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The Impact of Typhoon Pamela (1976) on Guam's Coral Reefs and Beaches[1]

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ABSTRACT: Located on a main typhoon corridor, Guam receives approximately one tropical cyclone per year. Typhoon Pamela, Guam's third most intense typhoon of this century, generated 8-meter waves, but these had little direct effect on Guam's coral reefs, even on the exposed northern and eastern sides of the island. Damage to the reefs was isolated and in the form of breakage due to extraneous material being worked over the reef by the surf and surge. These findings are contrasted with reports of typhoon-induced, large-scale reef destruction, mostly from areas off the major storm tracks. Guam's reef formations have developed in a way that enables them to withstand intense wave assault.

Pamela caused significant modification of Guam's northern and eastern beaches, however. Most vegetation was removed to an elevation of 3 to 4 meters above mean lower low water, and the beach profiles were reduced from pretyphoon 8°–5° slopes to 3°–5° slopes through the transport of sand seaward. The first stage of recovery is the retreat and steepening of the lower beach. Longshore transport of sand during the typhoon yielded net erosion or deposition of up to 25 m^3 per meter of beach face. The maximum height of the wave surges along the coast was linearly related to the width of reef flat and beach traversed. A 1-meter drop in maximum surge height per 115 meters of distance traversed with an initial potential head of 9 meters is indicated.

TYPHOON PAMELA PASSED DIRECTLY OVER the island of Guam (13° N, 144° E) on 21 and 22 May 1976, devastating the trees, crops, and buildings with estimated maximum sustained winds of 220 to 270 km/hr. The island experienced 18 hr of typhoon-force winds in excess of 115 km/hr and 6 hr in excess of 185 km/hr (100 knots). Pamela moved over Guam in a northwest direction at 13 km/hr. During the first half of the storm, due to its cyclonic circulation, the winds came from the northeast (wind direction 050–070), the usual direction from which storm winds are received (according to Fleet Weather Central/Joint Typhoon Warning Center).

Guam is located within a major typhoon corridor of the Caroline–Mariana–Philippine region. Over the period of the last 30 years, Guam has received an average of approximately one cyclone per year, 13 of which have generated typhoon-force winds. Typhoon Pamela was rated as the third most intense typhoon to strike Guam this century; Karen (1962) is rated of equivalent destruction, and the most intense typhoon was in 1900.

Catastrophic typhoons have been described as a major geomorphologic agent for tropical islands and reefs. The associated high waves can sweep accumulated reef debris and coral blocks from the outer reef slope and deposit it on the reef flat as rubble bars (Maragos, Baines, and Beveridge 1973) and beach ramparts and ridges (Blumenstock 1961, McKee 1961). The storm deposition of rubble is an important island-building process on atolls, as shown by the accumulation of successive

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platform horizons (Shepard et al. 1967). The damage to reefs can be long-lasting (Stoddart 1963, 1974) and the structures of reefs facing in the direction of storms differ markedly from the normal windward or leeward reefs (Emery, Tracey, and Ladd 1954). Interestingly, however, most of these reports are from areas—unlike Guam—that are only infrequently visited by typhoons [i.e., a frequency of one typhoon or less per 50 years; see Blumenstock (1961), Maragos, Baines, and Beveridge (1973)].

Our survey of Guam's reefs and beaches was conducted from 30 June to 6 July 1976, or about 6 weeks after Typhoon Pamela's passage over the island. Part 1 reports on the impact of the typhoon on Guam's coral reefs in relation to the more general question of the role of typhoons in coral reef ecology. Part 2 reports the results of a shore modification study, which investigated three major processes: alteration of beach profile, longshore transport of sand, and height of wave surges on the beaches.

Part 1. The Impact of Typhoon Pamela on Guam's Coral Reefs

The effects of typhoons (and hurricanes, the Atlantic equivalent) on coral reefs have been reported only irregularly in the scientific literature. Most typhoon impact surveys found in the literature describe spectacular instances of reef damage (Blumenstock 1961, Glynn, Almodovan, and Gonzalez 1965, Hedley 1925, Maragos, Baines, and Beveridge 1973, Stephenson, Endean, and Bennett 1958, Stoddart 1963). Some of these studies are of reefs infrequently struck by typhoons (Blumenstock 1961, Maragos, Baines, and Beveridge 1973), and some are of leeward reefs normally protected from wave stress (Stephenson, Endean, and Bennett 1958). Further studies implicate factors other than direct wave and surge stress as the prime cause of the reef damage—such as lowered salinity following heavy rainfall (Goreau 1964, Hedley 1925) or massive siltation (Cooper 1966).

Newman (1974) observed that there generally appears to be an inverse relationship between the frequency of tropical storms and deposition of terrestrial coral rubble. Newman hypothesized that reefs struck infrequently by tropical storms develop extensive formations that are unable to withstand the rigors of storm-induced surf and surge. The opposite appears to be true of reefs visited frequently by tropical storms. Hence, paradoxically, there are few reef blocks on reef flats regularly visited by major storms, and a great many of them on reef flats well off the main storm tracks. We report substantial evidence in relation to this hypothesis.

Our beach survey provides an estimate of 8-meter surf heights along the windward sides of the island during Typhoon Pamela. The surf is estimated to approach 5 to 6 meters during most tropical storms on Guam (W. Donat, Anderson Air Force Base, personal communication). (Although the wind direction reversed following the passage of the eye of the storm over Guam, surf conditions in the western leeward side of the island do not appear to have developed significantly.) The considerable beach erosion and deposition along the northern and eastern sides of the island further attest to the magnitude of the surf during the typhoon. It would therefore not be unreasonable to anticipate considerable storm damage to Guam's reefs as a result of Typhoon Pamela. In fact, however, surveys of the reefs around the island revealed little storm damage. Much of the damage that was found can be attributed only secondarily to the surf and surge.

