ANATOMY OF A FRINGING REEF AROUND GRAND CAYMAN: STORM RUBBLE, NOT CORAL FRAMEWORK

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ABSTRACT: **Our fair-weather perception of modern reefs has led to the implicit assumption that their development is controlled by processes that govern the siting of in-place coral growth. Yet more ephemeral processes, such as storms and hurricanes, assume much greater importance over longer time scales because few reefs escape their influence. To discover the importance of storms on reef development, we analyze the zonation, anatomy, and architecture of a fringing-reef complex around Grand Cayman. We find that the surface zonation of in-place corals is merely a facade and the reef core is in fact composed of meter-thick layers of coral-cobble rudstone capped by crusts of coralline algae. The large size and abraded condition of the rudstone clasts shows that these layers are not the product of fair-weather processes but the result of destruction and deposition during hurricanes. As hurricane waves cross coral-mantled zones of the inner shelf, they destroy live coral stands and deposit the clasts as a rubble layer covering the entire reef complex. Between storms, this rubble foundation is stabilized by coralline-algal crusts and recolonized by rapidly growing corals, leading eventually to full reef regeneration before the next hurricane. This cyclic pattern of destruction and regeneration consequently produces a fringing-reef complex with a core composed of hurricane-generated rubble—not coral framework as previously assumed.**

In addition to explaining reef anatomy, hurricane control also explains the variation in reef architecture along shelf, uniform reef location across shelf, and reef absence along certain shelf sections. As hurricane waves cross a mid-shelf scarp, they start to break and destroy coral growth over most of the inner shelf. Coral rubble generated by these waves is deposited 350 (± 50) m from the mid-shelf scarp on margins exposed to the largest waves, but only 250 (± 50) m on semi-protected margins that experience smaller, fetch-limited waves. In areas where the width of the inner shelf is < 250 m, hurricane waves throw rubble ashore and a fringing reef does not develop. During sea-level rise, this influence of shelf width on rubble deposition controls the timing of reef initiation, and that in turn controls reef architecture. Reefs initiate first on low-gradient coasts with wide shelves, and gradually extend around higher-gradient coasts as sea level rises and shelf width increases. Thus, older reefs are located farther offshore, front deeper lagoons, and have thicker and narrower profiles than younger reefs.

INTRODUCTION

"Let the hurricane tear up its thousand huge fragments; yet what will that tell against the accumulated labour of myriads of architects at work night and day, month after month?" (Charles Darwin 1839, p. 548).

In Darwin's view, corals triumphed over the greatest adversity to form reefs—not even hurricanes could prevent them from building to sea level. Indeed, he was so impressed with their tenacity that accounting for reef architecture became a simple deduction: by maintaining a position at sea level, fringing reefs developed into barrier reefs and atolls as their foundation subsided (Darwin 1842). Yet this simple deduction failed to explain why, within a single reef system, fringing reefs transformed laterally into barrier reefs (Semper 1881). Also, it was unclear why corals did not simply migrate up slope maintaining their contact with shore, rather than building vertically into a barrier (Steers and Stoddart 1977). Unable to reconcile these observations, later investigators emphasized the role of underlying shelf topography in controlling reef architecture. Daly (1915) postulated that the three reef types resulted from differential marine erosion of the shelf during glacial sea-level changes. Later investigators, however, favored differential subaerial erosion during sea-level lowstands as a mechanism to produce peripheral rims for reefs to colonize (Yabe 1942; MacNeil 1954; Purdy 1974). With the advent of portable underwater drilling units in the mid 1970s, however, reef architecture was found to be largely independent of underlying shelf topography and the internal structure of the reef core was composed as much of detritus than of in-place coral framework (e.g., Adey and Burke 1976; Davies and Hopley 1983).

Implicit in this history of reef study is the fundamental assumption that reef architecture is controlled by processes that govern the siting of in-place coral growth. Indeed, this paradigm has long preoccupied modern efforts to understand the processes that control coral distribution patterns (e.g., Goreau 1959; Geister 1977; Adey and Burke 1977; Done 1983; Glynn 1990). Yet these assumptions and preoccupations are clearly related to our fair-weather perception of modern reefs and limited time scale of observation. Acknowledging these limitations, ecologists have suggested that processes operating over longer time intervals, such as tropical cyclones, might have more control on reef development than was previously recognized (Connell 1978; Woodley 1992). For instance, Woodley (1992) recently suggested that the classic view of reefs as being composed of luxuriant stands of coral may be one extreme of a variable condition. He concluded that hurricanes should be considered as a continuous force because, over long time scales, few reefs escape their influence (Woodley 1992). This conclusion is of fundamental importance for development of modern reefs because, not only does it imply that fair-weather processes have been overstated, but it raises the intriguing possibility that reef architecture may be controlled by destructive processes rather than those controlling coral growth.

To assess the relative importance of storm processes on reef development, we describe the zonation, anatomy, and architecture of a fringing-reef complex around Grand Cayman. By integrating data from aerial and sonar profiles, sediment analysis, cores, and underwater sections, we show that hurricanes control the anatomy of the fringing-reef complex and dictate where the reef develops on the shelf. In addition, consideration of how these hurricane processes interact with sea-level rise allows us to propose a process-response model of reef development that not only explains lateral architectural variations along the fringing-reef complex but also provides a mechanism by which fringing reefs can develop into barrier reefs and eventually into atolls.

TERMINOLOGY

In this paper we use the general term "reef" to denote a rigid topographic structure consisting of two components: a reef core, which can be

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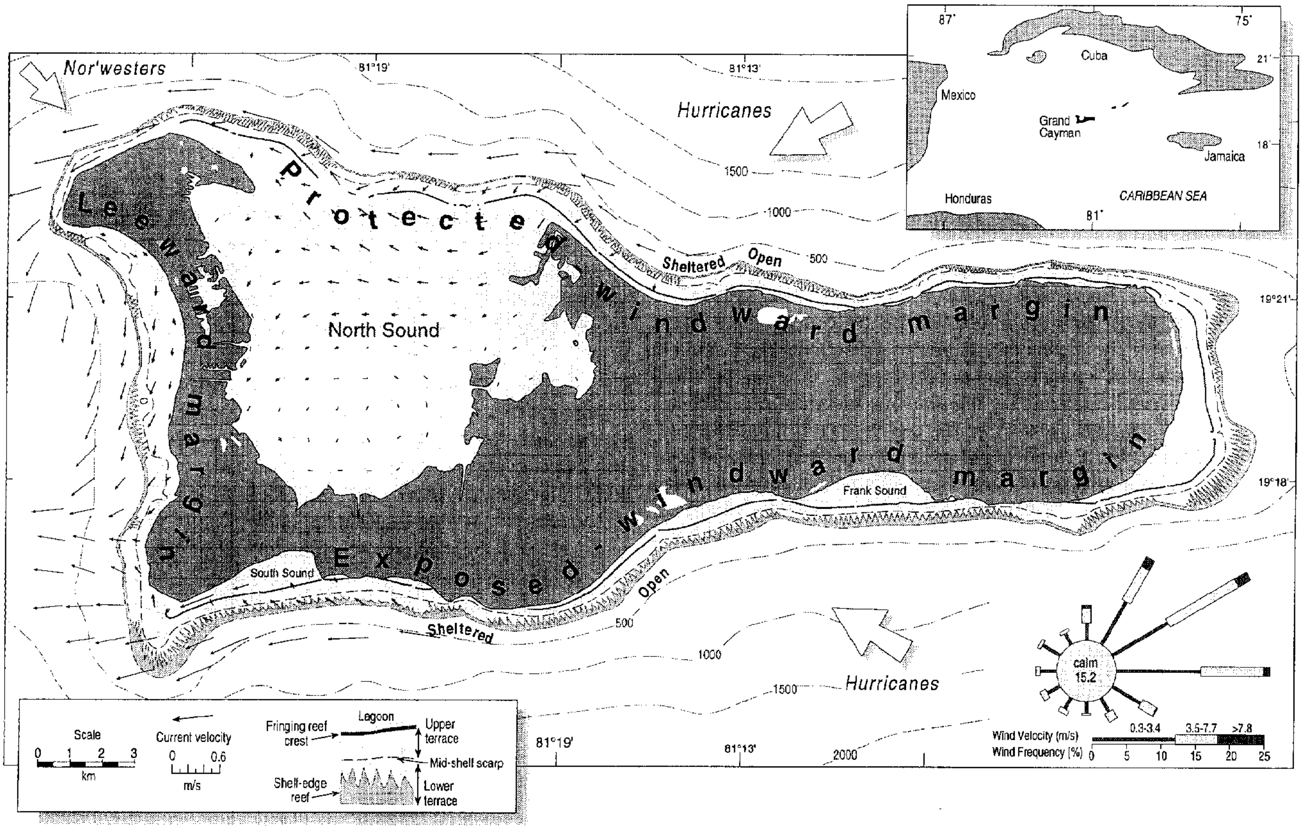


FIG. 1.—Grand Cayman: location (inset), bathymetry in meters, wind and storm directions, surface currents, and details of the shelf, including energy classification of island margins, position of the mid-shelf scarp, and distribution of fringing and shelf-edge reefs (modified from Blanchon and Jones 1995).

either contemporary or antecedent, and a mantling veneer of in-place corals and associated organisms. We use the term "reef complex" to denote a reef with all its contiguous, genetically associated sediment deposits (cf. Henson 1950). Furthermore we use fringing reef, barrier reef, and atoll to identify specific varieties of reef that develop in the surf zone and form natural breakwaters—as opposed to submerged varieties of reef (e.g., Hubbard et al. 1986; Messing et al. 1990; Blanchon and Jones in press). Such breakwater-reef complexes are divided by the reef crest into "back-reef" zones and "reef-front" zones.

SETTING

Climate

Grand Cayman, located in the northwest Caribbean Sea between Jamaica and Cuba, is a small (197 km^2), low-lying (< 18 m above msl), riverless island (Fig. 1). It enjoys a subhumid, tropical, maritime climate that is dominated by moisture-laden air masses of the Northeast Trade Wind System. Like many Caribbean islands subjected to this system, its climate is distinctly seasonal (Burton 1994). During the wet or summer season (May to November), the island is subject to high temperatures (averaging ~ 29°C), frequent showers (averaging 4–8 mm/day), high humidity, and easterly or southeasterly winds (averaging 4–5 m s^{-1}). During the dry or winter season (December to April), temperatures fall slightly (averaging 25°C), showers are less frequent (< 3 mm/day), and winds move round to the east and northeast (averaging 5–6 m s^{-1}).

