoon bottom.

4) Poorly sorted incongruous mixtures of the in place-formed skeletal fraction and varying proportions of the transport-produced populations. Sediments of this texturally and compositionally varied group constitute detrital lagoonal banks and occur as a substrate stabilized by seagrass and coral growths.

Strong mixing between the populations on the storm-degraded crests and on the lagoon bottom are related to depositional processes under highly variable energy conditions. Variability in energy conditions on beaches does not result in strong population intermixing as different size grades are either selectively sorted or winnowed away.

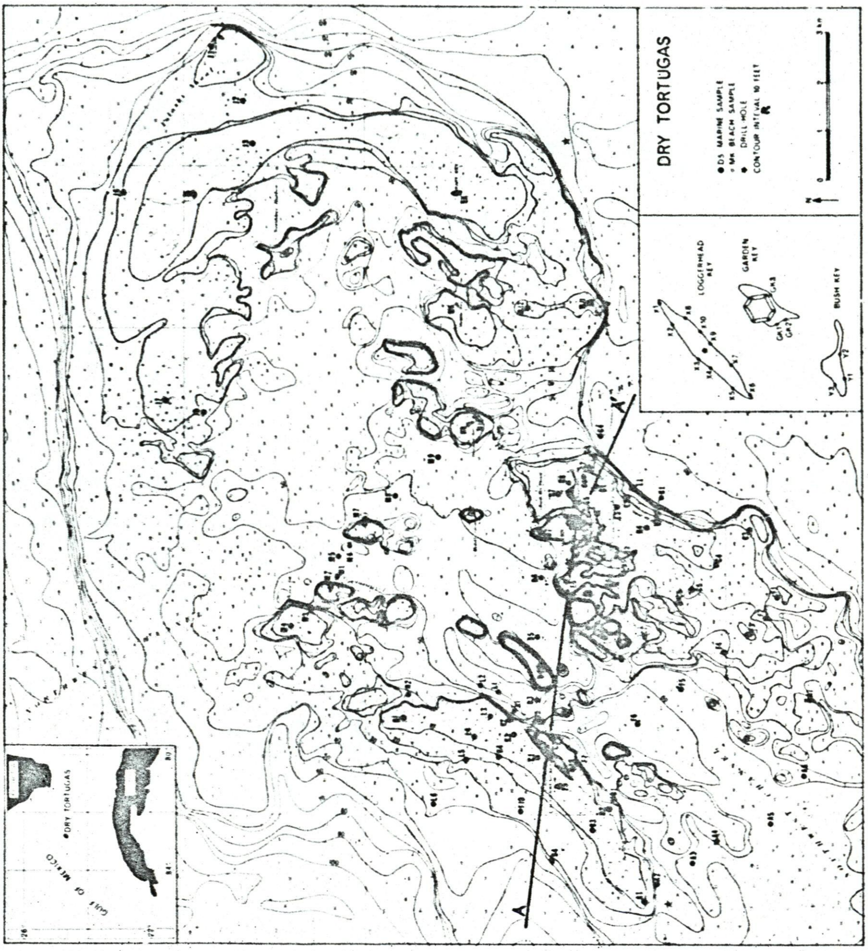


Fig. 1 - Bathymetric map of the Dry Tortugas showing sample locations. Shaded areas denote position of three main segments embracing lagoon and large lagoonal banks. Portion of the C. & G.S. 585.

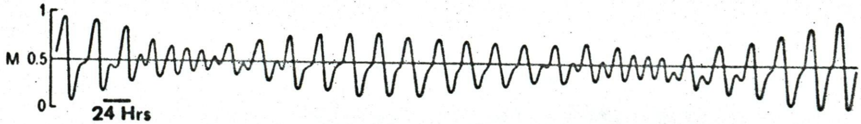


Fig. 2 - Mixed, dominant-diurnal tide. Dry Tortugas, July 1969.

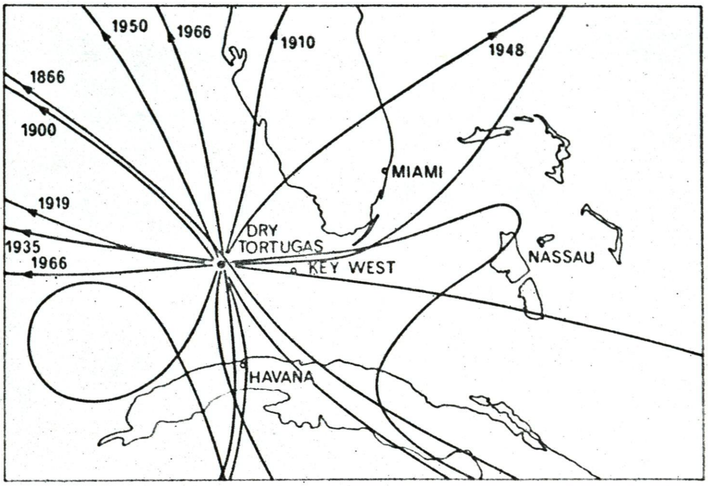


Fig. 3 - Tracks of major hurricanes that passed across the Dry Tortugas since 1873. (Redrawn from Sugg *et al.*, 1971.)

