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STORMS AND ISLAND BUILDING AT FUNAFUTI ATOLL, ELLICE ISLANDS.

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SUMMARY

Six weeks after a hurricane had caused the deposition of a storm beach on the atoll of Funafuti a scientific team began an investigation of the new structure. Hurricane generated waves from the SE had caused reef detritus from an offshore terrace to be elevated onto the reef flat from depths of <20 m to form the storm beach, 19 km in length and up to 4 m in height. Its formation was not observed and the precise time and mode of formation remain uncertain. The form of the storm beach differs where it is situated alongside islets from where it extends along reef flat between islets. An attempt is made to explain this difference and to consider its significance for the distribution of some motus on atoll rims.

Along the NE coast of Funafuti, where the energy of hurricane generated waves had been attenuated by refraction, deposition on the reef flat was restricted to discontinuous, low rubble tracts although offshore, close to the upper reef front, a reservoir of reef detritus was observed, so positioned as to constitute a potential source of storm beach material.

A "hurricane bank" had been a significant feature of the sea-ward shores of most motus of the SE rim of Funafuti before the recent hurricane. Some sections of this bank had been disturbed by man's activities and these parts were extensively eroded during the passage of a wave or waves over the bank. The stratified structure of this bank suggests that though rubble tracts may be a common occurrence during hurricanes, the formation of massive storm beaches is infrequent. The latter, it is suggested, could lead to a seaward prograding of motus and might in this way account for the seaward sequence of ramparts seen in some locations.

Changes in the position and form of the storm beach are expected. However, it is suggested that, whereas the material of similar, but smaller, structures elsewhere has been quickly moved landward it is conceivable that the Funafuti storm beach could lead to a seaward prograding of the motus.

I. INTRODUCTION

Marked alterations to the geomorphology of some parts of the atoll of Funafuti (Fig. 1) have recently been caused by a hurricane (code-named 'Bebe') which passed through the area on October 21, 1972.

This hurricane developed near to Funafuti, approached the atoll from the east and then headed south, passing over Rotuma and Fiji before losing storm strength. One of its most marked effects at Funafuti was the formation of a storm beach of coral rubble, 19 km long and in places almost as wide as many of the islets of the atoll. Between December 10 and December, 24, 1972 the authors investigated this new storm beach and other geomorphological alterations associated with the hurricane. Residents were interviewed, many islands of the atoll were visited, biological and geological samples were collected and a comprehensive photographic record was obtained. Storm beach profiles at seven points were surveyed and a surface particle analysis was conducted at one of these points. Underwater surveys were carried out by snorkeling and by use of SCUBA.

A short report presenting the main features of our findings has already been published (Maragos *et al.*, 1973). A comprehensive report incorporating details of the effects of Hurricane 'Bebe' throughout the atoll is in preparation.

II. THE HURRICANE

Deteriorating weather conditions were experienced at Funafuti from the night of October 20, 1972 as a cyclone approached the atoll. Winds reached hurricane force on the afternoon of October 21, intensifying rapidly to peak gusts in excess of 50 m sec. $^{-1}$ at 2200 hours (1000 hours G.M.T.). These winds were initially from the SE, changing through southerly to be SW at their maximum. A lull of one to two hours occurred, centering on 2330 hours, followed by strong winds from the west. Winds moderated as the cyclone moved south of the atoll. A barometric minimum of 954 mb. was recorded at 2200 hours.

