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Coral Reefs

Wave-energy distribution and hurricane effects on Margarita Reef, southwestern Puerto Rico

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Abstract. Wave measurements at Margarita Reef in southwestern Puerto Rico show that wave height decreases as waves travel across the forereef and into the backreef. Wave spectra reveal the presence of two wave trains impinging on the reef during the study: trade-wind waves and locally generated seas. Significant wave height calculated from the spectra show an average reduction of 19.5% from 20- to 10-m isobaths and 26% from 20- to 5-m isobaths. The significant wave height decreases an average of 82% for waves traveling across the reefcrest and into the backreef. Wave-energy reduction is 35% from 20- to 10-m isobaths and 45% from 20- to 5-m isobaths. Energy loss across the reef crest is 97% which translates into the formation of strong across-the-reef currents capable of moving coarse sediment. Refraction diagrams of waves impinging on the reef from the SE provide a display of wave energy distribution around the reef. The transmission coefficients calculated for trade-wind waves and locally generated seas have means of 18% and 39%, respectively. A wave height model with negligible energy dissipation, produces wave height estimates that are, in general, within the ± 15% error bands. Results of wave-energy changes from this study were applied to waves representative of hurricane conditions at the reef. Aerial photographs of the reef before and after the passage of hurricanes were compared to assess the reef changes. Changes observed in the photographs are interpreted as products of sediment transport by hurricane-generated waves. The patterns of change agree with the refraction diagrams suggesting that waves were the main agents of change at Margarita Reef during severe storms.

Introduction

The role of waves as an energy source to the reef ecosystem and as a contributor to the stability and development of coral reefs is becoming more apparent as more reef studies are conducted. Waves provide energy for mass transport of water across reefs and through backreef lagoons, as well as for the resuspension and transport of sediments (Roberts 1980). Wave-driven circulation also moves food through the reef, removes metabolic wastes of reef-building organisms, and contributes to the mechanical cleaning of the coral polyps (Stoddart 1969a).

The first study of waves in coral reefs was conducted at Bikini Atoll by Munk and Sargent (1948). From wave height observations over the atoll they estimated a 95% wave-energy dissipation for waves breaking and traveling across the reef flat. More recent field studies (e.g., Roberts et al. 1977; Suhayda and Roberts 1977; Roberts 1980; Roberts and Suhayda 1983; Lee and Black 1978; Kono and Tsukuyama 1980) found values of 75% to 86% wave energy reduction. At low tide the energy dissipation increased, by as much as approximately 10%. Dissipation of wave energy was not uniform across the spectrum: higher frequency waves lost more energy than those with lower frequencies. Gerritsen (198 1) found similar results studying wave attenuation on Pacific reefs. Other factors that influence energy reduction were reef geometry, morphology, and length (Roberts 1980).

As waves impinging on reefs are modified, they induce changes in reef morphology and on the coral themselves. Individual coral colonies align with the direction of incoming waves, and the morphology of the reef adjusts to the prevailing wave conditions (Munk and Sargent 1948; Roberts 1974; Hernández-Ávila et al. 1977; Graus et al. 1977). These adjustments distribute and dissipate wave energy to levels that minimize mechanical damage. However, some of the adjustments may be a response to food and disposal of wastes. Wave refraction and energy dissipation produce wave height and energy gradients that facilitate the segregation of organisms into zones and habitat development in the reef. Wave-energy intensity is also important for maintaining the reef community as a whole (Dollar 1982; Bradbury and Young 1981). Reef zonation is correlated with wave energy attenuation and the reef community is associated with energy intensity (Bradbury and Young 1981). Geister (1977) identified six different reef

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zonation patterns in the Caribbean that depend on wave exposure. However, he recognized that substrate and light affect reef zonation. In a review article, Hubbard (1989), presented examples of correlations between reef zonation and wave energy.

Storms and hurricanes that pass over coral reefs can have catastrophic effects on the organisms and reefs. Blumenstock (1958) observed geomorphic changes that involved sediment deposition and erosion after a hurricane passage over Juliat Atoll. Examples of depositional forms included the formation of gravel ridges on the reef flat and outwash features in the lagoon. Scoured channels cut across the reef flat into the lagoon from the seaward side of the reef represent storm-related erosional features.

Glynn et al. (1964) described the destruction of dense thickets of ***Acropora palmata*** on exposed reefs off La Parguera, Puerto Rico. Studies of coral cay damage by hurricane-generated waves (Stoddart 1962, 1969b) have identified damage patterns common to coral reefs frequently exposed to violent storms. These studies indicate that reef-derived debris is transported from the seaward side of the reef towards the lagoon. Even under normal wave conditions, reef-produced sediment is transported primarily into the backreef lagoon (Suhayda and Roberts 1977; Davies 1977). On forereef areas with gentle slopes ($< 25°$) and water depths of 18-20 m, most coral colonies impacted by hurricane waves were broken and transported lagoonwards (Harmelin-Vivien and Laboute 1986). At greater depths (15-30 m) and steeper slopes, coral colonies broken by waves were transported down the slopes and often destroyed coral communities in deeper water (Harmelin-Vivien and Laboute 1986). The resultant sediment transport was offshore, but appears to be a gravity driven process rather than wave driven.

Knowledge of wave height variations and energy attenuation on coral reefs is important for understanding reef morphology, sedimentation patterns, and ecology. In this study we present wave measurements made during a field experiment at Margarita Reef in southwestern Puerto Rico, as well as results from refraction diagrams to assess the distribution of wave energy around Margarita Reef. The processes of wave attenuation and transmission are incorporated into a simple model to estimate wave height under negligible bottom friction dissipation. Finally, we explain changes observed in reef and reef-associated environments from aerial photographs of the reef after hurricane passage as produced by sediment transport.

Study area

The study was conducted at Margarita Reef, near the village of La Parguera, on the southwest coast of Puerto Rico (Fig. 1). The offshore area in this location has a relatively broad (8 to 10km wide) and shallow shelf: the shelf break occurs at a depth of 20 m. Two lines of corals reefs. oriented in an east-west direction, divide the shelf into three distinct areas, each with different wave energy regimes (Morelock et al. 1977; Almodóvar 1962).

The bathymetry of the area is inherited from karst erosion of the underlying Cretaceous limestone (Morelock et al. 1977). Ancestral shelf topography has been subsequently modified by reef growth and sediment deposition (Morelock et al. 1977). Margarita Reef (Fig. 2) sits in the mid-shelf region off La Parguera. It is oriented roughly

