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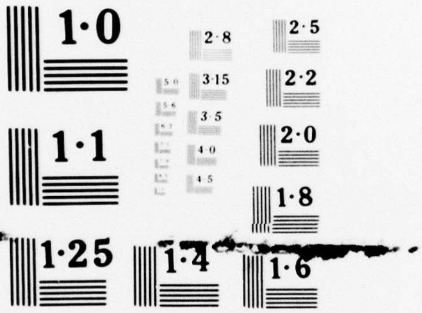

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HURRICANE-GENERATED WAVES AND COASTAL BOULDER RAMPART FORMATION

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ABSTRACT

Coral boulder ramparts along the south coast of Grand Cayman Island have no source area near the shoreline. Coral communities acting as a source of rampart rubble are found 0.3 km from shore and at a depth of 10-12 m. Theoretical calculations of wave-induced forces from wave refraction analyses of hurricane-generated waves indicate that the probable hurricane dynamic force spectrum *is sufficient to break and transport coral rubble from depths of up to 12 m.* *In situ* *breaking force* tests accomplished in Puerto Rico on *Acropora palmata* coral colonies support the theoretical calculations.

KEY WORDS: Coral, Boulder Ramparts, Wave Forces, Grand Cayman Island, Puerto Rico, Wave Refraction, Breaking Force

HURRICANE-GENERATED WAVES AND COASTAL BOULDER RAMPART FORMATION

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Introduction

Descriptive reports documenting the geomorphic and structural changes induced by extreme storm conditions on island coasts, atolls, and coral cays have been published (1), (2), (3), (4), (5), (6), (7), (8), (and others). One common observation has been the occurrence of linear coral rubble accumulations or ridges parallel to the coast; the coral constituents of these structures, usually called boulder ramparts, range in size from pebble to boulder. Formation of these topographic features, commonly found along high-energy coastal sectors, is generally attributed to wave-induced forces and storm-surge effects.

The objective of this paper is to calculate theoretically the magnitude of hurricane wave-induced forces instrumental in destruction of stony corals, which constitute the source of rubble for ridge formation on island coasts. Calculated wave-induced forces that result in the initial breakup of coral fragments are compared to actual mechanical breaking forces measured in situ.

The analytical procedure consisted of (a) a case study of a boulder rampart and its governing physical characteristics at a specific location on Grand Cayman Island, British West Indies, (b) theoretical determination of hurricane-generated swell characteristics, (c) calculation of wave-induced forces employing the resultant orbital velocities of the swells after refraction has taken place, and (d) a comparison of calculated wave force magnitudes with preliminary observations of actual mechanical forces that break Acropora palmata coral colonies.

Grand Cayman Boulder Rampart

Rigby and Roberts (8) described boulder ramparts on the coasts of Grand Cayman Island (Fig. 1) as being composed of hurricane-tossed coral fragments that reach 0.6 to 1.0 m in diameter in areas of coarsest accumulations. Rampart heights reach a maximum of 4.5 m above sea level. A study area near Spots Bay (sector 3 of Fig. 2) was chosen as the site for analyses of hurricane wave-induced forces. Constituents of the boulder rampart present in this sector have a mean width of 20 cm, a vertical thickness of 10 cm, and a maximum length of about 58 cm. For the purpose of analysis, a mean length of 30 cm was chosen. A. palmata fragments are the major constituent of the boulder ramparts (Fig. 3).

Two major observations relevant to this analysis are (a) the source of A. palmata fragments is found at an approximate distance of 0.3 km from the shoreline at depths ranging from 8 to 10 m (Fig. 4) and (b) the rampart's constituent fragments are relatively unabraided, a fact that suggests that transit time from growth areas was minimal.