METHODS

Within approximately 2 weeks after Typhoon Pamela, members of the Guam Environmental Protection Agency (GEPA), the Guam Fish and Wildlife Division (GFW), and the Marine Laboratory, University of Guam (MLUG), had surveyed selected sites by skin and scuba diving and by towed divers (Randall and Eldredge 1977). These sites were primarily on Guam's western leeward side, in the south, and on the eastern windward side (Figure 1). Members of the survey teams were familiar with most of the sites examined. Six weeks after the typhoon, we

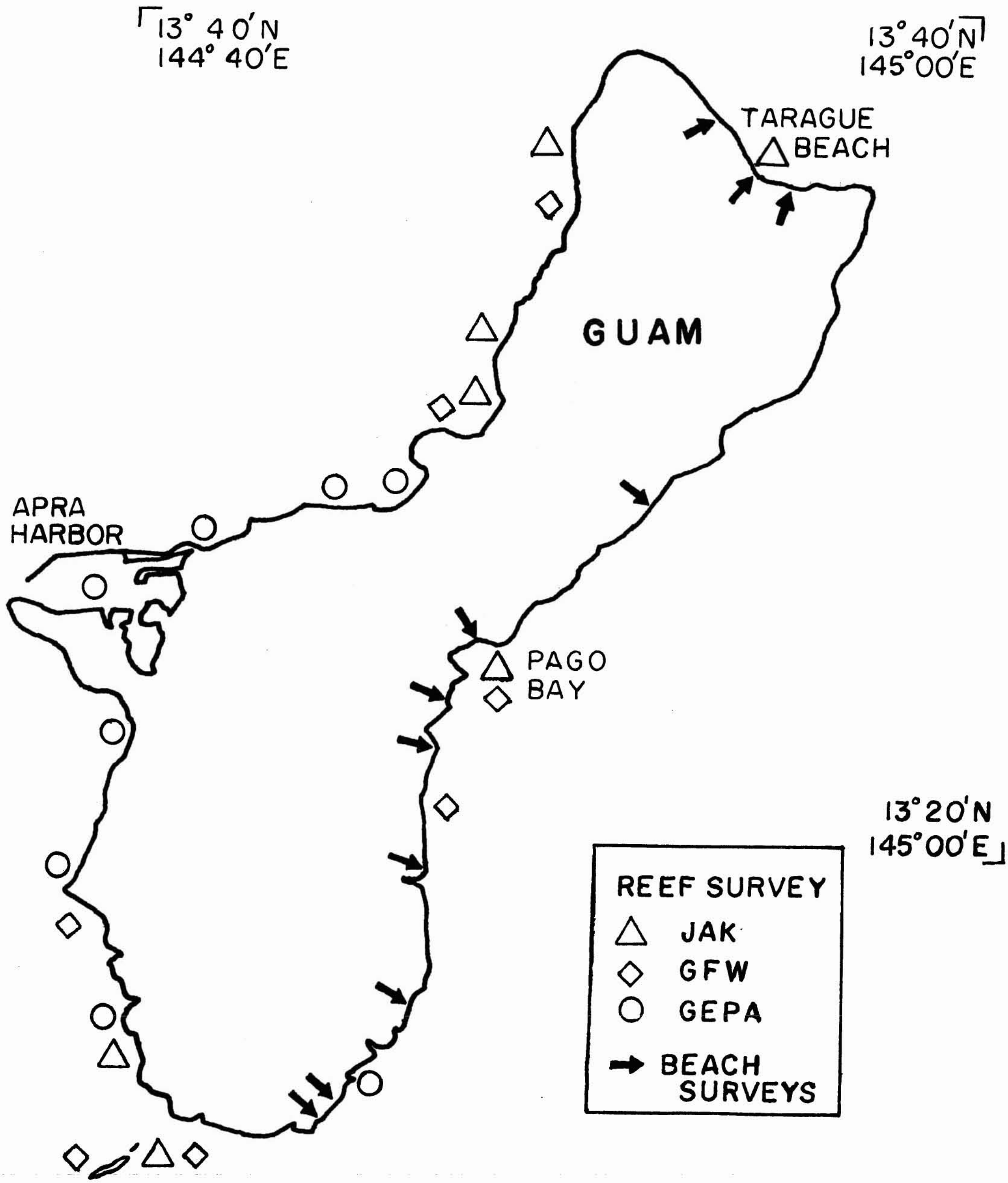

FIGURE 1. Map of Guam showing beach and reef sites surveyed by the Guam Environmental Protection Agency (GEPA), the Guam Fish and Wildlife Division (GFW), and the authors. Areas mentioned in the text are indicated. Randall and Eldredge (1977) also surveyed reefs and beaches around the entire island.

examined areas on the eastern, southern, and western coasts of Guam with personnel from GFW, MLUG, and other divers well acquainted with the areas. We also examined a reef area on the exposed north coast that is part of AAF with divers from AAF who were intimately acquainted with the area prior to the typhoon.