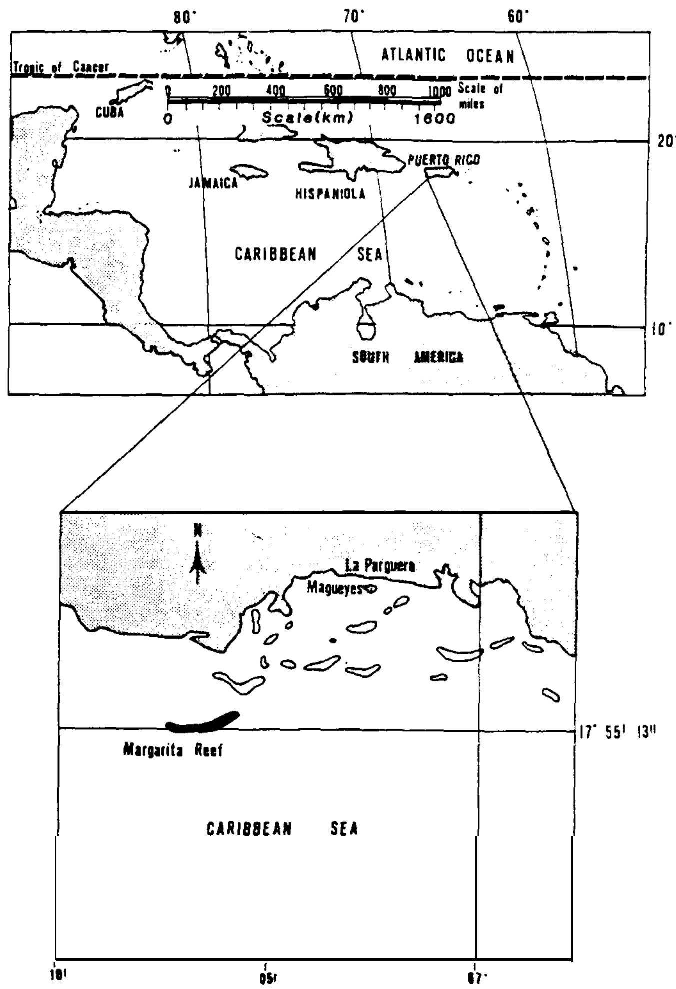

Fig. 1. Map of the Caribbean and insert showing Margarita Reef. the study site

east-west and has a length of nearly 3 km. Depth contours along the forereef are nearly parallel except in the east, where a diversion of the contours is evident (Fig. 2).

Composite forereef and backreef profiles across Margarita Reef are illustrated in Fig. 3. The forereef has a very gentle slope of approximately 1° and extends to a depth of 22m. Forereef coral zonation consists of *A. palmaia* in the shallower near-reef crest areas. a mixed zone dominated by *A. cervicornis*, massive corals in an intermediate zone, and hardgrounds covered by gorgonians and octocorals in the deepest parts of the forereef profile (below $\approx$ 14m). The reef crest is very shallow (water depth of 0.3 m or less) and is exposed at mean low tides. The lagoon has a shallow terrace with depths of approximately 4 m and a width of about 0.25 km and serves as a reservoir for sediments. The landward margin of the terrace ends in a steep slope that descends to a depth of 15 m.

The climate of the region is dry and warm with an annual mean temperature of 25 °C (Picó 1954). A rainy season. which is heavily influenced by hurricanes, extends from August through September. Prevailing winds are the easterly trade winds and the diurnal sea breeze from the southeast. Peaks in wind velocity occur during winter ($\approx 6\ m \cdot s^{-1}$) and summer ($\approx 7\ m \cdot s^{-1}$). The wind-speed range in this area is from 4 to 7 $m \cdot s^{-1}$ (Glynn 1973). Sea-surface temperature has an annual mean of 27 °C with maximum temperatures occurring in July and minimum temperature in January (Glynn 1973). Mean surface salinity varies from a high ($\approx$ 37ppt) in April or May to a low ($\approx$ 33 ppt) in October or November (Glynn 1973). The high salinities are due to high evaporation and low freshwater input. The

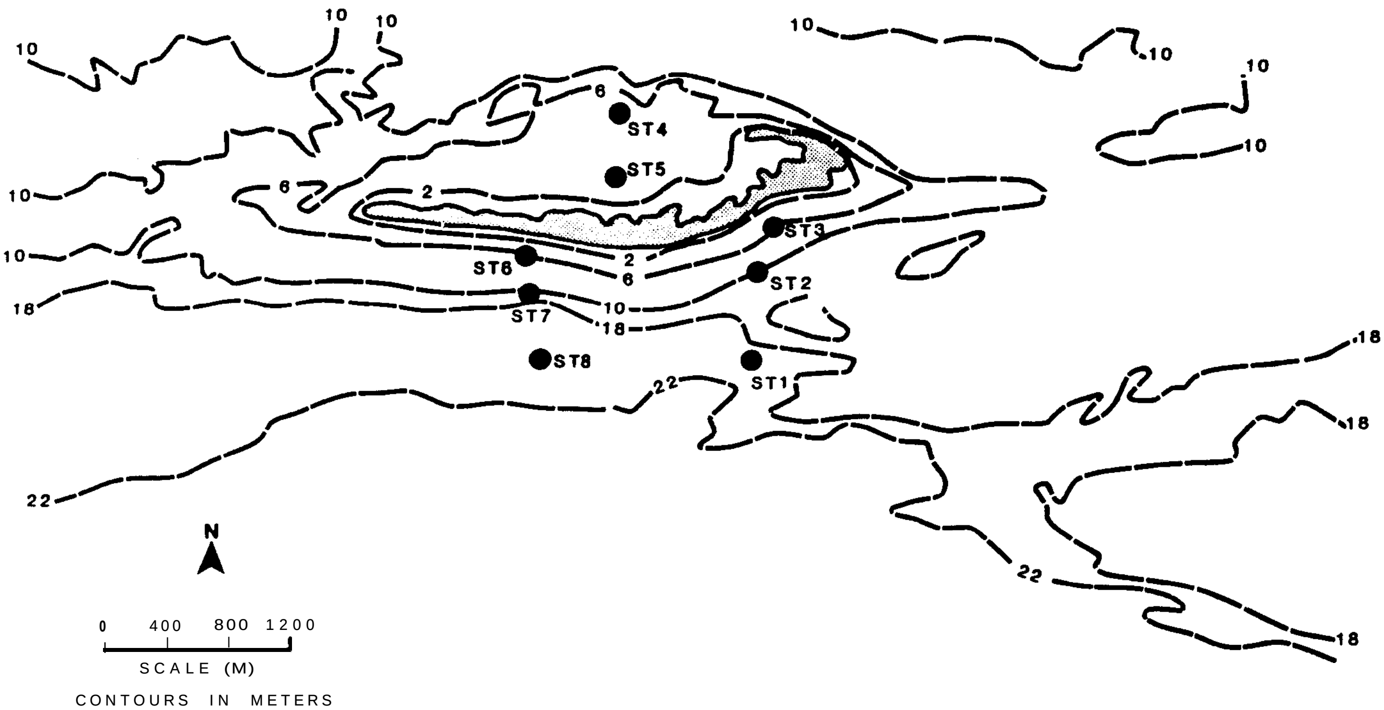

Fig. 2. Location and arrangement of stations for the experimental design around the study area, Margarita Reef

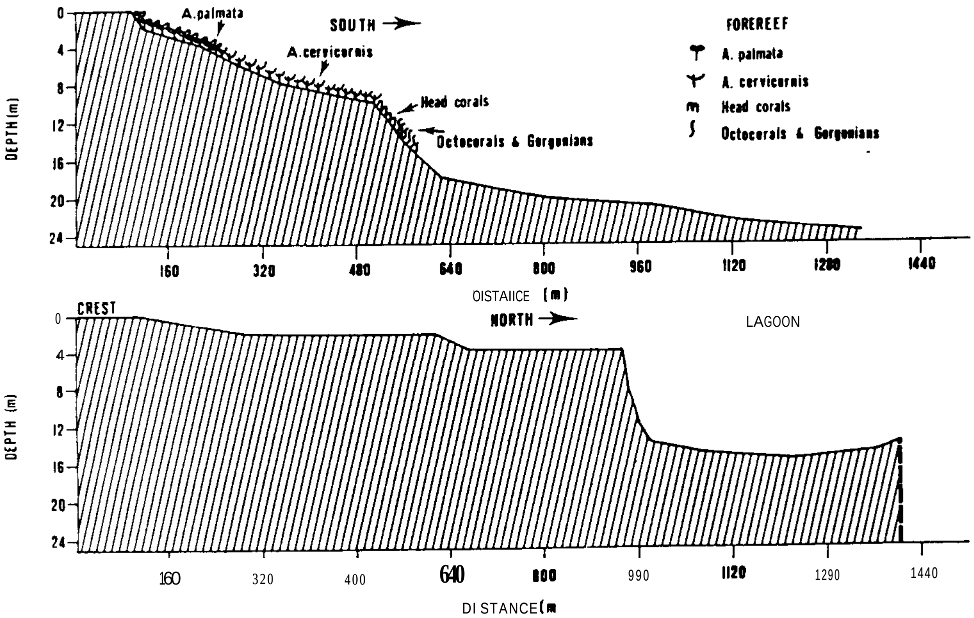

Fig. 3. Typical forereef (top) and backreef (bottom) area profiles with coral zonation according to Aponte (1977)

tidal regime is mainly diurnal with a small range (daily maximum 40 cm. yearly maximum 5.5 cm) (Glynn 1973; Kjerfve 1981).