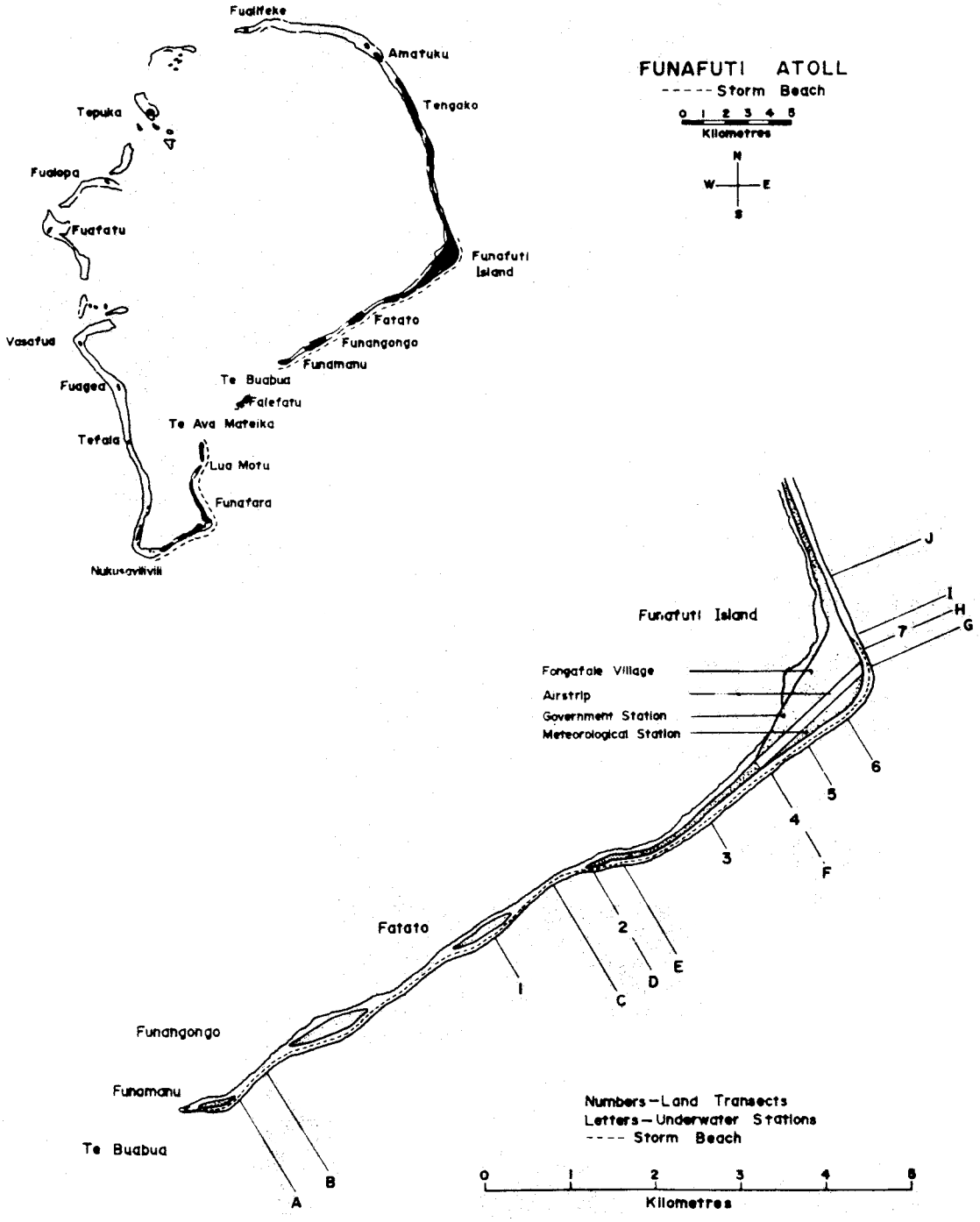

Figure 1. Location map.

At about 2215 hours, a large wave, possibly supplemented by one or two smaller waves immediately afterwards, swamped the eastern half of Funafuti Island, destroying many buildings and killing several people. After crossing the seaward reef flat, the wave inundated the "hurricane bank" before passing lagoonward. The "hurricane bank" had stood about 3 m above mean high water (M.H.W.). At the meteorological station, 42 m from the "hurricane bank" and about 0.5 m above M.H.W., the wave appears from eye witness accounts to have been in excess of 3 m above ground level. The wave travelled westward across the airstrip to the outskirts of Fongafale village and the government station situated on the lagoon margin of the island.

Sea level in the lagoon appeared to have remained high during the evening of October 21 and was a little above high water spring tide level at the height of the storm, coinciding with an astronomical low tide. This elevation of a little more than 2 m suggests a storm surge forerunner. For some hours before the large wave, waves spilled over the "hurricane bank" and poured through low points to flood the airstrip and meteorological station. The apparent high water level on the outer reef flat was probably the result of storm wave action on the reef edge. The coincidence of the large wave with the barometric minimum suggests that it may have been a storm surge. After the large wave flooding continued and storm waves battered the coast for several hours.

III. REEF RIM DEPOSITION

A. THE STORM BEACH

The elevation of a new storm beach or rubble rampart almost continuous along the 19 km of the SE rim of the atoll was the most significant event during the hurricane. It was calculated to have a volume of 1.4×10^6 m^3 and a mass of about 2.8×10^6 tonnes. Gravel tracts formed on reefs by tropical cyclones at Marcus Island (Bryan, 1903) and Jaluit Atoll (Blumenstock, 1958; McKee, 1959), were very much smaller. This storm beach was located on the ocean side reef flat. It was continuous both offshore of the islands and across the inter-island gaps from just north of the eastern elbow of Funafuti to south of Funamanu. The islands of this section share a common reef platform. The storm beach along this section averaged about 3.5 m in height above the reef flat and 37 m in width. It was separated from the shore of adjacent islands by a shallow moat covering the inner reef flat. Water level in this moat fluctuated with the tide. No storm beach was observed to occur across the two major passes through the SE atoll rim, Te Buabua and Te Ava Mateika, with depths in excess of 20 m. The storm beach was present elsewhere along the SE rim as far as Nukusavalivali, with occasional minor discontinuities where rubble deposition had been insufficient to cause the storm beach to be raised above high water.

