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The Impact of Cyclone Isaac on the Coast of Tonga[1]

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ABSTRACT: Cyclone Isaac passed through the limestone and sand islands of the Ha'apai and Tongatapu groups of the Kingdom of Tonga on 3 March 1982 and was probably the most severe storm experienced in southern Tonga in more than 100 years, causing extensive damage to buildings and crops. The limestone islands most affected by the storm are composed principally of reefal limestones, and the coastal terraces are late Pleistocene in age, many having been dated to the last Interglacial. There is little evidence of past storms preserved on the coast, and storm blocks and extensive rubble deposits on reef flats are rare or absent. The worst hit islands were in the Ha'apai group. Here the raised reefal limestone cliffs of the eastern shores of islands on the barrier reef resisted the storm, except for blocks of up to 2 m in diameter detached from the upper visor of a wave-cut notch on Ha'ano. Coastal scrub, however, was stripped, coconut palms were felled and *Pandanus* was broken for more than 50 m on Ha'ano, 30 m on Lifuka, and locally on Foa and 'Uiha. Some regeneration of the dominant shrubs, *Messerschmidia argentea*, *Hibiscus tiliaceus*, and *Bikkia tetrandra*, was observed at the time of survey, 11–15 weeks after the storm. Both deposition and erosion were noted on pocket beaches between cliffs of reefal limestone, with at least 28 m^3 per m of sand removed from the beach face on one beach on Lifuka. The island of Tatafa was severely devastated; the cyclone had passed directly over the southern end, causing the sandy shoreline to retreat by 200 m, scouring a channel through the island, leaving scour holes on the western side, and destroying much of the coastal scrub. Tongatapu also sustained much damage to buildings and crops, and much of the north coast was flooded. The greatest change was observed to have occurred on sand cays off the northern coast. Four of these underwent change since a survey in 1969, and much of the change could have been attributed to Cyclone Isaac. The greatest change occurred on the smallest island, Manima, with coconut stumps left on the reef flat to the east indicating at least 12 m of shoreline retreat. On Oneata and Pangaimotu deep-rooted individuals of *Excoecaria agallocha* were left exposed more than 8 m on the eastern shore by destruction of the coastal scrub. On Makaha'a retreat of the shoreline was localized, and along much of the coast a sand cliff occurred which had changed little since it was mapped in 1969. Undercutting of the shore and formation of a sand cliff appear to be related to the presence of beachrock at the foot of the beach, and the storm did not cause much shoreline retreat. On the northern sand cays off Tongatapu patterns of change were variable. On Fafa recession occurred on the eastern and northeastern shore, but also occurred to the south, reflecting the configuration of the reef flat. Monuafe and Tufaka lost some scrub but the lack of woody vegetation meant that little evidence of former island shape remained. Deposition occurred on Malinoa, the sand cay nearest to the path of the storm, which is situated on a narrow reef flat and is open

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to a long fetch and deep water to the east. Few of the topographic changes brought about by Cyclone Isaac will remain for long before they are obscured, except the reshaping of Tatafa. Similarly, rapid regrowth of vegetation implies that coastal vegetation will soon be restored, but changes in composition may persist. Though Cyclone Isaac was a severe storm, a type which occurs infrequently, its effects on the coastal landforms and vegetation of Tonga appear to have been less than those of similar storms on more isolated atolls elsewhere in the Pacific.

THE MAJORITY OF THE CORAL reefs and islands of the world lie in areas which are susceptible to tropical cyclones. Although the frequency of catastrophic storms varies, those of greatest magnitude can be important in shaping reef morphology, reef island topography, and coastal vegetation communities (Stoddart 1971). In the last two and a half decades knowledge of the effects of storms on such environments has increased considerably. Detailed studies have been undertaken, not only on the immediate impact of storms (Blumenstock 1958, 1961; McKee 1959; Craighead and Gilbert 1962; Stoddart 1962, 1963; Ball, Shinn, and Stockman 1967; Maragos, Baines, and Beveridge 1973; Baines, Beveridge, and Maragos 1974), but also on the effects of subsequent storms on the same coast (Sauer 1962, McIntire and Walker 1964, Perkins and Enos 1968) and on landform adjustment and vegetation recovery (Blumenstock, Fosberg, and Johnson 1961; Stoddart 1965, 1974; Baines and McLean 1976).

Studies of the effects of Typhoon Ophelia (1958) on Jaluit Atoll in the Marshall Islands and Tropical Cyclone Bebe (1972) on Funafuti Atoll in Tuvalu have shown the immense erosional and depositional impact that storms of hurricane force can have on isolated reefs in the Pacific. On both of these atolls rubble ramparts were deposited on the eastern reef flats of the atoll, and these deposits subsequently migrated landward, adding a new lithological unit to the reef islands (Blumenstock, Fosberg, and Johnson 1961, McLean 1974, Baines and McLean 1976). Cyclones have also been observed to have had important effects on the morphology of reef islands on the Great Barrier Reef (Moorhouse 1936, Gleghorn 1947, Stephenson, Endean, and Bennett 1958, Hopley 1974, Flood and Jell 1977).

In contrast to the studies on isolated atolls or on the Great Barrier Reef, relatively little is documented about the effects of intense storms on raised limestone islands and sand cays of island groups in the southwest Pacific. There are reports of the impact of tropical cyclones in the Lau Islands, Fiji (Phipps and Preobrazhensky 1975, McLean 1977), and of sedimentological effects of a cyclone in New Caledonia (Baltzer 1972). This study describes the impact of Cyclone Isaac on the coast of both limestone and sand islands in the Kingdom of Tonga. Cyclone Isaac, which hit the Ha'apai group and passed close to the Tongatapu group on 3 March 1982, was probably the most severe storm experienced in southern Tonga this century.

GEOLOGY AND GEOLOGICAL HISTORY OF THE AREA

The Kingdom of Tonga consists of more than 150 islands with a total surface area of a little over 700 km^2. Most of the islands lie in a discontinuous chain, from Tafahi in the north (16°10′ S, 173°40′ W) NNE–SSW to Ata in the south (22°08′ S, 176°08′ W). To the west along the submerged Tofua Ridge there are a series of volcanic islands, several of which are still active, composed predominantly of basaltic andesite, andesite, and dacite rocks (Bauer 1970, Bryan, Stice, and Ewart 1972, Ewart, Bryan, and Gill 1973). To the east the Vava'u, Ha'apai, and Tongatapu groups of islands are composed mainly of reefal limestones of Pliocene to Recent age, but with exposures of older rocks on some islands (Figure 1). These islands represent at least five distinct fault blocks—the Vava'u, northern Ha'apai, southern Ha'apai, Nomuka, and Tongatapu blocks —on the Tongan frontal arc which extends

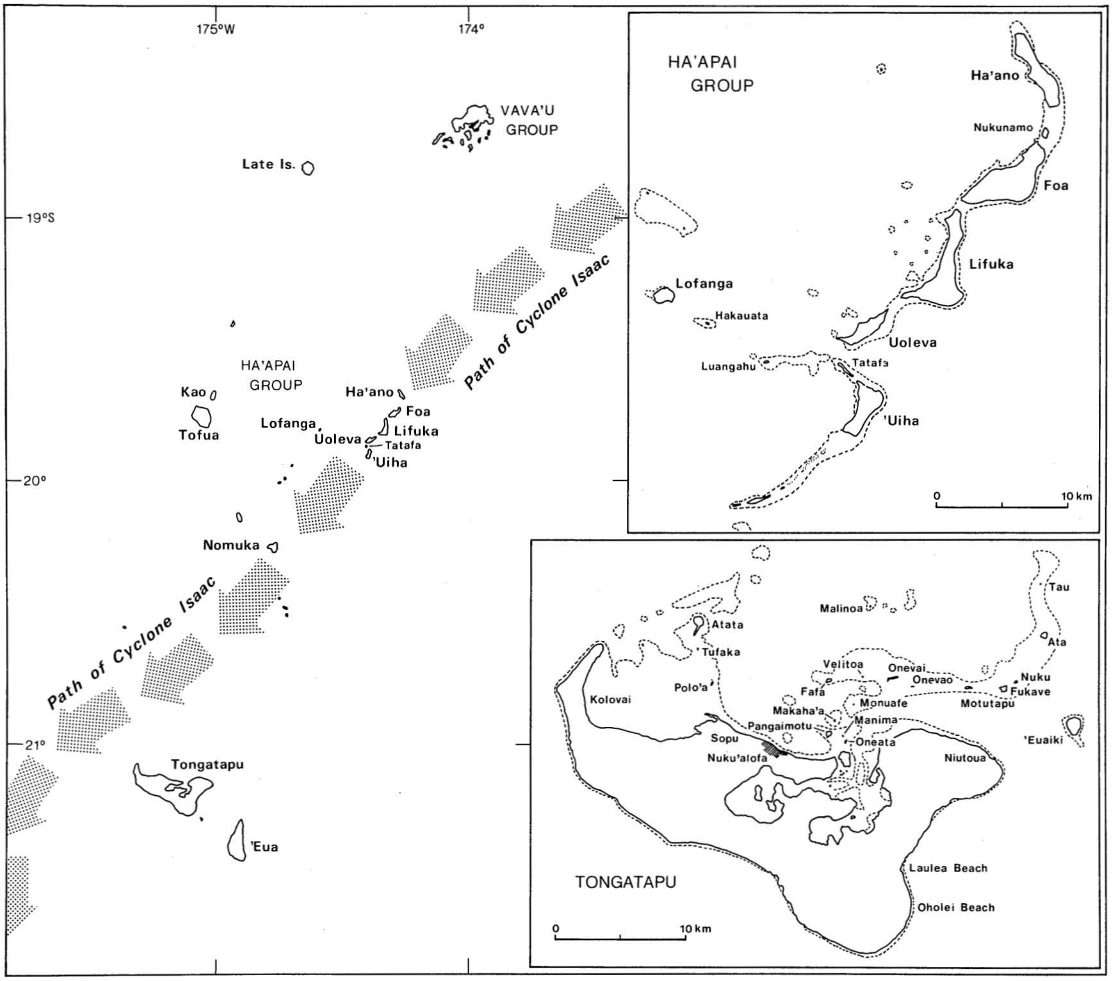

FIGURE 1. The Kingdom of Tonga, showing the path of Cyclone Isaac and islands in the Ha'apai and Tongatapu groups (insets).

SSW to join the Kermadec arc (Taylor 1978). The frontal arc is separated from the Tofua Ridge to the west by the Tofua Trough, and is bounded to the east by the Tonga Trench with water depths increasing rapidly to more than 10,500 m. The fault blocks have evidently had independent tectonic histories continuing at least into the Pleistocene (Katz 1976); Eua has undergone pronounced uplift, while Vava'u, with a deeply embayed coastline, appears to be subsiding.

Cyclone Isaac had its more devastating effect on the islands of the Ha'apai group, Tongatapu, and the sand cays off the northern coast of Tongatapu, and it was these islands that were visited in this study. The Ha'apai group consists of a series of limestone islands, the largest, Foa, being 7.3 km long and 2.3 km wide, lying along a barrier reef on the margin of the Tonga Trench. To the west and south there are numerous smaller islands, the largest, Lofanga, being 1.8 km long. The southern Tongatapu group is dominated by two larger islands, Tongatapu itself, 35 km long and 25 km wide, and Eua, 20 km long and 7 km wide.