Materials and methods

Field data collection

Wave and wind data for this study were collected during the period November 25-December 12, 1980. Measurements were taken for 15 minutes each from a small boat at eight stations around the reef (Fig. 2). If the sea state appeared to have changed, measurements at Station 1 were repeated at end of the day. A total of seven data-sets was collected during this period, consisting of a wave record at each station (Fig. 2) taken over a period of approximately six to eight hours.

Wave-height measurements were made with an absolute pressure transducer system (Model Mark II, Specialized Ocean Instruments of Louisiana, USA). The instrument electronically filters the hydrostatic pressure component and records the wave pressure fluctuations in analog format. Deployment modes of the sensor during the study are illustrated in Fig. 4. Sensor (Z,) and water-column depth (h) were

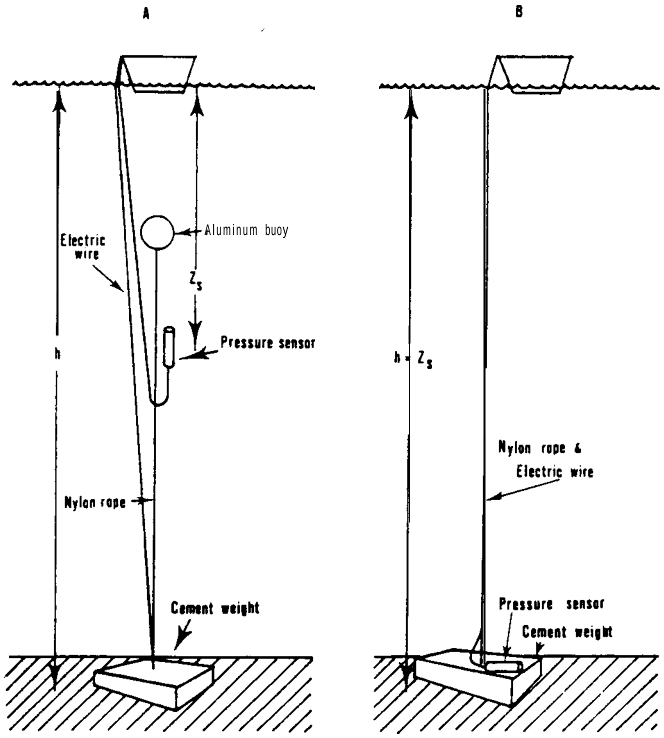

Fig. 4. Deployment modes of the pressure sensor during the study; (A) deployment for water depths (h) greater than 10 m, (B) deployment for water depths less or equal to 10 m. The sensor depth is denoted by Z_s

recorded for each station. The direction of wave approach was measured in deep water from a small boat.

Wind speed and direction were measured at Magueyes Island (Fig. l), with a cup anemometer (Model 026-1, Climet Instruments Inc.) at a height of 26m above the mean sea level. The wind speed and magnetic direction measurements were recorded in analog form. Wind direction was afterwards corrected for the magnetic deviation of the area.

Analysis of field data

Wave-pressure records were digitized using a Calma Graphic Digitizer Model CG11, and the results were stored on magnetic tape for computer processing. Wave-frequency spectra were calculated using a Fast Fourier Transform (FFT) algorithm (Cooley et al. 1969) and smoothed following the averaging procedure described by Otnes and Enochsen (1972, p. 302-306). The spectrum estimates were corrected for water-pressure filtering using the procedures of Kim and Simons (1974). To reduce variability and facilitate the identification of main peaks, all spectra for a given water depth were averaged. This procedure yielded mean frequency spectra at three depths in the forereef (20, 10, and 5 m) and at the two backreef stations. Significant wave height and period were calculated using standard techniques (US Army Corps of Engineers (USACE) 1984) from the energy spectrum. The transmission coefficients were calculated from the significant wave height estimates at the 5-m station and the backreef station closest to the reef crest, Station 5 in Fig. 2.

Wave refraction and height calculations

In order to calculate the energy distribution and height changes around the reef, wave shoaling, refraction, and bottom friction dissipation were considered. Shoaling effects were accounted for with the coefficient (K,) calculated from linear wave theory (Kinsman 1965; USACE 1984). Refraction diagrams were constructed according to procedures in Arthur et al. (1952). Bathymetry necessary for constructing wave refraction diagrams was obtained from Morelock (unpublished). Wave periods and direction used in construction of refraction diagrams were derived from wave data and hindcast analysis for Hurricane David. The wave hindcast under hurricane conditions followed the methodology described in the Shore Protection Manual (USACE 1984).

From the diagrams, the refraction coefficient (K,) was computed for each station. Wave-height changes were calculated according to Grosskopf (1980), which combines the effects of refraction, shoaling, and bottom friction. Bottom roughness values necessary to determine C_f were estimated according to Stenberg (1968).

Pre-hurricane and post-hurricane aerial photographs of Margarita Reef were secured for analyzing the effects of hurricane-generated waves. The two photos were compared. Changes in tonal patterns and shapes were assumed to be related to changes in benthic communities and exposed sediments. Observed changes identified in the photos were interpreted considering wave refraction and wave height variations.

Results

The mean wave-frequency spectra at depths of 5, 10, and 20m are presented in Fig. 5. At the 20-m station the spectrum has a single peak centered around 0.18 Hz (T = 5.6 s). At the 10-m station the peak centered at 0.18 Hz