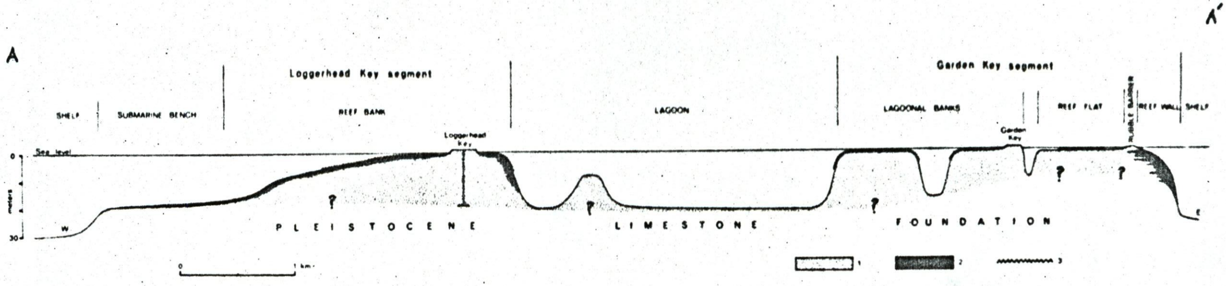


Fig. 4 - Section across the Dry Tortugas reef complex showing its physiography and inferred internal facies. 1) Unconsolidated sediments of the lagoonal-bank facies, including rubble beds and detrital aprons. 2) Rigid frame of the *Montastrea* reef-bank facies and *Acropora palmata* reef facies, possibly with intercalated beds of cemented reef rubble. 3) Distribution of abundant coral growths (dominantly *A. cervicornis*).

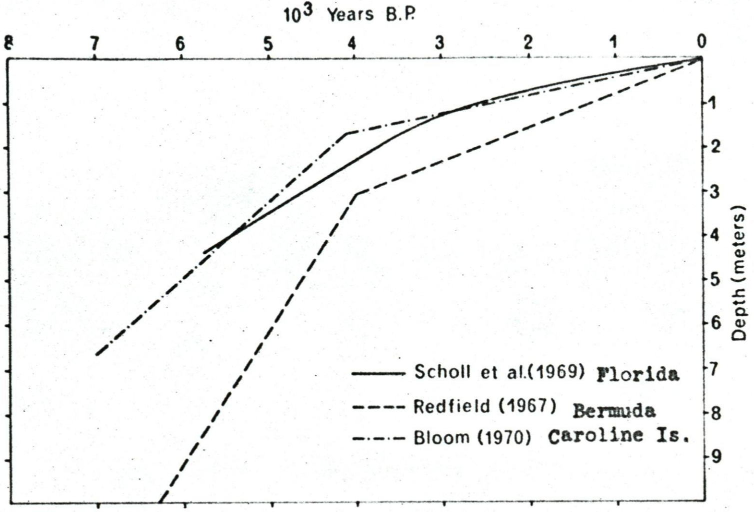


Fig. 5 - Holocene sea level curves from Florida, Bermuda and the Caroline Islands.

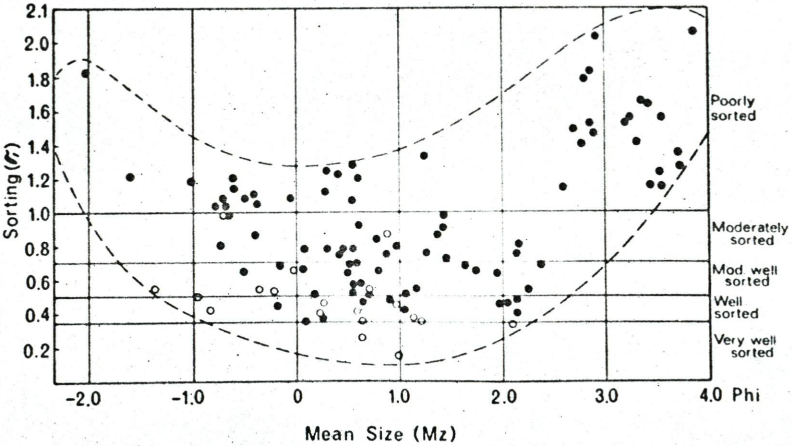


Fig. 6 - Diagram of sorting and mean grain size for the Dry Tortugas sediments. Beach samples are shown in open circles.