Coastal Geomorphology of the Ha'apai and Tongatapu Groups

The coastal geomorphology of the limestone and sand islands of Tonga is a function of the geology and lithology of the islands, tectonic movements of the fault block on which the islands lie, oscillations of sea level during the Quaternary, and the supply of sediment and energy conditions, including storms, to which the coast is subjected. The geology of Eua is best known as this island, reaching a height of 312 m, has undergone the most rapid uplift. The stratigraphy consists of Eocene tuffs, gabbros, and basic to intermediate lavas into which dykes of basalt have intruded; Eocene foraminifera-bearing fine calcareous tuffs; Eocene massive foraminifera-bearing limestones; and Eocene highly-fossiliferous limestones, overlain unconformally by Miocene volcanoclastic sediments, above which are Pliocene and Quaternary reefal limestones (Hoffmeister 1932, Stearns 1971, Tongilava and Kroenke 1975, Taylor 1978). Evidence of former still-stands of sea level is preserved in the form of terraces identified by Hoffmeister (1932) at heights of approximately 30, 60, 105, 120, 170, and 230 m, several being tilted to the northwest. Taylor and Bloom (1977) and Taylor (1978) identified a further terrace at approximately 7 m, in which corals up to 5.5 m above high-tide level were dated using U-series radiometric dating to 133,000 ± 12,000 years B.P., and a lower emerged coral reef, first described by Ladd and Hoffmeister (1927), 1.0 m above high-tide level dated at 6120 ± 110 years B.P. by ^{14}C and 5700 ± 500 years B.P. by U-series.

The other limestone islands of the Ha'apai and Tongatapu groups do not reach as great an elevation as Eua and have not been uplifted as rapidly; and the most extensive rocks are the reefal limestones of Pliocene to Recent age. Although the underlying stratigraphy is probably the same as on Eua, the Miocene volcanoclastics are exposed on only a few other islands in the Nomuka-Mango group (Lister 1891); they do not appear on the islands of the Ha'apai barrier reef and are not exposed on Tongatapu, where they have been encountered at 137 m in bores and are more than 1500 m thick (Katz 1976).

The larger islands in the Ha'apai group lie on the barrier reef (Figure 1) and are generally limestone-cored. Lifuka is typical of the islands from Ha'ano to 'Uiha. On this island several profiles were surveyed to illustrate both coastal morphology and the effects of the storm (Figure 2). Smaller islands such as Uoleva and Tatafa are composed of sand. To the east of the barrier reef water depths increase rapidly into the Tonga Trench; the nearly horizontal reef flat, 50 m–1 km wide, has a pronounced algal rim, often prominently terraced and in several instances rising 50 cm or more above high-tide level (profile 1a, Figure 2); elsewhere isolated outcrops of raised reefal limestone occur on the reef flat (profile 2a, Figure 2). To the west of the islands the reef flat is less continuous, with patches of reef more than 1 km from the islands.

The limestone-cored islands of the barrier reef rise with a gradual gradient from the western shore, much of which is a sandy beach, to a maximum height of more than 15 m toward the eastern shore. The raised reefal limestones form a cliff on the eastern shore, with a number of pocket beaches between headlands. The cliff rises steeply 3 m from the reef flat and then less steeply to 6 m high (ie, profiles 1a, 1b, 2a, 2b, 6, and 8, Figure 2). Within this limestone numerous corals can be seen in their position of growth. The coastal terrace evidently represents an emergent fossil coral reef, equivalent to the *makatea* of other Pacific islands. Taylor and Bloom (1977) and Taylor (1978) reported U-series ages of 130,000 ± 12,000 and 158,000 ± 14,000 years B.P. on corals up to 4.2 m above high-tide level from Foa and imply that a raised reef of last Interglacial age surrounds older limestone cores on these islands. There are a number of erosional sea-level features on these cliffs between high-tide level and 3 m above high-tide level (Figure 2). These often combine to form a complex composite notch up to 3 m high along the eastern coast, though Taylor found an absence of datable material in similar features on Eua and Tongatapu and was unable to relate erosional features to constructional sea-level features (Taylor 1978).

Taylor (1978) did not find a raised Holocene reef in his brief survey of Ha'apai. However, there are corals in position of growth and

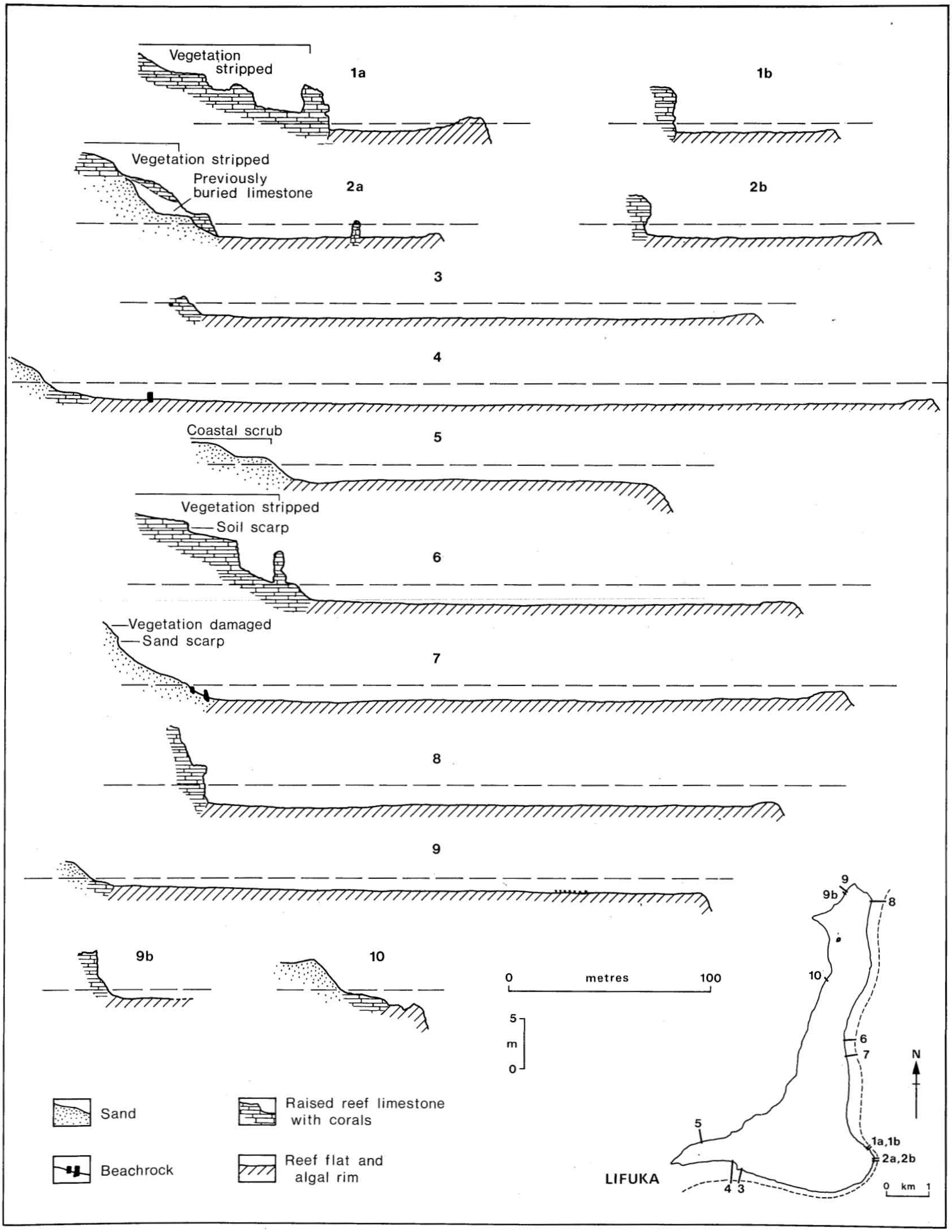

FIGURE 2. Profiles of coastal morphology and storm damage, Lifuka (with respect to high-tide level).

TABLE 1

RADIOCARBON AGES OF RAISED CORALS FROM HA'APAI AND TONGATAPU

SAMPLE	N.Z. ^{14}C NO.	LOCATION	GRID REFERENCE	MATERIAL	^{14}C AGE*
Tonga/fW1	6133	Foa	853174	Raised in situ coral	3200 ± 40
Tonga/fW2	6134	Foa	841158	Raised microatoll	5810 ± 60
Tonga/fW4	6136	Lifuka	789122	Raised in situ coral	5600 ± 60
Tonga/fW5	6137	Tongatapu	842635	Raised microatoll	4490 ± 60

* Radiocarbon ages determined at the Institute of Nuclear Sciences, New Zealand Radiocarbon Dating Laboratory. Ages quoted on the basis of ^{14}C half-life of 5568 ± 30 years, and reservoir corrected with respect to Fiji Shell Standard.

above the present limit of coral growth at several places around Lifuka: at high-tide level on profile 10, 40 cm below high-tide level on profile 9, and 1 m below high-tide level on profile 4 (Figure 2), and there are raised corals and degraded microatolls on the north and west coasts of Foa. A ^{14}C age of 5600 ± 60 years B.P. was determined for a coral from the raised reef on profile 9, and ages of 5810 ± 60 and 3200 ± 40 years B.P. were determined for a microatoll on the west coast and for a coral from a raised reef on the north coast of Foa (Table 1). These are evidently remnants of a Holocene raised reef and are of similar age to the raised reef on Eua, with the coral at the north of Foa appearing rather younger.

Tongatapu is the largest island in Tonga and is roughly triangular. It reaches a maximum elevation of 65 m to the southeast, where there is a palaeo-island core of Pliocene–Pleistocene limestones. Much of the island is composed of a terrace at 20–35 m, which represents a series of reefs fringing the palaeo-island core, and adjacent patch reefs. Elsewhere there is a lower terrace at about 7 m, within which Taylor and Bloom (1977) and Taylor (1978) describe two barely distinguishable coral reef formations; the older but lower reef, with corals reaching to 3.0 m above high-tide level dated to 240,000 ± 40,000 and 205,000 ± 20,000 years B.P. by U-series dating; the younger, with corals reaching to 5.4 m above high-tide level, dated to 135,000 ± 15,000 years B.P. These late Pleistocene reefs, though with older limestones exposed at some locations, form cliffs around much of the southwest, south, and east coasts of Tongatapu, often with basal erosional features and fringed with a generally narrow reef flat up to 200 m wide. In several places this reef flat has a well-developed algal rim, prominently terraced, while elsewhere the reef flat is replaced with a ledge or narrow platform at the base of the raised reefal limestone cliffs (Ladd and Hoffmeister 1927).