Cyclonic disturbances, which provide much of the annual rainfall, are common during both seasons. Tropical storms and hurricanes track east to northeast during summer, and storms associated with continental cold fronts track west to southwest during winter (Fig. 1). Although few measurements are available, surges associated with these storms are usually < 1 m because the island lacks wide-shelf areas where storms can pile water. Similarly, there are few measurements of storm-wave heights. However, historical records of breaching along 5-m-high cliffs on the south coast suggest that storms with large wave heights (≥ 5 m) have a 64 yr recurrence interval (Fig. 2). These records also illustrate the high frequency of storms affecting Grand Cayman and thereby confirm the potential importance of storm impact on the island's marine environments.

Oceanography

Because of the microtidal setting, large-scale oceanic currents and waves dominate fair-weather water movement around Grand Cayman. Sheltered from high-latitude storm swells by islands of the Greater Antilles, the island's wave field is a product of the Northeast Trades and storm swells generated in the southwest Caribbean. Values of annual mean wavepower hindcast for different sections of the coast show that, at a depth of 10 m, south and east coasts receive the highest and most enduring wave energy (~ 4 × 10^9 ergs/s), the north coast receives large to moderate energy (~ 0.9 × 10^9 ergs/s), and the west coast receives the least energy (~ 0.08 × 10^9 ergs/s) (Roberts 1974). This variation enables three margin types to be delineated (Fig. 1): the south and east coasts, being exposed to high-energy long-fetch waves, constitute an *exposed-windward margin*; the north coast, being affected by limited-fetch moderate-energy waves, constitutes a *protected-windward margin*; and the west coast, being sheltered from major wind-generated waves, constitutes a *leeward margin* (Blanchon and Jones 1995). Each of these margin types can be further divided according to shelf

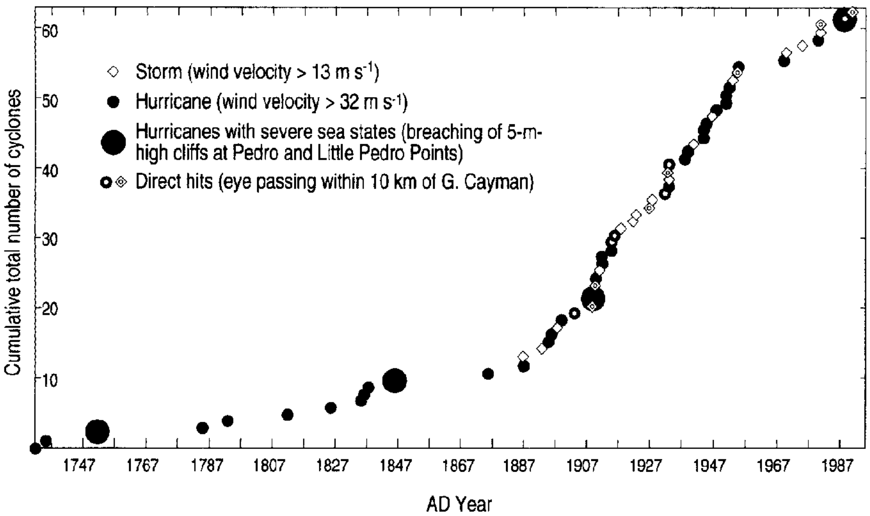


FIG. 2.—Historical record of tropical cyclones passing within 80 km of Grand Cayman. Hurricane recurrence interval is ~ 7 yr (38 hurricanes in 264 yr). Recurrence of hurricanes passing within 10 km of the island is ~ 20 yr (5 hurricanes in last 100 yr), but recurrence time gaps range from 1 to 55 yr. Since 1731, when records began, four hurricanes have breached the 5-m-high cliffs on the south side of the island between Great and Little Pedro Points (these cliffs are fronted by a deep, narrow, reefless shelf that allows deep-water waves to reach the shore). These large-magnitude hurricanes have a 64-yr recurrence interval with time gaps from 20 to 95 yr. (Data compiled from Hirst 1910, Williams 1970, Clark 1988, and Burton 1994. Note: only hurricanes confirmed by at least two of these sources were used; prior to 1887 only hurricanes are recorded—see Blanchon 1995 for historical accounts.)

orientation and the angle of wave approach: shelf sections facing into approaching waves (i.e., with an east-facing component) are described as *open* whereas sections oblique to approaching waves (i.e., with a west-facing component) are described as *sheltered* (Fig. 1).

Marine Environments

The marine shelf around Grand Cayman is typically less than a kilometer wide, and slopes gradually from shore to the ~ 30 m isobath, where it is abruptly terminated by a vertical wall that forms the upper-island slope. This narrow shelf is characterized by two seaward-sloping terraces separated by a small mid-shelf scarp (Blanchon and Jones in press). The upper terrace is a gently sloping (0–10 m) marine planation surface cut into the island bedrock (Blanchon and Jones in press). Partially mantling its surface on the windward margins of the island is a fringing-reef complex that consists of a concentric belt of coral- and sediment-dominated zones. Although the biotic surface communities forming this complex and the narrow lagoons it fronts have been well documented (Roberts 1971; Rigby and Roberts 1976; Raymont et al. 1976; Logan 1981; Acker and Risk 1985; Tongpenyai and Jones 1991; Hunter 1994; Kalbfleisch 1995), little is known about the anatomy or genesis of the reef core.

The lower terrace, which slopes from ~ 15–30 m below msl, is a zone of active coral growth and sedimentation associated with submerged shelf-edge reef development (Blanchon and Jones 1995). These deposits are underlain by a bedrock terrace that slopes seawards from the base of the mid-shelf scarp to ~ 40 m below msl. This buried terrace-scarp unit, which is the geomorphic equivalent of the upper terrace and coastal cliff, formed during a Holocene sea-level slowstand from ~ 10–7.5 ka (Blanchon and Jones 1995; Blanchon and Shaw 1995).

METHODS

Five scuba transects were run across the fringing-reef complex on the south and east sides of the island (Fig. 3). Along each transect, sediment was collected and substrate character, including bedforms and biota, recorded at 20 m intervals. Sediment thickness was determined using either a stainless-steel push probe or a drill probe powered by compressed air and fitted with a masonry bit (cf. Jones et al. 1992). Transect locations were estimated from triangulation on shore-based markers and plotted on aerial photographs. Where lagoon depths permitted, profiles were made using a shipboard depth sounder (accurate to within ± 15 cm), and located using a Magellan GPS Nav 5000. In waters too shallow for the boat, profiles were completed using depth gauges on scuba.

In addition to the surface transects, all sections through the reef complex (e.g., boat channels) that exposed the underlying foundation (shown in Figure 3) were measured, logged, and sampled to determine reef anatomy. These observations were supplemented in back-reef and reef-front zones by sediment and hard substrate cores (Fig. 3). Sediment cores were collected in back-reef zones by driving a 10-cm-diameter PVC pipe into soft substrate using an air hammer powered from an ordinary scuba tank (Jones et al. 1992). The longest core was 1.65 m, and recovery was limited only by the sediment thickness. Cores from hard substrate in the reef-front zones were obtained using a diver-operated hydraulic drilling system similar to the one described by Macintyre (1978).

Sediment size analysis at 1/4 phi (ϕ) intervals was conducted on 40 sediment samples from four out of the five transects using the procedures described by Folk (1974). All samples contained less than 5 wt % silt and clay; this was removed by wet sieving, concentrated, dried, and weighed prior to sieving the rest of the sample. Statistical parameters—graphical mean and standard deviation—were derived using the formulas of Folk and Ward (1957) on the sand and very-fine-pebble size fraction (-1.75 to 4.0 ϕ). Errors due to variations in sieve-screen openings and aggregation of sediment during drying were eliminated using tests described by Folk (1966). Sediments collected contained a variable weight fraction of gravel, but statistical analysis of this fraction was not attempted because samples were too small for the gravel fraction to be statistically meaningful.

Sediment composition was determined for the gravel and sand fractions. Analysis of the gravel, which consisted largely of cobble-size fragments of coral, was made by random selection of 100 clasts across a 50–100 m^2 area of the reef surface and on the walls of the excavations cut through the reef. Each clast was split, coral genus identified, and the condition described. Sand components were point-counted using thin sections (e.g., Harwood 1988).

FRINGING-REEF COMPLEX

Surface Zonation

Parallel to the coast around Grand Cayman's inner shelf, less than 1 km offshore, is a well developed fringing-reef complex (Fig. 1). Transects and aerial reconnaissance show that this reef complex consists of five shore-parallel zones (Fig. 4). In a seaward direction these are (1) the bare-sand zone, (2) the knob-and-rubble zone, (3) the reef-crest zone, (4) the stump-and-boulder zone, and (5) the spur-and-groove zone (Fig. 4). The bare-sand and knob-and-rubble zones consist largely of unconsolidated sediment that slopes back into the lagoon, whereas the reef-crest, stump-and-boulder, and