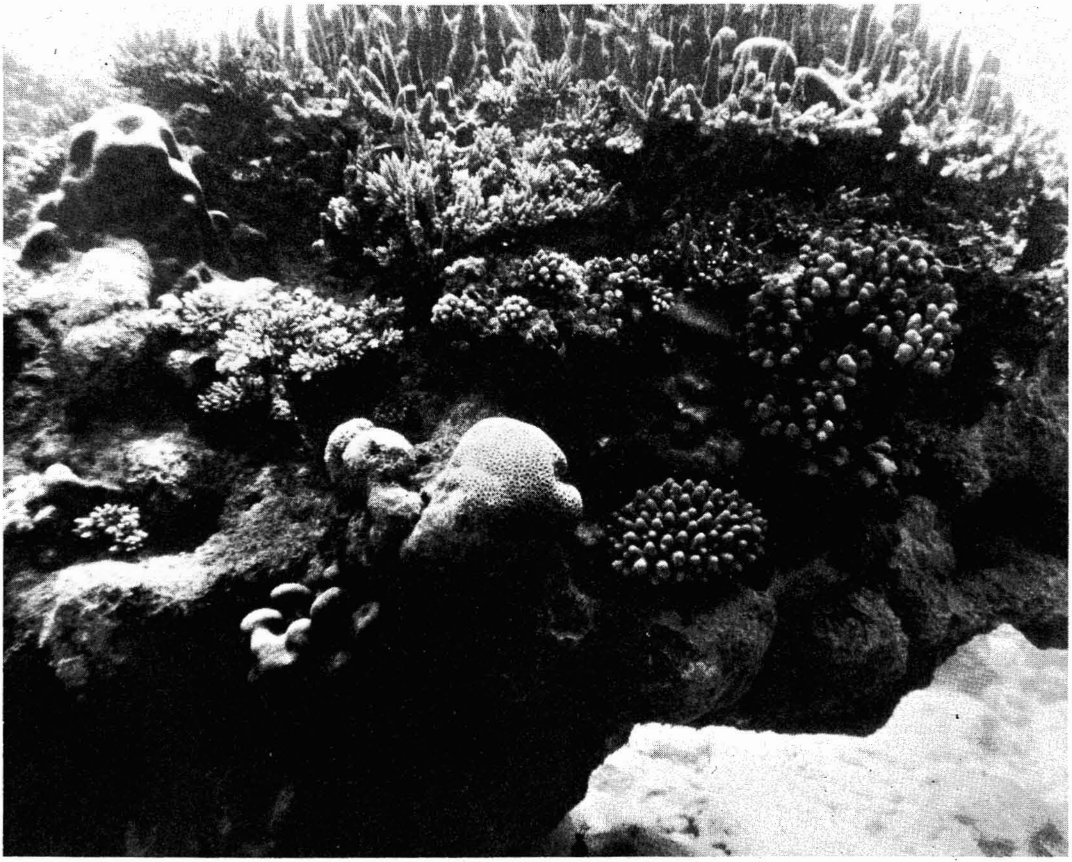

FIGURE 2. Coral assemblage at 7 meters depth on the reef front, Tarague Beach area. Note isolated breakage of coral fingers.

RESULTS

At most sites, little to no damage was seen. Extensive damage was found only in Apra Harbor, where grounded vessels extensively damaged certain areas, and at Pago Bay and several other isolated sites along Guam's east coast (Figure 1). At other sites, most damage was limited to the upper 10 meters in the form of minor breakage of branching hard corals, especially *Porites*, *Pocillopora*, the staghorn coral *Acropora*, the foliaceous *Pavona*, and the fire coral *Millepora* (GEPA, MLUG, and GFW 1976, Randall and Eldredge 1977). Minor breakage was noted to a depth of 20 meters. We report on two critical areas more intensively surveyed by ourselves.

Tarague Beach is one of the only reef areas on the exposed north coast of Guam that is accessible by beach entry.[3] Despite the prevailing heavy surf conditions, the reef front corals at 5 to 10 meters depth comprise a diverse assemblage with many forms represented that seem moderately delicate (i.e., *Acropora*, *Porites*, *Pocillopora*, *Millepora*; Figure 2). Maximum surf heights at Tarague Beach were an estimated 8 meters, causing extensive alteration to the beach itself (see below). Typhoon-related damage to these corals was patchy, however, and even in

[3] We were fortunate to be able to survey the area thoroughly with retired Lt. Col. Henry Moore (AAF), who had dived off Tarague Beach an estimated 300 to 400 times.

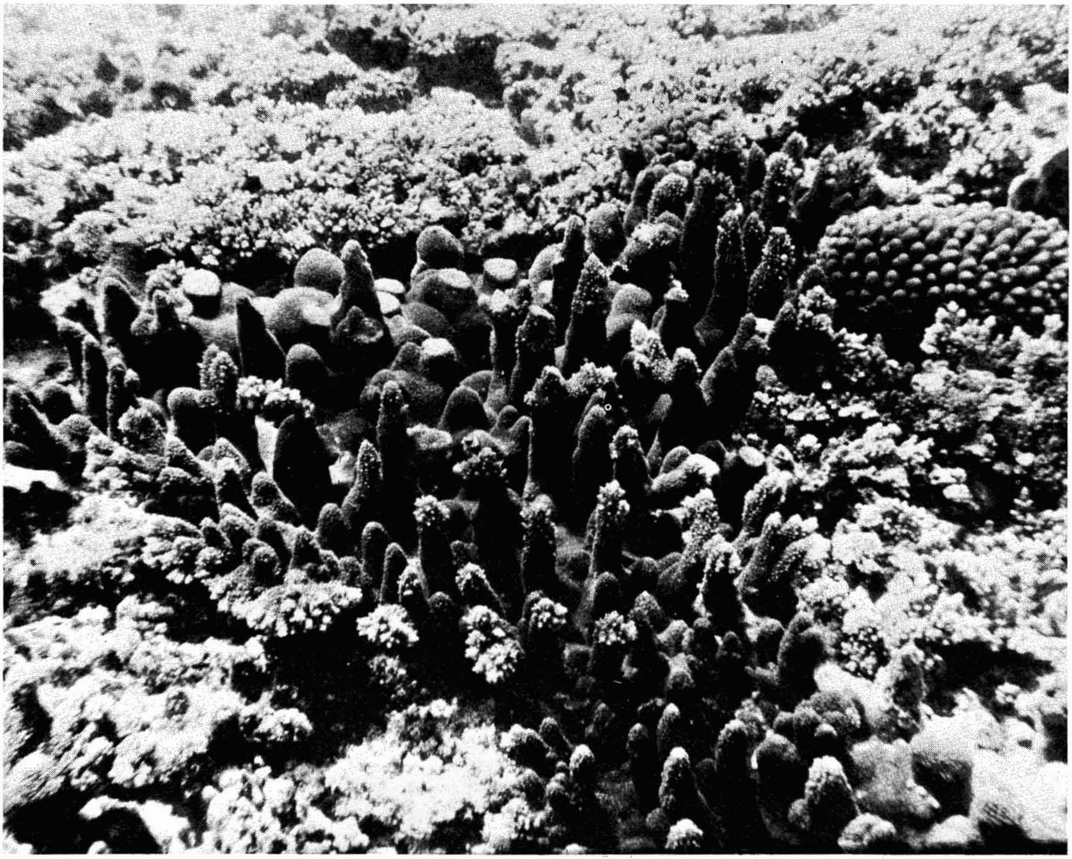

FIGURE 3. Typical damage to hard corals at 5 meters depth, reef front, Tarague Beach area.

those areas that exhibited damage, only between 10 to 25 percent of the coral cover (see Figure 3 for a typical example) was usually affected.