Hurricane-Generated Wave Characteristics

The yearly mean shore wave power distribution for six sectors along the coast of Grand Cayman Island is shown in Fig. 2. A similar analysis employing the same bathymetric data (9) was used as input to a wave refraction-wave power computer program (10) for an analysis of hurricane waves. Four hurricane conditions were assumed to be generating swells at fetches located in the southeastern Caribbean Sea. It was determined from wave hindcasting analyses, employing accepted methods (11), (12) and corroborating the results with historical data, that swells reaching the study area from these storm centers would have the characteristics shown in Table 1. These values were employed in the wave refraction-wave power computer program to determine their variations at a depth of 12 m over the A. palmata reef section, which was the probable source for the boulder rampart constituents. Results of the wave refraction

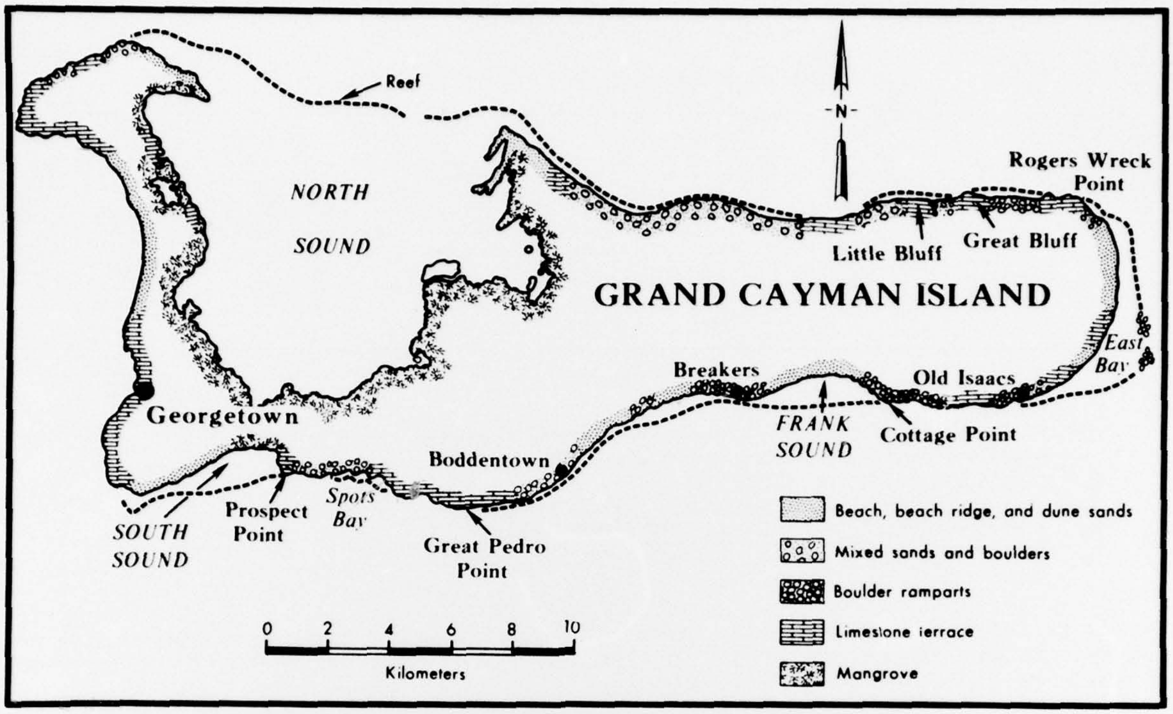
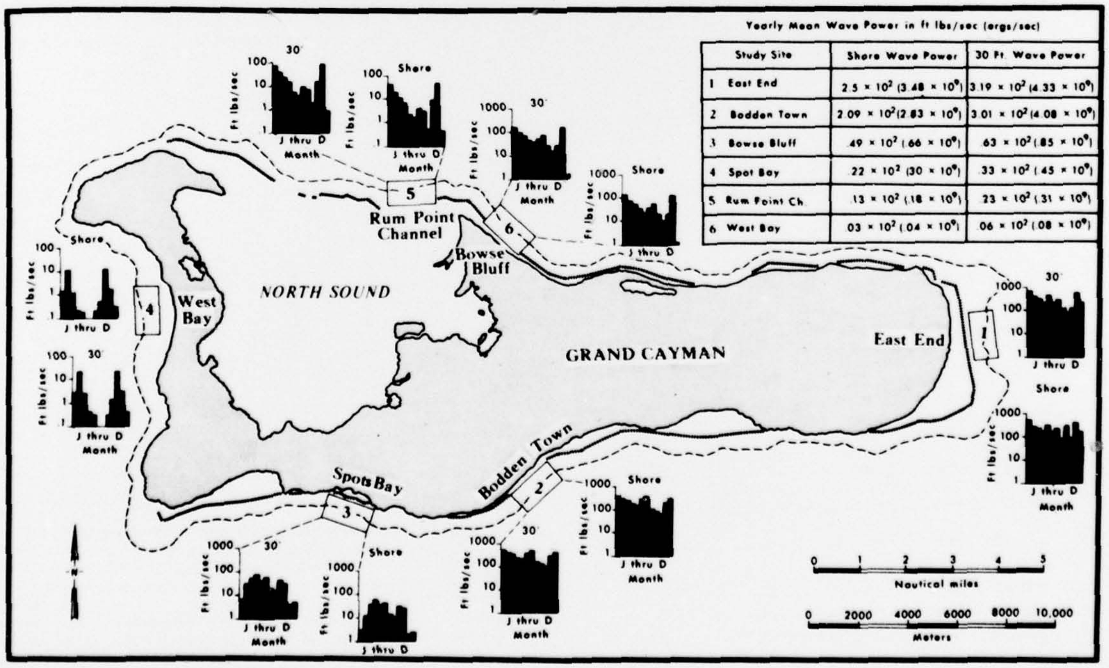