The position of the storm beach between Falefatu and Nukusavalivali was determined from aerial oblique photographs, observations from the air, and by brief visits to Lua Motu and Falefatu. However, vertical aerial photographs taken on December 19th, 1972, from an altitude of 500 m. have permitted a detailed analysis of the shape and distribution of the storm beach from its northern extremity to the termination of its northern half at Te Buabua. The section north from Fatato was examined at close quarters during the visit and topographic profiles were surveyed at seven points (Fig. 1) across the storm beach from the ocean to, approximately, M.H.W. on the shorelines of the adjacent islets, using tape, staff and level. On each of these transects a brass peg was cemented into the shoreline conglomerate as a benchmark for future surveys. The storm beach form along the section from Te Buabua to the northern extremity exhibited marked differences in form correlated with island position and reef-edge contour.

1. Storm Beach Adjacent to Islands

Along the nearly straight 3 km SE aspect of Funafuti islet the storm beach illustrated well the form and position shown adjacent to islands, (Figs. 2B, 3A). The outer edge of the storm beach lay virtually parallel to the reef rim, leaving an outer reef platform about 30 m wide exposed at low water spring tide. A groove-spur system was well-developed in the outer 15 m of this platform. The storm beach was situated entirely landward of this system except at the eastern extremity of Funafuti islet where a few unusually long and deep fissures extended beneath the storm beach into the moat. Profiles were measured on this section at four points (Fig. 1: 3-6; Fig. 4 D, E). From the outer reef flat a steep, often concave seaward face ascended at an angle of 20 deg.-30 deg. to a single berm, 1 m. lower and about 2 m seaward of the crest. According to a resident, the berm had formed since the hurricane. The average crest height for these four profiles was 3.8 m with a maximum height of 3.9 m. Large boulders, frequently with a green, filamentous algal cover, were present along the foot of this slope. The largest of these observed, near Funangongo, measured 7 m x 3 m x 3 m. From the crest the lagoonward slope descended steeply for a short distance followed by a slope angled at 3 deg.-9 deg. which extended to the steep moat escarpment. The edge of this escarpment stood about 1 m -1.5 m above the reef flat and corresponded approximately to high tide level

A
B
D
E
F

in the moat (Fig. 2A). Since the tidal range at Funafuti is about 1.5 m , much of the storm beach lies between tidal extremes.

Deposition of storm beach material along the coast of Funafuti had not been uniform at all points and the shoreward margin of the beach was irregular. At a number of points the inner margin of the beach narrowed to widths of as little as 21 m. Between these narrow points, the inner margin of the beach curved gently landwards, the maximum width being 50 m while the average width was 34 m. Nowhere in this section did the storm beach margin contact the adjacent shore although the gap was reduced to about 8 m where the storm beach attained its maximum width (Fig. 2A).

2. Inter-island Storm Beach

No profile measurements were made on inter-island sections of the storm beach. However, the section between Funafuti and Fatato (Fig. 2C) was traversed by foot and, in addition, measurements were made from aerial photographs.

The seaward beach face slope, berm and crest were similar in their position and dimensions to those of the storm beach alongside islands. Lagoonward, however, in most places it descended steeply to unite with a rubble sheet of low relief projecting lagoonwards and submerged for much, if not all, of the tidal cycle. The width of the section linking Funafuti and Fatato, measured from the seaward margin to the union of storm beach with rubble sheet, varied little from an average of 36 m. The maximum extension of the rubble sheet behind the storm beach in this section was 75 m. Boulders were absent along the seaward margin of the storm beach, which was separated from the reef edge by approximately 8 m of reef flat lacking grooves and spurs.

Conspicuous cusps were present along the seaward face, extending upwards almost to the berm. The cusp surfaces were covered with relatively fine, light-coloured, sorted material while the intervening sections of the face were composed of coarser and darker fragments. Cusp breadth and spacing were approximately equal and in the Funafuti-Fatato section ranged from 6 m near Funafuti to 9.5 m nearer Fatato where the beach had its maximum orientation towards the east. Cusps were not present on storm beach alongside islands.

The storm beach crossing the gaps south of both Fatato and Funangongo displayed similar features, although cusps were less well developed. The storm beach tip by Te Buabua, like the tip at the northern extremity, showed evidence of having been worked by wave action and currents. At Te Buabua the beach had been curled back for 65 m upon its lagoon slope.

3. Narrow Sections

Deposition of storm beach material had been reduced in places where the reef edge was not oriented towards the SE. The 0.75 km section of the storm beach extending from the eastern elbow of Funafuti along the NE coast was uniformly narrow, averaging 20 m. The crest height of approximately 3 m (Fig. 4 F) was lower than that of other profiles. The seaward margin of the storm beach was located about 30 m from the reef edge except at the northern extremity where the beach curved inwards to the original islet shore. Observers reported that, immediately after the hurricane, the storm beach had terminated on the outer edge of the reef flat. Within two weeks, landward movement of storm beach material had caused the end of the storm beach to curve inwards to meet the shore. Moderate swells, breaking on this coast at high water spring tide eight weeks after the beach's formation, generated sufficient swash to tumble large boulders from the foot of the seaward slope over the crest.