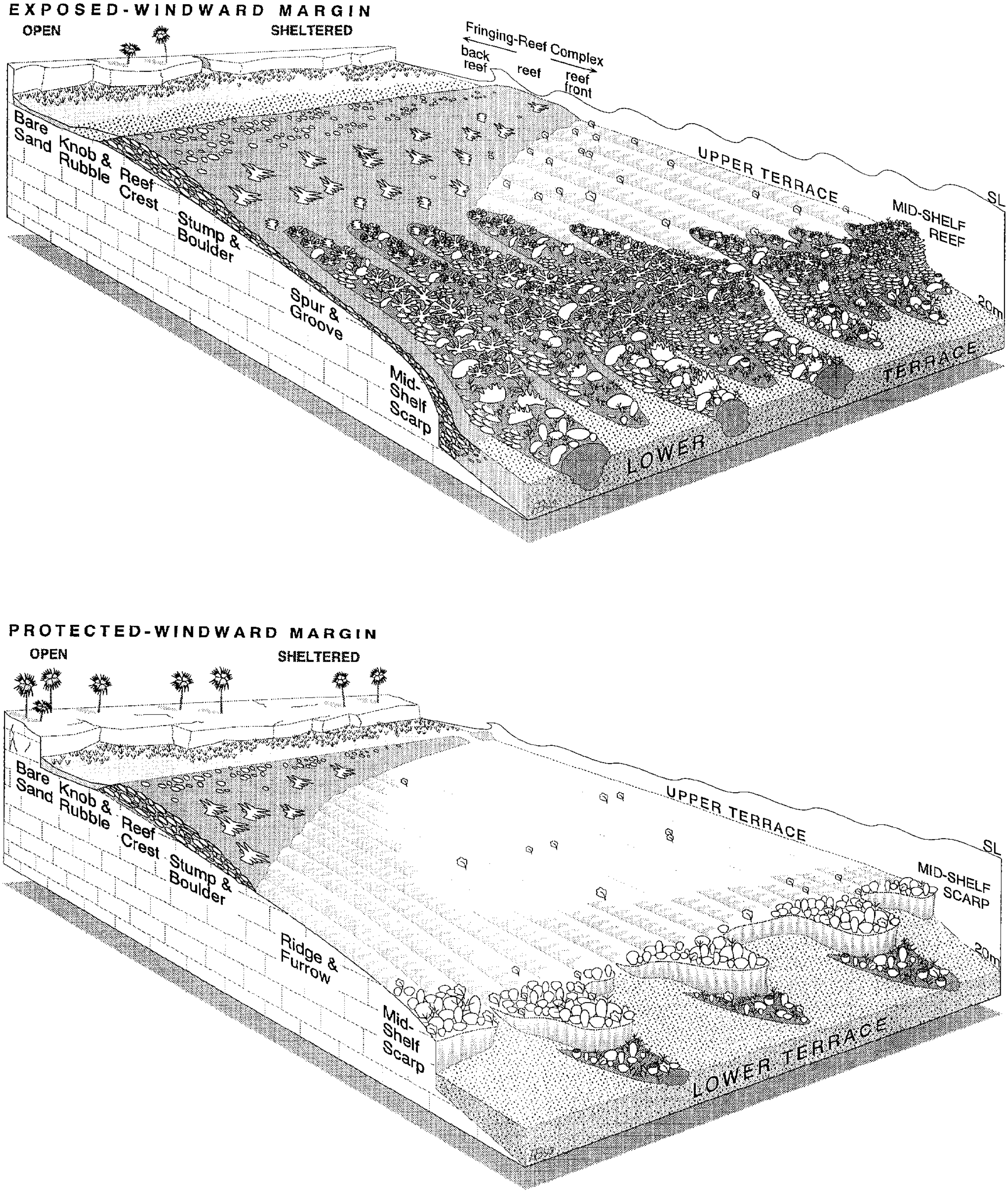


FIG. 3.—Schematic summary of Grand Cayman's shelf morphology and fringing-reef zonation, showing how zonation varies as margin orientation changes. Note that spur-and-groove development occurs only along open sections of the exposed-windward margin, and that stump-and-boulder and reef-crest zones become narrower along sheltered sections of both windward margins. For a more detailed description of these zones and terraces, see Blanchon and Jones (1995).

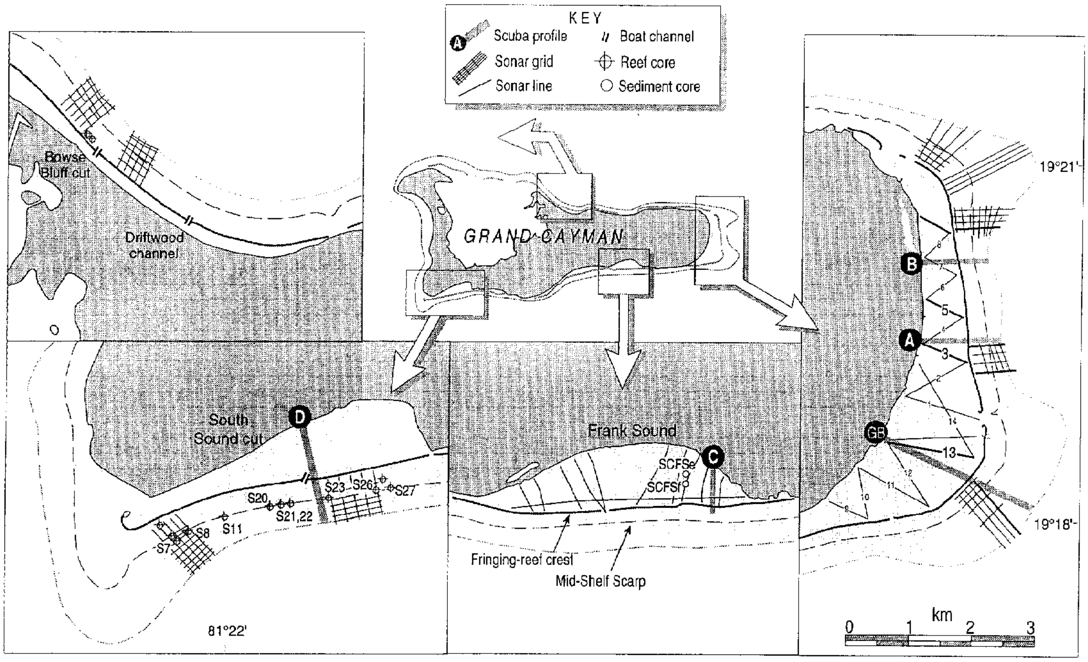


FIG. 4.—Transect map, showing location of scuba profiles, sonar profiles, boat channels, and cores. Reef cores are numbered after Natural Resources Unit dive-site mooring installations (See Blanchon 1995 for coordinates).

spur-and-groove zones are seaward-sloping substrates covered by crusts of coralline algae and thickets or colonies of coral. Sedimentological and ecological characteristics of the fringing-reef zones are summarized in Figure 5 and illustrated in Figure 6 (see also Blanchon 1995).

Zones of the fringing-reef complex vary systematically as the orientation of the shelf, and its exposure to major ocean swells, changes (Blanchon and Jones 1995). Along open sections of the exposed-windward margin, this complex covers the entire upper terrace and merges with reef development on the mid-shelf scarp (Fig. 4). This is largely due to the development of the spur-and-groove zone. Along the protected-windward margin and sheltered parts of the exposed-windward margin, however, the spur-and-groove is absent and the aerial extent of the fringing-reef complex is much reduced, exposing the furrowed bedrock surface of the upper terrace (Fig. 4). Along the leeward margin, the fringing reef complex is not developed.

Surface Sediment Character

Because zones seaward of the reef crest usually lack loose sand, sediment was analyzed only in the knob-and-rubble and bare-sand zones. Gravel and sand fractions in those zones show a distinctive size decrease away from the reef crest (Fig. 7). In the knob-and-rubble zone close to the reef crest the gravel fraction constitutes $>$ 50 wt % of the surface sediment and is medium-cobble in size, whereas the matrix is a coarse sand (0 to 1 ϕ). Some 50 m into the knob-and-rubble zone the proportion of gravel abruptly decreases to $<$ 30 wt %, and drops to medium-pebble size. By the time the bare-sand zone is reached, the sand fraction dominates, having a mean size of coarse to medium sand (0 to 2 ϕ), and a gravel content of $<$ 10 wt %. Across the bare-sand zone this gradually decreases to a medium to fine sand (1 to 3 ϕ) with $<$ 5% gravel (Fig. 7).

In all zones the sand fraction is typically poorly sorted and the size distributions are almost invariably unimodal (Fig. 7). Only where sea grass colonizes the bare-sand zone does the size distribution become significantly polymodal (as in Transect D; Fig. 7D).

Composition of sand-size sediment is fairly uniform, being dominated by coral detritus with subordinate foraminifera (Fig. 8). The only change observed back from the reef crest is an increase in micritized grains in the bare-sand zone. Cobble composition on the reef crest is dominated by *Acropora palmata* (Fig. 8) but, as the clast size decreases shoreward from the reef crest, *A. cervicornis* becomes more dominant.

Internal Anatomy

Sediment probings show that the bare-sand zone is a wedge-shaped deposit that thins from as much as 9 m on its reefal side (but more commonly 3–5 m) to $<$ 1 m along its lagoonward limit. Cores up to $\sim$ 1.5 m long show that the upper part of the deposit is a structureless coral-sand grainstone with rare pebble stringers (Fig. 9). The mean sediment size, sorting, and constituent abundances are uniform down-core and largely reflect surface sediment characteristics.

Examination of submarine sections (boat channels) through the fringing-reef complex show that, without exception, the upper 3 m of reef core beneath the knob-and-rubble, reef-crest, and stump-and-boulder zones consists of a coral-cobble rudstone with a skeletal pebbly sand matrix—in-place coral framework is conspicuously absent (Figs. 9, 10). Like clasts on the surface, those constituting this rudstone core are commonly rounded and abraded (calical surface truncated) and in several sections have distinct seaward-dipping imbrication fabrics. From visual estimates along the exposures, clast size is generally well sorted and tends to increase gradually seaward from small–medium cobble to medium cobble–small boulder size. Clast composition is dominated at all sites by *A. palmata* (e.g., Fig. 8). In the deepest section through the fringing-reef core, shown in Figure 7D, two distinct coral-cobble-rudstone layers are exposed. Each layer is $\sim$ 1 m thick and capped by a centimeter-thick crust of coralline algae, with the crust on the upper layer representing the present reef surface and the crust on the lower representing an older surface. Clast size in each layer is consistent at any particular site, but differs between layers, with the upper layer being coarser than the lower. Both layers dip $\sim$ 5° seaward from the reef crest.