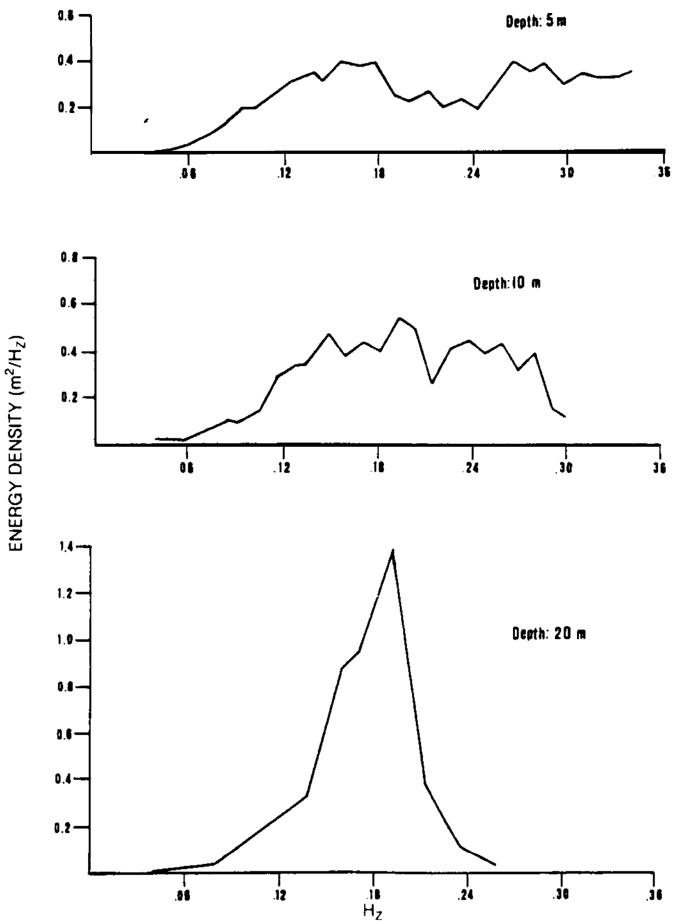

Fig. 5. Mean wave spectra across the forereef

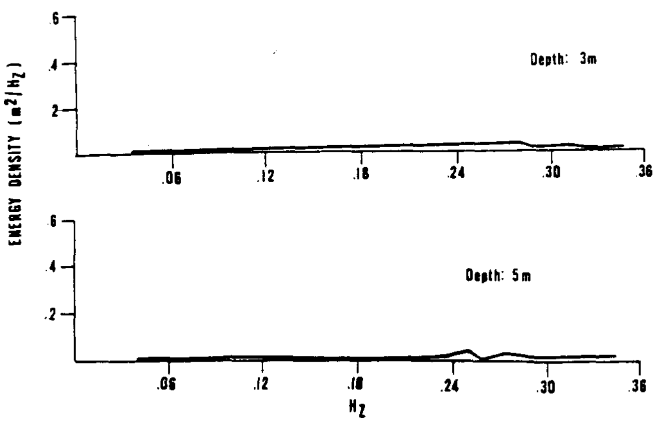

Fig. 6. Mean wave spectra across the backreef

decreased in amplitude and some energy is transferred to lower frequencies. A second broad peak centered around 0.24 Hz (T = 4.2 s) is evident. This peak was not seen at the 20-m station because the sensor was too deep to detect the pressure fluctuations of a 4-s wave. At the 5-m station the peak at 0.18 Hz is still visible but with a reduced amplitude and some energy shifted to lower frequencies. The energy associated with the 0.24 Hz peak has decreased and shifted to higher frequencies and a drop in energy occurs between 0.18 and 0.24Hz. The two peaks present in these spectra are related to two wave trains of different origins. The predominant peak represents trade-wind waves with a period of 5 to 6s and a significant wave height between 0.62 and 1.47 m. These wave characteristics are similar to those observed for trade-wind waves measured at Grand Cayman Island (Roberts et al. 1975). The second peak, with a period of approximately 4s, represents waves produced by the local winds and has a significant wave height ranging between 0.27 and 0.74-m.

The combined effects of redistribution and dissipation of wave energy produced a reduction of peak amplitude (Fig. 5) toward the shallower stations. The trade-wind wave heights were reduced an average of 19.5% from the 20- to 10-m contour, and 26% from the 20- to 5-m contour. Wave energy changes based on wave heights estimates decrease 35% (20 to 10m) and 45% (20 to 5m). The decrease in wave energy across the forereef was somewhat smaller than that reported in studies by Roberts et al. (1975, 1977) and Gerritsen (1981).

Mean wave spectra for the backreef stations have no predominant peaks and are flat (Fig. 6). The lack of predominant peaks in these spectra is attributed to waves breaking at the reef crest. Average wave height reduction is 82% for the trade-wind waves and 61% for the local waves. These changes in wave height represent an energy dissipation of 97% and 85% respectively. As illustrated here and in other studies (e.g., Roberts and Suhayda 1983), wave breaking is the dominant process of energy dissipation.

The lack of predominant peaks in the backreef wave spectra also suggests that no incident waves pass over the

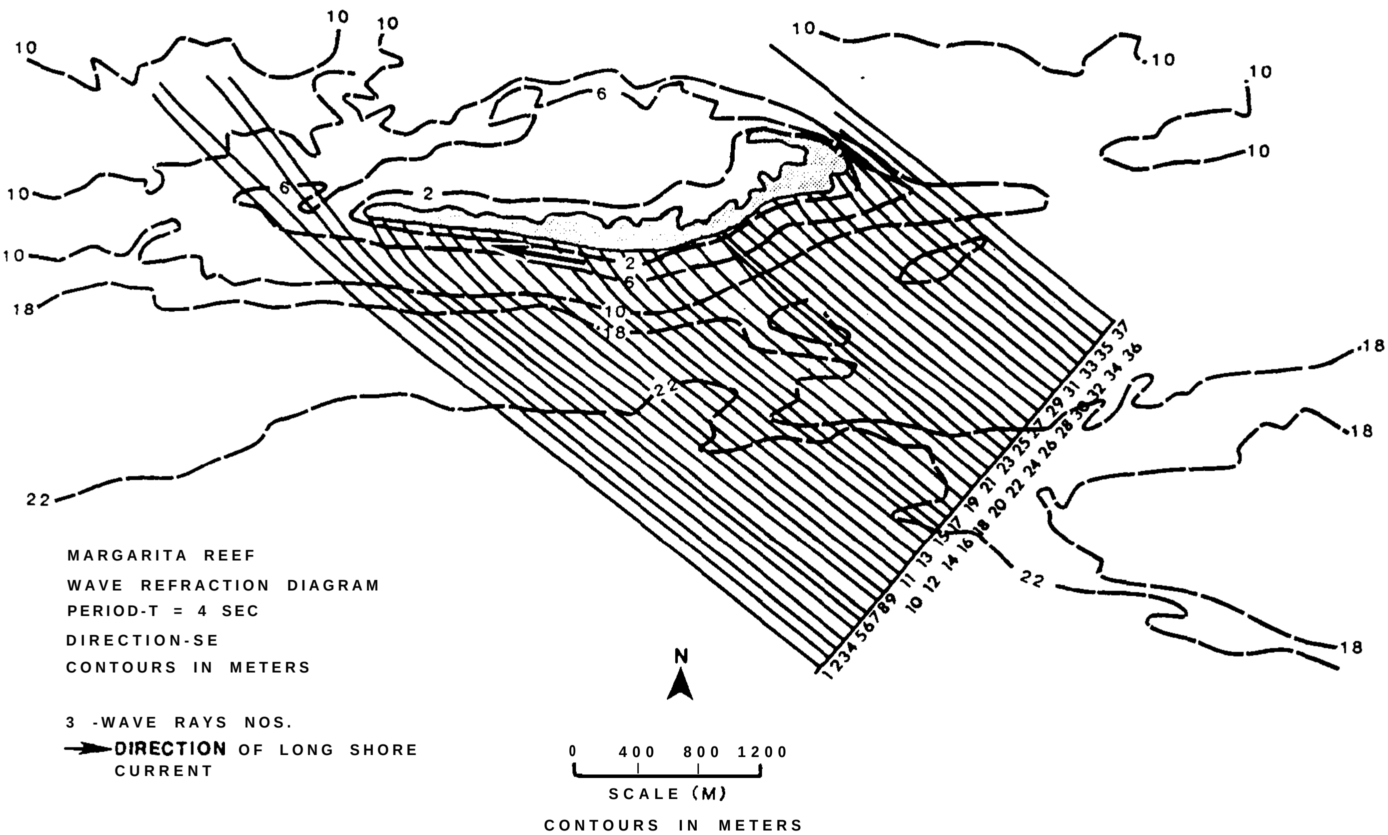

Fig. 7. Wave refraction diagram around the study area for 4s period waves impinging from the southeast. The stipple area represents the reef crest