Other points of reduced deposition occurred where convexities of the ocean reef rim orient the edge more to the south. These were seen opposite Funamanu, Funangongo and the south end of Funafuti. The narrow storm beach at these localities was interrupted by low washover features, fully or partially closed by longshore transport of storm beach material.

4. Storm Beach Material

As with the rubble bars produced at Jaluit during the passage of typhoon Ophelia (McKee, 1959), old, rounded and subangular, often plate-like coral and *Porolithon* rubble, of cobble and boulder size were the major components of the beach. No material of island origin was found on the storm beach.

The surface composition of the storm beach on transect 5 (Fig. 1) was investigated under a line stretched from the upper edge of the moat escarpment to the crest. The visible intercepts of fragments under this line were measured. The maximum dimension of each particle having a dimension greater than 3 cm. was measured to the nearest cm. parallel to the plane of the surface by re-

Figure 2. **A.** The eroded Funafuti coastline and the moat from the inner edge of the storm beach; **B.** Eroded "hurricane bank" on Funafuti; the storm beach to the left, airfield to the right; **C.** Inter-island storm beach, seaward margin, viewed from the tip of Funafuti towards Fatato; **D.** "Hurricane bank" relict on Funafuti; **E.** Scour trench in beachrock on ocean shore of Funafuti, storm beach to left; **F.** "Hurricane bank" profile, Funafuti. Upper section is 1 m thick.

Figure 3. Stereo pairs: **A.** Storm beach on Funafuti's SE coast (1 — storm beach, 2 — cuesta-like beachrock ridges, 3 — eroded "hurricane bank", 4 — meteorological station, 5 — airstrip); **B.** Rubble tracts on Funafuti's NE coast (1 — rubble tracts, 2 — disturbed "hurricane bank").

Table I. Storm beach particle analysis under a 15.3 m line from crest to moat escarpment on transect 5.

Size classes: maximum dimension	Sum of intercepts for each class as percentage of transect length.	Particle frequency as percentage of total particles of at least 4 cm maximum dimension
> 32 cm	16	6
16-31 cm	37	26
8-15 cm	36	52
4- 7 cm	6	16
< 4 cm	5	

moving overlapping upper fragments where necessary. An analysis is given in Table I.

Though few conclusions might normally be possible from a single transect, qualitative examination of the storm beach elsewhere suggested that these data were reasonably representative for lagoonward slopes, where little evidence of sorting was present. No sand-sized fragments were encountered on this slope.

Fragments of recently killed corals, mollusc shells and the remains of sponges were present. Coral genera represented included *Acropora, Pocillopora, Favia, Plesiastrea, Montipora, Pavona, Pavona (Pseudocolumnastrea)* and *Acanthastrea.* In the particle study, freshly-killed corals were intercepted by no more than 5 per cent of the transect.

Finer particles were found on the seaward face where there was evidence of abrasion, comminution and sorting.

B. LOW PROFILE RUBBLE TRACTS

Along the NE coast of the atoll north of the storm beach hurricane Bebe was responsible for the elevation of low profile tracts of rubble on the inner reef flat (Fig. 3B). Immediately north of the storm beach these deposits were nearly continuous along the reef flat. Further north, between Tegako and Amatuku, they were separated by intervals of 100 m or more. One of the tracts near the fuel storage tank, about 2 km north of the storm beach, was determined by pacing to be about 18 m wide. The tract became thicker shoreward and ended in a 0.5 m escarpment. No particle analysis of this material was conducted. It consisted of white abraded coral plates together with more angular material.

IV. ORIGIN OF THE STORM BEACH MATERIAL

Underwater observations were made at a number of points along the NE and SE coasts by snorkeling and also with SCUBA. At two stations adjacent to the storm beach (Fig. 1A, D) SCUBA assisted dives were made to a maximum depth of a little over 40 m and the bathymetry, substrate and cover in shallower water were determined by use of marked transect lines, writing slates and depth gauges. Substrate and cover were enumerated under 50 points at 1 m intervals on a 50 m line placed twice at each station. In addition, an exploratory dive to a depth of 10 m was made with SCUBA beyond the northern extremity of the storm beach where the hurricane had left only a low rubble tract on reef flat (Fig. 1J). Observations by snorkeling were also made (Fig. 1B, C, E-I) both where the storm beach lay adjacent to motus and where it extended across inter-island gaps.