The patchy nature of the coral damage indicates that it was only secondarily caused by the typhoon surf conditions. Abrasion by rubble and tree limbs was directly responsible for the coral breakage, rather than the hydraulic action of the surf. There was considerable evidence that such debris had been carried across the reef during the typhoon. Figure 4 shows a pile of tree limbs found at the base of a surge channel of approximately 20 meters depth; the limbs were not present prior to the typhoon (H. Moore, personal communication). Overturned, but still living coral heads were also found at the base of surge channels.

The exposed eastern coast of Guam was surveyed by MLUG (Randall and Eldredge 1977) and GFW (GEPA, MLUG, and GFW 1976) within days after the typhoon, as well as by ourselves 6 weeks later. The most extensively damaged sites were found on this side of the island. The damage to the reefs was localized, however; only a few areas suffered extensive damage. Within days of the typhoon, a bright green mat of early colonizing algae (*Bryopsis* and *Enteromorpha* spp., identification by R. Tsuda) had grown over these areas, distinguishing them from coral areas barren prior to Pamela. The green algal mat was succeeded by profuse growth of a red algae by the time of our survey. Within 18 months after Typhoon Pamela, the algal community had been largely replaced by newly recruited corals

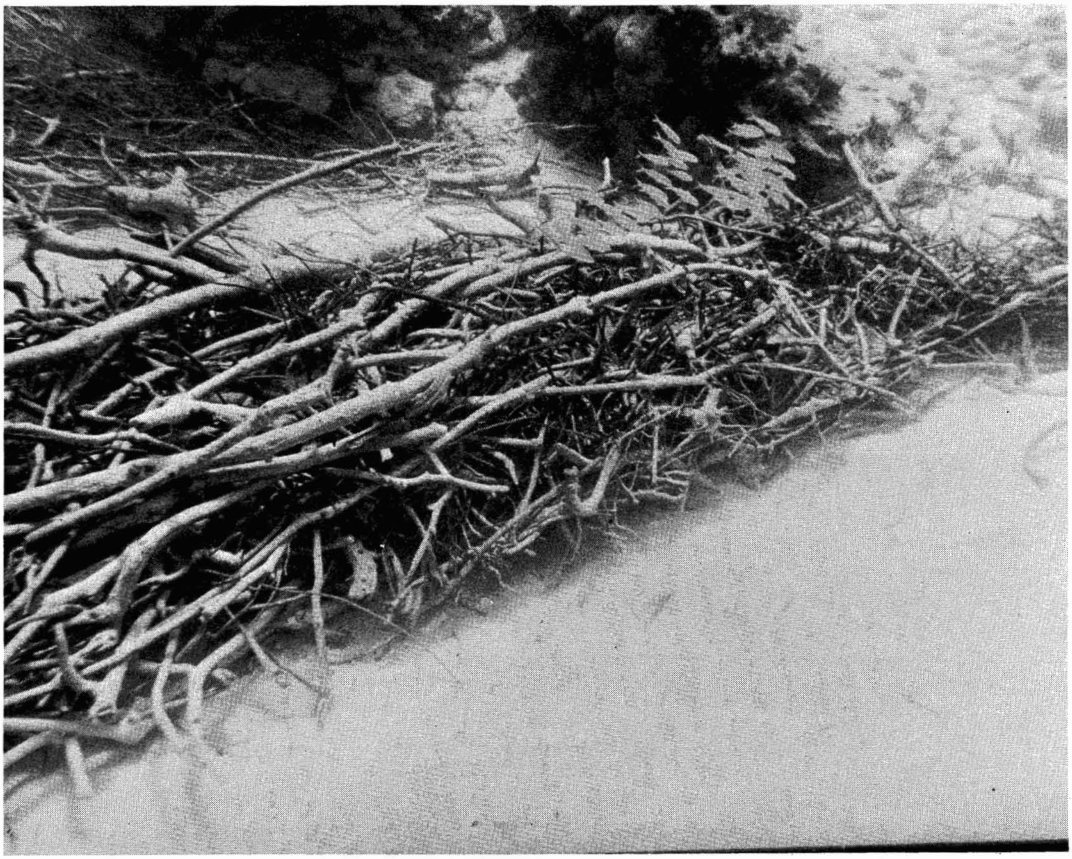

FIGURE 4. Pile of tree limbs found deposited at 20 meters depth at the base of a surge channel, post-Typhoon Pamela, in the Tarague Beach area.

(S. Neudecker, personal correspondence). There was no evidence in any of the surveys of extensive early colonization by toxigenic blue-green algae, hypothesized to be responsible for posttyphoon outbreaks of ciguatera.

Only two sites on the windward side, both in the Pago Bay area, were found by the scientific survey teams to have received extensive damage. At one site, the damage was caused by a section of cliff breaking loose, causing an underwater rockslide. The other site was, conveniently, the well-studied reef directly in front of the MLUG.

Six weeks following Typhoon Pamela, the reef at 5 to 10 meters depth, previously noted for its well-developed coral colonies, was covered by profuse growth of a red alga (Figure 5). A transect was made from 6 to 20 meters depth, and two 1 m^2 quadrats were placed at 6, 13, and 20 meters depth. Destruction to the coral cover was greater than 50 percent generally and approached 90 percent in patches. Branching corals were generally found broken to 20 meters depth.