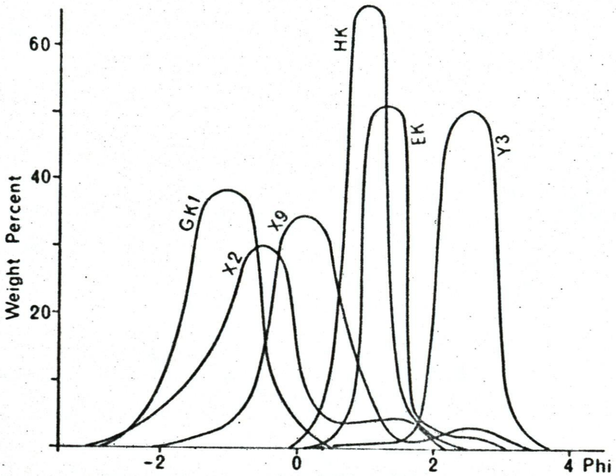


Fig. 7 - Size-frequency curves of representative beach samples from Garden Key (GK-1), Loggerhead Key (X2,X9), Hospital Key (HK), East Key (EK), and Bush Key (Y3).

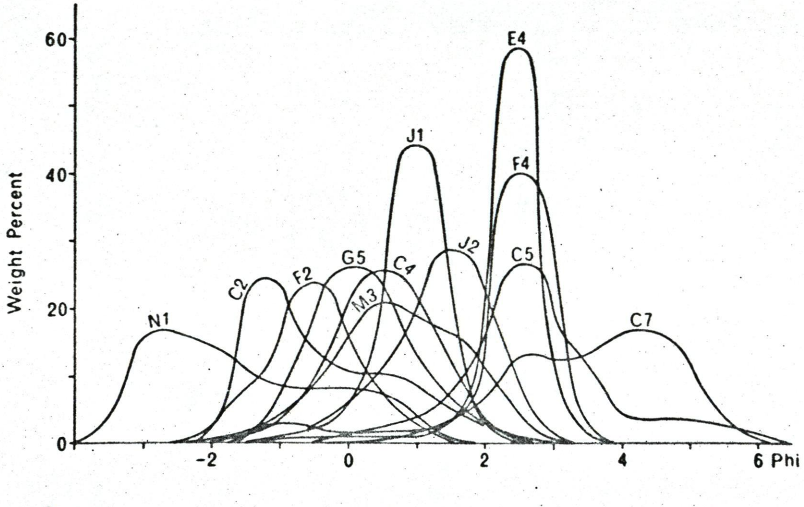


Fig. 8 - Size-frequency curves of representative marine samples from the rocky bottom (N-1), substrate stabilized by seagrass and corals (C2,F2,G5,M3), and sandy bottom (C4,C5,C7,E4,F4,J1,J2).