Lister (1891) described large coral heads in the streets of Nuku'alofa, and these occur up to 1.0 m above high-tide level. Taylor (1978) has reported U-series ages of 6200 ± 300, 7600 ± 800, 6200 ± 300, 5900 ± 900, and a ^{14}C age of 6360 ± 110 years B.P. on these corals, showing them to be part of a Holocene raised reef. In addition, there are numerous degraded emergent microatolls which occur on the reef flat to the west of Nuku'alofa and can be seen amongst the mangroves on the reef flat at least as far as Fatai and to the north of Nukunukumotu. These occur up to at least 53 cm above the present limit to coral growth on this reef flat; a ^{14}C age of 4490 ± 60 years B.P. was determined on one north of Sopu (Table 1) implying that they are of an age similar to or slightly younger than that of the features described and dated by Taylor from Nuku'alofa.

The island of Tongatapu decreases in elevation toward the northern coast, which is generally low lying and which is fringed with mangroves. The reef flat is most extensive on the northern coast, reaching more than 7 km to the north; on this reef flat extension and on separate reef flats to the northeast there are several small islands. The larger ones, such as Atata, are cored by reefal limestone, while the smaller islands are sand cays. Stoddart (1975) has described and mapped four of the sand cays and noted deposits of beachrock and undercutting along parts of their shore.

Taylor and Bloom (1977) and Taylor (1978) propose, on the basis of the similar age and elevation of late Pleistocene raised reefs of Eua, Tongatapu, and Ha'apai, that there has been no net differential movement of the fault blocks on which these islands lie since the last Interglacial. Their interpretation is complicated by the presence of an emergent Holocene reef on Eua and Tongatapu and its apparent absence from Ha'apai. Radiocarbon ages reported in Table 1 indicate that there are remnants of an emergent Holocene reef on the reef flat of islands in the Ha'apai group and that microatolls on the northern coast of Tongatapu are part of a raised Holocene reef which is more extensive than previously reported on that island. These corals are presently intertidal, and none reach the level of 1.0 m above high-tide level recorded for the Holocene reef on Eua or beneath Nuku'alofa. Nevertheless, they reinforce the suggestion that all three areas have undergone similar histories since the late Pleistocene.

Little direct evidence of past storms is preserved on the coast of Tonga. There are relatively few storm blocks on the reef flats, and rubble ramparts or partially consolidated rubble fields are generally absent.

CLIMATE AND PREVIOUS TROPICAL STORMS

Tonga lies in the belt of the southeast trades, and prevailing winds come from the east and southeast and less commonly from the south and northeast. Mean annual rainfall is 1801 mm in Ha'apai (range: 1093–2664 mm, period: 1947–1980), and 1878 mm in Nuku'alofa, Tongatapu (range: 1254–2655 mm, period: 1947–1980), the wettest months being January to March and the driest June. Mean daily temperature is 27.5°C and mean daily minimum is 21.9°C for Ha'apai; comparable figures for Nuku'alofa are 26.9°C and 20.5°C, respectively.

Lying in a chain across 6° of latitude, the Tonga islands are susceptible to tropical cyclones formed to the north. The hurricane season extends from November to April, with most storms recorded in January and March. Many of these cyclones travel south or southeast and may affect part of the Tonga chain; others, such as Cyclone Isaac, travel to the southwest and can be felt along the entire chain. Visher (1925) recorded 58 storms affecting Tonga in the 100 years before 1924, of which 16 were severe. That is an average of more than one in two years, but in several years more than one storm was recorded and in 1848 two severe storms occurred during two weeks in April. Kerr (1976) noted 19 additional storms in southern Tonga up to 1969, and there were storms in 1970 and 1973 and two in 1977 (Revell 1981). Those in 1912, 1937, 1961, and 1963 were particularly devastating.

CYCLONE ISAAC

Cyclone Isaac was undoubtedly one of the worst storms to hit Tonga this century. It claimed six lives and caused enormous devastation to buildings and crops; the damage to buildings on Tongatapu alone exceeded Tonga $10 million, and to crops more than Tonga $8 million (*Tonga Chronicle*, 12 March 1982). The cyclone developed about 160 km northeast of Western Samoa. It traveled southwest at an average speed of 12 knots, hitting the Ha'apai and Tongatapu groups on 3 March 1982. The system deepened as it moved toward Tonga; it was a small diameter storm in which hurricane-force winds were probably confined within a 50-km-wide zone. It was felt in Vava'u, though relatively little damage was done there. It passed through the Ha'apai group of islands where it is believed that sustained winds of 80 knots with gusts of 120 knots were experienced, though records were lost after a wind speed of 57 knots (N.Z. Meteorological Service). Cyclone Isaac then passed to the northwest of Tongatapu, and in Nuku'alofa a peak gust of 92 knots was measured. Wind direction appears to have changed during the passage of the storm and trees fell in all directions. The barometric pressure dropped to 976.4 mb at 1:45 pm (local time). More than 120 mm of rainfall fell on Tongatapu on 3 March.

Tides in Tonga are semidiurnal; the tidal range is about 1.22 m at springs and 0.98 m at neaps. Cyclone Isaac coincided with a high spring tide of 1.2 m at Nuku'alofa, predicted for 1:27 pm on 3 March. No tide gauge was in operation at the time of the storm and no record of the height of the storm surge is available, but the extensive flooding of coastal areas on the north coast, and the fact that almost the whole of Nuku'alofa was under water, testify that the water level was several meters above the high-tide level.

METHODS

The observations described in this paper were made during a visit to Tonga from 24 May to 21 June 1982, 11–15 weeks after the passage of Cyclone Isaac. Particular attention was paid to the impact of the storm on coastal landforms and coastal vegetation. The smaller sand islands were mapped using a rapid pace and compass traverse in the same manner as the 1969 survey of four of the islands by David Stoddart (Stoddart 1975). These surveys are therefore comparable and are both drawn with respect to magnetic north, though the absence of relocatable reference points and imprecisions of closure and scale determination inherent in the technique prohibit direct overlaying of maps. Beach profiles were surveyed with a clinometer, and a series of more detailed profiles using a Sokkisha automatic level were made and related to high-tide level.

RESULTS

The Ha'apai Group

Cyclone Isaac passed through the Ha'apai group of islands and caused widespread damage to buildings, crops, and coconut woodland, felling about 15% of the coconut palms. Extensive damage was obvious on much of the coast along the barrier reef. The islands along this barrier reef were studied in detail with visits to Ha'ano, Foa, Lifuka, Uoleva, Tatafa, and 'Uiha, and with a further visit to Lofanga (Figure 1). The storm also affected the isolated outlying islands in the western and southern Ha'apai group, but these were not visited.

RAISED REEFAL LIMESTONE COASTS: The limestone cliffs of the eastern shores, rising 2–3 m from the present reef flat, offered substantial resistance to the high seas of the storm and have undergone little morphological change. An exception is along the northeastern coast of Ha'ano where several fallen blocks of reefal limestone, up to 2 m in diameter and with white, recently exposed fractured surfaces, were observed detached from the upper visor of the wave-cut notch and dropped onto the reef flat, in some cases shifted a few meters to the east.

The coastal scrub of the raised reefal limestones was devastated. The prestorm vegetation of the cliff tops evidently comprised a scrub dominated by *Bikkia tetrandra* and *Hibiscus tiliaceus*, in which *Messerschmidia argentea*, *Clerodendrum inerme*, *Excoecaria agallocha*, *Terminalia litoralis*, and *Desmodium umbellatum* were important, with dwarfed *Pemphis acidula* to seaward, and much *Pandanus* sp. forming a zone about 10 m from the seaward edge. To landward of the *Pandanus* zone *Cocos nucifera* became increasingly prominent.

In the worst-hit areas the vegetation was severely damaged by the wind, and soil was completely removed, with local deposition of coral gravel suggesting flooding of the cliffed coastline up to 6 m above high-tide level. The damage was worst on the northeastern coast of Ha'ano, from which the vegetation was stripped for more than 50 m inland, and in places up to about 80 m. Woody plants generally lost all foliage, but the root systems remained interwoven amongst the rock. Along this coast of Ha'ano the low *Pemphis*, less than 30 cm above the rock surface, remained, having been little damaged. Most evident in the area are the broken stumps of *Pandanus*, almost all snapped off either just above the prop root system or just below the first branch. Few retained any branches and even fewer had any foliage left. Several of the shrubs also remained rooted on the rock, though their canopy and most branches were gone. Many had commenced regrowth from the stump, including *Messerschmidia*, *Terminalia*, *Hibiscus*, *Bikkia*, *Desmodium*, and *Excoecaria*. Less frequent, but in some cases having survived

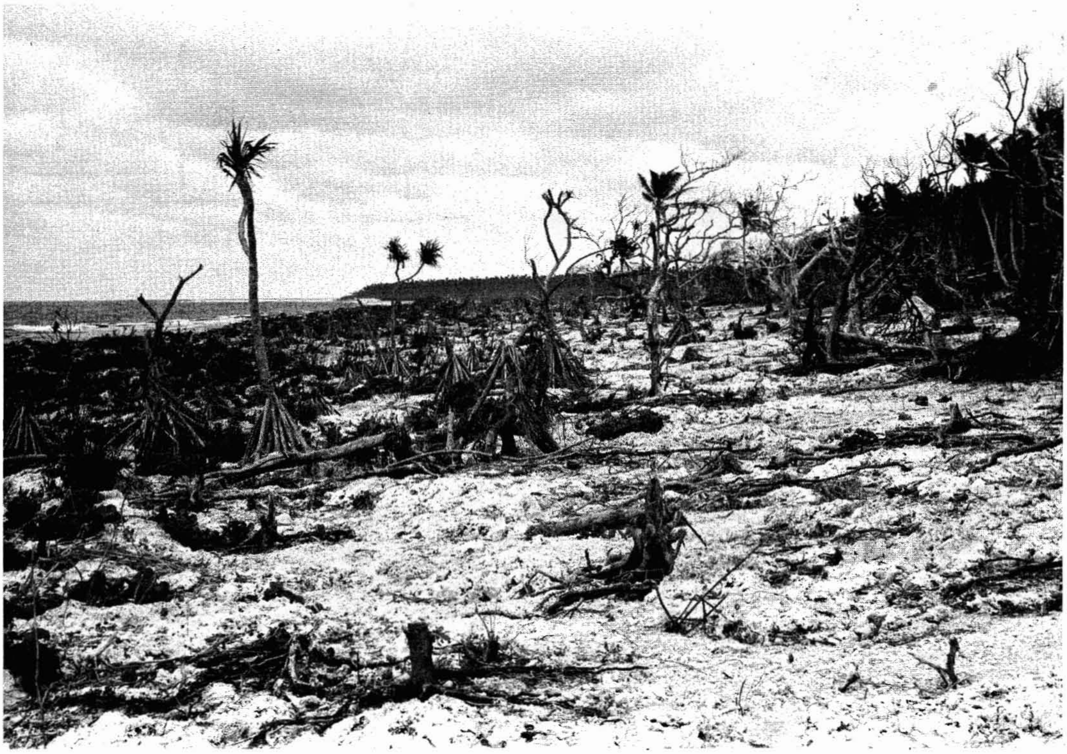

FIGURE 3. Coastal scrub stripped from the raised reefal limestone coast of northeastern Ha'ano.

the storm, were *Scaevola taccada*, *Euphorbia ramosissima*, *Leucaena insularum*, *Xylosma simulans*, *Acacia simplicifolia*, and *Canavalia sericea*. *Hernandia nymphaefolia* and *Pisonia grandis* had not been common along this coast, although individual trees were seen which had been left standing but entirely stripped of foliage and of the smaller branches. Coconut palms had also been snapped off in this belt of destruction. The coconut woodland behind the cleared area consists of *Pandanus* and coconut palms still standing but with damage to their crowns (Figure 3).