The reef flat at this site was reported to have been covered prior to the typhoon by gravel (which had accumulated during construction of the laboratory) and an algal mat, both of which were no longer present. Presumably the movement of the gravel in the surf scraped the platform bare of the algae. The damaged subtidal also appeared to have been scraped, paving the way for the algal crop. It is proposed that the movement of gravel, once it began to break the corals, created a chain reaction, with the

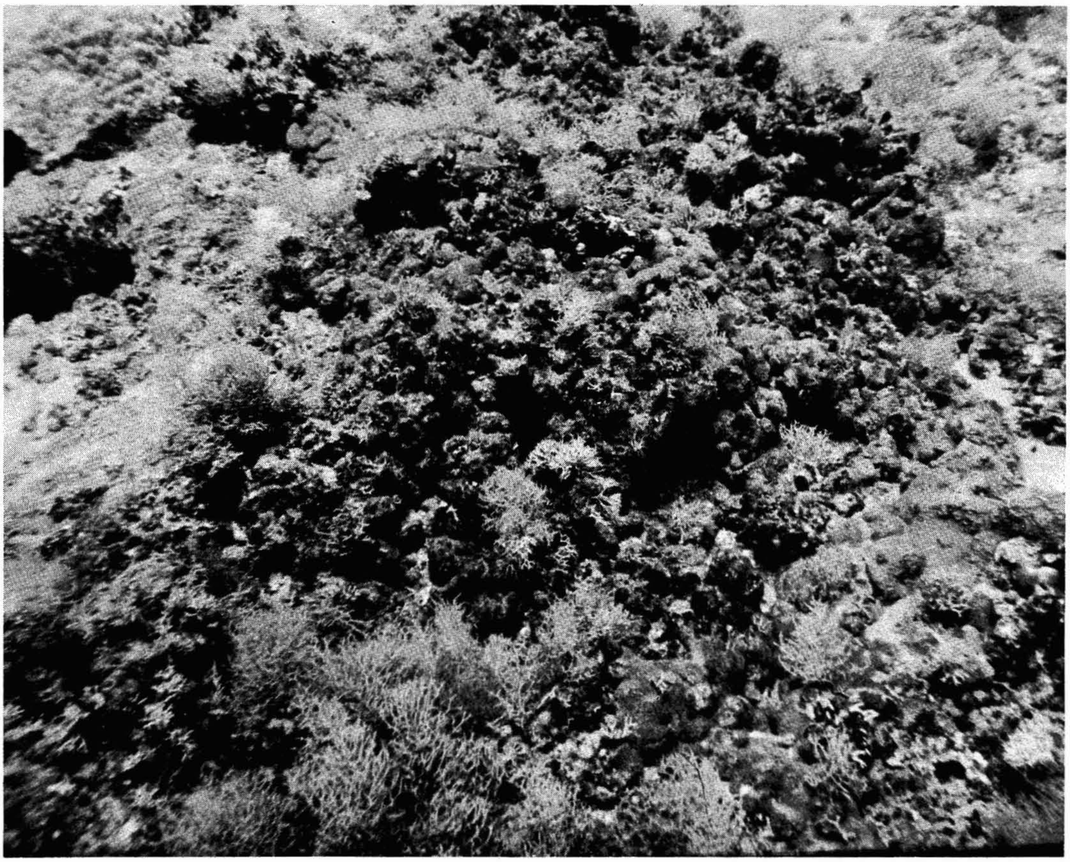

FIGURE 5. Typical bottom configuration at 6 meters depth, Pago Bay 6 weeks after Typhoon Pamela. Prior to the typhoon, the community composition was similar to that found at Tarague Beach. Hard corals are extensively damaged; most knobs are broken at their base. The area is extensively colonized by the red algae in foreground.

broken corals proceeding to break other corals, resulting in the massive, but localized destruction of the corals. It is worth noting that the surge during the typhoon in this area uprooted, twisted, and broke a transect made of 1/2-inch-diameter steel reinforcing bar laid down along the bottom from the surface to a depth of 30 meters and largely cemented into place through the coral growth. A several-ton concrete tank was carried 30 meters across the reef flat.

DISCUSSION

Typhoon Pamela caused only scattered and, with a few exceptions, relatively minor damage to the hard coral reef formations even in exposed areas. Previous studies of reef damage and recovery (Stoddart 1974) indicate that except in those isolated sites receiving extensive damage, the effects of the storm will not be noticeable in a few years. For several of the sites examined, there was good evidence that the damage to the corals was not caused primarily by the surge itself, but through the interaction of grounded vessels, landslide material, tree limbs, and rubble.

Previous studies of the impact of typhoons on reefs have been based on spectacular instances of marine destruction. These reports generally come either from normally protected sites (Stephenson, Endean, and Bennett 1958) or sites only infrequently visited by major storms (Blumenstock 1961, Maragos, Baines, and Beveridge 1973). Often, the reef damage is caused by a more complex chain of events, such as the conjunction of extreme low tides and torrential rains, which drastically lower salinity (Goreau 1964, Hedley 1925). In one instance, a 42-inch rainfall led to massive flooding and consequent siltation, which caused a large-scale fish kill. This in turn created anoxic conditions on the reef flat, ultimately destroying the shallow-water coral community (Cooper 1966).

The minor impact of a major typhoon, such as Pamela, on a reef system can provide significant insight into coral reef dynamics. Recent observations (Stoddart 1974) indicate that reef recovery from massive incidents of destruction may be on the order of 25 to 75 years; reef recovery from minor damage is on the order of several years. Regions off the main storm tracks can therefore be significantly affected by a rare but destructive typhoon (i.e., one that occurs on the order of every 50 years). On the other hand, reefs in areas along the main storm tracks seem to develop so that, barring exceptional circumstances, even the rare supertyphoon, by itself, appears to have little long-term impact. The coral colonies, even at less than 10 meters depth, clearly grow so as to be able to withstand direct typhoon-induced wave assault.

We have no information on the immediate overall impact of tropical storms and lesser typhoons on the coral reefs of an island such as Guam. But if lesser storms also cause minor breakage over wide areas and extensive damage in isolated areas, this frequent cropping could maintain a variety of successional stages in the reef community, as well as preserve the low, rugged reef profile. The incidence of typhoons and their short- and long-term effects should be more consistently noted in the future so that we can better understand the dynamics of coral reefs in relation to these natural catastrophes.