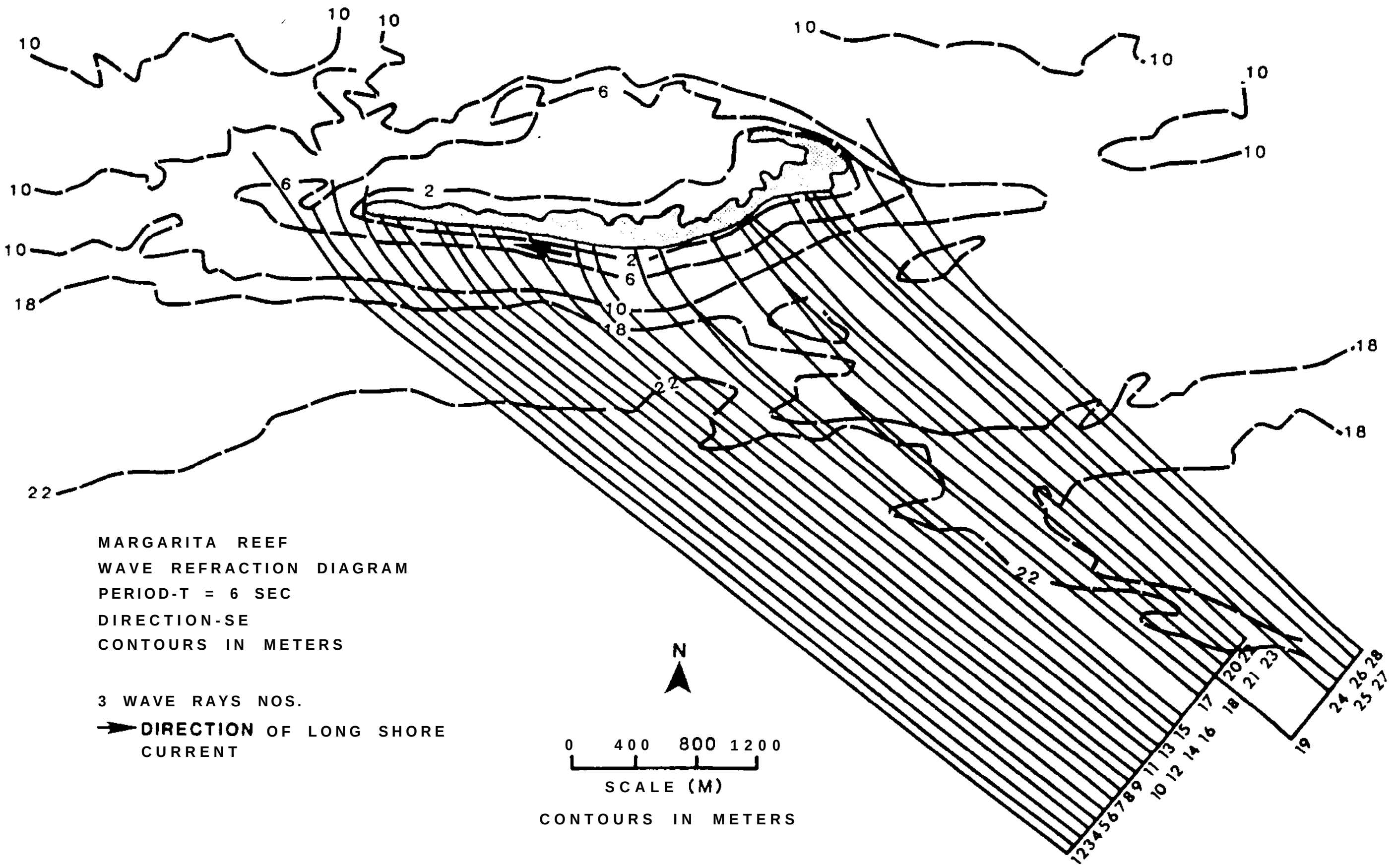

Fig. 8. Wave refraction diagram around the study area for 6s period waves impinging from the southeast. The stipple area represents the reef crest

reef crest. These results corroborate previous observations of flattened lagoon spectra (Suhayda and Roberts 1977). However, they contradict the observation that the peak frequency can still be detected at the backreef lagoon and that significant amounts of energy remain in the low frequencies (Roberts and Suhayda 1983). These differences in results may be related to differences in general reef morphology between measurements sites.

Wave refraction

Refraction diagrams (Figs. 7, 8, and 9) were constructed from the dominant wave periods measured during the study. The angle of wave incidence was limited to the southeast because this was the direction observed during the study. This angle of approach was consistent with dominant local winds, which blow from the southeast; the wave spectrum should be at a maximum along this direction. Despite the fact that hurricane-generated swell arrives from different directions as the hurricane moves, historic storm tracks indicated that the southeast was the most frequent direction of storm approach for this area. Thus, only the southeast direction was used for construction of refraction diagrams that model hurricane waves.

The response of typical trade-wind and local waves of 4 and 6 s (Figs. 7 and 8) is very similar. Using wave orthogonals as indicators, these refraction diagrams show that a wave shadow occurs behind the reef crest. The shadow results because of wave breaking at the reef crest. Limited wave energy propagates to the backreef because of shallow water at the reef crest. Near the end of the reef refraction and diffraction allow some energy to leak to the backreef. However, the main wave front tends to propagate in a SE direction as the water deepens behind the reef. This pattern is observable in Fig. 7. Orthogonals near the reef ends in Fig. 8 behave similarly since wave refraction depends on the bathymetry which is a constant. Under both wave conditions the oblique ray incidence at the crest suggests a longshore current flowing to the west.

Refraction modeling of 8-s waves (Fig. 9), generated by the storms, shows a similar behavior at the western and eastern ends of the reef. Even though the wave orthogonals do not bend much near the ends of the reef, given the effect of refraction, they should behave more like they did in Figs. 7 and 8. This bending is predicted because refraction depends on bathymetry and direction of incidence which have not changed. A caustic (orthogonal crossing) formation at the forereef section makes this diagram more difficult to interpret. Shoal effects in the eastern forereef are evident in all cases (Figs. 7, 8, and 9). This eastern shoal creates alternating zones of high and low energy along the reef. Refraction coefficients, calculated from the diagrams, and the shoaling coefftcients demonstrate that both processes

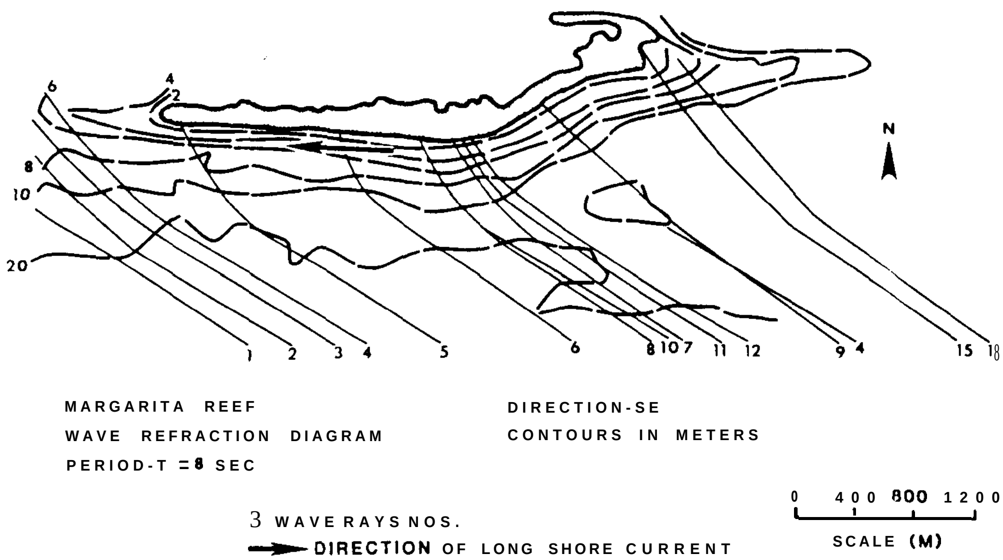

Fig. 9. Wave refraction diagram around the study area for 8 s period waves impinging from the southeast. The apparent discrepancy of the orthogonals input between this and the other refraction diagrams is because deep water in this case begins farther offshore and goes outside the figure limits. The stipple area represents the reef crest

tend to reduce the wave height because they spread the energy over a larger area.