Similar devastation occurred along the eastern coast of Lifuka and was observed locally at sites visited on the east coast of Foa and 'Uiha. The width of the belt was less than on Ha'ano, but exceeded 30 m on Lifuka (profile 1a, Figure 2). To the southeast of Lifuka stumps of *Pandanus*, *Hibiscus*, and *Messerschmidia* were left after the storm, with low *Pemphis* on some of the seaward cliff tops. On Lifuka *Bikkia*, *Canavalia*, *Leucaena insularum*, *Wedelia biflora*, *Euphorbia cyathophora*, *Terminalia*, *Clerodendrum*, and *Portulaca* sp. survived locally on this raised reef limestone shore.

Lofanga has a similar raised reefal limestone coast. In the center of the island many big trees were uprooted, but the coastal vegetation did not suffer such severe damage. On those coasts on which damage was sustained, and from which soil was removed, regeneration will presumably be slow and restricted initially to regrowth from the stumps.

BEACH MORPHOLOGY: The greatest changes to beaches in the Ha'apai group occurred on the pocket beaches found along the eastern shore of the islands, between headlands of the raised reefal limestone. Erosion took place on the shorter beaches and deposition on many of the longer beaches. No study of prestorm beach forms exists, but some record of the prestorm profile was derived from outcrops of limestone on which a line was detectable (like that described by Ogg and Koslow, 1978, from beaches after a storm on Guam) between white limestone previously buried beneath sand and not exposed long enough to have an algal coating and that subaerially exposed limestone on which algal growth had discolored the rock to a dark gray. Several such locations were found on the east coast of Lifuka and on the east coast of Ha'ano, illustrating removal of as much as 1 m depth of sand. The greatest depth of removal was observed at the site surveyed on profile 2a (Figures 2 and 4), where more than 1.9 m of sand was removed at the landward edge of the beach. The limestone outcrop does not extend to the foot of the beach and hence the change of volume near the foot is unknown, but at least 28 m^3 per m of sand was removed from the beach face from the mid to upper beach.

Elsewhere along the eastern shore of Lifuka there was deposition of sand, particularly on the longer beaches. Profile 7 (Figure 2) is one site at which sand was deposited. The vegetation at the back of the beach, predominantly *Messerschmidia*, *Hibiscus*, and *Pandanus*, was broken and uprooted and is fronted by a sand cliff 1 m high. Stumps of *Messerschmidia*, with branches broken off but with some regrowth of leaves visible, occur up to 9 m from the present vegetated sand cliff, on the beaches, with sand deposited around them. These indicate the distance of vegetation retreat. The beach has a prominent berm at about high-tide level, and the lower beach is relatively steep, 8°, while the upper beach is at a lower angle and about 30 m wide. At the foot of the beach there is an outcrop of beachrock, which would seem to imply that there has been little progradation or recession of the foot of the beach; though the beachrock need not have coincided with the foot of the prestorm beach (beachrock is presently found 45 m to seaward of the foot of the beach on profile 4, Figure 2). Beachrock was not observed at the foot of all of the beaches on which deposition occurred; on some it may have been buried.

A similar depositional beach with a steep berm occurred on eastern Foa, where the lower beach reaches 9° and the upper beach 4–7°, with a total beach width of 40–50 m. At other sites along the eastern coast of Lifuka, the lower beach reaches 7–8°, while sand deposited on the upper beach is at 5° or less; total beach widths are 18–30 m, again frequently with buried stumps of *Messerschmidia* in the mid-beach showing signs of regrowth.

By contrast, little evidence of change was found on the beaches of the western coast of the islands on the barrier reef, or on any of the shores of Uoleva, which was presumably sheltered behind Lifuka. On these beaches angles of the lower beach are 5–7°, and beaches are rarely more than 20 m wide. On the northeastern shore of 'Uiha erosion was evident along the western end of the beach and a sand cliff up to 1.3 m high was scoured, but deposition appears to have occurred on the upper part of the eastern end of the same beach. The angles of the lower beach are 7–8° along the entire beach, but to the east the beach is considerably wider, up to 35 m.

The beaches that have received sand in the Ha'apai group have angles of the lower beach of 7–9°, while the unaffected beaches of the western shores and of Uoleva have angles of the lower beach of 5–7°. This steeper beach may result from the deposition of sand by the cyclone, or it may be a feature of the higher energy experienced along these coasts; the line between the white and the algal-colored rock on Ha'ano shows a prestorm beach angle of 9°, while that on Lifuka (Figure 2, profile 2a) indicates an angle of the upper beach of 4–6°. Deposition appears to have occurred mainly above high-tide level. No obvious relationship was observed between poststorm beach morphology and the width of the reef flat.

TATAFA: The island of Tatafa was probably the most severely devastated in Tonga as a result of Cyclone Isaac. Tatafa is a sand island lying to the north of 'Uiha and separated from Uoleva by a deep channel more than 1 km wide. The island is oriented NW–SE and is composed of sand, with no exposure of reefal rock though with beachrock around much of its perimeter. The cyclone seems to have passed directly over the southern end of Tatafa resulting in total removal of much of that part of the island. The Directorate of Overseas

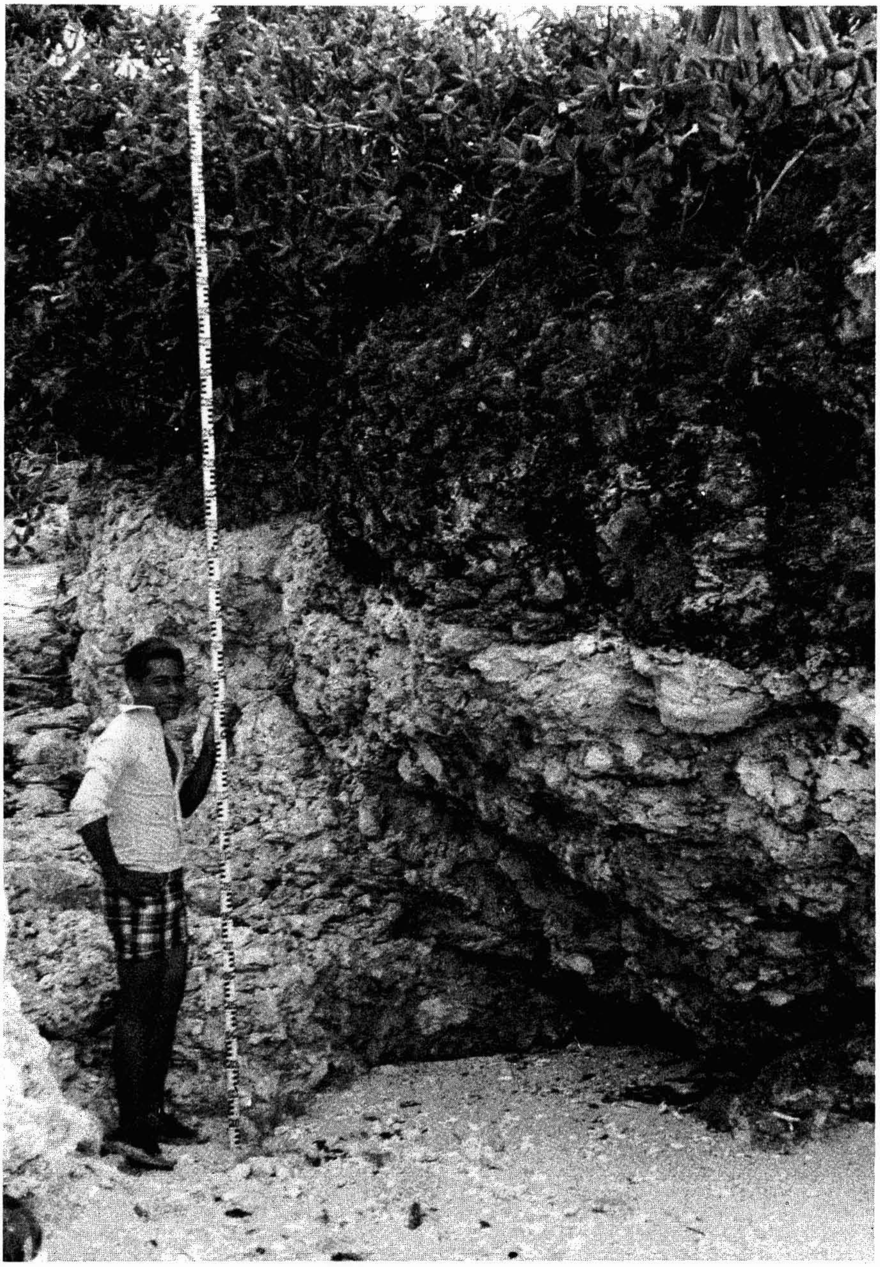

FIGURE 4. Removal of sand from the beach, profile 2a, Lifuka; the white limestone was previously buried by sand, while the darker limestone has been exposed and has an algal cover.