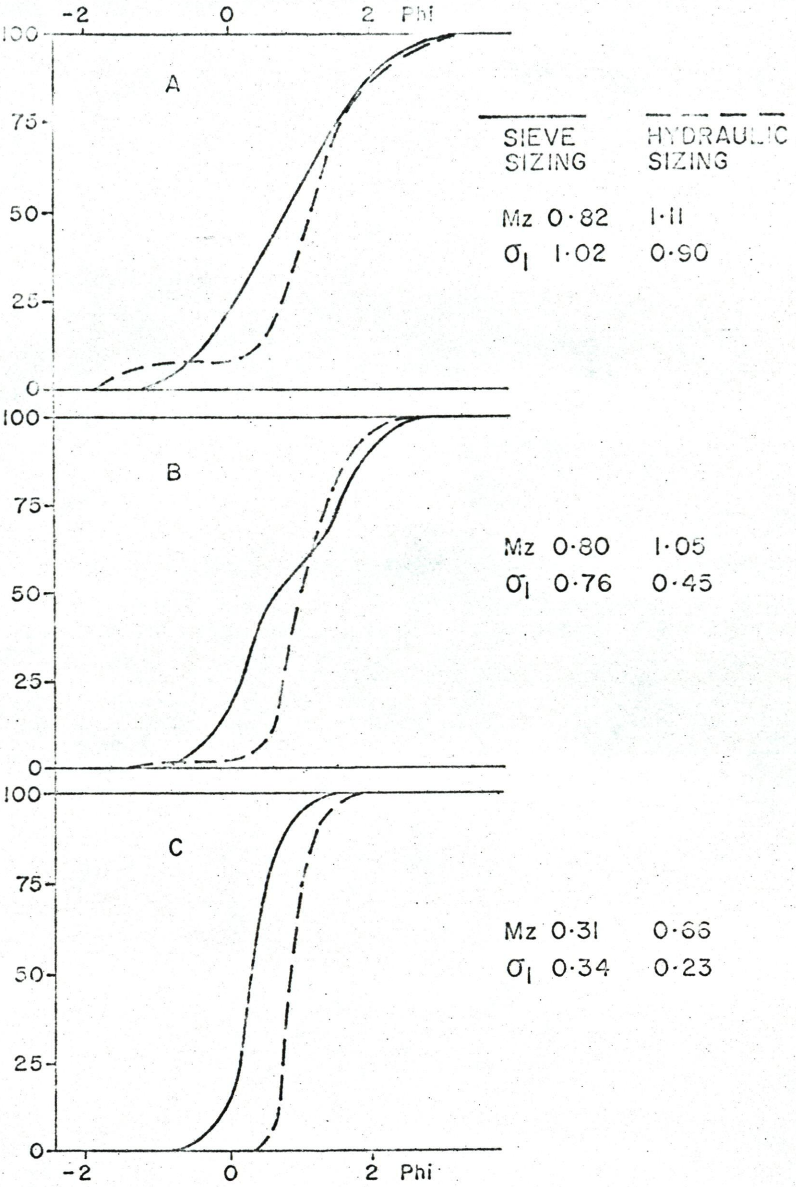
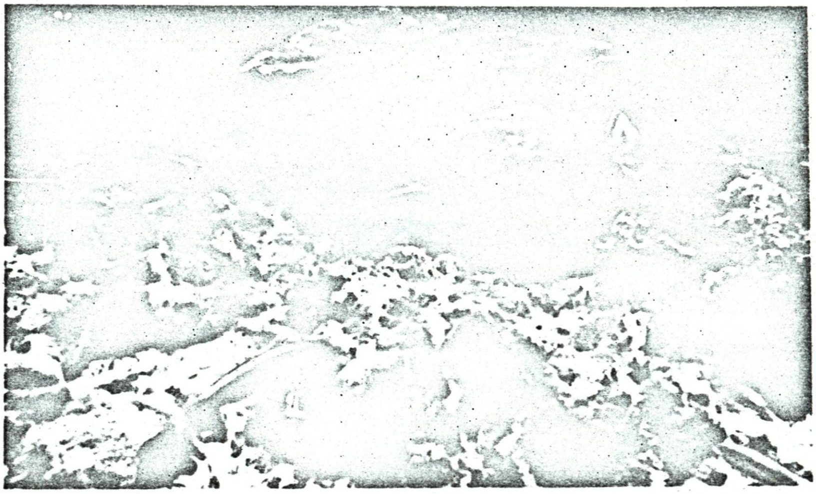


Fig. 9 - Cumulative frequency curves showing the difference between sieve sizing and hydraulic sizing (samples from reef flat, Lord Howe Island, Tasman Sea). See text for explanation.

Fig. 10 A,B - Upper reef-wall slope on Garden Key segment. The picture shows two of a few large *Acropora palmata* colonies found preserved on the storm-degraded reef crest. Reef ruble containing *A. palmata* fragments testifies to the former extensive growth of this coral species now being replaced by brown algae, alcyonarians, and *Millepora* sp.(fig. 10 A).

A



B

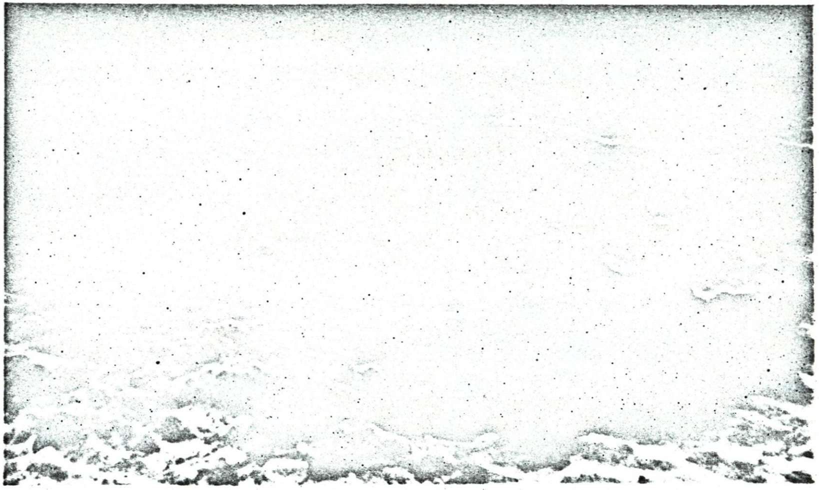


Fig. 11 - Seaward view on a steep, undercut spur wall, about 2 m high, eroded into A. cervicornis reefrock and truncated at the top. The spur surface is heavily encrusted by coralline algae. Rippled very coarse sand veneers the groove floor at about 4 m depth (sample station G2). Upper reef-wall slope, Garden Key segment.