Part 2. The Impact of Typhoon Pamela on Guam's Beaches

Typhoons play a major role in determining beach morphology. The long-period storm surges and accompanying short-period, wind-driven surf are effective agents in redistributing beach sand. The surf is the main erosive agent, but the storm surges play a major role in elevating the high water level on the beaches (Jelesnianski 1976). The net beach profile is lowered and the eroded sand is swept offshore or deposited as a blanket landward, depending on the water levels experienced (Emery 1962). Studies of a Florida hurricane show that this erosion can be as much as 30 m^3 per meter of beach face (Morton 1976) and cause an average lowering of the beach profile of over 0.8 meter (Tanner 1976). In addition, accelerated longshore transport can redistribute large quantities of sand longitudinally along the coastline.

The shore modification study investigated three major processes: alteration of beach profile, longshore transport of sand, and height of wave surges on the beaches.

METHODS

Fourteen beaches were examined on the northern, eastern, and southeastern coasts of Guam (Figure 1) to determine beach profile alteration, longshore sediment transport, and maximum height of wave surge. The leeward western coastline was protected from the typhoon waves. Transects were surveyed on seven of the beaches and less detailed profiles were made on the rest. Pretyphoon photographs taken by local residents were useful at three of the locations. Recently exposed tree roots, buried vegetation, and blankets of sand swept over shore roads and structures were surveyed. Valuable records of pretyphoon beach profiles were obtained from upraised reef limestone blocks and headlands on or bordering the beaches. The limestone is discolored to a dark gray by algal growth on all exposed surfaces over a period of time, whereas the covered or newly exposed limestone is the original white color. The dark gray-to-white transition indicates the prior beach level and the extent of sand removal or burial (Figure 6).

In addition, a set of photographs was made at each location. Several of these were retaken

FIGURE 6. Recently exposed limestone at Jinapsan Beach, indicating extent of beach sand removal. Pretyphoon sand level was at contact between algal-discolored, dark gray surface and newly exposed white surface. Hammer in center for scale.

by a visiting Scripps geologist 6 months later to enable documentation of the recovery of the beaches from the typhoon alterations.

BEACH PROFILE ALTERATION

The northern and eastern beaches had been swept by typhoon surge and surf to a height of 4.5 to 8.0 meters above mean lower low water (MLLW), well above the 0.6-meter tidal range and normal surf. Most vegetation had been removed to a height of 3 to 4 meters above MLLW, and debris piled up to 2 meters high were common near the maximum surge mark. In this vegetation-cleared portion of the beach, the posttyphoon profile was a uniform, gentle 3° to 5° slope, littered with broken coral pieces. This is in marked contrast to the mean pretyphoon beach slope of 8° to 10° [Emery (1962), whose profiles unfortunately cover only the zone to 3 meters above MLLW]. Comparison to the pretyphoon photographs of Tarague Beach on the north revealed a 5- to 10-meter seaward extension of the beach. At Tagachan Beach on the east coast, a local bather remarked that the deepest water inside the reef had shoaled about 1 meter. The middle zone of the beaches, in addition to being stripped of vegetation, had been lowered, as evidenced by newly exposed white limestone at Tarague (north), Jinapsan (north), and Perez (east) beaches. At Acho (southeast), Guijen (south-

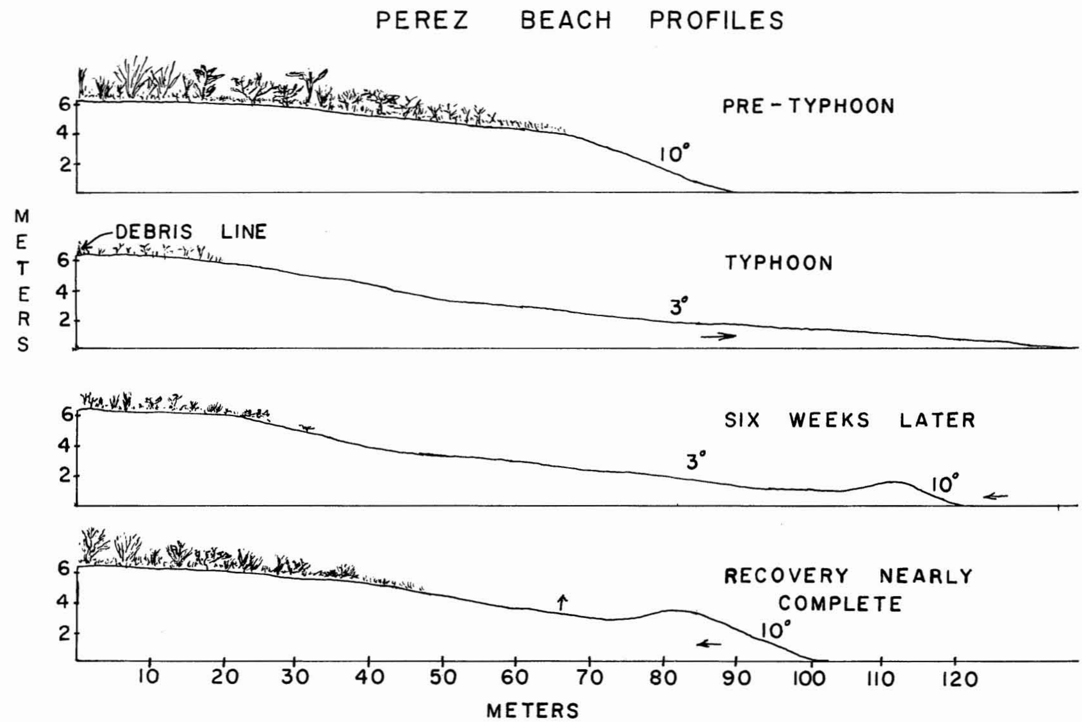

FIGURE 7. Typhoon modification and stages of recovery of typical beach profile. The typhoon waves swept sand seaward to form a wide, gently sloping beach. Surf and wind action had begun to move the displaced sand landward at the time of the survey, creating a beach ridge. This landward transport will continue until the beach regains its pretyphoon profile.

east), West Tarague (north), and possibly Perez (east) beaches, a 30- to 50-cm blanket of sand had been swept over the uppermost portion of the beach.