Figure 1. Grand Cayman Island boulder rampart distribution [after Rigby and Roberts (8)].



Yearly Mean Wave Power in ft lbs/sec (ergs/sec)

Study Site	Shore Wave Power	30 Ft. Wave Power
1 East End	2.5×10^2 (3.48×10^9)	3.19×10^2 (4.33×10^9)
2 Bodden Town	2.09×10^2 (2.83×10^9)	3.01×10^2 (4.08×10^9)
3 Bowse Bluff	$.49 \times 10^2$ $(.66 \times 10^9)$	$.63 \times 10^2$ $(.85 \times 10^9)$
4 Spot Bay	$.22 \times 10^2$ (30×10^9)	$.33 \times 10^2$ $(.45 \times 10^9)$
5 Rum Point Ch.	$.13 \times 10^2$ $(.18 \times 10^9)$	$.23 \times 10^2$ $(.31 \times 10^9)$
6 West Bay	$.03 \times 10^2$ $(.04 \times 10^9)$	$.06 \times 10^2$ $(.08 \times 10^9)$

Figure 2. Case study location (sector 3) and wave power distribution [after Roberts (9)].

Table 1

Hurricane-Generated Swell Characteristics

Hurricane No.	T (sec)	H_o (m)	α_o (°)	L_{12} (m)	H_{12} (m)	U_{max} (m/sec)	H_b (m)	d_b (m)
I	15	9.1	90	158	9.8	4.0	10.0	12.2
II	13	4.3	90	135	4.3	1.8	8.8	1.5
III	12	6.1	90	124	6.1	2.4	8.8	1.5
IV	13	4.6	90	109	4.6	1.8	7.0	1.5

T = = wave period
H_o = deepwater wave height
α_o = wave angle of approach in deep water (east direction, in this case)
L_{12} = shallow-water wavelength at the 12-m depth contour
H_{12} = wave height at the 12-m depth contour
U_{max} = maximum wave orbital velocity at the 12-m depth contour
H_b = breaker height (mean value of 40 orthogonals)
d_b = depth of wave breaking (mean value of 40 orthogonals)

analyses are also tabulated in Table 1. These shallow-water swell characteristics were employed in calculation of wave-induced forces. Note in Table 1 that in Hurricane I the waves would break on the *A. palmata* reef flat.