Along the SE coast between Funamanu and the eastern extremity of Funafuti significant differences were observed, but not measured, in the shallow water bathymetry adjacent to islands and the inter-island gaps. Adjacent to islands a well-developed groove-spur system was found at the outer edge of the reef flat. The spurs appeared to have an average width of about 2.5 m with grooves about 2 m across and 2 m deep at their outer extremities. Below the outer edge of the groove-spur system the reef front dropped steeply to a sloping terrace at a depth of 7-8 m although in places buttresses, as extensions of the spurs, projected further onto the slope. By contrast, a groove-spur system seemed to be all but absent in the middle of the inter-island gaps examined (Fig. 1 B, C). The reef edge was itself inconspicuous, merging with the seaward slope which maintained an angle of 10 deg. or less to reach depths of 8 m at a considerable distance from the reef edge. This slope was relatively smooth, or broken by rounded ridges and furrows oriented at a normal to the reef edge.

The profiles examined in greatest detail, (Fig. 1 A, D; Fig. 4 A, B) were at positions near the ends of motus and appeared to be intermediate in character between the extremes described above. Below the reef edge a sloping terrace at an average angle of 10 deg. extended to a depth of 20 m or more.

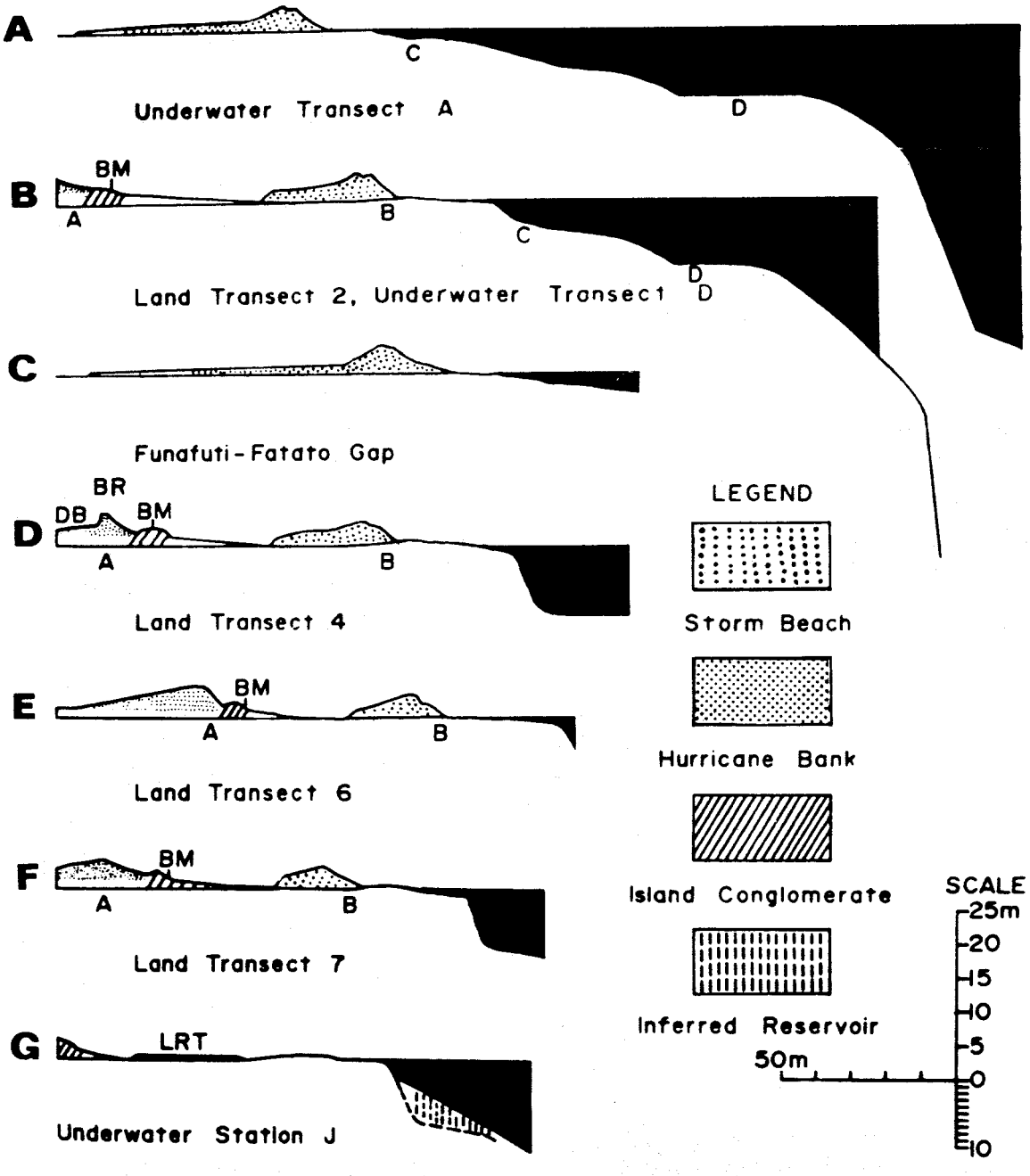

Figure 4. Reef rim and offshore profiles (Transect numbers and letters refer to Fig. 1): **A** and **B** — the limits of the surveyed land transects; **C** and **D** — the limits of the underwater transects; **BM** — brass peg benchmark in island conglomerate; **BR** — "hurricane bank" relict; **DB** — displaced "hurricane bank"; **LRT** — low rubble tract. Sea level shown corresponds approximately to extreme low water spring tide. Dimensions above water level not otherwise labelled are from aerial photographs. Underwater profiles not surveyed have been drawn from notes made during dives.