Fig. 12 - Dense thicket of A. cervicornis leveled by storms at the Loggerhead Key segment, 3 - 4 m depth. Individual coral branches are encased in and welded by algal encrustation. Cavernous framework as an effective trap for acummulation of disarticulated Halimeda segments.

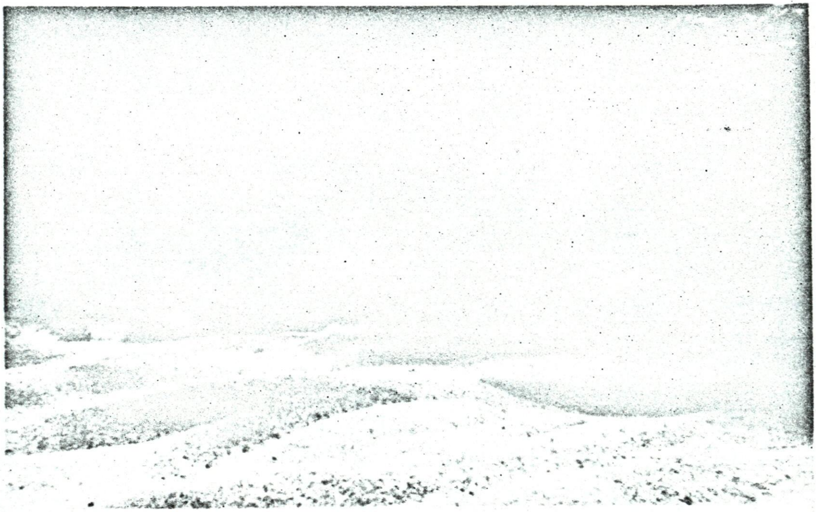


Fig. 13 - Detail of a partly dissected spur wall eroded in *A. cervicornis* reefrock, windward front of Pulaski Shoal, East Key segment. The reefrock is thoroughly encrusted by coralline algae. Parts of the eroded wall are organically healed by encrustation of coral *Diploria* sp.(see arrow). Several slabs of a dead *A. palmata* were found on top of the truncated spur at about 2.5 m depth.

Fig. 14 - Eroded groove in *A. cervicornis* reefrock, windward front of Pulaski Shoal. Note abundant sea urchin *Diadema antillarium* grazing upon the rubble-floored groove.

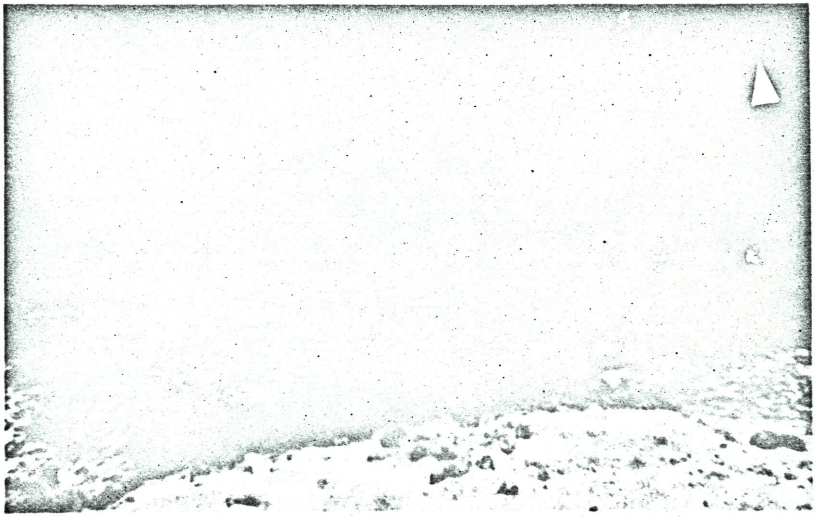


Fig. 15 - Thinly bedded *Halimeda* sands in a cliffed beach on Loggerhead Key. Camera lense lid in the center is 5 cm in diameter.

Fig. 16 - View on part of the rubbly spit projecting seaward from Bush Key. Note the frontal rampart of well-sorted *A. cervicornis* rubble overlying the coarse rubble of massive coral heads containing slabs of *A. palmata*.