Wave-Induced Force Calculations

Forces exerted by waves on submerged objects have been studied theoretically (linear wave theory) (13; and many others). Several summaries of the theories for calculating these wave-induced forces have been presented (14), (15), (16).

The methods and equations employed in the analyses (15) are as follows:

The horizontal component of force equation expressed as a function of time is:

$$F_h = -2\pi^2 C_M \rho V \frac{H}{T^2} (W) \sin \sigma t + \frac{1}{2} C_D \rho A \pi^2 \frac{H^2}{T^2} (W)^2 \cdot |\cos \sigma t| \cos \sigma t$$

where

$W = \frac{\cosh [k(y+d)]}{\sinh kd}$
k = wave number $(\frac{2\pi}{T})$
σ = wave angularity frequency $(\frac{2\pi}{T})$
L = wavelength
T = wave period
d = water depth
y = depth of object from still-water level (negative downward)
V = volume of object
A = area of object
ρ = density of water (1031 kg/m^3)
H = wave height
t = time measured as positive from the time the crest of the wave passes the center of the object
C_M = coefficient of mass or inertia
C_D = drag coefficient

The phase angle (15), B_{hf}, at which the maximum horizontal component of force occurs can be found by differentiating the above equation with respect to σt and setting it equal to zero:

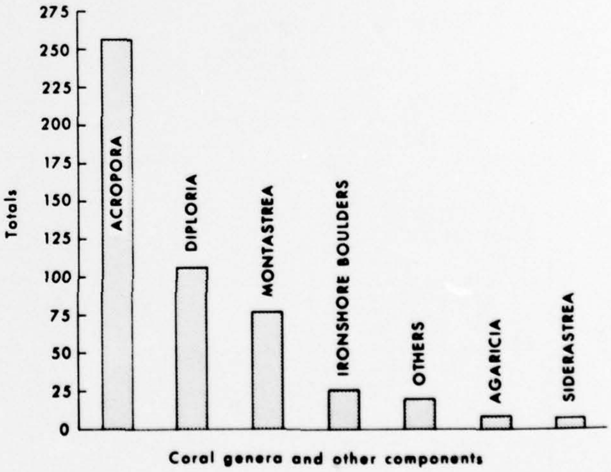


Figure 3. Histogram of constituents of a boulder rampart near Spots Bay, along the south coast of Grand Cayman Island, British West Indies [after Rigby and Roberts (8)]. Data were generated from 500 counts on a grid randomly placed over the outcrop.

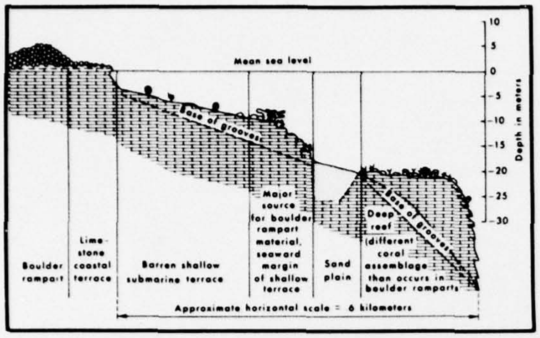


Figure 4. Schematic profile of the fore-reef shelf, adjacent to the boulder rampart study area [after Rigby and Roberts (8)].

$$\frac{\partial F_h}{\partial \sigma t} = - 2\pi^2 C \ \rho V \frac{H}{T^2} (W) \cos \sigma t$$

$$- C_D \ \rho A \pi^2 \frac{H^2}{T^2} (W)^2 \cdot |\cos \sigma t| \sin \sigma t = 0 .$$