Much of this terrace at a depth of about 10 m was a broad flat shelf. Below 20-30 m the profile dropped abruptly over rocky walls and piles of loose coral rubble to a depth of 45-65 m., ending above a more gentle slope of *Halimeda* sand.

Although not abundant, a variety of corals was found on the rocky walls below 20-30 m. Corals and algae were more common along the upper margin of this cliff, the lowest limit at which recently-damaged corals were found. At depths shallower than 15-20 m, however, corals, calcareous algae and other organisms expected at this depth and recorded for Funafuti by Finckh (1904) were virtually absent. The slope and platform between depths of 8 m. and 20 m. were covered with loose-lying rubble similar in shape and size to that of storm beach on the adjacent reef flat. This rubble and the rock slopes of and below the groove-spur system supported a growth of a filamentous green alga, *Chlorodesmis*, which at 10 m depth covered more than 85 per cent of the substrate.

At shallower depths within the reef edge grooves on underwater transect D, the echinoid, *Echinometra*, the calcareous alga, *Porolithon*, and remnants of the corals *Acropora* and *Pocillopora*, usually little more than their encrusting bases, were found confined to cracks and recessed pockets which would have afforded protection from wave action and abrasion. On underwater transect A corals, including *Porites*, *Acropora*, *Pocillopora*, *Montipora*, *Favia*, *Plesiastrea*, *Symphyllia* and *Hydnophora*, were found in the grooves in the shallow water to depths of about 4 m. The total coral cover on these two profiles at depths of less than 4 m. was less than 1 per cent, *Chlorodesmis* again providing the dominant cover. In turbid water seaward of the inter-island gaps where visibility was reduced to as little as 0.5 m. *Chlorodesmis* was less abundant and grew in shorter tufts, matted with fine sand and sediment. In these areas a brown alga resembling *Ralfsia* was more common than elsewhere.

The dive which was made at a point beyond the northern extremity of the storm beach revealed much less disturbance (Fig. 4 F). Seaward of the steep front of the spurs a slope at an angle of about 20 deg. extended from a depth of 2 m to 10 m or more beyond which the gradient gradually steepened. Across this slope and onto the base of the reef front buttresses a variety of corals, including *Millepora*, *Acanthastrea* and *Favia* in addition to those genera recorded for shallow water on transect A, were found, mainly in scattered clumps with a cover of about 10 per cent. The dominant cover was provided by *Porolithon* which cemented the substrate fragments in position and gave a rounded contour to the undulations of the slope. Finckh (1904) had previously noted the dominance of this alga on the seaward slope at Funafuti. Loose rubble fragments were found in the shallow furrows that cut down the slope as extensions of the reef front grooves. These fragments were numerous at the upper ends of the furrows, but became less abundant with depth and were all but absent at 10 m *Chlorodesmis* was dominant on the reef front buttresses and the upper walls of the grooves though present on the slope only on the loose fragments in the furrows.

Three snorkel dives adjacent to the NE section of the storm beach (Fig. 1 G-I) revealed an area of intermediate storm damage. Opposite the end of the storm beach (Fig. 1I), minimal disturbance was seen. Off the NE end of the airstrip (Fig. 1G), the profile differed little from those seen off islands along the SE coast of Funafuti. The third dive was made between these two points and about 150 m south of the end of the storm beach (Fig. 1H) *Porolithon*-encrusted spurs with scattered coral cover extended across the slope alternating with deeper, boulder-strewn, level areas covered with filamentous algae. Corals persisted at the base of the buttresses. Little evidence was seen during any of these dives of damage to the buttresses and spurs.

V. THE "HURRICANE BANK"

A. HUMAN MODIFICATION OF THE "HURRICANE BANK"

Stoddart (1968) has drawn attention to the modification of atoll morphology consequent upon airfield construction. During the Second World War Funafuti was developed as a forward base, an airfield occupying much of the main island (Fig. 1). Fill for airfield construction was obtained by removing unconsolidated material from the centre of Tengako and from Funafuti north and south of the airstrip. Much of this material came from the landward slope of the "hurricane bank" which was trimmed back to leave an almost vertical escarpment 2-5 m landward of the crest. David and Sweet's maps (1904) show its previous landward extent. Along the SE aspect of Funafuti this excavation into the "hurricane bank" extended from just south of transect 3 (Fig. 1) to a point 160 m north of the present meteorological station, a total distance of 2 km. More recently, vegetation had been removed from a section of the "hurricane bank" at the SW end of the airstrip to comply with glide path regulations. A trench excavated through the "hurricane bank" near the meteorological station in 1970 was open when hurricane Bebe struck.