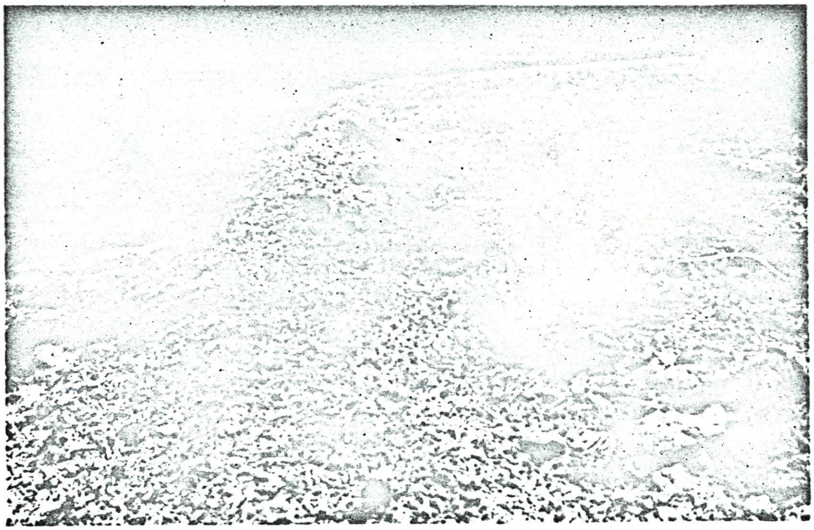
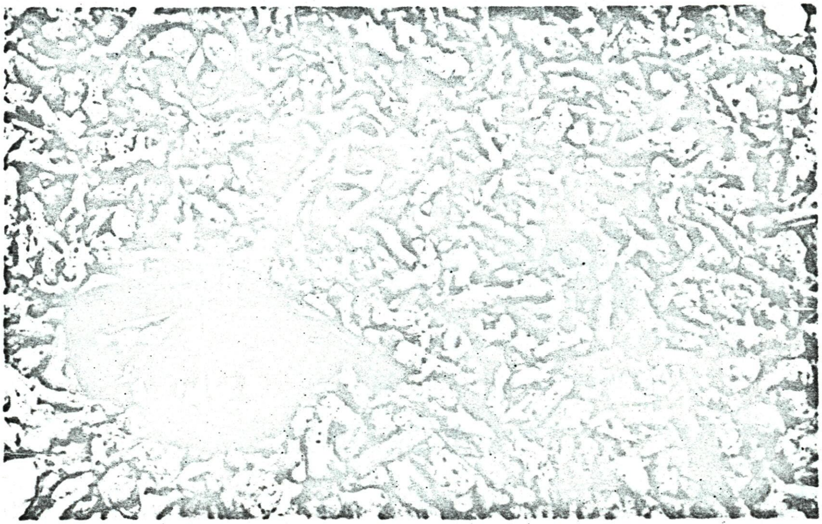


Fig. 17 - *A. cervicornis* rubble from rubbly spit at Bush Key.

Fig. 18 - Coral-mollusc sandy gravel from the storm-degraded rocky shoal (sample N1). Subround but poorly sorted grains are characteristic of this sediment type.



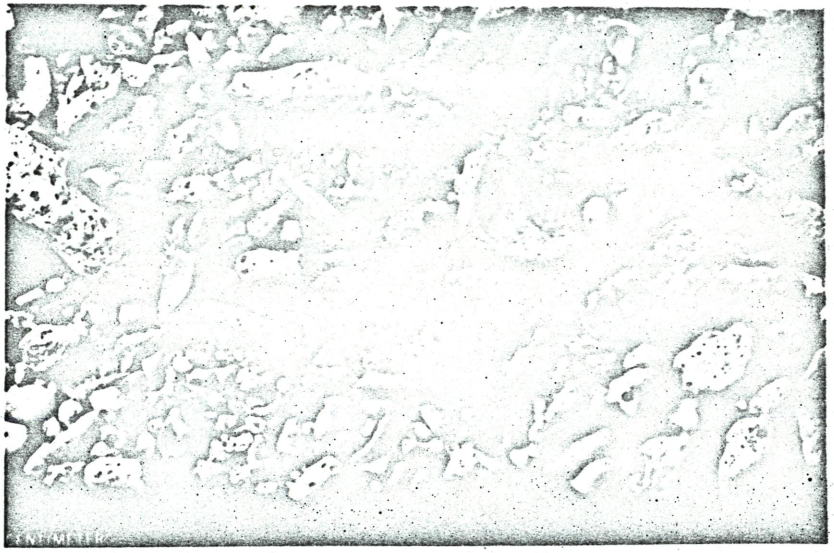

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Fig. 19 - Sandy gravel as a substrate stabilized by *A. cervicornis* growths (sample C2). It is composed almost entirely of unabraded *Halimeda* segments.

Fig. 20 - Gravelly silty sand as a substrate stabilized by seagrass (sample H3). A bulk of this sediment is a coarse, in place-formed fraction of unabraded *Halimeda*, molluscs and some coral fragments (*Porites porites*).