Transmission coefficients

Transmission coefficients are ratios of incident wave height to transmitted wave height. They are dimensionless and quantify the wave energy that crosses the reef crest. Transmission coefficients are used to assess the reef's efficiency as a filter of wave energy and provide a quick partition of the incident wave energy.

Trade-wind waves in this study had an average transmission coefficient of 0.18 $\pm$ 0.06 while the local waves had a mean transmission coefficient of 0.39 $\pm$ 0.16. These values suggested that shorter waves can transmit more energy than longer waves, possibly by overtopping and run-up (Ahrens 1987). Our results are contrary to field observations of Roberts and Suhayda (1983) and Roberts (1980), who found that higher frequencies were selectively filtered out at the crest and that longer waves were less attenuated.

The contradiction between this study and other regarding the fact that lower frequencies are less attenuated than higher ones can be explained in terms of wave overtopping, water depth at the crest, and wave period. The wave energy at the structure is:

$$H_i^2 = H_t^2 + H_r^2 + H_d^2 \quad (1)$$

where H_i is the incident wave height, H, and H_r are the transmitted and reflected wave heights, repectively, and H_d^2 is the dissipated wave energy (Silvester 1974). Dividing Eq. (1) by H_i^2 yields

$$1 = K_t^2 + K_r^2 + K_d^2 \quad (2)$$

where K, and K_r are the transmission and reflection coefficient, respectively, and K_d is related to energy dissipation. Wave transmission occurs both through the reef K_{tT} and over the crest, K_{to} (USACE 1984). If it is assumed that reefs are impermeable at surface wave time scales, then transmission through the reef can be neglected ($K_{tT} \approx 0$) and wave-energy transmission will occur completely across the reef crest by overtopping ($K_t = K_{to}$). Wave reflection at Margarita Reef can be evaluated according to the methodology described in the Shore Protection Manual (USACE 1984), which is based on the surf similarity parameter (6). The calculated values of the surf similarity parameter varies from 0.017 to 0.101, based on the wave heights observed at stations closest to the reef crest. With these values of δ, K_r is less than 0.01 and the square is even less (using Fig. 2.65 of the Shore Protection Manual, USACE 1984); thus, wave reflection can be neglected. The fact that K_r is small should not be surprising, considering the gentle forereef slope. Equation (2) can therefore, be rewritten as:

$$1 = K_{to}^2 + K_d^2 \quad (3)$$

This equation demonstrates that wave energy available for transmission across the reef crest from overtopping is the residual of the incident wave energy minus the energy dissipated durrng wave breaking. Shorter waves (higher frequencies) tend to break in waters shallower than longer waves. The shallowest part of a reef is the crest; therefore, shorter waves will break closest to the reef crest. Shorter broken waves travel a smaller distance to the reef crest then longer waves. Because the bore stage dissipates large amounts of energy, shorter waves retain more energy than longer waves. This remaining energy is available for transmission to the backreef.

This simple model based on wave overtopping explains our observation that shorter waves transmit more energy than longer ones. However, this model applies only if the depth at the reef crest is close to zero. This explanation agrees with observations that wave run-up decreases as the wave period increases for certain subaerial breakwaters, all other factors remaining constant (USACE 1984).

In systems where water depth at the crest is on the order of 1 m or deeper (submerged breakwaters), transmission will occur by waves traveling across the reef crest. Submerged breakwaters tend to filter large waves more effectively than small ones (USACE 1984). Ahrens (1987) found that wave transmission in submerged breakwaters is a function of the water depth at the crest, and the greater this depth, the greater the transmission of energy. He found three modes of wave transmission: (1) waves crossing over the reef crest, (2) overtopping and run-up transmission, and (3) transmission through the reef.

At Margarita Reef, water depth at the reef crest is 0.3 m or less. In effect, this reef is acting as a subaerial breakwater. In this case, transmission of wave energy is accomplished mainly by overtopping during wave breaking.

Wave height estimations

The equation used to calculate wave height changes is

$$H_{s2} = H_{s1} K_s K_r \left(\frac{C_f H_{s1} \phi}{mT^2} + 1 \right)^{-1} \quad (4)$$

where H_{s1} and H_{s2} are the significant wave heights at consecutive stations. The factors K_s, K_r, and C_f are the shoaling, refraction, and friction coefficients, respectively. The parameter m is the slope of the forereef, T the significant wave period, and ϕ is a function presented graphically in Grosskopf (1980).

Defining X as:

$$X = \frac{C_f H_{s1} \phi}{mT^2} \quad (5)$$

Equation (4) can be rewritten as:

$$H_{s2} = H_{s1} K_s K_r (1 + X)^{-1} \quad (6)$$

Based on typical values of the variables in the definition of X ($C_f \approx 10^{-1}$–10^{-2}, $H_{s1} \approx 1$, $\phi = 10^{-1}$, $m \approx 10^{-2}$, and $T \approx 6$), X is on the order of 10^{-2} to 10^{-3}. This small value of X and application of the binomial theorem helps to approximate Eq. (6) as:

$$H_{s2} = H_{s1} K_s K_r \quad (7)$$

This equation shows that bottom friction is negligible in this reef environment. However, if $C_f \approx 1$, the approximation is not valid and the full equation has to be used. Gerritsen (1981) and Roberts et al. (1975) have found that C_f can attain such values on coral reefs. The friction coefficient depends on the roughness of the substrate, which in turns depends on the coral heads present in the reef. In this reef, the destruction of coral heads by hurricane waves reduced the roughness and therefore, produced smaller values of C_f. The same equation could have been obtained by assuming that sea water is a frictionless fluid.

Comparison of observed and predicted wave heights based on Eq. 7 are in reasonable agreement (Fig. 10). The $\pm$ 10 and $\pm$ 15 error bands in Fig. 10 representing the uncertainties in the refraction coefficients and lack of consideration of bottom friction both appear to be small. Sixty-seven percent of the predictions are within the $\pm$ 15% error band, supporting the argument that bottom friction is small over this reef.

An integrated representation of the results is presented in Fig. 11. On the basis of wave height three areas may be

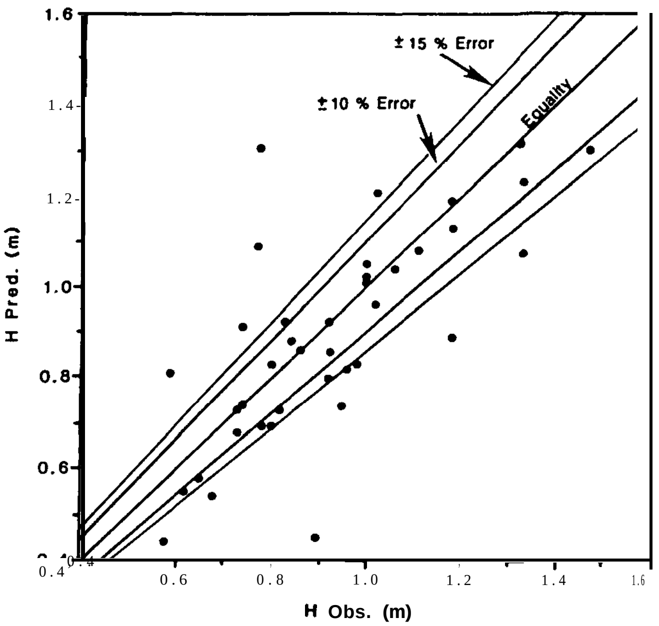

Fig. 10. Comparison of observed wave heights with predicted wave heights from Eq. 7

defined: a far field region that serves as a source of wave energy (H), a shoaling region of intermediate wave height and energy (IH), and the attenuated zones of low wave energy (L). The far field region is located in deep water seaward of the forereef, where waves do not "feel" the bottom. The shoaling region is located in the forereef, and extends slightly lagoonwards of the breaking point. In this region, rapid wave-height transformations occur due to shoaling, refraction, and wave breaking. The low-energy region located in the backreef is caused by the sheltering effect of the reef crest, where wave breaking occurs. The western reef is a low energy area, except very close to the reef, where orthogonals bend towards the reef lagoon. Arrows in Fig. 11 indicate energy flux around the reef. The small arrows in this diagram positioned over the reef crest indicate that water is being forced across the reef by breaking waves.