B. MODIFICATION DURING HURRICANE BEBE

Landward movement of "hurricane bank" material along the SE coast of Funafuti was extensive. Along the NE coast, however, disturbance was slight. Although portions of the bank which had not been modified by man — those NE of the meteorological station and at the southern end of Funafuti — retained their general form, much of the material of the seaward surface had been displaced over the crest. North of the meteorological station at a point where David and Sweet's map showed the landward slope to extend some 40 m behind the crest, sheets of whitened rubble extended inland for about the same distance.

The 2 km section from which rubble of the lagoonward slope had been removed for airfield construction had been extensively damaged. About 40 per cent of the total length of this section was eroded to about 1.5 m below its former level and transported inland to be deposited as white rubble sheets (Fig. 2B; Fig 3A). The largest single section to collapse in this way was at the SW end of the airstrip, where vegetation had been removed. Rubble from this 500 m section extended 50 m from its former position onto the runway. Elsewhere along this section scour channels, similar to those observed at Jaluit (McKee, 1959), extended through the bank leaving it as a series of relicts, their surfaces covered by tangled root mats and their crests 1 m-1.5 m above the channels (Fig. 2D). A conspicuous scour channel, 8 m wide, had developed along the line of the narrow unfilled trench previously excavated near the meteorological station. This appeared to have facilitated erosion of the "hurricane bank" at this point by the wave which inundated the island.

Landward displacement of the seaward slope of the "Hurricane bank" along the SE coast of Funafuti produced a scour trench, similar to that described by McKee (1959), up to 0.5 m deep behind the shore conglomerate (Fig. 2 E).

C. "HURRICANE BANK" STRUCTURE

At a point just north of the meteorological station, where the landward side bank had been excavated to produce an escarpment, stratification was evident. In a 2 m section above a pile of rubble there were four layers, lacking any cohesion. The upper stratum, about 1 m thick, of rounded, imbricated cobbles up to 40 cm maximum dimension and averaging 15 cm, overlay 35 cm of fine, angular fragments (Fig. 2F). The third stratum of less-rounded rocks, of similar dimensions to those in the upper layer and about 50 cm thick, also rested on finer fragments.

Stratification was also seen in the "hurricane bank" relicts south of the airstrip. A pumice laver was present 0.5 m below the root mat together with a high component of small rounded stones and sand. Within these relicts lithification had occurred to a height conservatively estimated as 1 m above M.H.W.

VI. DISCUSSION AND CONCLUSIONS

Evidence from both deposition and erosion on the atoll indicate that waves generated by hurricane Bebe arrived from the SE. An attenuation in storm wave effects was seen in a northerly direction along both the NE and SW coasts.

The absence from the storm beach of material of terrestrial origin, the presence of the remains of recently killed marine organisms, and the sharply defined gap separating the landward margin of the storm beach from the shore, all indicate a submarine origin for the rubble of the new storm beach. From our underwater observations we have deduced that the rubble had been elevated from a sloping offshore terrace from depths of less than 20 m., most of the material probably having come from an almost level shelf at a depth of about 10 m. In the process the benthonic communities above 10 m were destroyed. In inter-island gaps this rubble source apparently lay at a greater distance from the reef edge than was the case adjacent to islands. Our dives north of Funafuti's eastern extremity, where the energy of hurricane generated waves had been attenuated by refraction, revealed a reservoir of material close to the upper reef front (Fig. 4G). This material was not loose but united by a *Porolithon* veneer and cemented onto the slope. We believe that this material is so positioned as to constitute a potential source of storm beach rubble.

It seems clear that the large wave which crossed the "hurricane bank" by the meteorological station and caused considerable damage and death there effected the major erosion of the bank. Erosion of the bank elsewhere probably occurred at the same time. The distinct space between erosion on the shore and deposition on the reef flat suggests that the former preceded the latter. The form of the storm beach adjacent to the SE coast of Funafuti with its single crest, uniform landward slope and its undulating, cuspate landward margin, suggests formation mainly or wholly as a single deposition. Variations in bathymetry or reservoir size could, however, explain the marked variation in width. The formation of the storm beach was not observed and the precise time and mode of formation remain uncertain. The inter-island storm beach, however, cannot be explained as the product of a single event. The position and form of the beach would appear to have been a consequence of the material originating at a greater distance from

the reef edge and of the gentle offshore profile. If elevation from the reservoir were by a single wave, this wave, dissipating its energy over a long profile, may have deposited its load both seaward and lagoonward of the reef crest. The characteristic low rubble sheet on the lagoon side of the crest could have been formed from that part of the load carried over the crest and deposited gradually by the wave in moving towards the lagoon. Subsequent storm waves could have worked the material lying in shallow water seaward of the reef crest into a relatively uniform beach crest on the reef flat. These depositional features could, however, also be explained as the consequence of multiple elevations of material from the reservoir.