The solution to this equation is either

$$\sin B_{hf} = \pm \frac{2 C_M V}{C_D A H} \cdot \frac{\sinh kd}{\cosh k(y+d)} ,$$

where B_{hf} is in the second and fourth temporal quadrants of the wave form, or

$$\cos B_{hf} = 0$$

when

$$\frac{2 C_M V \sinh kd}{C_D A H \cosh k(y+d)} > 1 .$$

The equation to determine the vertical component of force is

$$F_v = - 2\pi^2 \rho C_M V \frac{H}{T^2} [\frac{\sinh k(y+d)}{\sinh kd}] \cos \sigma t$$

$$- \frac{1}{2} \rho C_D A \frac{\pi^2 H^2}{T^2} \{\frac{\sinh k(y+d)}{\sinh kd}\}^2 \cdot |\sin \sigma t| \sin \sigma t$$

The phase angle, B_{vf}, at which the maximum vertical component of force occurs is either

$$\cos B_{vf} = \frac{2 C_M V}{C_D A H} \cdot \frac{\sinh kd}{\sinh k(y+d)}$$

or

$$\sin B_{vf} = 0 ,$$

when

$$\frac{2 C_M V}{C_D A H} \cdot \frac{\sinh kd}{\sinh k(y+d)} > 1 .$$

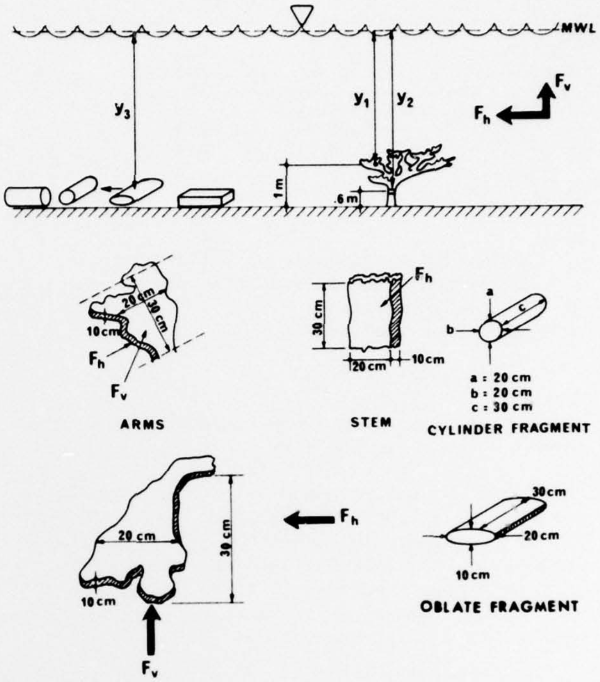


Figure 5. Conceptual model employed in the analysis and calculations of wave-induced forces on an oblate and a cylindrical coral fragment at the bottom and suspended above the bottom.

Analysis of wave-induced forces was made for cylinders and oblate cylindroids because A. palmata structural units and fragments approximate these shapes and forms. Figure 5 shows the conceptual models for boulder-sized fragments at the bottom and for the structural units in situ. The calculations that follow are made for coral fragments of the dimensions indicated in this figure.

The great difficulty in calculating (or choosing) values for the coefficient of drag and inertia according to geometrical characteristics of the objects has been explicitly shown by many investigators (13), (15), (14), (17), (18), (16). The coefficients of drag for cylindrical fragments were obtained from a curve published by Wiegel (15). The coefficient of drag for oblate fragments was chosen from a middle value for a cylinder because no published values for this shape could be found. The coefficient of mass for both shapes was the theoretical value for cylinders (15). A change in the coefficient of mass from 2.0 to 1.6 produced no significant difference in the calculated forces. The values of

Table 2

Values of C_D and C_M

Hurricane Number	C_D	C_{DO}	C_M
I	0.34	0.6	2.0
II	0.80	0.6	2.0
III	0.32	0.6	2.0
IV	0.70	0.6	2.0