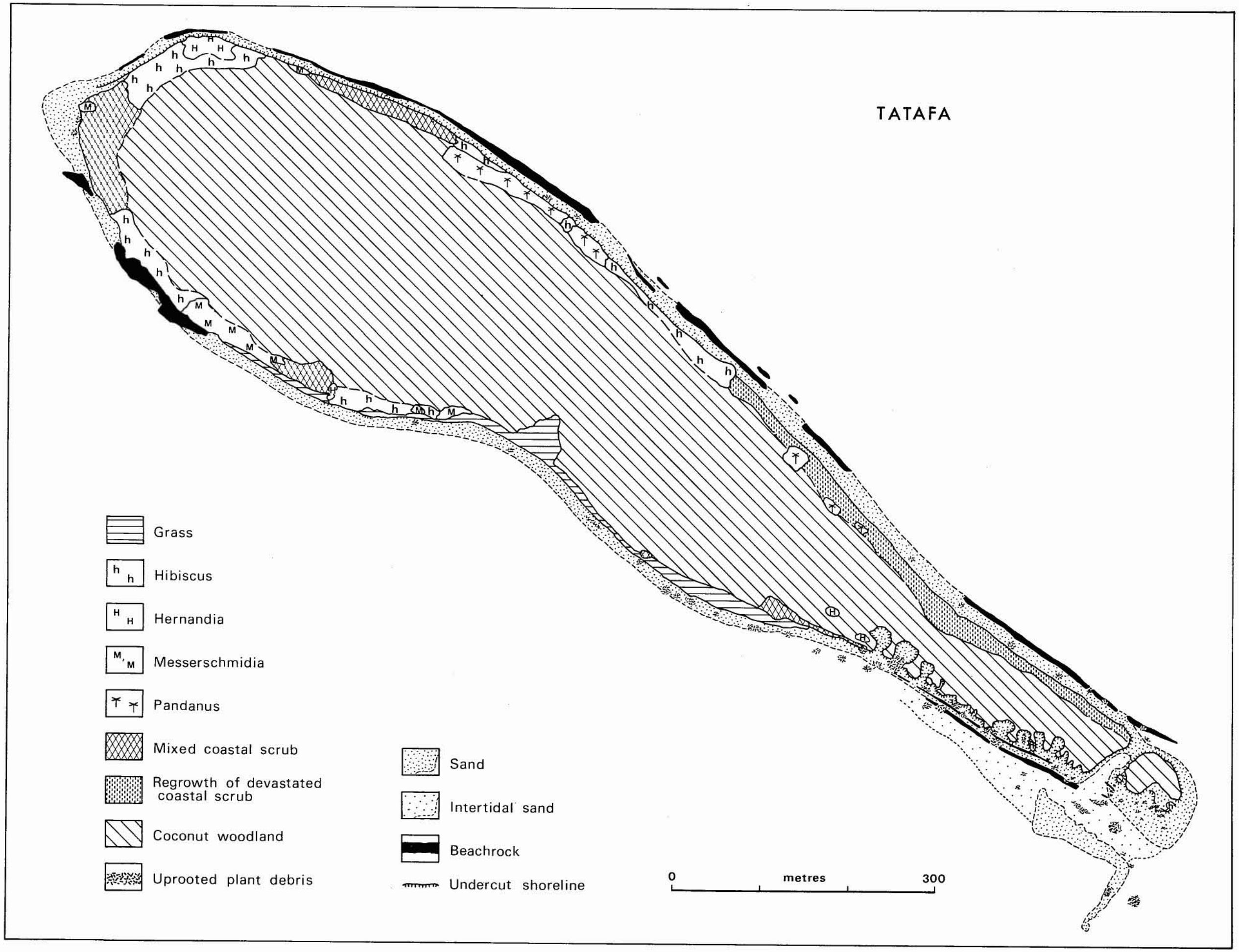

FIGURE 5. The island of Tatafa.

FIGURE 6 The channel scoured through the southern end of Tatafa, seen from the west, showing the coconut and other uprooted plant debris scattered on the leeward sand flats.

Surveys (DOS) topographic map (1 : 25,000), based on aerial photography in 1968, shows Tatafa to have been 1710 m long, separated from 'Uiha by a shallow channel about 240 m across. In 1982, after Cyclone Isaac, the shape of the northern end of the island had changed little since 1968 (Figure 5), but the total length is 1484 m, and the distance from the south of Tatafa to 'Uiha has increased, with more than 450 m of intertidal sand flats to the south of Tatafa.

In addition to removing much of the southern end of the island, Cyclone Isaac also scoured a channel through the middle of the island (Figure 6), leaving two smaller islands, the larger one 1398 m long and 348 m wide, and the smaller 70 m long and 52 m wide. The channel scoured between these is 16 m wide, sand floored, and flooded by the highest tides.

Around most of the island there are intermittent outcrops of beachrock varying from 1–2 m wide to 7–8 m wide, and to the northwest there is a larger outcrop of beachrock, heavily cemented, which appears to rise above the highest tide level. The beachrock generally occurs at the foot of the beach and implies that the island to the northwest has undergone little change in configuration since the beachrock formation. Beachrock is less developed to the southeast of the island but may be buried beneath the sand flats. Some beachrock in this area was exposed as a result of removal of sand by the storm.

The eastern beach is generally wider and steeper than the western beach and has had sand deposited on it like the eastern beaches of Lifuka and Foa. Vegetation has retreated and been buried as shown by the presence of partially defoliated stumps of *Messerschmidia* emergent from the upper part of the beach.

Around much of the island the shoreline is undercut; there is a sand cliff up to 80 cm high on the northern side and found intermittently to the northwest, sometimes at the top of beaches which have received sand. A sand cliff occurs to the southeast and is up to 1 m high through the scoured channel. Along the southern shore it is 1.2–1.5 m high. In addition, along this part of the coast there are semicircular scour holes formed on the leeward side by water passing over the island, up to 25 m across and often with a narrower neck only 8 m across. These have plant debris in some of them, but others have been scoured clean, and to such a depth that there may be small pools of water retained in the deeper part.

The vegetation of most of the island is

coconut woodland in which *Scaevola* and *Phymatosorus grossus* are found, and it is this coconut woodland that overhangs the eroded sand cliff. Many trees have been felled and are lying in all directions around the island (Figure 6), while the canopies of those still standing have been badly damaged.

Around much of the perimeter of Tatafa there is a belt of coastal scrub or woodland, up to 30 m wide. In many places this is dominated by *Hibiscus*, elsewhere by *Messerschmidia*, and in other places by a mixed scrub of both *Hibiscus* and *Messerschmidia*, with *Scaevola*, *Acacia*, *Suriana maritima*, and occasional *Pandanus* and *Hernandia* emergent. Along the northern coast there was a belt of *Pandanus*, 15–30 m wide before the storm; many of these trees were snapped or felled during the storm. Adjacent coastal scrub was also stripped; most of the branches and canopy were lost from scrub in a badly devastated area to the east, but rapid regrowth is occurring from the stumps. *Hibiscus* in particular had leaves sprouting from the damaged trunks at the time of survey, and isolated *Messerschmidia* were also growing back.

The greatest destruction occurred at the eastern end of Tatafa. The leeward beach and sand flats here were strewn with plant debris, much of which was coconut and the rest largely unidentifiable. Several large trees were toppled, including the only individual of *Casuarina* seen on the island, and several *Hernandia*. The changes in island configuration that have taken place appear largely irreversible.

Tongatapu

Cyclone Isaac passed north of Tongatapu and caused extensive damage to low-lying settlements along the north coast, such as Sopu and Fatai which were flooded and Kolovai which was devastated by high wind speeds. The raised reefal limestone cliffs of the west, south, and east coasts suffered little damage. Many trees, in particular coconut palms, breadfruit, and mango, were felled by the wind on the island, but the coastal scrub on the raised reefal limestone cliffs was not devastated in the same way as on the eastern coast of the barrier reef islands of the Ha'apai group, except to the northeast of Tongatapu in the vicinity of Niutoua. Here the vegetation was stripped; *Pandanus* was broken off, generally just above the prop roots, and shrubs such as *Messerschmidia*, *Bikkia*, and *Hibiscus* were defoliated and had most branches snapped off; but these were already sprouting from the stumps at the time of survey.

THE NORTH COAST OF TONGATAPU: Cyclone Isaac left a trail of destruction in Nuku'alofa, both along the waterfront and inland as a result of widespread inundation. The seawall was badly damaged and 10–20 cm of fine-grained sediment was deposited on Vuna Road. The mangroves along the northern coast suffered surprisingly little damage as a result of the storm. Partial defoliation of individual mangroves occurred in Sopu and on the reef flat to the west of Nuku'alofa. Clumps of *Rhizophora samoensis* on the reef flat were particularly affected, as well as a few trees of *Lumnitzera littorea* in plantations inland. Along much of this northwest coast of Tongatapu there is a seaward belt of *Rhizophora*, replaced to landward by a belt of *Excoecaria agallocha*. In the last week in May *Excoecaria* was observed to be losing its leaves as a result of a heavy infestation of the caterpillar *Achaea janata* which was grazing the young regrowth. The seawall enclosing an area of reclaimed mud flat (Straatmans 1954) had been breached by the storm, and renewed tidal inundation in the area had meant loss of several hectares of grassland. Much of the storm surge associated with Cyclone Isaac must have been buffered by the great width of reef flat along this coast, and its impact was not enormous.

Between Polo'a and Nuku'alofa, about 50 m from the reef edge, there is a spread of gravel and rubble-sized material on the reef flat. This forms a low ridge of debris in a gravelly matrix of coral sticks, with larger coral fragments up to blocks 30–40 cm in diameter. The larger corals are generally flat or pedestal shaped. The material did not appear to be fresh, some having a partial covering of the encrusting algae, and much probably predates Cyclone Isaac. Some of the platy corals, however, are still covered with delicate projections and have undergone minimal weathering; this material may have been added during the storm.

BEACH MORPHOLOGY: No systematic study of the beaches around Tongatapu was undertaken; however, local accounts reported deposition of sand on the eastern beaches, most notably Oholei beach. Accordingly, profiles were surveyed on Oholei and Laulea beach and on beaches to the northeast and north of the island. Deposition of sand had occurred on the upper part of both Oholei and Laulea beach, with a prominent berm at or just above high-tide level. On Oholei beach the lower beach was observed to be steep, 8°, and 15–18 m wide, with an upper beach 1–2°, and up to 14 m wide. Laulea beach is steeper; the lower beach is 8–11°, and 13–18 m wide, while the upper beach varies considerably in angle and width.

Sand Cays of Tongatapu

The islands off the northern coast of Tongatapu consist of limestone-cored islands and sand cays. Those formed of the raised reefal limestone, such as Polo'a, Alakipeau, and Velitoa, were little influenced by the storm, apart from some scrub damage. The sand islands, however, had been more susceptible to the storm surge associated with Isaac. A series of sand cays, in a north-south transect approaching the path of the cyclone, were visited and surveyed. The four southernmost islands—Oneata, Manima, Pangaimotu, and Makaha'a—had previously been surveyed by Stoddart in 1969 (Stoddart 1975), and the more northerly islands were mapped for the first time in this study. The resurvey of the islands surveyed in 1969 allowed assessment of the change that had occurred in 13 years; not all of this change resulted from the passage of Cyclone Isaac.

ONEATA: Oneata is an elongated sand island lying less than 500 m to the north of Nukunukumotu on an extension of the reef flat of Tongatapu. It has no exposure of reefal rock, nor of beachrock, and is similar in shape in 1982 to that mapped in 1969 (Figure 7). Many of the changes which have occurred between surveys result from settlement on the island, with a complex of buildings to the south of the island and extensive gardens in the center. Coconut woodland and woodland of *Hernandia nymphaefolia* and *Calophyllum inophyllum* appear less extensive than in 1969, and to the north there is an area of grass, probably *Lepturus repens*, with *Excoecaria agallocha*, *Vitex trifolia*, and *Hibiscus tiliaceus*. Coastal woodland forming a belt around the island is dominated by *Hibiscus* with *Scaevola taccada*, *Pandanus* sp., and *Clerodendrum*, and with monospecific stands of *Thespesia populnea* and *Cordia subcordata* on the west coast, and appears more disturbed than in 1969.

Cyclone Isaac had its greatest impact on the eastern shore, which had evidently retreated. Uprooted plant debris was particularly widespread, composed especially of *Hibiscus*, but including several large undercut and toppled *Calophyllum* and *Hernandia*, as well as numerous coconut palms. The retreat of the vegetation has left deep-rooted individuals of *Excoecaria* isolated now on the foreshore; these trees appear to have survived the storm, but were undergoing defoliation in May through the grazing of the caterpillar, *Achaea*.