Reef zonation

Waves are recognized as a major factor controlling reef zonation (Geister 1977; Bradbury and Young 1981; Dollar 1982). It is therefore important to understand and physically model wave height changes across coral reefs. The segregation of organisms into zones also depends on evolutionary adaptations of corals to wave energy levels (Bak 1977; Graus et al. 1977). Graus et al. (1984) used wave effects on coral growth and zonation to develop a computer model to study reef zonation. The model (COREEF) calculates wave height attenuation and particle velocities which are then used to segregate corals into different zones across a given transect normal to the reef. Results of the Margarita Reef study have direct bearing on the Graus et al. (1984) model. They could be used as input to improve COREEF by taking into account wave refraction which can distri-

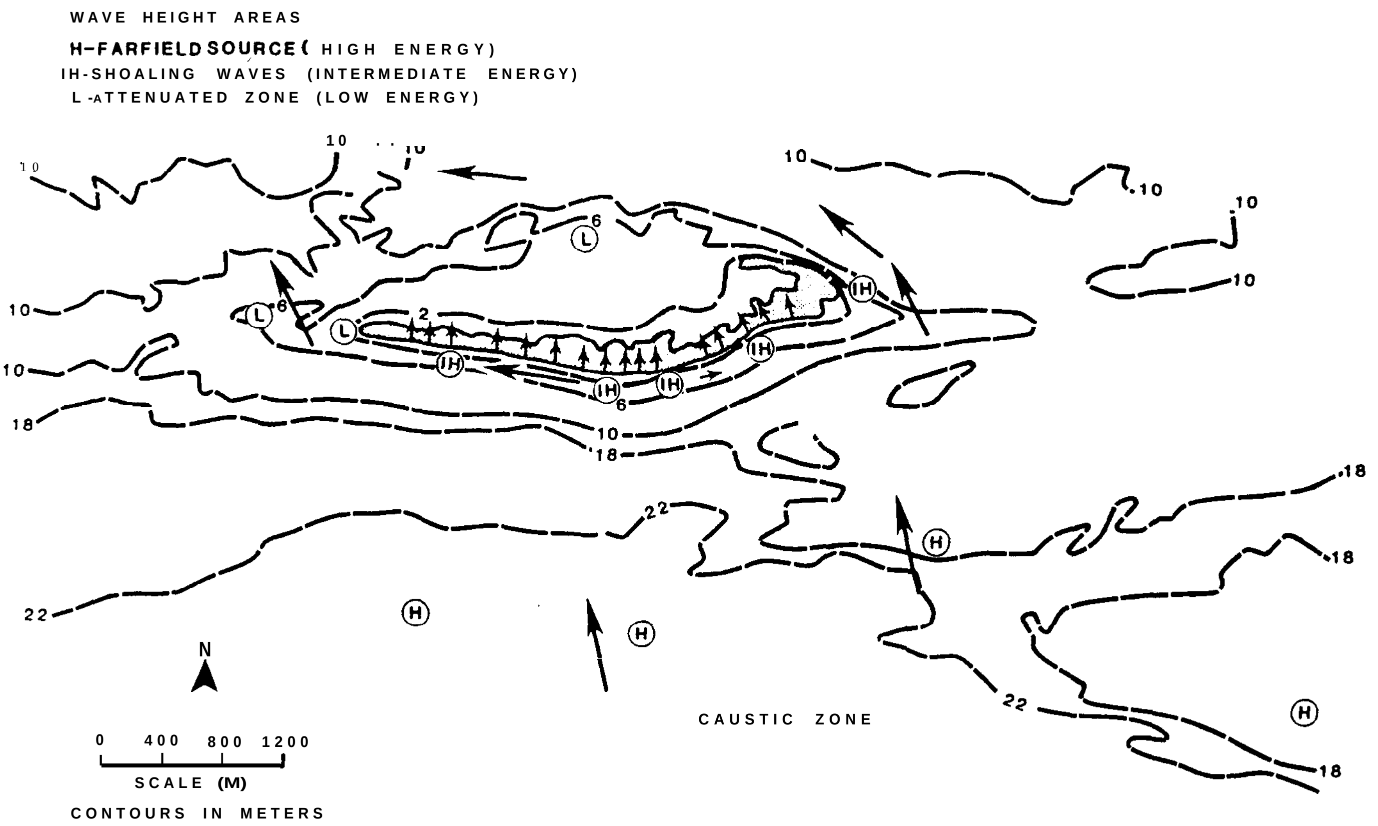

Fig. 11. Diagram illustrating the inferred wave energy distribution around Margarita Reef. The stipple area represents the reef crest

bute energy to areas that otherwise would receive little or no wave energy. Also, areas in the forereef may receive wave energy that could be substantially different from that estimated computing wave height changes due to bottom friction across the reef. Furthermore, analysis and interpretation of wave height reduction across the reef based only on bottom friction would yield higher bottom friction coefficients. Higher bottom friction coefficients will underpredict wave heights and quantities depending on wave height when the refraction patterns change. Our results also provide an empirical data base to calculate wave transmission across the reef crest instead of reliance upon the use of equations for breakwaters.

Sediment distribution patterns

Waves from Hurricane David (1979) impacted the southern coast of Puerto Rico from a southeasterly direction. Hindcast techniques used in this study indicated that although larger, the significant waves at Margarita Reef from this storm were of a 6-s period. Wave refraction patterns discussed previously show that this would have produced a concentration of energy on the eastern end of the reef. Both the seaward and landward parts of the eastern end of this reef system were impacted by refracted waves from a southeasterly direction (Figs. 7 and 8). Pre-hurricane (1977) and post-hurricane (1983) photographs of Margarita Reef corroborate the conclusion that storm wave energy concentrated on the reef's eastern end and by wave-overwash modified the backreef sediment plain by sediment transport and deposition. Changes in areas of exposed sand versus areas dominated by ***Thalassia-Syringodium*** beds are interpreted as storm-related.

Comparing the 1977 and 1983 photos reveals that the geometry of the reef remained unchanged after Hurricane David in 1979. However, the reef crest was strongly damaged. Swells generated by Hurricane David in 1979 destroyed nearly all colonies of ***A. palmata*** on the crest and in the forereef, leaving a carpet of rubble in these zones (L. Almodóvar 1982 personal communication). Dark-tone areas identified as ***Thalassia*** and ***Syringodium*** beds (Goenaga-Porte1 1993 personal communication) in the eastern backreef decreased in area and others disappeared completely. ***Thalassia-Syringodium*** beds (henceforth ***Thalassia*** beds) in the central and western section of the backreef increased in size. The 1983 photo indicates more exposed sand area in the eastern reef system. We suggest that this change was a product of erosion and sediment transport forced by wave overwash concentrated on the eastern end of the reef. Our data base does not indicate whether changes in the area of ***Thalassia*** beds were related to sediment removal, burial, or both. However, the fact that ***Thalassia*** beds increased in size between the 1977 and 1983 photographs (Fig. 12) in the central and western backreef areas may imply deposition as opposed to erosion. Recolonization of eroded areas is expected to be a slower process than repopulation and continued growth of ***Thalassia*** beds that are partially buried by rapid influx of sediment. That is, wave energy concentrated from both