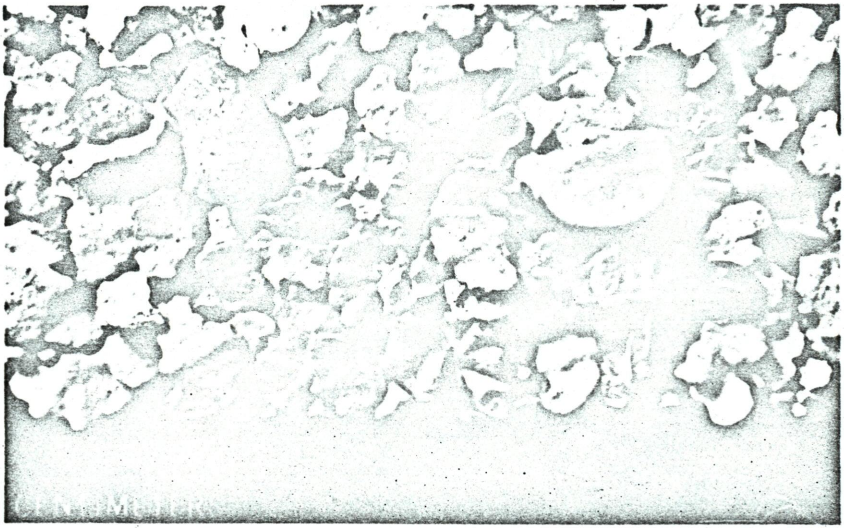
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Fig. 21 - Coarse sand from the current-swept entrance of Southwest Channel (sample A4). The sand is a mixture of coral and mollusc fragments having a low content of Halimeda fragments.

Fig. 22 - Medium sand from shoals bordering lagoon (sample F7). Halimeda coral and mollusc fragments are represented in subequal amounts.

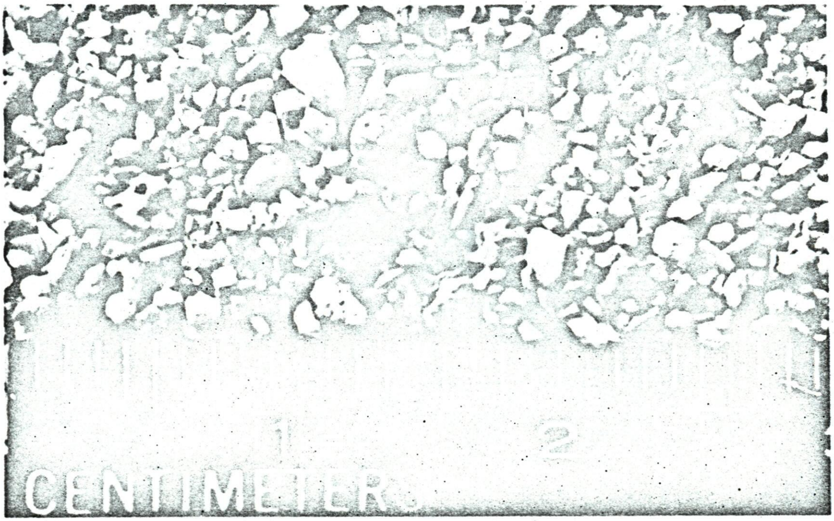
1
2
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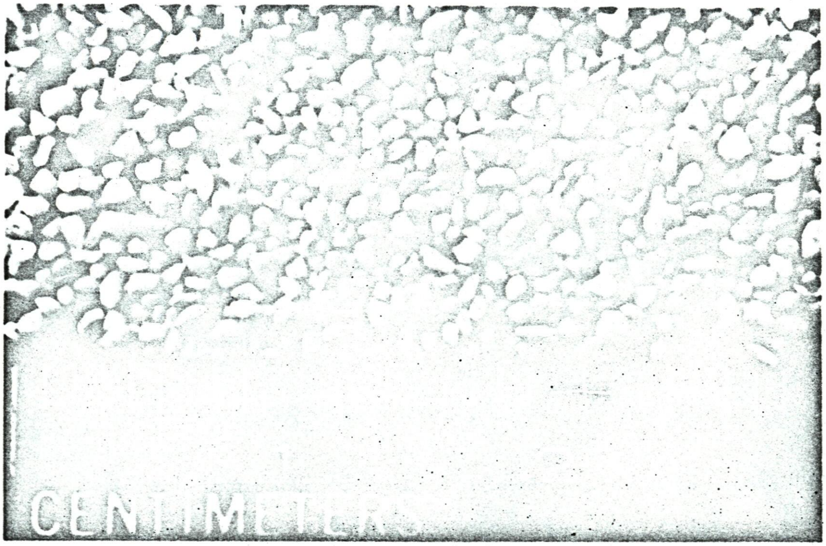
Fig. 23 - Coarse sand from the Hospital Key beach (sample HK). Note the high roundness and grain polish.