C_D = drag coefficient of a cylinder
C_{DO} = drag coefficient of an oblate cylindroid
C_M = mass coefficient

Table 3

Calculated Horizontal Forces

Fragment	Cylinder			Oblate		
Orientation	X	Y	Z	X	Y	Z
Depth (m)	12.0	12.0	11.4	12.0	12.0	11.0
Hurricane						
I	8.6*	17.9	17.9	8.5	16.2	32.5
II	3.5	7.6	7.6	1.4	2.8	5.9
III	1.6	5.4	5.4	2.8	5.4	11.5
IV	1.9	4.6	4.6	0.9	2.0	4.1

Orientation: X = long axis of fragment parallel to bottom and to wave orthogonals
Y = long axis of fragments parallel to bottom and perpendicular to wave orthogonals
Z = long axis of fragments perpendicular to bottom - large cross section of oblate fragment perpendicular to wave orthogonals

*Measurements in kilograms

these coefficients that were used in the calculations are found in Table 2.

Water current-induced forces, breaker impact forces, and alignment and structural properties of the A. palmata units have not been considered in this analysis. Calculated values of wave-induced forces are shown in Table 3. Values of the vertical component of force, F_V, proved to be negligible for all cases considered.

Field Experiment

A graduated industrial spring balance was used to estimate the force that breaks the branches and stems of A. palmata structural units in situ (Fig. 6). Maximum range of the balance was 68 kg. An effort was always made to apply the force on the visually estimated center of gravity. The turnbuckle was rotated until breaking took place. A plastic band moving with the balance force indicator remained in place at the measured force limit after breaking occurred.

Tests for the breaking threshold were also performed in the laboratory by holding the stem of a broken structural unit with a vise and applying the force on an extended branch. Force was applied in the direction of dominant wave advance as estimated from field observations.

The experiment was conducted on the reef flat off Cayo Turrumote at a depth of $\sim$10 m. Cayo Turrumote (Fig. 7) lies $\sim$4.0 km southeast of La Parguera, Puerto Rico. It is 500 m long and an average of 24 m wide on its exposed parts. This reef is concave to the south-southeast, trending east-west, and a wave-built rampart on the windward (east) end reaches an average height of 1.5 m above mean tide level and is about 50 m long. The rampart slopes on an angle of 44° on its seaward side and 23° toward the lagoon (Fig. 8). Boulder-sized coral rubble on the rampart is 80% A. palmata fragments; it ranges from 3.5 cm to huge boulders that reach lengths of up to 2.5 m. The source of A. palmata fragments starts at a depth of 1.5 m, 10 m from the boulder rampart shoreline. This reef surface extends around the cay to a depth of $\sim$20 m. In 1962 the reef was found to be nowhere wider than 20 m and nowhere longer than 300 m (19). After Hurricane Edith (September 1963) the effects on the coral reefs of La Parguera shelf were surveyed (20), and a large change in Cayo Turrumote was detected. Three years after Hurricane Betsy (September 1965) the cay was surveyed by Hernandez (unpublished report); length, width, and height of the ramparts and the entire cay had increased markedly to the dimensions cited above. Lateral and lagoonward migration of the ramparts had taken place between the surveys.

Ten A. palmata colonies were tested in situ for mechanical breakage of their stems and branches. Their stem diameters varied from 5 to 15 cm and ranged in height from 0.5 to 1.5 m. The thicker and stronger colonies were found close to shore, at 3 m depth. Test results showed that these colonies always broke at the stem where boring by organisms had taken place. The range of breakage was found to be from 23 to 35 kg force for a mean diameter of 13 cm. Two of the broken colonies were taken to the laboratory, where further tests were conducted. Both colonies broke again at the stem with a force of 40 kg, although the force was applied to one of the thicker branches. Degree of boring was found to be the controlling factor. When a healthy stem was tested, it resisted forces as high as 50 kg.