Short cores from reef-front zones away from boat channels confirm that the coral-cobble-rudstone deposit extends the full width of the stump-and-

ZONE depth/width	CHARACTERISTICS	EQUIV. ZONES
	Boundary: bare sand zone slopes (5-20°) into *Thallasia*-sand zone in lagoon.	
BARE-SAND ZONE (BSZ) 1-8 m bmsl/ 50-300 m (See Fig. 5H)	Shoreward-sloping field of rippled and burrowed sand. **Infauna**: includes shrimp (*Callianassa major*), fish (*Malancanthus plumieri*), sea urchins (*Meoma ventricosa, Clypeaster* sp.), worms (*Arenicola* sp.), and pelecypods (*Tellina radiata*). **Surface biota**: conch (*Strombus gigas*), stingrays (*Dasyatis americana*), sea grass (*Thalassia, Syringodium*), green algae (*Halimeda, Penicillus*). **Variation**: sand stabilized by sea grass on protected-windward margin, bare on exposed-windward.	**Barren sand sheets** (Rigby and Roberts 1976), **Bare sand zone** (Macintyre et al. 1987).
	Boundary: bare sand grade into knob and rubble zone.	
KNOB & RUBBLE ZONE (KRZ) 1-2 m bmsl/ 50-120 m (See Fig. 5G)	Shoreward-sloping field of coral rubble sparsely colonised by coral knobs. **Knobs**: monospecific knobs of *M. annularis* dominate, but others include *Diploria* spp. *Siderastrea* spp. and *A. cervicornis*. Understory species of *Agaricia agaricites*. **Rubble**: cobble to boulder-sized clasts (mean -7ϕ) of abraded *A. palmata*, encrusted by *Homotrema rubrum, Carpentaria utricularis*, bryozoa, boring sponges, and coralline algae. Interstitial sand and pebbles. **Variation**: more *A. cervicornis* knobs on protected-windward margin; rubble commonly stabilized by corallines on exposed-windward margin.	***M. annularis* community** (Rigby and Roberts 1976), ***Turbinaria-Sargassum* rubble** and ***Laurencia-Acanthophora* sand and gravel** (Macintyre et al. 1987)
	Boundary: knob and rubble shallows into the reef crest zone.	
REEF-CREST ZONE (RCZ) 0-1.5 m bmsl/ 10-20 m (See Figs. 5E and 5F)	Thickets of *A. palmata* on a ridge of stabilized coral rubble. **Thickets**: in waters 1.5 m deep, robust *A. palmata* colonies (up to 1.5 m tall) with understory of *M. complanata, P. astreoides*, and near spherical *Diploria strigosa*. In waters <1 m, encrusting forms of *A. palmata, M. complanata*, and coralline algae dominate. **Rubble ridge**: cobble to boulder-sized clasts (mean -8ϕ) of abraded *A. palmata* stabilized by crust of coralline algae, particularly *Porolithon pachydermum*. **Variation**: exposed-windward margin has predominantly shallow rubble-dominated ridges, whereas protected-windward margin has deeper coral-dominated ridges.	**Upper *Palmata*** (Goreau 1959). ***A. palmata, M. alcicornis, P. astreoides* and *Lithothamnium* communities** (Rigby and Roberts 1976). **Coralline-coral-*Dictyota* pavement** (Macintyre et al. 1987).
	Boundary: reef-crest zone slopes seaward into stump-and-boulder zone.	
STUMP & BOULDER ZONE (SBZ) 0-5 m bmsl/ 10-100 m (See Figs. 5A, 5B, and 5C)	Broad, seaward-sloping field of coral boulders colonized by sparse *A. palmata* colonies and stumps. **Stumps**: robust, surf oriented *A. palmata* colonies, broken *A. palmata* stumps and thickets of *Millepora complanata*. **Boulders**: large cobble to boulder-sized clasts of abraded *A. palmata* fragments (mean -9ϕ), stabilized by a mm-thick crust of coralline algae. **Variation**: see Blanchon and Jones (1995).	**Lower *Palmata*** (Goreau 1959).
	Boundary: stump-and-boulder passes into spur-and-groove along open sections of exposed-windward margin, but in other areas there is a distinct edge to the deposit (see Fig. 5D).	
SPUR & GROOVE ZONE (SGZ) 5-10 m bmsl/ 150-200 m (See Fig. 12)	Seaward-projecting coral spurs separated by cobble floored grooves. **Spurs**: topped by *Acropora palmata* and *Acropora cervicornis* thickets, sides reinforced by *Montastrea annularis*. **Grooves**: cobble to boulder-sized clasts (mean -8ϕ) of abraded *A. palmata*. **Variation**: spur-and-groove zone only developed along open sections of the exposed-windward margin.	**Buttress Zone** (Goreau 1959). **Spur & Groove** (Shinn 1963).
	Boundary: spurs extend over mid-shelf scarp onto lower-terrace (spur-and-sand zone)	

FIG. 5.—Characteristics of fringing-reef zones around Grand Cayman (see Figure 6 for views of each zone).

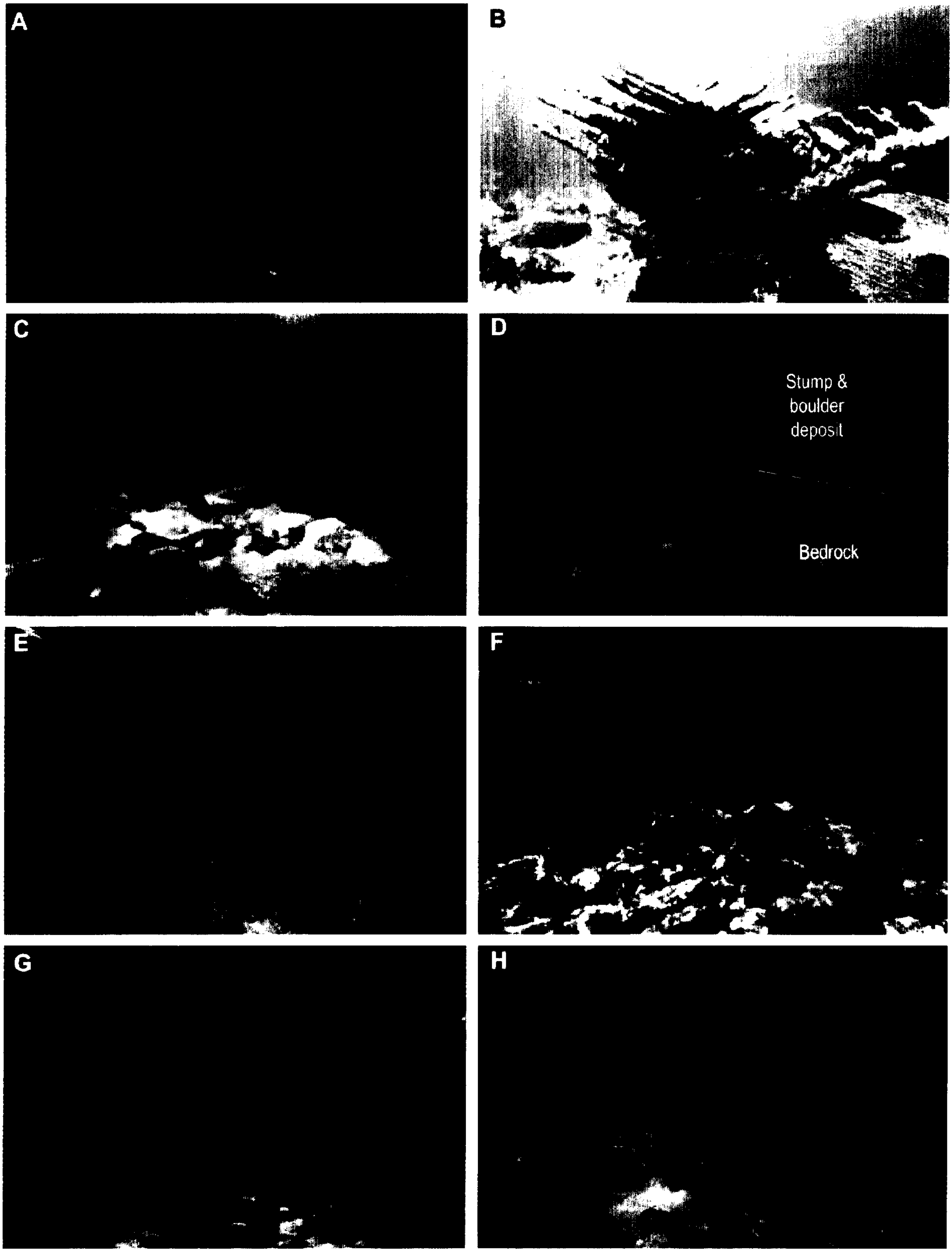
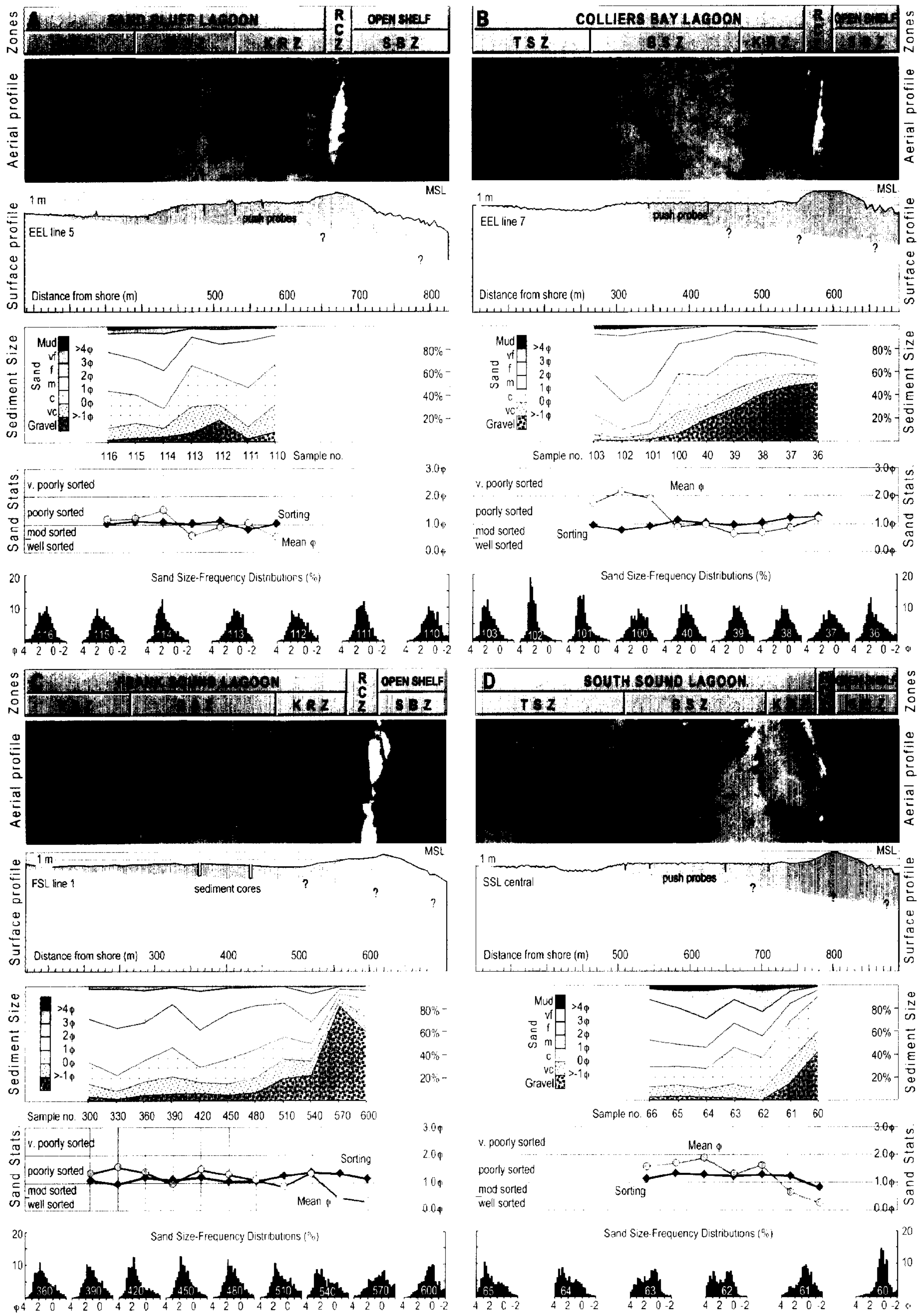