Fig. 24 - Coarse sand from the East Key beach (sample EK). Although less rounded and polished than the Hospital Key sand, it is the best sorted sediment recorded from the Dry Tortugas.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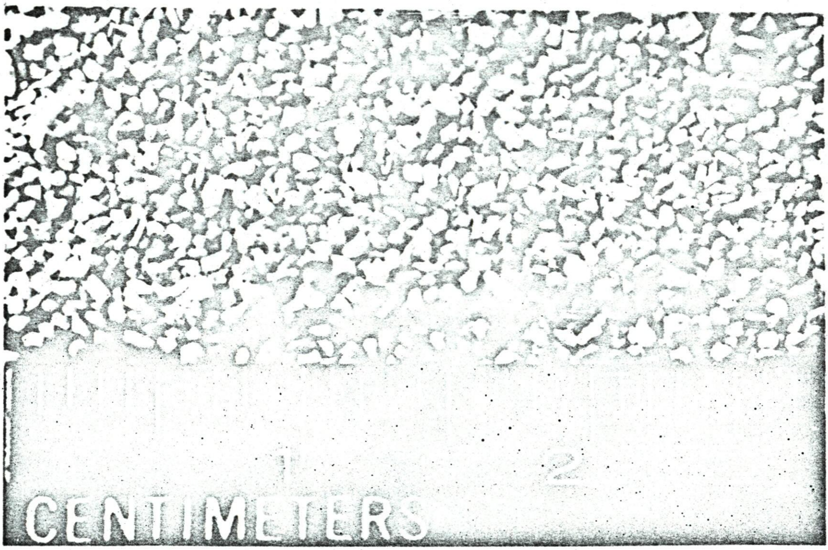
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Plate 1 - Common species of green calcareous algae from the Dry Tortugas.

- A - *Halimeda* *incrassata*
- B - *H*. *opuntia*
- C - *H*. *monile*
- D - *H*. *incrassata*, forma *tripartita*
- E - *H*. *tuna*
- F - *Udotea* *flabellum*
- G - *Penicillus* *capitatus*

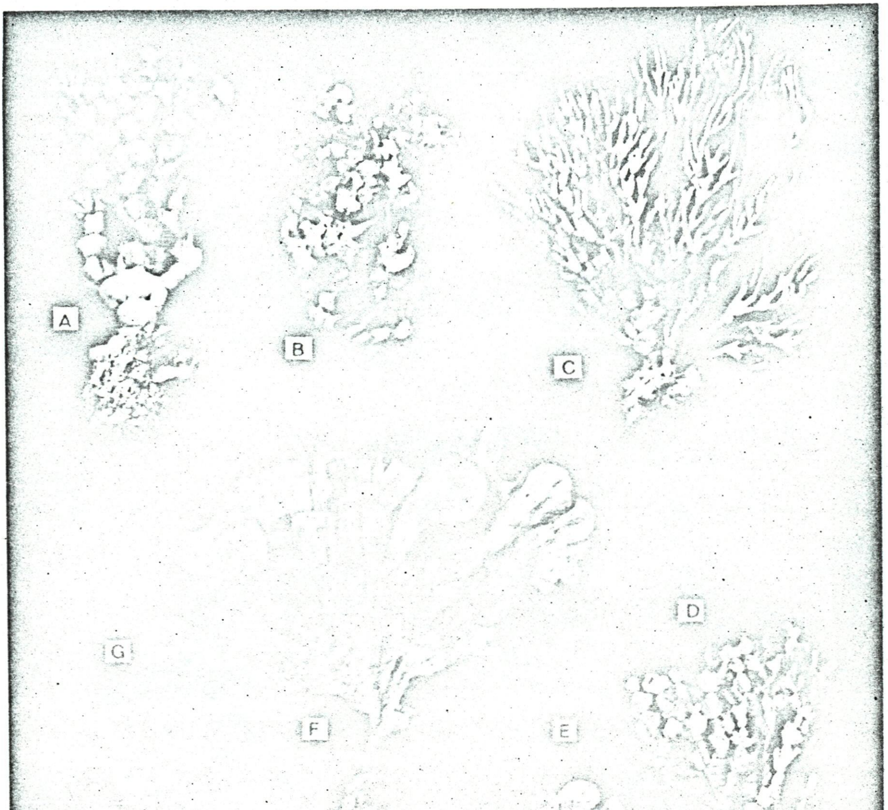
A
B
C
D
G
F
E
5 cm

Plate 2 - Examples of algal encrustation.

A - Side view of a chip sample showing part of a dead, truncated colony of *Diploria* sp. The surface (top of the sample) is encrusted by *Lithothamnium* sp. and extensively bored. Note the vertical boring of *Lithophaga* sp. Storm-degraded rocky shoal, Loggerhead Key segment.

B - Coral cobble encased in a crust of *Lithothamnium* sp. Intertidal zone at the rubble barrier, windward front of the Garden Key segment.

C - Dead clump of the coralline alga *Goniolithon* sp., partially encrusted by *Lithothamnium* sp. Windward rim of the reef flat (*algal zone*), Garden Key segment.


A
B
5 cm

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