At the time of the visit, the first recovery stages of the beaches to the pretyphoon profiles had taken place. The seaward edge of several of the beaches had retreated, forming a 1- to $1\frac{1}{2}$-meter-high lowermost zone having a 10° to 15° slope.

The profiles of Perez Beach on the eastern coast illustrate the process of typhoon wave modification and later recovery (Figure 7). The pretyphoon beach profile, as indicated by newly exposed white limestone of the bordering headlands, had a steep face about $1\frac{1}{2}$ to 2 meters high, with perhaps a 10° slope, followed by a gently sloping-to-level, vegetated terrace. The typhoon waves cut back the terrace and shifted sand onto the reef flat. A featureless, 3° to $3\frac{1}{2}$° slope resulted, extending about 130 meters from the high water debris line. The profile, as surveyed 6 weeks later, had a 10-meter-wide, ocean-bordering, coarse coral sand ridge, rising from the MLLW level with a 15° slope to 1.5 meters elevation, and then dropping 0.5 meter to the main beach slope. This beach ridge probably originated from posttyphoon, landward transport of sand by the waves and wind. Six months later, this beach ridge had migrated another 10 to 15 meters inland. The beach ridge should continue to migrate inland, while vegetation reclaims the upper beach, until the profile is again stabilized.

LONGSHORE TRANSPORT

Typhoon waves striking the coastline at an angle cause accelerated longshore transport of beach sand. Changes in the distribution of

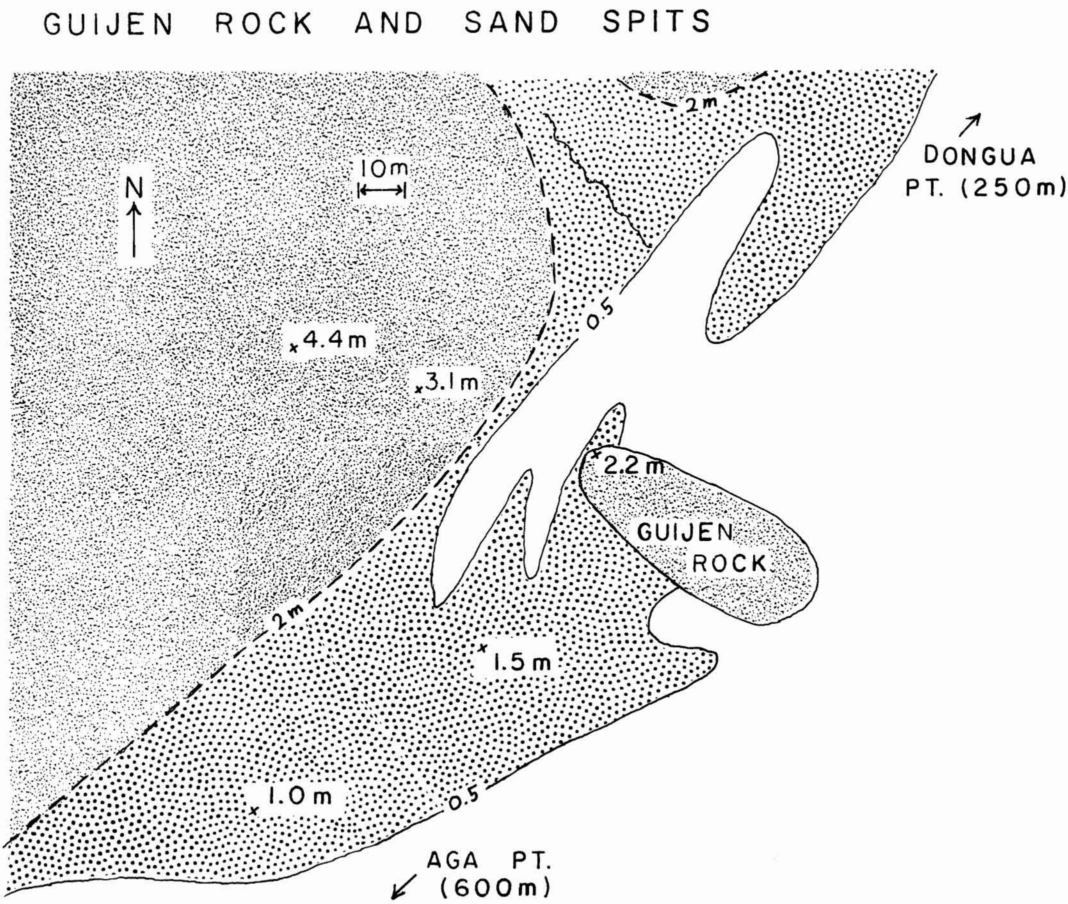

FIGURE 8. The distribution of sand at Guijen as surveyed when tide level was at +0.5 meter. Two sand spits had been created by sand transport during the typhoon. Six months later Guijen Rock was again isolated from the shore.

sand were observed at Tarague Beach in the north and Guijen Beach in the southeast. Neither has a major stream outlet, so stream discharge effects were not significant.

At the west end of the 5-km-long Tarague Beach a 50-cm blanket of sand was deposited on access roads and picnic facilities over approximately a 50-meter-wide zone of the upper beach. The beach was also extended seaward. Part of this sand was from the smoothing of the beach profile, but pre-typhoon photographs showed that this beach already had a gentle slope. Thus, there was a net deposition of about 25 m^3 per meter of beach face. This end of Tarague Beach terminates at a limestone point. On the opposite side, the beginning of Jinapsan Beach, a white band at the base of the limestone cliff, recorded the removal of a 28-meter-long and 1.2-meter-wide lens of sand (Figure 6), a net removal of about 20 m^3 per meter of beach face. We assume a similar amount of sand was involved in accelerated longshore transport on the east end of Tarague Beach (access prohibited, Strategic Air Command munitions disposal area).