FIG. 6.—Zones of fringing-reef complex. **A)** sparsely distributed stumps of *A. palmata* in the stump-and-boulder zone (−3 m, Transect B). **B)** robust colony of *A. palmata* with surf-adapted form also from stump-and-boulder zone (−3 m, Site S23). **C)** large field of *A. palmata* boulders in stump-and-boulder zone (−3.5 m, site N32). **D)** seaward edge of stump-and-boulder zone with stabilized clasts overlying bedrock of upper terrace (−5 m, Old Man Bay). **E)** reef-crest zone dominated by *A. palmata* (−1.5 m, Grape Tree Point). **F)** reef-crest zone dominated by *A. palmata* cobbles (site: Driftwood Village). **G)** coral knob (*M. annularis*) in knob-and-rubble zone (knob is 1.5 m high, Site GB). **H)** lagoonal edge of bare-sand zone with 20° slope into lagoon (−3 to −9 m, site GB).


Zones
Aerial profile
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Sediment Size
Sand Stats.
OPEN SHELF
R C Z
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MSL
1 m
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Distance from shore (m)
Mud
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Sand
Gravel
>4φ
3φ
2φ
1φ
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80%
60%
40%
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116 115 114 113 112 111 110 Sample no.
Sample no. 103 102 101 100 40 39 38 37 36
v. poorly sorted
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Sorting
Mean φ
3.0φ
2.0φ
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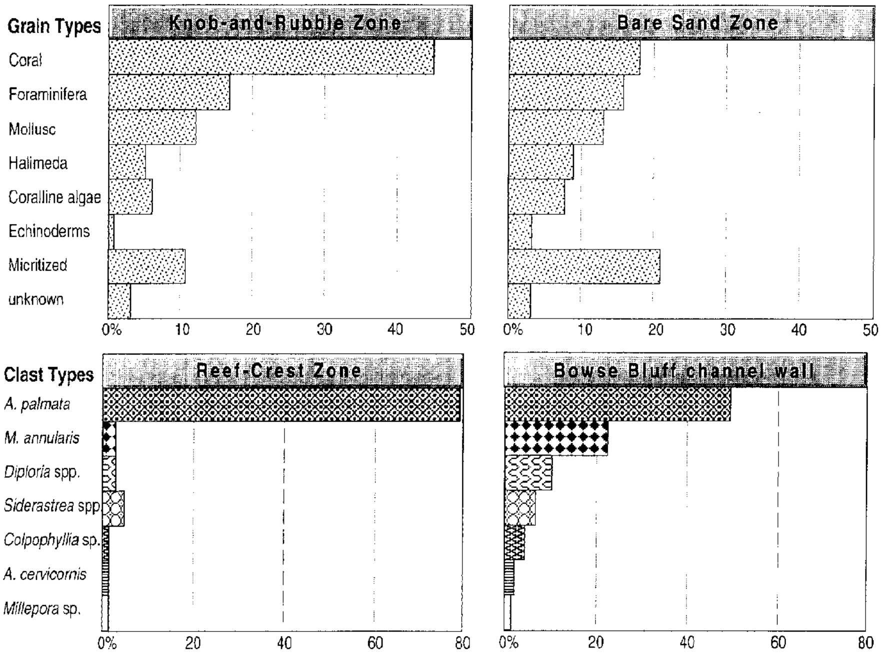

FIG. 8.—Composition of clasts and sand in different back-reef zones of fringing-reef complex (Transect C) and from boat-channel walls cut through the reef core (Bowse Bluff cut).

boulder zone and even underlies groove substrates in the spur-and-groove zone (Fig. 9). Cores from the spurs, however, generally encounter in-place framework dominated by heads of *Montastrea annularis, Diploria* spp., *Siderastrea siderea,* and irregular stumps of *A. palmata.* Interstices between these corals are filled with *Millepora* pebble gravels with grainstone or packstone textures. All interstitial sediment in the cores from stump-and-boulder and spur-and-groove zones is cemented by bladed circumgranular crusts of Mg calcite.

Architecture

Data from probings, sections, sonar, and aerial profiles over the fringing-reef complex show that two distinct architectural styles can be differentiated on the basis of distance from shore, lagoon depth, and thickness of the core deposit. Most of the reef complex around the island has a typical fringing-type architecture, characterized by a nearshore location (~ 0.5 km), a shallow lagoon (< 5 m), limited deposit thickness (< 5 m), and wide back-reef zones (up to ~ 300 m) (Fig. 11A). Along certain sections of the exposed-windward margin, however, the fringing type passes laterally into a barrier-type architecture, characterized by a location farther from shore (~ 1.7 km), a deeper lagoon (~ 10 m), greater deposit thickness (> 5 m), and narrow back-reef zones (100–200 m) (Fig. 11B).

In both architectural types, the position of the reef crest across the upper terrace shows an interesting relation: although no correlation exists with lagoon or open-shelf width, the reef crest is uniformly located 300 (± 100) m from the mid-shelf scarp (Fig. 12). This distance varies slightly on the different margins (Fig. 12). On the exposed-windward margin the reef crest is 350 (± 50) m from the scarp, whereas on the protected-windward margin the distance is only 250 (± 50) m. Also, along sections of the exposed- and protected-windward margins where the fringing-reef complex is absent, the distance from shore to the mid-shelf scarp is invariably less than 200 m (Fig. 11C). This previously undocumented linkage between reef-crest position and mid-shelf scarp is also apparent from a reexamination of shelf profiles in other areas, such as the Belize Barrier Reef (Rützler and Macintyre 1982; Burke 1982), suggesting that it may be common in barrier as well as fringing reefs.

HURRICANE CONTROL ON REEF ZONATION AND ANATOMY

The sediment/coral zones of the fringing-reef complex around Grand Cayman are comparable to many other reefs in the Caribbean. Although early attempts to explain such zonation largely ignored substrate character, coral zonation clearly correlated with variations in fair-weather wave energy (Geister 1977; Adey and Burke 1977; Done 1983). Attempts to replicate both substrate character and coral zonations using computer modeling, however, showed that higher-energy waves, more consistent with annual winter-storm activity, were necessary before even the most basic sediment/coral zonation was achieved (Graus et al. 1984). This finding was also supported by decreasing grain-size trends in back-reef zones of several reef complexes (e.g., Macintyre et al. 1987). Interestingly, however, hurricanes were considered to exert minimal control on fringing-reef zonation because their return period was longer than the reef recovery period (Graus et al. 1984).

Changes in reef-front zonation with varying margin orientation (Fig. 4) and decreasing grain size into the back reef (Fig. 7) support the idea that the development of the fringing-reef complex on Grand Cayman is con-

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FIG. 7.—Transect profiles over the fringing-reef complex showing zonation, sediment thickness, and sediment size characteristics (TSZ: *Thalassia*-sand zone. BSZ, bare-sand zone; KRZ, knob-and-rubble zone; RCZ, reef-crest zone; SBZ, stump-and-boulder zone). **A, B)** Transects across the East End lagoon, showing typical decrease in sediment size into the lagoon and unimodal sand-size frequency distributions. **C)** Transect across Frank Sound, showing similar profile and sediment characteristics (locations of the sediment cores are projected onto this profile). **D)** South Sound transect, showing where sea grass has rapidly overgrown the bare-sand zone. This has produced a distinct increase in very fine sand and mud, and has resulted in a typical bimodal sand-size frequency distribution. Despite this "lagoonal overprint", the decreasing size trend and poor sorting typical of other transects can still be recognized. (Note boat channel through knob-and-rubble, reef-crest and stump-and-boulder zones; see Figure 4 for its location).

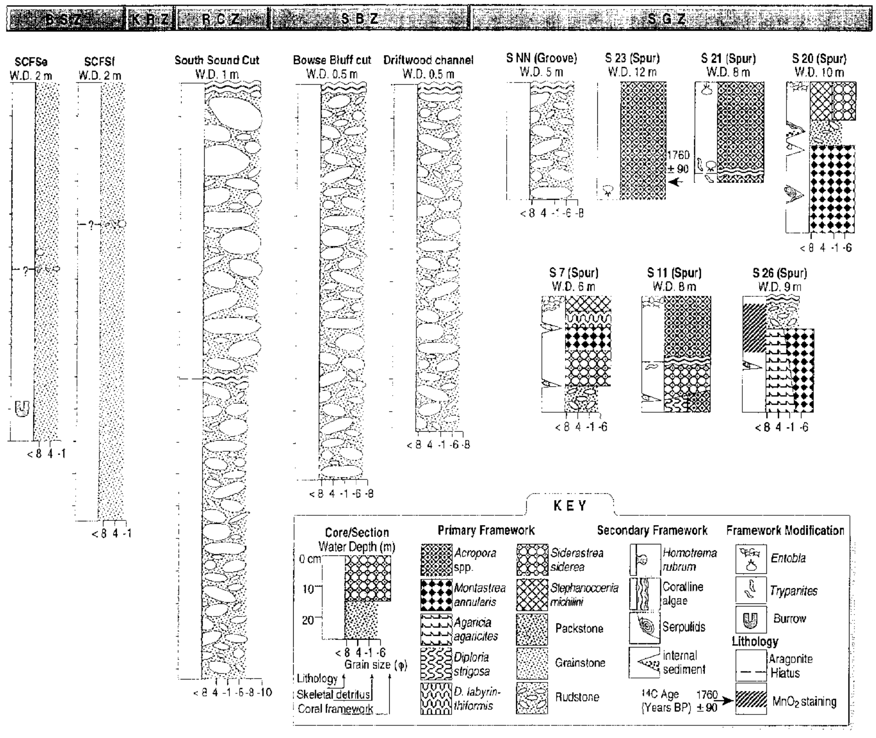

FIG. 9.—Boat-channel sections, drill cores, and sediment cores from different zones of the fringing-reef complex around Grand Cayman (BSZ, bare-sand zone; KRZ, knob-and-rubble zone; RCZ, reef-crest zone; SBZ, stump-and-boulder zone; SGZ, spur-and-groove zone). These show that the reef core is composed of coral rubble and, except for spurs of spur-and-groove, no in-place coral framework was encountered.

trolled by the influence of fair-weather and storm waves. However, although annual winter storms (Nor'westers) could account for the zonation on the protected-windward margin, they cannot account for exposed-windward zonation because that margin is fully protected from the predominantly northwest winter-storm waves. This protection, together with the lack of fringing reef development on the leeward margin (west side), implies that less frequent tropical storms and hurricanes approaching from the east must play a more significant role in controlling zonation patterns than previously recognized (e.g., Graus et al. 1984, p. 65).