The coconut palms on Oneata were not devastated as on other islands, though the foliage is badly knocked and few nuts remain; most of those felled or broken were on the east coast.

MANIMA: Manima is a small sand island lying NW–SE situated about 200 m to the northwest of Oneata on the same reef flat. Neither reefal rock nor beachrock are exposed on the island, and Figure 8 shows that the major change since 1969 has been aggradation of the western end of the island and reshaping of the intertidal sand spits. The vegetation of this western end of the island is grass with *Ipomoea pes-caprae*, *Vigna marina*, and *Euphorbia chamissonis*, with isolated *Colubrina asiatica*, *Scaevola*, and *Vitex*. The interior of the island is composed of coconut woodland, the overall area of which appears less extensive than in 1969, and which was particularly badly ravaged by the storm. Many of those palms left standing lost their crown and nuts, and there are low-lying areas in the center of the island stripped bare of undergrowth with

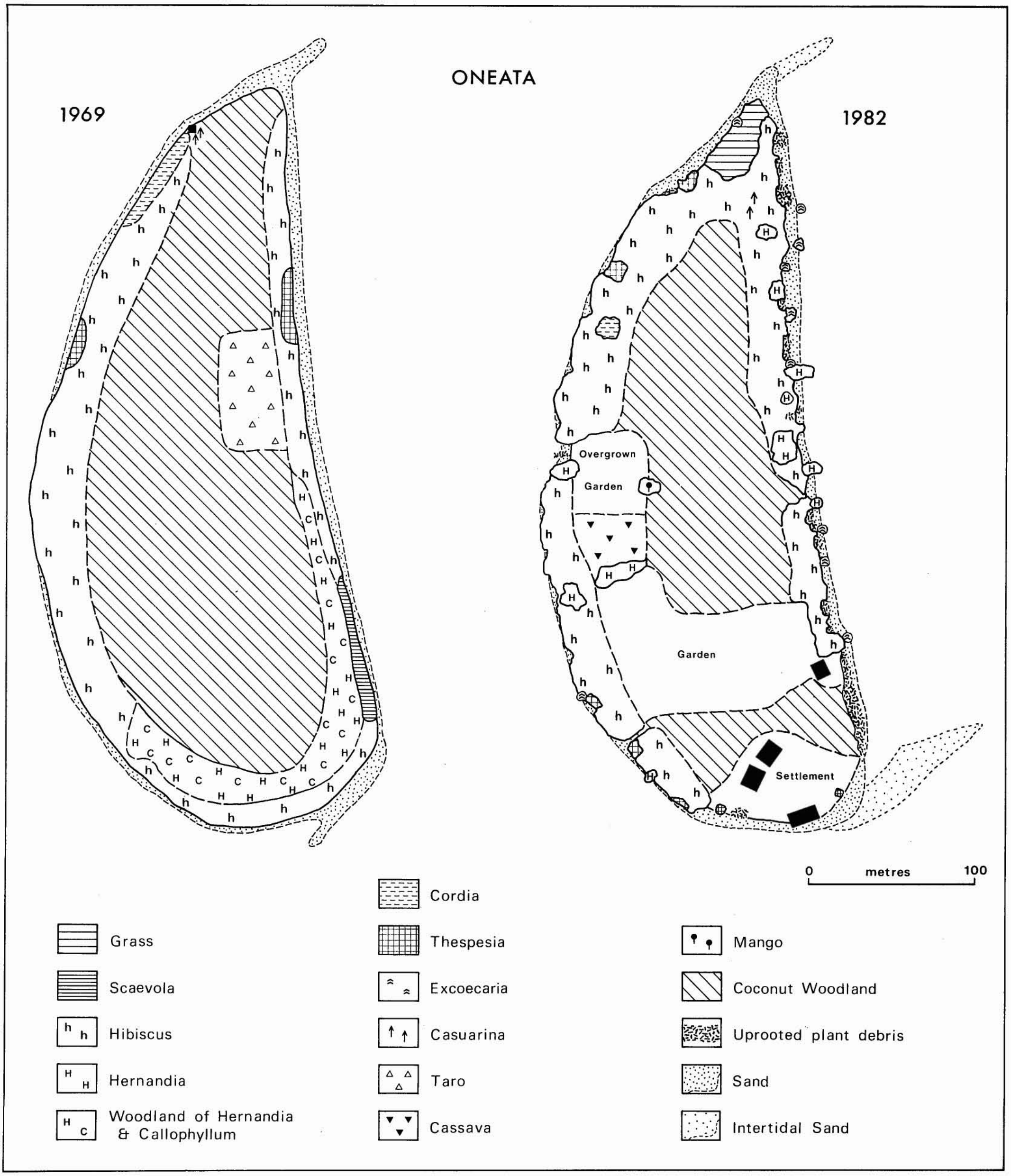

FIGURE 7. The island of Oneata, 1969 (after Stoddart 1975) and 1982, after Cyclone Isaac.

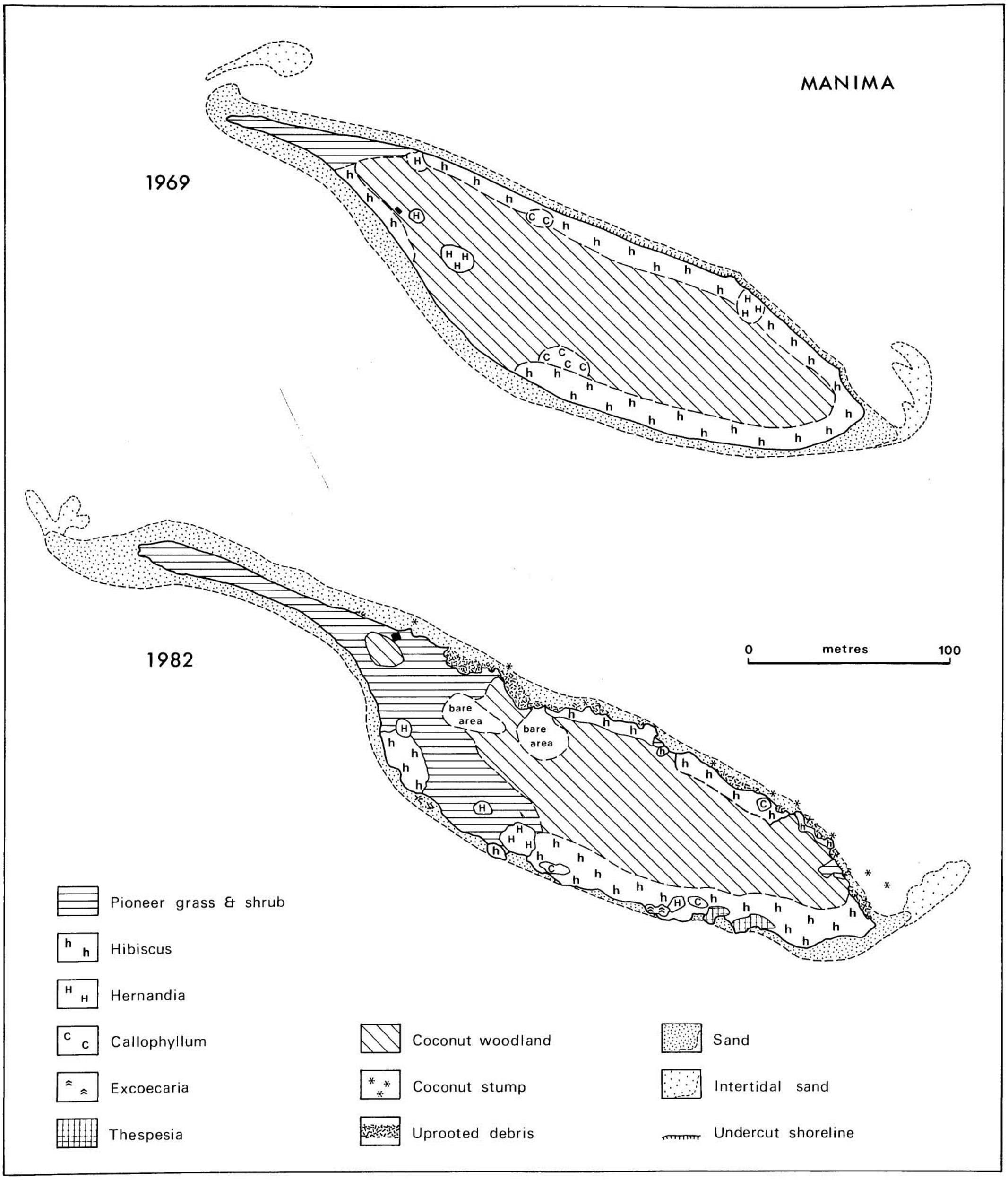

FIGURE 8. The island of Manima, 1969 (after Stoddart 1975) and 1982, after Cyclone Isaac.

dead and sometimes broken palms in them. Elsewhere around the coast is a woodland up to 20 m wide but less continuous than in 1969, composed predominantly of *Hibiscus* in which *Pandanus*, *Calophyllum*, and *Colubrina* are important.

The main evidence of Cyclone Isaac's impact occurs along the northern coast. Despite the existence of undercutting for more than 200 m of this coast in 1969 (Stoddart 1975), there was no pronounced undercutting of the shore in this survey (Figure 8), except for a small sand cliff less than 40 cm high fringing a grassed area to the east. There was, however, much tangled, uprooted plant debris, particularly of *Hibiscus* and *Thespesia*, as well as fallen and defoliated *Calophyllum* and numerous coconut palms. Further evidence of recession of the coconut area was observed to the east where several stumps or root remains of palms were found on the reef flat, indicating retreat of the shoreline by more than 12 m.

PANGAIMOTU: Pangaimotu is the largest island in the group immediately north of the coast of Tongatapu. The island was mapped and described by Stoddart (1975) and has changed little in its general configuration since 1969 (Figure 9). The interior of the island is composed of a coconut woodland, and the coastal woodland around the outside is dominated by *Hibiscus*, with *Colubrina* and *Clerodendrum* abundant and *Cordia*, *Scaevola*, *Pandanus*, *Calophyllum*, *Hernandia*, *Grewia crenata*, and *Diospyros elliptica* locally important. Isolated low individuals of *Rhizophora samoensis* grow at the northern end of Pangaimotu and appear to have changed little in extent since 1969. The most apparent differences since 1969 result from expansion of settlement on the island, especially to the south and west, with extension of a picnic area.

The only extensive outcrop of beachrock is to the west of the island, extending 95 m along the shore up to 6 m wide, with further degraded outcrops to seaward. Also in this area the shoreline has been undercut, and a sand cliff up to 80 cm high occurs at the top of the beach.

The impact of Cyclone Isaac was most apparent along the northeast and east shore where there was a discontinuous tangle of plant debris, especially of uprooted *Hibiscus*, *Thespesia*, and *Cerbera manghas*, along with several fallen coconut palms. Where retreat of the coastal woodland has occurred, outposts of *Excoecaria* have been left on the foreshore, often with individuals of *Thespesia* directly landward. Comparing the 1982 and 1969 surveys, there appears to have been about 10–11 m of retreat along this coast in 13 years. Obviously not all of this need have resulted from Cyclone Isaac: indeed, Stoddart recorded (1975: 5) that erosion was taking place at the eastern point of the island with *Hernandia* trees exposed on the coast. *Hernandia* presently seems less extensive than in 1969; the retreat of coastal woodland around the *Excoecaria* trees left on the foreshore implies that at least 8 m of the erosion did occur during the cyclone.