At the center of Tarague Beach, the reef is cut by a channel and the shoreline direction changes from WNW to NNW. A significant quantity of sand was swept over the reef edge near this channel to form a 1- to $1\frac{1}{2}$-meter-thick, rolling sand blanket at the base of the steep, outer reef slope at a depth of 15 meters. This was not present prior to the typhoon

(H. Moore, personal communication). Comparison of profiles and photographs to pretyphoon photographs showed that the local beach profile was modified, as explained previously, but that no net removal was involved. This sand blanket is thought to be mainly the result of an interruption in longshore transport at the bend.

At Guijen on the southeast coast, an oval of uplifted reef rock of 2.2 meters elevation is separated from the coastal terrace by a 20-meter-wide channel (Figure 8). At the time of the survey, the rock and shore were connected by an arcing, exposed sand spit, extending about 140 meters to the southwest with a maximum elevation of 1.5 meters above MLLW. A similar sand spit, about 100 meters long, approached from the northeast, ending 30 meters from the rock, but probably connected at low tide. These opposing bars enclosed a 100-meter-long, 15-meter-wide bay of 30 cm average depth below MLLW. The pretyphoon maps show no exposed sand bars. Six months later the rock was again isolated by a wide channel of about 1 meter depth through which a current flowed at an estimated 1 knot (R. Kieckhefer, personal communication). Therefore, it appears that the sand spits are temporary relics of the typhoon. The sand sources would be longshore transport from the northeast and perhaps the wide reef flat. Guijen Rock disrupted the wave-current flow, resulting in the tombolo bar. The northeast spit could be the result of a change in flow direction and velocity after Dongua Point. Under normal wave conditions, longshore transport is slower and these sand bodies are not maintained.

TABLE 1

MAXIMUM WAVE SURGE HEIGHTS

LOCATION	HIGHEST DEBRIS LINE (m)	AFFECTED BEACH WIDTH (m)	REEF FLAT WIDTH (m)	TOTAL DISTANCE (m)
East Tarague*	5.0	35	80	115
Tarague Channel	7.2	60	100	160
West Tarague	6.8	135	150	285
Sasajyan-Guae	8.0	100	0	100
Pago	5.0	10	500	510
Tagachan	7.5	90	120	210
Ylig	4.5	170	300	470
Togcha	6.2	90	300	390
Asanite†	6.0	40	50	90
Perez	6.3	120	220	340
Acho	4.5	65	450	515
Guijen‡	2.4	170	450	620
Achang‡	2.5	50	500	550

*Outcrops of elevated reef limestone on present reef flat act as wave baffle; omitted in analysis.
† Base of cliff; surge may have climbed higher; omitted in analysis.
‡ Southeastern beach.

HEIGHT OF WAVE SURGES

The elevation of the debris lines, which record the maximum height of typhoon wave surges on the beaches, were surveyed at thirteen locations (Table 1). These were compared to the combined width of the swept beach and reef flat, or the total distance the wave surge traveled after breaking on the reef edge. The data indicate a linear relationship between the heights of the maximum wave surge and the distance it traveled (Figure 9). This relationship may be explained by using a simple model of waves losing energy as they travel across the reef flat and beach.

A breaking wave at the reef edge has an initial potential hydrostatic head equal to its height plus forward momentum. Suppose this potential head were equal to 9 meters as projected from the graph; this is also consistent to the estimated breaker heights of 8 meters. Then, if there were no energy loss, the wave would be expected to surge to an elevation of 9 meters on the shore regardless of how far it travels. However, energy loss occurs as the wave travels inland due to turbulence, bottom friction, return flow, and other factors. The potential head is steadily reduced, resulting in a lower height of maximum surge. The empirical value as given by the slope of the line fit to the data is a 1-meter reduction of head or run-up height per 115 $\pm$ 20 meters of landward travel. The southeastern beaches probably received indirect waves, and a lower initial potential head is indicated.

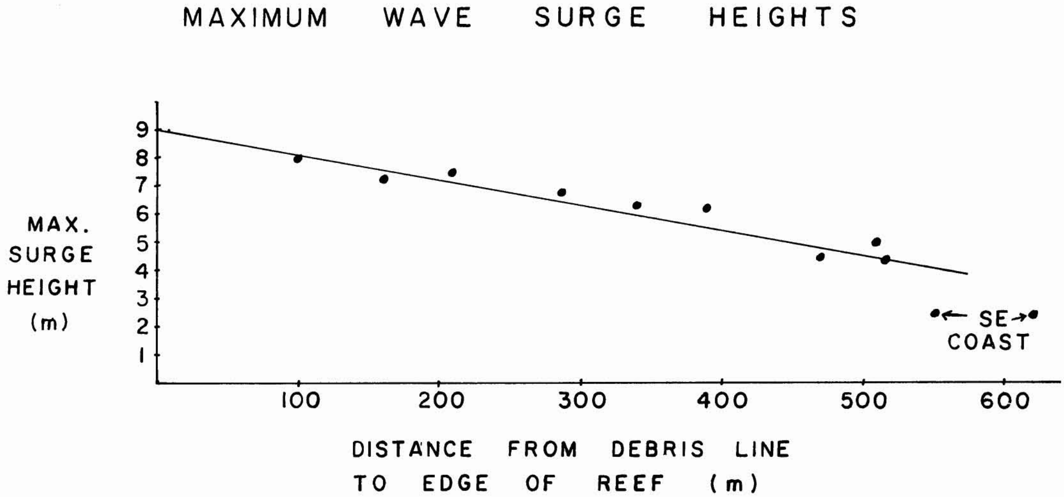

FIGURE 9. Maximum wave surge height versus distance from the highest debris line to the seaward edge of the reef. Data are given in Table 1. The linear fit is a 1-meter height decrease per 115 meters of distance.

This empirical model may be useful for predicting storm wave damage from future typhoons. Intersection of the reef flat–beach profile with the 1:115 slope projected landward from the estimated potential head of waves breaking on the reef edge will yield the approximate level of maximum wave surge on the beach.

ACKNOWLEDGMENTS

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