The most compelling evidence that hurricanes control the development of Grand Cayman's fringing-reef complex is the discovery that the reef core lacks *in situ* framework and consists instead of coral-cobble rudstone layers. The large size, abraded condition, and imbrication of coral clasts in these layers indicates that they were transported by shoreward-moving hurricane waves with heights ≥ 5 m (Hernandez-Avila et al. 1977). Although the effects of such waves can only be speculated upon, it is likely that they destroy *A. palmata* coral associations in all zones seaward of, and including, the reef crest (Fig. 13). Coral clasts generated from these zones are subsequently entrained in saltation and traction loads and, under the influence of wave surge, move back and forth over the upper terrace. During this process, smaller clasts are progressively transported towards the reef crest but larger clasts remain closer to their source area, producing a shoreward-fining cobble layer that covers the stump-and-boulder, reef-crest, and knob-and-rubble zones (Fig. 13). The hurricane waves also carry a suspended load of sand- and pebble-size detritus entrained from the sediment reservoir on the lower terrace. Although some of this sediment infiltrates interstices in the cobble layer, most is carried onto and over the reef crest by storm-wave surf and deposited in the back-reef zones (Fig. 13). If these back-reef areas are shallow, turbulence and velocity are maintained longer, and the surf transports sand- and pebble-size sediment considerable distances into the lagoon. If the back-reef areas are deeper, however, turbulence and velocity are quickly damped by the water column and sediment is dropped a limited distance into the lagoon. Hence, sections of the reef complex that front deeper lagoons have narrow back-reef zones (Fig. 12)

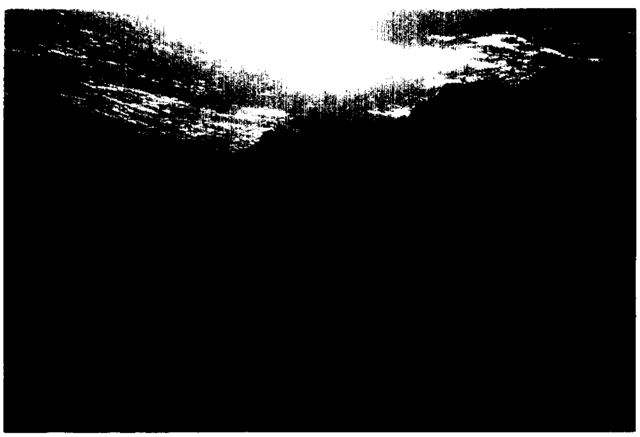

FIG. 10.—View of boat-channel section through the reef core on the protected-windward margin. View is taken beneath the stump-and-boulder zone looking seaward (3 m below msl; site, Bowse Bluff cut).

Following a hurricane, the rubble layer over the stump-and-boulder and reef-crest zones provides a foundation for new coral growth and is quickly colonized by crustose coralline algae and colonies of *A. palmata* (Fig. 13). For healthy *A. palmata*–dominated communities, which have rapid growth rates of up to 15 cm yr^{-1} (Gladfelter and Monahan 1977), full recovery may take less than 50 years (Stoddart 1974; Pearson 1981). On Grand Cayman, the 64-year recurrence interval of reef-destroying hurricanes (i.e., those with wave heights ≥ 5 m) is longer than this recovery interval, implying that pre-hurricane conditions can be fully attained before the next major hurricane strikes (Fig. 2). Even though lower-intensity storms and hurricanes may recur before full recovery takes place, destruction will be less severe and localized as a result of variations in shelf orientation and

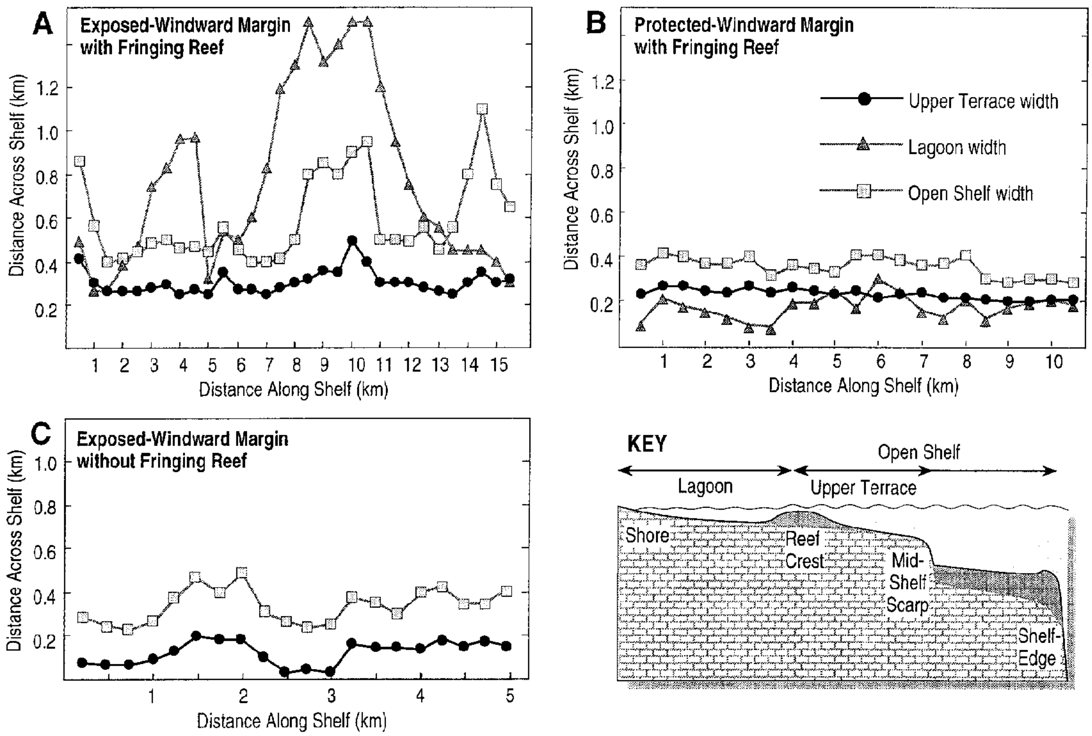

FIG. 11.—Bivariate plots showing variation in width of lagoons, open shelf, and upper terrace. **A)** Variation along exposed-windward margin shows that the distance from reef crest to mid-shelf scarp (upper terrace width) is relatively uniform at ~ 350 (± 50) m when compared with lagoon or open shelf widths. **B)** Along the protected-windward margin, the reef-crest to mid-shelf scarp distance is slightly less at ~ 250 (± 50) m. **C)** In areas of the exposed-windward margin that lack a fringing reef, the distance from shore to mid-shelf scarp is < 200 m.

angle of wave approach (Woodley et al. 1981). Consequently, individual sections of fringing reef may survive relatively unscathed for many years before being destroyed by larger hurricanes. Over thousands of years, therefore, the reef undergoes a cyclic pattern of destruction and renewal, producing a reef core that is built up by successive layers of coral rubble, each stabilized by crusts of coralline algae. The only zone where in-place coral framework survives is in spurs of the spur-and-groove zone and, even there, coral framework shows condensed accretion due to repeated shedding of corals (Fig. 14).

This hurricane model of reef anatomy and zonation contrasts with studies that have traditionally emphasized the dominance of in-place coral frameworks in reef cores (e.g., Macintyre and Glynn 1976; Adey and Burke 1976; Easton and Olson 1977). This emphasis is due to several factors. First, traditional descriptions of reefs concentrated on the zonation and form of corals (e.g., Goreau 1959) and therefore tended to emphasize the fair-weather processes (e.g., Geister 1977; Adey and Burke 1977). Second, although the impact of destructive storms on reef communities has long been recognized (e.g., Stoddart 1962; Connell 1978; Woodley et al. 1981), the cumulative affect on reef anatomy over time has been overlooked. Even drilling investigations directly concerned with detailing reef anatomy have overemphasized the importance of in-place coral framework despite the widespread problem of poor core recovery and the inherent limitations of using small-diameter cores to identify in-place corals (e.g., Macintyre and Glynn 1976; Adey and Burke 1976; Easton and Olson 1977). Furthermore, interpretation of coral framework is inconsistent with the common dating reversals found in most cores with detailed chronologies (e.g., Macintyre and Glynn 1976; Fairbanks 1989). And yet, when investigators have had the opportunity to examine excavations into the reef core they have concluded that reef anatomy is detrital. Buddemeier et al. (1975), for example, used blasting to reveal the anatomy of the immediate fore-reef, reef-crest, and back-reef zones of the windward margin of Enewetak Atoll. They found that all three zones were underlain by a core of coral-cobble rudstone stabilized by a 15-cm-thick surficial crust of coralline algae and concluded from this that "...the present biological record on the atoll reef flat represents no more than a fleeting glimpse of how the reef flat grows and is destroyed through geological time" (Buddemeier et al. 1975, p. 1583).

HURRICANE CONTROL ON REEF ARCHITECTURE?

As well as providing a compelling explanation for fringing-reef zonation and anatomy, hurricane control can also account for uniform reef location across the shelf, reef absence along windward shelf sections, and along-shelf variation in reef architecture.