Conglomerate platforms with a plain upper surface at about the level of high tide have been noted beneath motus or isolated on the reef flats of many atolls. Their widespread distribution has been taken by many authors (cited by Newell and Bloom, 1970) as evidence of a Holocene eustatic higher stand of the sea. More recently they have been regarded as clastics consolidated between tidal limits during a period of relatively stable sea level (Curray *et al.*, 1970; Newell and Bloom, (1970). The elevation at Funafuti of a storm beach of such magnitude lends support to the latter view. David and Sweet (1904) considered their observations of *in situ* corals above present low water, and lithification at high levels in motu conglomerates as evidence of a higher sea level at Funafuti in the past. If this were the case a recent fall in sea level could have accelerated the rate of accumulation of material in the reservoir and at the same time increased its potential for deposition on the reef flat by reducing the depth of water above the terrace. Determination of the age spectrum of the material in the storm beach could be instructive in indicating the period of accumulation of the reservoir and in suggesting the time required for replenishment. It could also assist in interpreting the radiometric dates available for atoll island conglomerates (Curray *et al.*, 1970).

A change in the position and form of the storm beach under the action of storms and SE swells can be expected. Some seaward erosion may occur and shoreward movement of much of the rubble is possible. This was the fate of the gravel tracts at Jaluit (Blumenstock *et al.*, 1961) and storm debris on British Honduras cays (Stoddart, 1965). However, the Funafuti storm beach is much larger than were these rubble deposits. Also, shoreward movement, colonization by strand vegetation, and lithification, should they occur, would all tend to stabilize the material and lead to a seaward prograding of the motus. Lithification is known to occur rapidly and this process would be facilitated in the storm beach by the presence of fine interstitial material. Fine sediment, thought to have been derived from wave action on the face of the storm beach and to have been transported through the beach, was observed settling in the moat and similar material is likely to be accumulating at the base of the storm beach.

Wave action on the inter-island sections of the storm beach appears already to have been more active and seaward transport of fine sediment is taking place. The present distribution of motus may itself suggest that the inter-island storm beach is in a less stable location than is the storm beach adjacent to islands. The three elongate, lenticular islands between Funafuti and Te Buabua are located where the reef platform is relatively broad with a convex seaward reef rim. By contrast, seaward reef rim concavities and a relatively narrow reef flat characterize inter-island gaps. Offshore, the terrace contour appears to follow a less sinuous line than does the reef edge. A similar observation was made at the atoll of Bikini by Emery *et al.*, (1954). Whether or not this reef configuration, the result either of growth at the convexities or erosion in the concavities, predated the formation of the motus, material which may have existed on the reef-surface of inter-island gaps in the past has not persisted. David and Sweet (1904) considered that the motus of Funafuti had been more extensive in the past. If correct, this would suggest the formation of concavities by erosion.

Funafuti, lying north of the region in which tropical cyclones normally intensify to hurricane strength has experienced only two other hurricanes in the past 100 years, in 1891 and 1958 (Vischer, 1925; NZ Meteorological Service, 1960). Surprisingly, David and Sweet (1904) make no reference to the 1891 hurricane although they postulate that a pumice layer present in the "hurricane bank" under 0.6 m of rubble in 1898 had originated in New Britain in 1878. If this view is correct then the upper layer of the "hurricane bank" was probably deposited on the reef flat in 1891 and worked into its observed position by the time of David and Sweet's visit. The stratification of the "hurricane bank" suggests that such events have occurred periodically. The presence of conglomerate blocks and slabs in the "hurricane bank" and on its landward slope indicate that storms at Funafuti have effected landward displacement of the motu shore. Cuesta-like ridges on Funafuti's SE coast (Fig. 3A), similar to those noted at Raroia by Newell (1954), together with seaward projecting conglomerate spurs would seem to confirm this view. The quantity of material elevated along the Funafuti NE coast as low rubble tracts was much less than that of the SE coast storm beach and this difference appears to reflect differences in wave direction and energy rather than variations in reservoir size. The quantity of material in the "hurricane bank" upper stratum (Fig. 2F) appears to be

of the same order of magnitude as that in the newly deposited rubble tracts. The elevation of rubble tracts may be a common occurrence during hurricanes (Newell and Bloom, 1970) and may often be accompanied by the net erosion of the seaward shores of motus as noted on a number of atolls (Wiens, 1962). However, the formation of massive storm beaches, while infrequent, could lead to a seaward prograding of motus and might in this way account for the seaward sequence of ramparts seen in some localities (Wiens, *loc. cit.*). The formation of motus in the manner postulated by Cloud (1952) probably would require events of this magnitude for initiation.

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