MAKAHA'A: Makaha'a is a small sand island lying on an isolated reef flat, separated from that on which Pangaimotu lies by a narrow channel about 10 m deep. Much of it is covered by coconut woodland which appears to have been little damaged by the storm and which has been described by Stoddart (1975). Seedlings of *Casuarina* and *Rhizophora* recorded in 1969 seem to have taken hold and young trees of both species were observed to the southeast of the island. Coastal scrub and woodland, up to 20 m wide, is dominated by *Hibiscus*, with several *Hernandia* to the west of the island apparently having become prominent since 1969.

Makaha'a shows several marked changes from 1969 to 1982. The patterns of beachrock mapped in the two surveys are broadly similar and serve as a reference for the rest of the island. Changes in the beachrock itself may reflect burial or exhumation of beachrock, or erosion and degradation of beachrock between surveys. An area of settlement with three buildings has grown up on sand which has aggraded to the southwest of the island since the earlier study. Also in this area of sand build up is pioneer vegetation of grass, *Vigna* and *Messerschmidia*.

An undercut shoreline was recorded along the eastern margin of the island in 1969

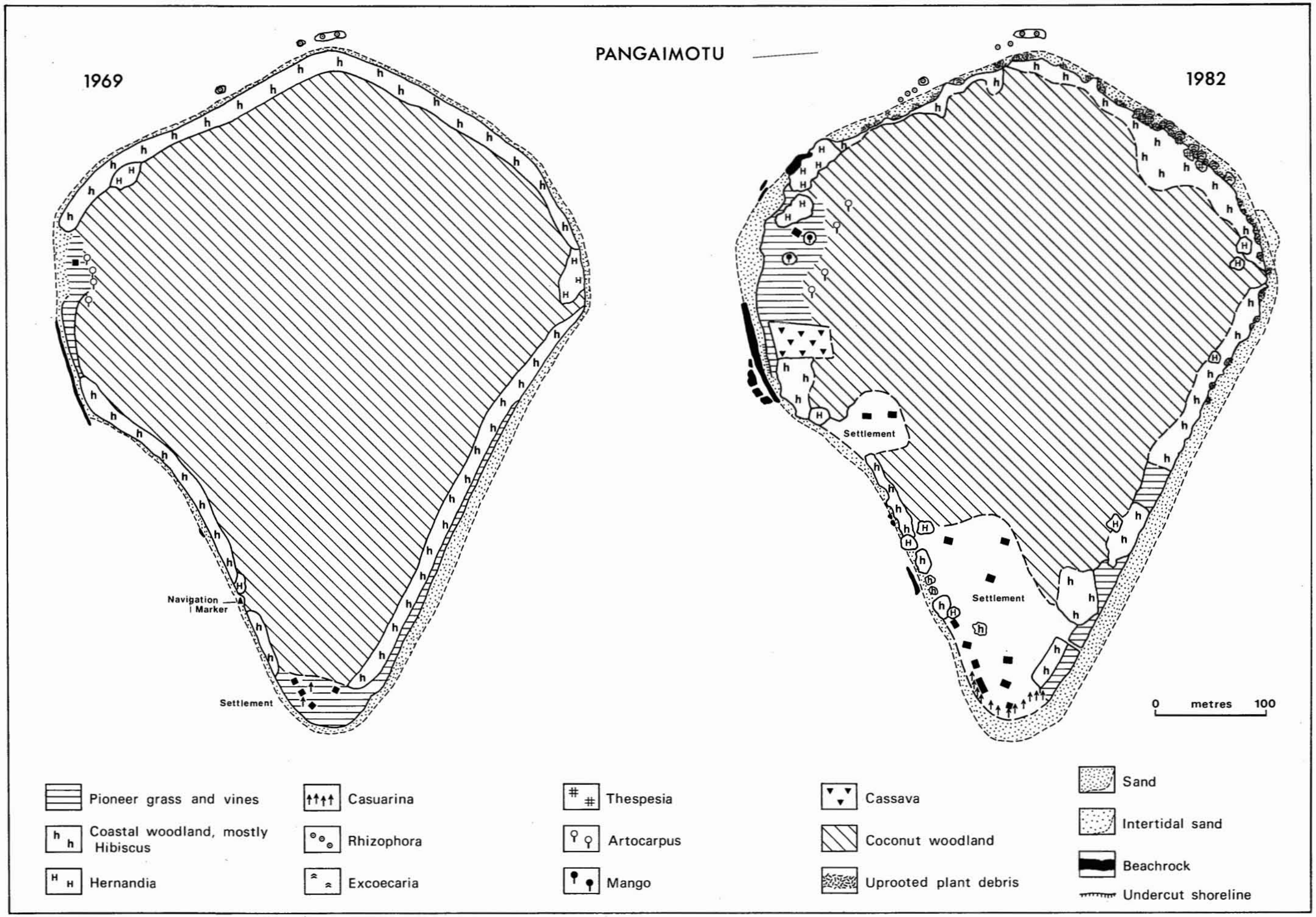

FIGURE 9. The island of Pangaimotu, 1969 (after Stoddart 1975) and 1982, after Cyclone Isaac.

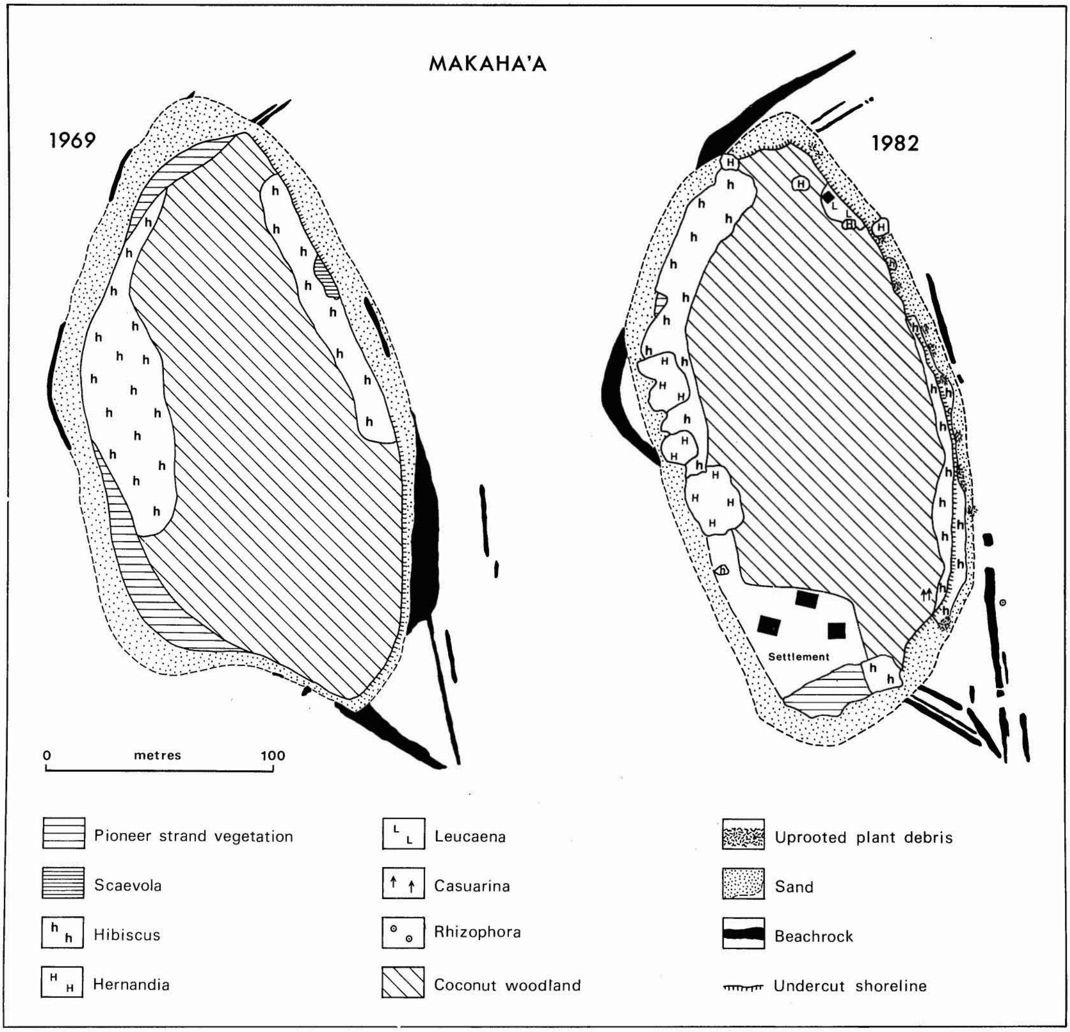

FIGURE 10. The island of Makaha'a, 1969 (after Stoddart 1975) and 1982, after Cyclone Isaac.

(Stoddart 1975) with sand cliffs ranging from 1.5 to 2.0 m high to a maximum of 3 m high in the southeast. Stoddart (1975: 3) concluded that the island was migrating across the reef flat to the northwest. An undercut shoreline was also observed along the eastern shore in 1982, rising from 1.4 m at the south to 2 m to the southeast, and being approximately 1 m high on the eastern shore. However, along much of the central part of this eastern shore the cliff is covered by growth of *Hibiscus* presently extending 3 to 4 m to seaward and showing little or no evidence of disturbance resulting from Cyclone Isaac. It would appear that the present undercutting predates the recent storm, and from its similar configuration to the central eastern coast of the 1969 survey, and the similar distance from the beachrock outcrop, it seems to be a "fossil" feature having changed little from that mapped by Stoddart (Figure 10).

To the southeast where the sand cliff is not protected by growth of *Hibiscus*, some retreat appears to have occurred; coconut woodland is exposed on the coast and coconuts are undermined. In these areas retreat of 20 m or more has occurred since 1969, and there was debris of *Pandanus*, *Hibiscus*, and *Hernandia*.

MONUAFE: Monuafe is a sand island, 176 m long and 56 m wide, lying to the northeast of a deep channel, called the Narrows, separating it from Makaha'a. There are outcrops of beachrock to the north and east (Figure 11), indicating the island to have been more extensive, or to have migrated since the time of that beachrock formation. An expanse of intertidal sand, exposed at low tide and up to 70 m wide, separates the vegetated island from a discontinuous line of beachrock to the east.

The vegetation of Monuafe is not well developed and is composed largely of grass and scrub. Grass, probably *Lepturus*, and *Ipomoea pes-caprae* cover much of the west and south of the island, and here the only coconut palms occur, several well-spaced young palms less than 7 m tall. The dominant plant in the scrub on Monuafe is *Leucaena leucocephala*, forming a thicket up to 3 m tall, with occasional emergents to 6 m tall. On the eastern shore there is a small stand of *Leucaena* which has been partially defoliated.