Although previous work on reefs has emphasized the role of either coral growth or antecedent topography in determining reef position and architecture (Hopley 1982; Braithwaite 1987; Macintyre 1988; Hubbard 1988; Purdy 1974), neither can reasonably account for the position and architecture of the fringing-reef complex around Grand Cayman. This problem is clearly illustrated in attempting to explain the uniform spatial relationship between the reef crest and the mid-shelf scarp (Fig. 12). The uniform distance between these two features cannot be attributed to the interplay between coral growth and fair-weather waves because much of the upper terrace along the protected-windward margin is below fair-weather wave base. Nor can it be explained by inferring initiation on an antecedent topographic ridge, because sections through the reef complex show no core of bedrock (Fig. 9). The only physical connection between the reef crest and the mid-shelf scarp comes under storm conditions when large waves cross the mid-shelf scarp and experience abrupt shallowing and a concomitant increase in frictional attenuation. This abrupt shallowing causes waves to start breaking from the outer part of the upper terrace, thereby destroying

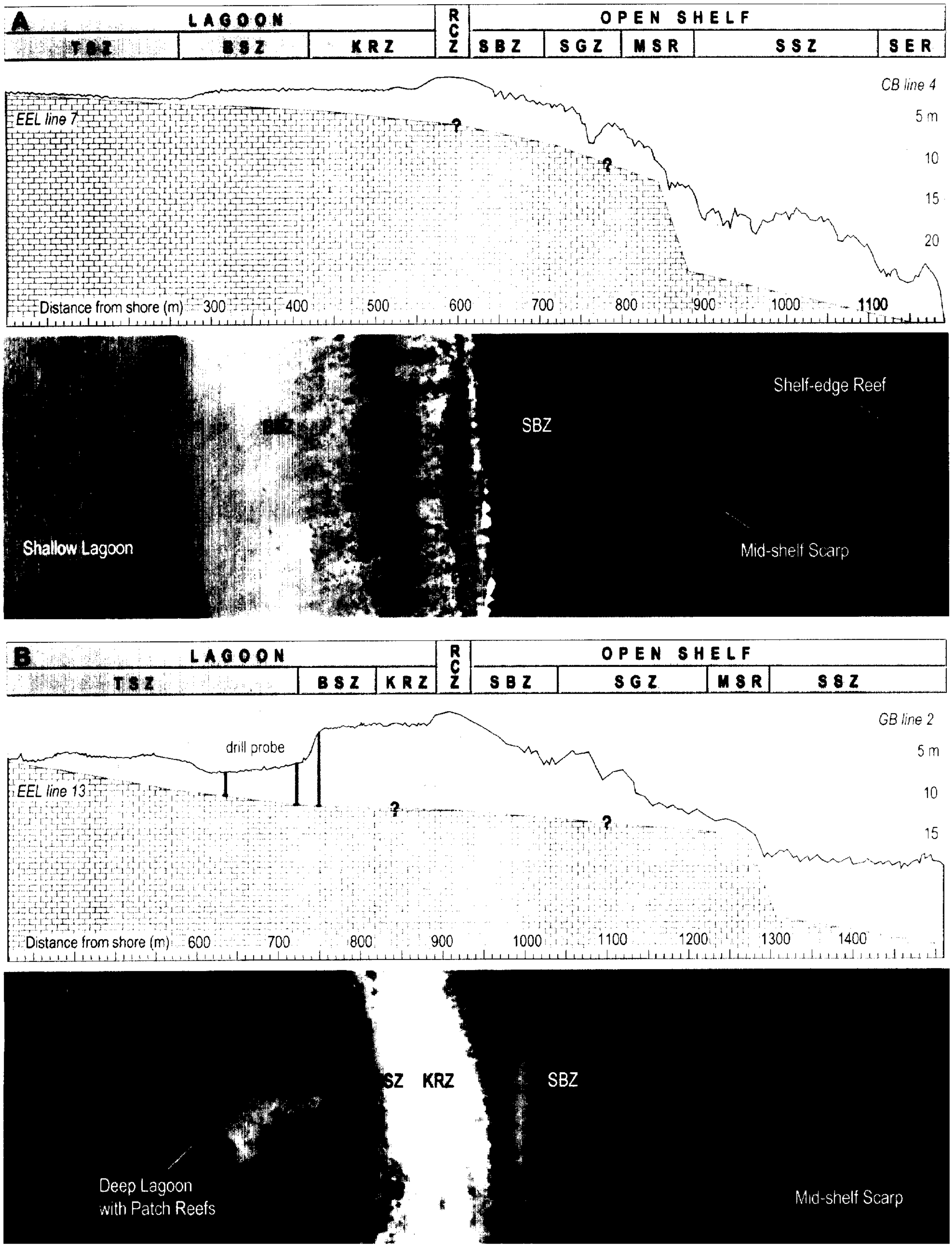

FIG. 12.—Aerial and depth profiles over exposed-windward shelf. **A)** Profiles over reef with fringing-type architecture (Transect B, Fig. 4). **B)** Profiles over reef with barrier-type architecture (Transect GB, Fig. 4). (TSZ, *Thalassia*-sand zone; BSZ, bare-sand zone; KRZ, knob-and-rubble zone; RCZ, reef-crest zone; SBZ, stump-and-boulder zone; SGZ, spur-and-groove zone; MSR, mid-shelf reef; SSZ, spur-and-sand zone; SER, shelf-edge reef).

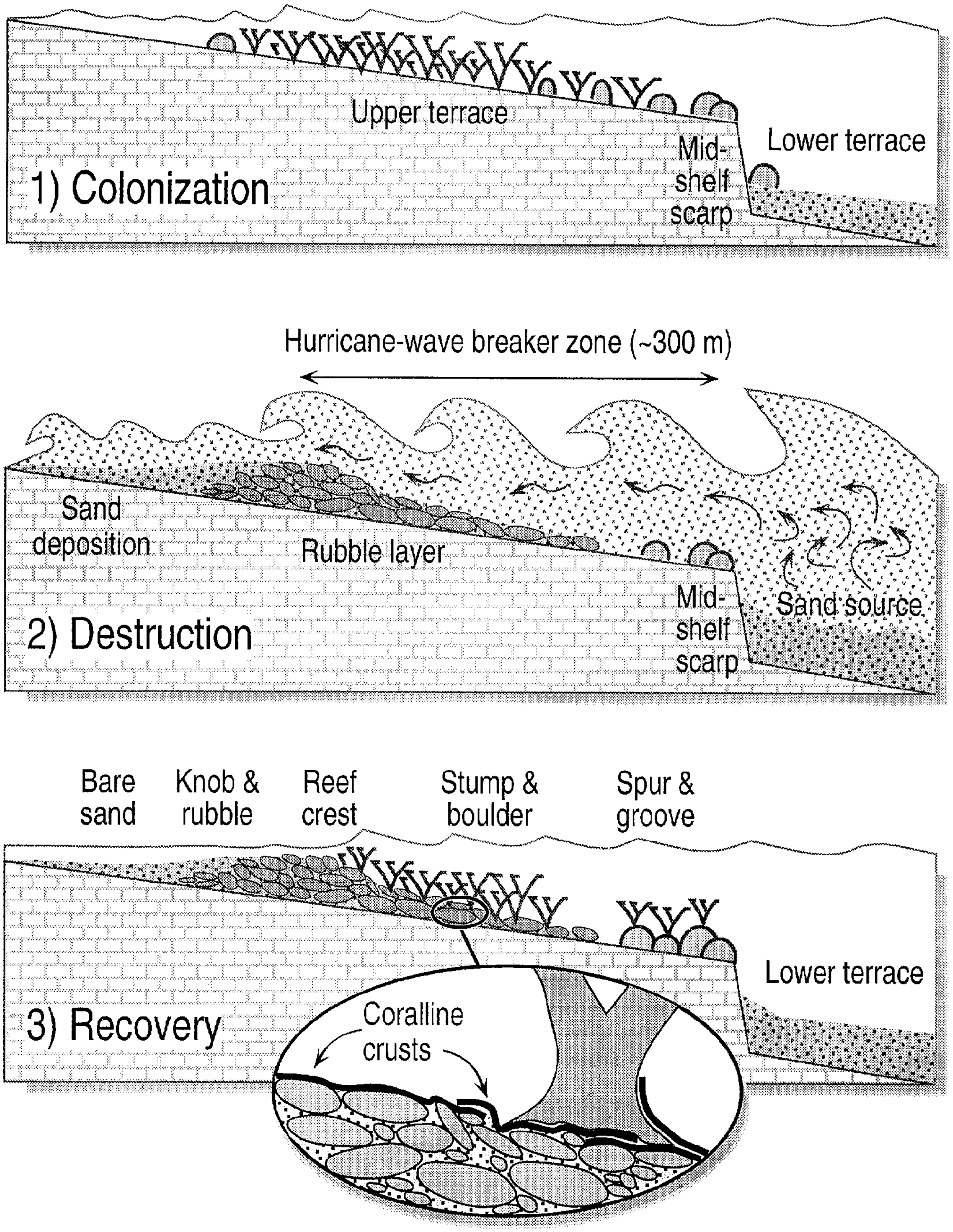

FIG. 13.—Schematic showing a full cycle in the development of a fringing-reef complex. Initial colonization of the substrate by *A. palmata* thickets is controlled by extent of fair-weather surf zone. These thickets are destroyed by hurricane waves ≥ 5 m, and the coral clasts are deposited as a wedge-like rubble layer that forms a breakwater ~ 300 m from the mid-shelf scarp. This rubble breakwater is stabilized by coralline algae and recolonized by *A. palmata* thickets before the next hurricane hits. Further cycles produce a reef core composed of rubble layers.

all coral thickets between there and the reef crest (Fig. 14). The uniform distance from the reef crest to the mid-shelf scarp is therefore proportional to wave energy and represents the extent to which waves can fragment, entrain, and transport coral detritus across the upper terrace. Thus, the average distance from the mid-shelf scarp to the reef crest along the exposed-windward margin is greater than along the protected-windward margin because the latter is impacted by smaller, lower-energy hurricane waves due to the limited fetch.