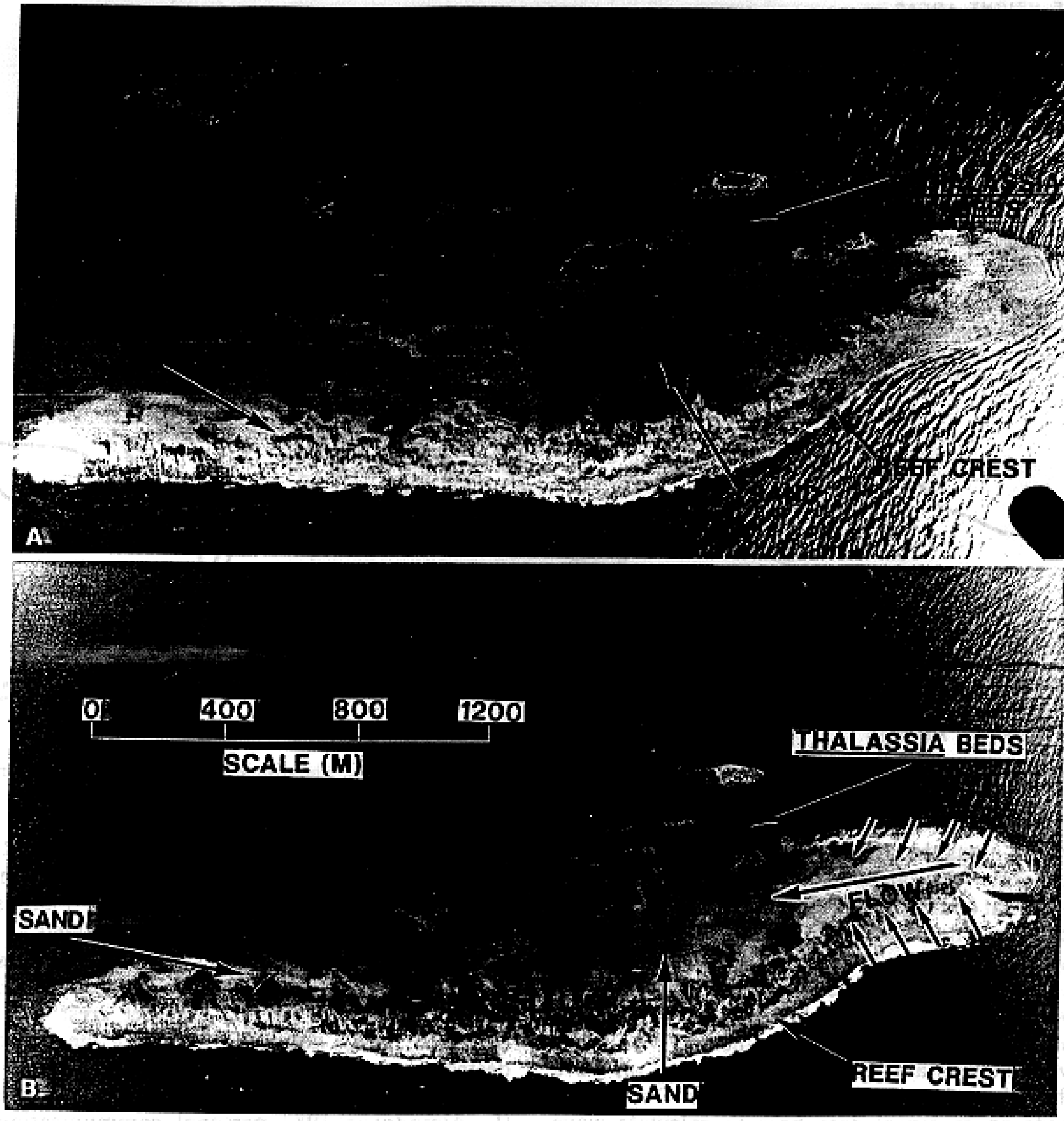

Fig. 12. Aerial photographs of Margarita Reef (A) before Hurricane David (1977) and (B) after Hurricane David (1983). Note waves impinging the seaward and landward sides of the reef system on the eastern end by wave refraction. The arrows inside the eastern backreef area indicate wave induced water and sediment movement as inferred from the refraction patterns

seaward and landward sides at the eastern end of the reef would tend to create a strong overwash current directed roughly reef-parallel, undoubtedly creating a zone of erosion (Fig. 12B). These observations are consistent with wave refraction results generated from this study. Additional support for significant lagoonward sediment movement is provided by Goenaga-Portel (1982) who reported that a boulder rampart of loose coral colonies formed lagoonwards of the reef crest during Hurricane David at another reef off La Parguera. Wave induced currents are responsible for this sediment transport. Roberts and Suhayda (1983) measured currents of 90 to 180 cm s^{-1} directed lagoonwards during normal trade-wind wave conditions. Breaking hurricane waves induce stronger lagoonward-directed currents that impact larger areas of the reef. Once in the immediate backreef area, wave-induced overwash currents undergo rapid energy reduction and sediments eroded from the reef crest are deposited. As interpreted from the wave refraction data generated from this study, it is likely that the eastern end of Margarita Reef experienced mostly erosion while deposition occurred in the central and western backreef areas.

Summary

This investigation provides a physical process data base to help explain the modifying effects of reef topography on storm waves and resulting probable sediment transport routes and sinks. By means of a simple model, it is shown that the water depth at the reef crest is a significant parameter controlling the wave transmission characteristics

of the reef. If the crest is at or above the water level. the reef becomes a high-pass filter controlled by wave overtopping. This is contrary to many Caribbean reef systems (Roberts and Suhayda 1983), where the crest water depth is typically 1 m or greater, allowing the reef to function as a low-pass filter controlled by wave dissipating mechanisms. The main findings of this study are the following:

1. Two wave trains were monitored during the study on Margarita Reef: the trade-wind waves (period 5-6s, heights 0.62-1.47m) and the local wind-generated seas (period approximately 4 s, heights 0.62-0.74 m). Trade-wind wave heights decreased across the forereef, and measurements showed a 25% reduction between the 20 m and 5 m isobaths. This wave height reduction represents a 45% energy reduction. A simple model based on wave refraction and shoaling explains most of the wave height changes observed in the forereef. Wave breaking at the reef crest dissipates the most energy (85-97%).

2. The transmission coefficient of waves at the reef crest shows a dependency on wave period (0.18 for trade-wind waves and 0.39 for local waves). Wave transmission at the reef crest occurs mainly by overtopping and run-up during wave breaking. Water depth at the reef crest is a critical parameter in the process of wave transmission. Refraction and diffraction of waves in the eastern end of the reef are resposible for leakage of wave energy into the backreef.

3. The observed wave height reduction across the reef creates wave energy gradients that are favorable to corals adapted to wave-induced water movements. These adaptations produce reef zonation. Wave refraction can distribute wave-induced water movement to areas that may otherwise receive little or no wave energy.

4. Comparison of pre-hurricane (2 years) and post-hurricane (4 years) aerial photos shows changes in the exposed sediment and *Thalassia-Syringodium* beds in the eastern backreef where energy is concentrated by wave refraction and extensive erosion is expected. The post-hurricane photo indicates elimination of *Thalassia-Syringodium* beds in the eastern backreef where energy is concentrated by wave refraction. A corresponding increase in the size of *Thalassia-Syringodium* beds is indicated in the central and western sectors. This pattern is interpreted to represent sediment accumulation in this area. It is assumed that in the four years between the hurricane and post-storm photo that recolonization and growth was a more efficient process in the central and western sectors where deposition rather than intensive erosion is expected. Changes in the areas of exposed sediment and *Thalassia-Syringodium* beds in the post-hurricane photo are consistent with energy distributions and interpreted sediment transport processes estimated from this study of wave refraction.

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