Outer parts of colony branches, in the

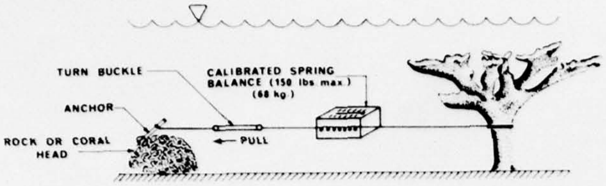


Figure 6. Illustration of method used in measurement of mechanical breaking forces in the in situ experiment.

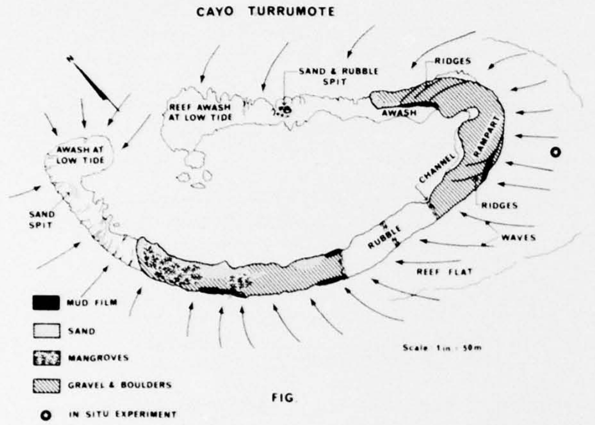


Figure 7. Location of in situ experiment and description of Cayo Turrumote.

small units tested at depths of 10 m, broke at pulls of 6 to 40 kg whenever the colony stem withstood the same range of force. Thicker (3 cm) branches of healthy coral colonies withstood forces greater than the industrial balance's scale (68 kg). Most of the broken parts in these tests had a mean length of 40 cm, varying in width from about 10 to 30 cm. The range in dimensions of A. palmata colonies is so varied that preliminary tests performed in this experiment should be greatly increased for statistical tests suitability.

Conclusions

Theoretical calculations indicate that the spectrum of forces generated by hurricane swells as a function of depth (12 m), object dimensions, and wave refraction are greater than mechanical forces necessary to break coral colonies tested in situ and in the laboratory. Forces were calculated on both cylindrical and oblate objects that had average characteristic dimensions similar to those of coral fragments comprising subaerial boulder ramparts at the field site, south coast of Grand Cayman Island. Magnitudes of forces for Hurricane I on these objects, oriented with the long axis perpendicular (Z) to the bottom, fell within the general range of forces necessary for breaking A. palmata stems as measured in the field. Forces generated by waves from the other three hurricanes were significantly smaller than field-measured breaking values. However, with the exception of forces generated by Hurricane IV, calculated values for cylindrical and oblate fragments in the Z orientation were comparable to the range of forces necessary to break colony branches as measured in field tests. Calculated forces are considered minimal values because of the selection of a drag coefficient. The rough-surfaced coral fragments would certainly have a higher drag coefficient than the smooth-surfaced objects used in the theoretical calculations.

Figure 8. Cayo Turrumote boulder rampart seen from the lagoon.

Using a porosity of 0.5 (21) and a specific gravity for aragonite (2.93 g/cm^3), the weight of the cylindrical object in seawater is approximately 9 kg and of the oblate fragment is ≈4.5 kg. Horizontal forces on these objects exerted by waves of Hurricane I at a depth of 12 m exceed the object weights and probably would result in shoreward transport. The coefficient of friction for this setting is unknown, but considering the forces involved it is reasonable to assume that shoreward displacement of particles would occur.

Laboratory as well as field experiments indicate that breaking strength of A. palmata colonies depends considerably on the degree of skeletal weakening caused by boring organisms.

Comparisons of wave forces generated during hurricanes with field measurements of A. palmata breaking forces indicate that coral colonies at a depth of 12 m could be the source for boulder ramparts along the adjacent shoreline. The average-sized particles in these coral rubble accumulations could be transported onshore by hurricane waves generated in this theoretical study.

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