This interaction between hurricane waves and the upper terrace not only explains the uniform position of the fringing reef but also reef absence along narrow sections of the exposed-windward shelf (Fig. 1). Where the width of the upper terrace is less than the distance hurricane waves can

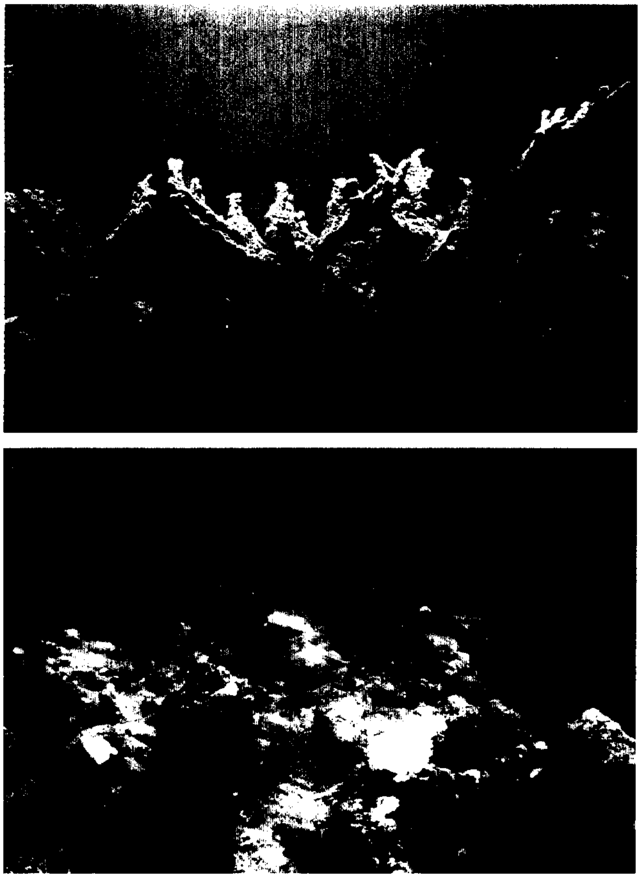

FIG. 14.—**A**) Before and **B**) after shots illustrating destructive effect of Hurricane Gilbert (1988) on spur-top *A. palmata* community of the spur-and-groove zone along the exposed-windward margin (~ 5 m below msl, Site S5). Triggerfish is ~ 25 cm long. Courtesy of Phil Bush.

transport detritus (i.e., < 200 m), no fringing-reef complex develops because the rubble is either thrown ashore to form coastal cobble ramparts or is driven downslope by powerful currents deflected from coastal cliffs. Although this is true for all narrow parts of the upper terrace along the exposed-windward margin, rare discontinuities in fringing-reef development along sheltered parts of the protected-windward margin can also result from limited *A. palmata* growth (and therefore lack of clast supply) induced by low fair-weather wave energy—the very reason fringing reefs are absent along the leeward margin.

If the key factor for the initiation of fringing reefs is shelf width, then the interplay between sea-level rise and coastal gradient controls both the timing of reef initiation and the architectural style of subsequent reef development (Fig. 15). Where sea-level rises over a low-gradient shore, it floods broad coastal tracts, producing a wide, shallow shelf. If this shelf is wider than the distance waves can transport coral clasts, rubble immediately begins to accumulate during hurricanes, and a fringing-reef complex develops early. Where sea level rises over a higher-gradient shore, it floods only a limited coastal tract, producing a narrow shelf. Although corals can grow on this narrow shelf, the detritus produced during storms does not accumulate and a fringing-reef complex does not develop until the terrace width exceeds the distance hurricane waves can transport detritus. This shelf-gradient hypothesis predicts, therefore, that the age of fringing-reef initiation varies along the shelf, being oldest along former low-gradient coasts and youngest along former high-gradient coasts. This prediction is supported by two recent studies of fringing reefs around St. Croix and New Caledonia (Burke et al. 1989; Cabioch et al. 1995). On St. Croix the fringing-reef complex initiated some 6 ka ago on a wide section of shelf, but started growing along narrow shelves only 1.5 ka ago (Burke et al. 1989). Similarly on New Caledonia, the initiation of the fringing reef varies irregularly along shelf (Cabioch et al. 1995), possibly as a function of gradient.

The shelf-gradient hypothesis also accounts for the variations in architectural style of the fringing-reef complex around Grand Cayman. On low-gradient sections of the shelf, early-formed fringing complexes aggrade vertically as sea level rises and gradually develop thicker, narrower profiles and front wider, deeper lagoons (Fig. 15). In other words, fringing reefs progressively develop a barrier-type architecture as sea level rises. But in addition to building vertically, reef complexes also extend laterally along the shelf as sea-level rises. As higher-gradient sections of the shelf are progressively inundated, their width eventually exceeds the 250 m initiation threshold, enabling fringing-reef development. Thus in a single reef system, a barrier reef can transform laterally into a fringing reef as a result of differences in shelf gradient.

Vertical and lateral development of fringing-reef complexes could potentially be accompanied by changes in reef position across the shelf. Where the accretion of reef-front zones (particularly the spur-and-groove) fails to keep pace with sea-level rise, the frictional interaction of storm waves decreases and rubble deposition starts to retrograde over back-reef deposits in an effort to maintain the hurricane-wave transport distance (Fig. 15C). By contrast, if reef-front accretion keeps up with or exceeds the rate of sea-level rise, the reef complex either aggrades vertically or progrades seawards in order to maintain the hurricane-wave transport distance (Fig. 15B). This hurricane control on reef position predicts, therefore, that fringing-reef complexes developed along protected-windward margins (where lower energy limits reef-front coral growth) will have retrogradational geometries, whereas those developed along exposed-windward margins (where higher energy enhances coral growth) will have aggradational or even progradational geometries.

By highlighting this potential interaction between hurricane-mediated fringing-reef development, shelf gradient, and sea-level rise, we have identified a genetic succession between fringing and barrier reefs. With continued sea-level rise, and complete inundation of Grand Cayman, the next step in this succession would probably be the development of an atoll (Fig. 15C). Although this same sequence of reef development was first proposed by Charles Darwin over 150 years ago, it was suggested to be the result of simple upward coral growth during relative sea-level rise (Darwin 1842). Perhaps if Darwin had actually observed a hurricane-impacted reef, rather than one with luxuriant stands of coral, he might well have realized the geological importance of hurricanes over time.

CONCLUSIONS

Although the reef paradigm has failed to reconcile development from fringing reef to barrier reef to atoll, the realization that hurricanes constitute a continuous force in geological time has important implications for explaining development of modern reefs. By documenting the zonation, anatomy, and architecture of a fringing-reef complex around Grand Cayman we have shown that:

- the reef core consists not of coral framework, but of coral-rudstone layers whose large clast size and abraded condition clearly implicate hurricanes as the major controlling agent;
- reef-crest position is located a uniform distance (~ 300 m) from the mid-shelf scarp; this distance varies slightly as margin orientation changes and is proportional to the varying power and carrying capacity of hurricane waves as they break over the upper terrace; and
- fringing reefs do not develop where the upper-terrace width is less than the distance storm waves can carry coral clasts (i.e., < 250 m)

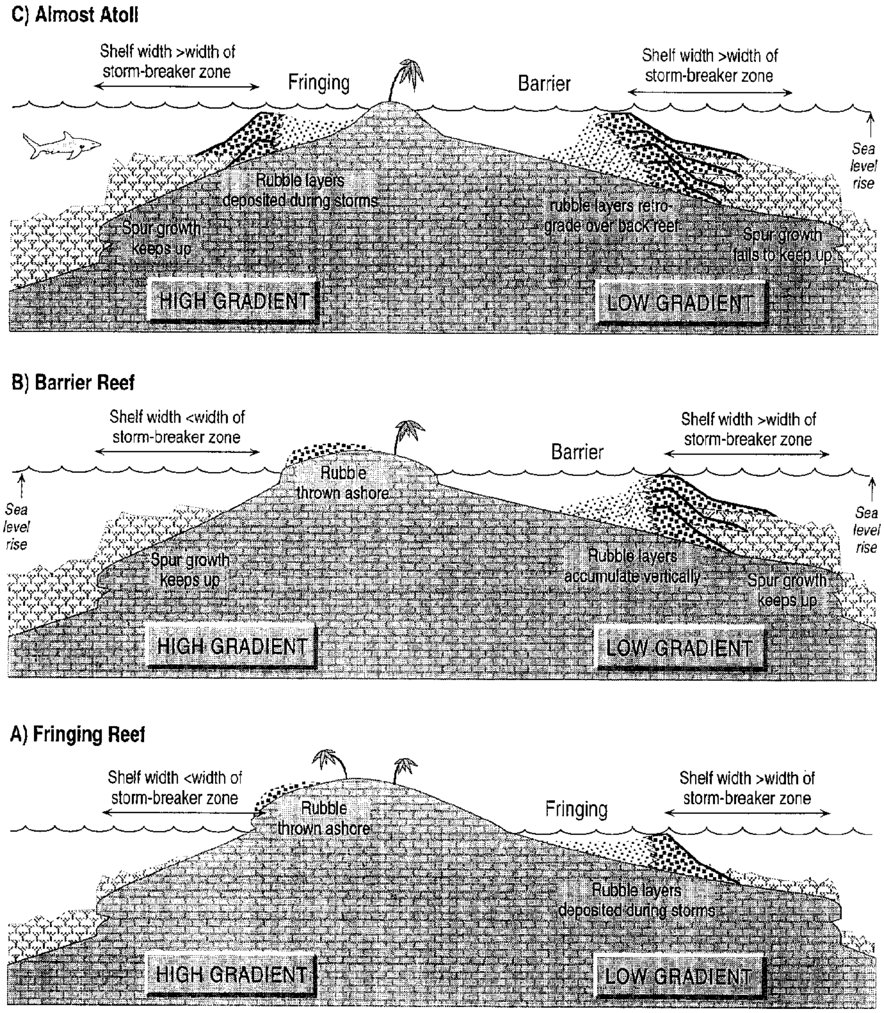

FIG. 15.—Schematic showing the effect of shelf gradient on position and architecture of fringing reefs during rising sea level. **A)** Fringing reef initiates first where the shelf is wider than the hurricane breaker zone. **B)** As sea level rises, these early reefs accumulate vertically and the lagoon increases in width and depth until the reef has a barrier-type architecture. **C)** As sea level continues to rise, sections of shelf that were previously too narrow to allow fringing-reef development eventually become wider than the hurricane breaker zone, thus enabling fringing reef rubble to start accumulating. Note that, where reef-front zones fail to keep pace, the reef retrogrades over back-reef deposits in order to maintain the hurricane wave transport distance.

because clasts are thrown ashore rather than accumulating to form a foundation for reef growth.

This hurricane control on Grand Cayman's reef anatomy and position has important implications for reef development during sea-level rise. Fringing-reef complexes initiate early on wide shelves and subsequently develop a barrier-type architecture as sea level rises. They also gradually extend from low-gradient to high-gradient areas as shelf width increases during sea-level rise. This interplay between sea-level rise, shelf gradient, and hurricane-mediated reef development may explain why some fringing reefs transform laterally into barrier reefs within the same reef tract. But more importantly, it may also provide a mechanism whereby fringing reefs develop into barrier reefs and atolls during relative sea-level rise—the genetic sequence postulated by Darwin over 150 years ago.

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