Little evidence of storm damage has been observed on this island, partly because the scrub has little woody vegetation which might be preserved in contrast to the tangle of uprooted plants on the islands to the south. The only undercutting of the shoreline has been to the north of the island where a sand cliff up to 70 cm high can be traced for 30 m along the shore, at the point where the beach is narrowest, and beachrock is found at the base of the beach. The large intertidal flat to the east results from recession of the island but there is no indication whether this occurred during the cyclone or whether it predates the storm.

FAFA: Fafa is a rectangular sand island, 422 m long and 216 m wide, lying to the west on an elongated reef flat offshore of Tongatapu which extends northeast as far as Tau. Unlike most other islands in the chain, Fafa has no exposure of reefal limestone. It is covered with coconut woodland with a broad area of grass and *Ipomoea* to the northwest, where one building is standing and one that was flattened by the cyclone has only the base remaining (Figure 12). Around much of the northern and western shores coconut woodland reaches to the coast, while to the east there is a localized patch of grass with *Acacia* and a stand of *Leucaena*, 4–5 m tall, which has suffered some defoliation.

Beachrock is discontinuous along the southern shore and occurs to the northeast where it exceptionally reaches 9–10 m wide. It is also along these shores, as well as much of the eastern shore, that undercutting was recorded. The sand cliff is up to 80 cm high to the north and west, 1 m high in the southwest, and 1.2–1.3 m high along much of the south shore, reaching 2 m in the center of the latter.

The coastal woodland belt, up to 25 m wide on the southern shore and composed of *Hibiscus*, *Pandanus*, *Ochrosia oppositifolia*, and individual *Pisonia*, with coconut palms relatively infrequent, was extensively damaged by the cyclone; there was much uprooted plant debris. More coconut debris occurs to the southwest where coconut woodland is found on the coast, and the outlying beachrock indicates that recession of the shoreline of more than 35 m has occurred since the formation of that beachrock. Retreat of a shoreline on which coconut woodland is found is also indicated to the northeast (Figure 12).

Not only has Fafa been hit on the eastern and northeastern shores, as have the islands to the south, but it has been severely damaged on the southern shore also. This reflects the configuration of the reef flat on which Fafa lies, which is extensive to the east, and offers some protection to the island, but which is much narrower, in some places only 50 m wide, on the southern shore and which was much less effective as a buffer against the storm surge.

TUFAKA: Tufaka is a sand island lying about 8 km to the northwest of Nuku'alofa on the reef flat which extends out to Atata. It lies approximately 1 km to the west of the reef edge and is 320 m long and 84 m wide. The island was badly damaged by the cyclone, and the coconut palms in particular were devastated; many palms have fallen and several have been broken off 2–3 m above the ground. Of the 15 palms that were left standing, only

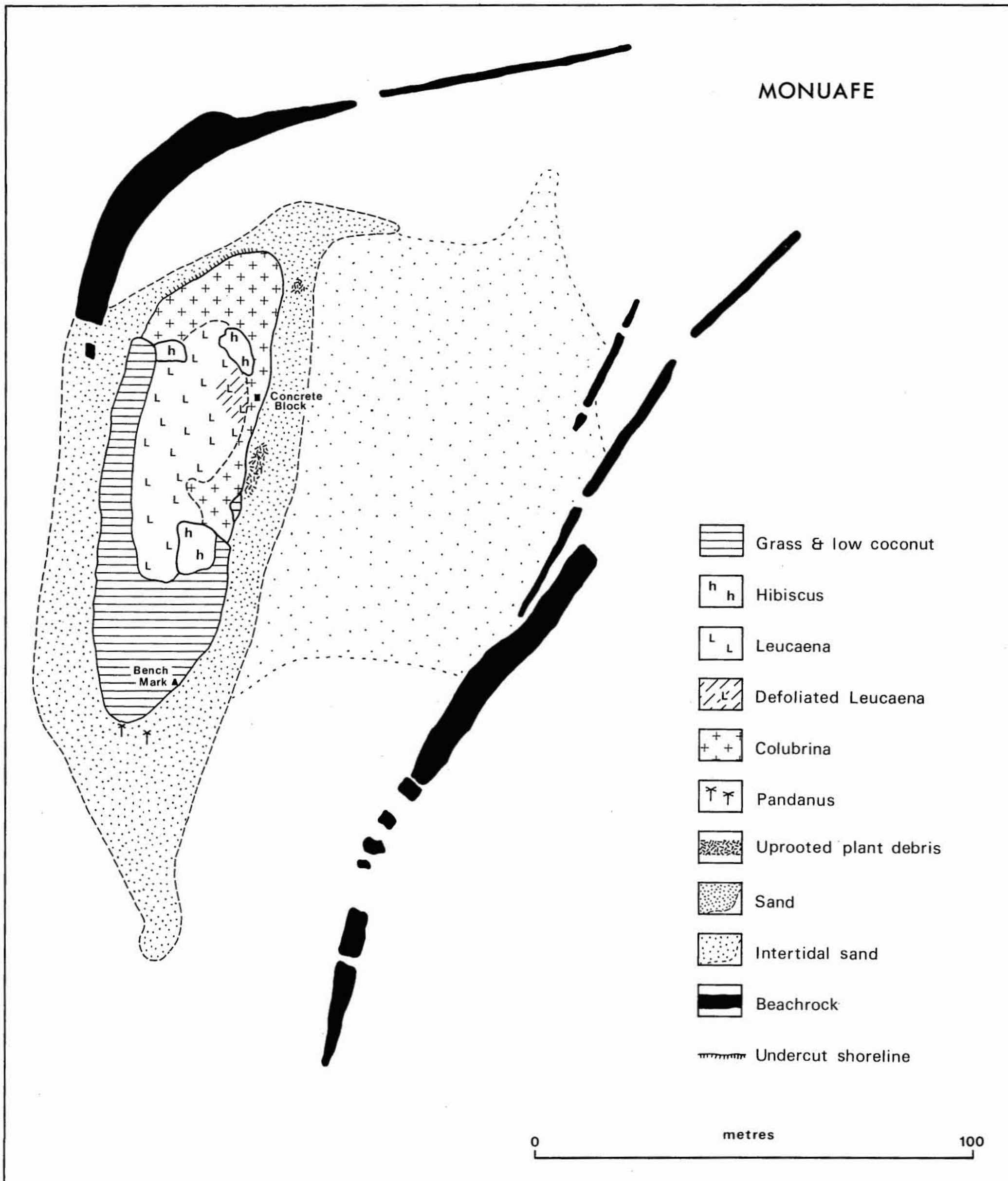

FIGURE 11. The island of Monuafe after Cyclone Isaac.

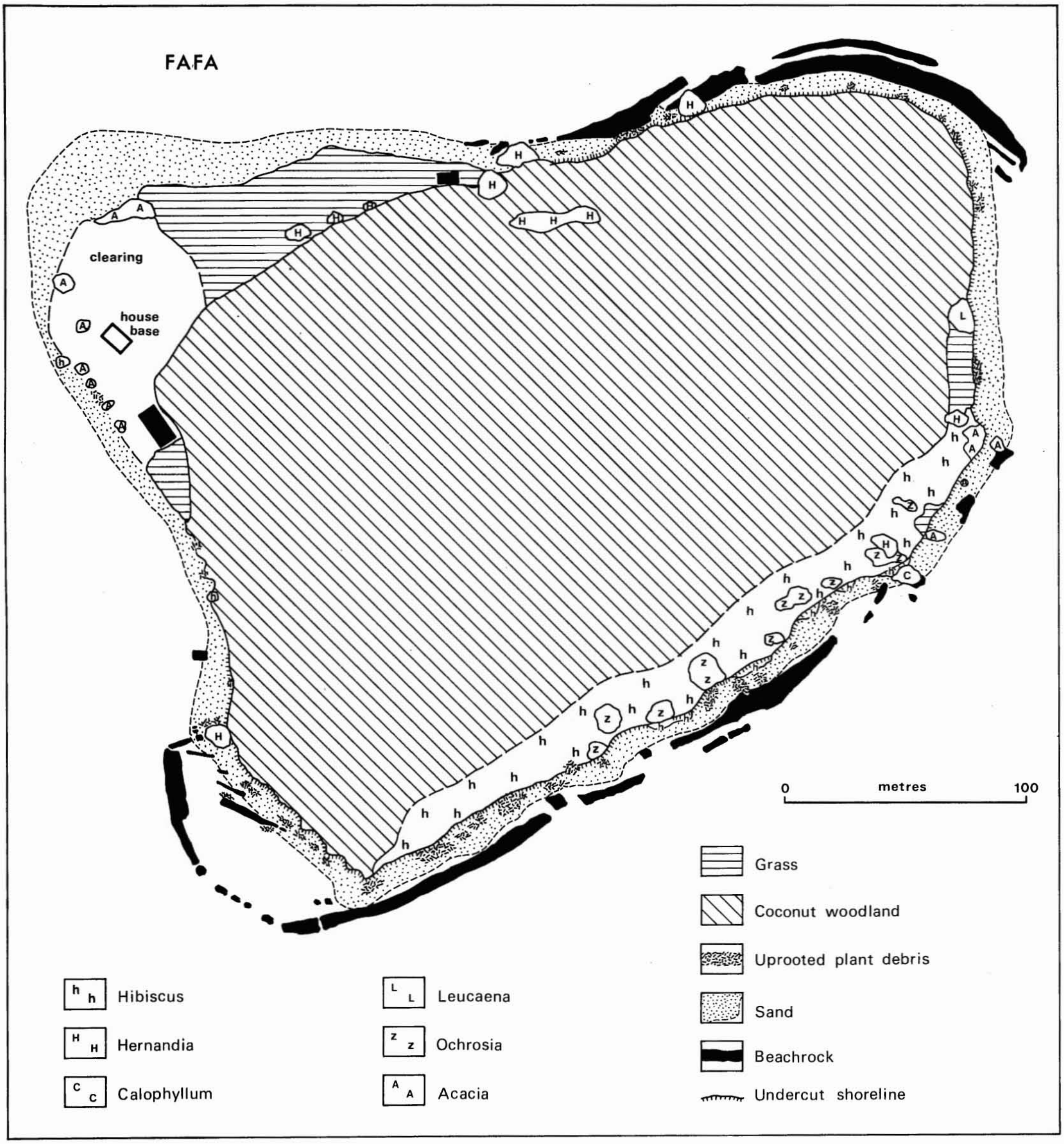

FIGURE 12. The island of Fafa after Cyclone Isaac.

11 had crowns on them, and these severely knocked (Figure 13).

To the north of the island there is a sand spit 63 m long and to the south a spit 88 m long, which is particularly broad to the east and may have received deposits of sand during the storm. The vegetation is dominated by a scrub of *Leucaena leucocephala*, rarely more than 2 m tall, but with emergents to 4 m. In many areas to the east *Leucaena* has been defoliated, but the thicket is regenerating fast, with new shoots growing from ground level amidst the divaricating leafless branches.

Around much of the island there are broad deposits of well-consolidated beachrock up to 11–12 m wide to the east and 32 m to the

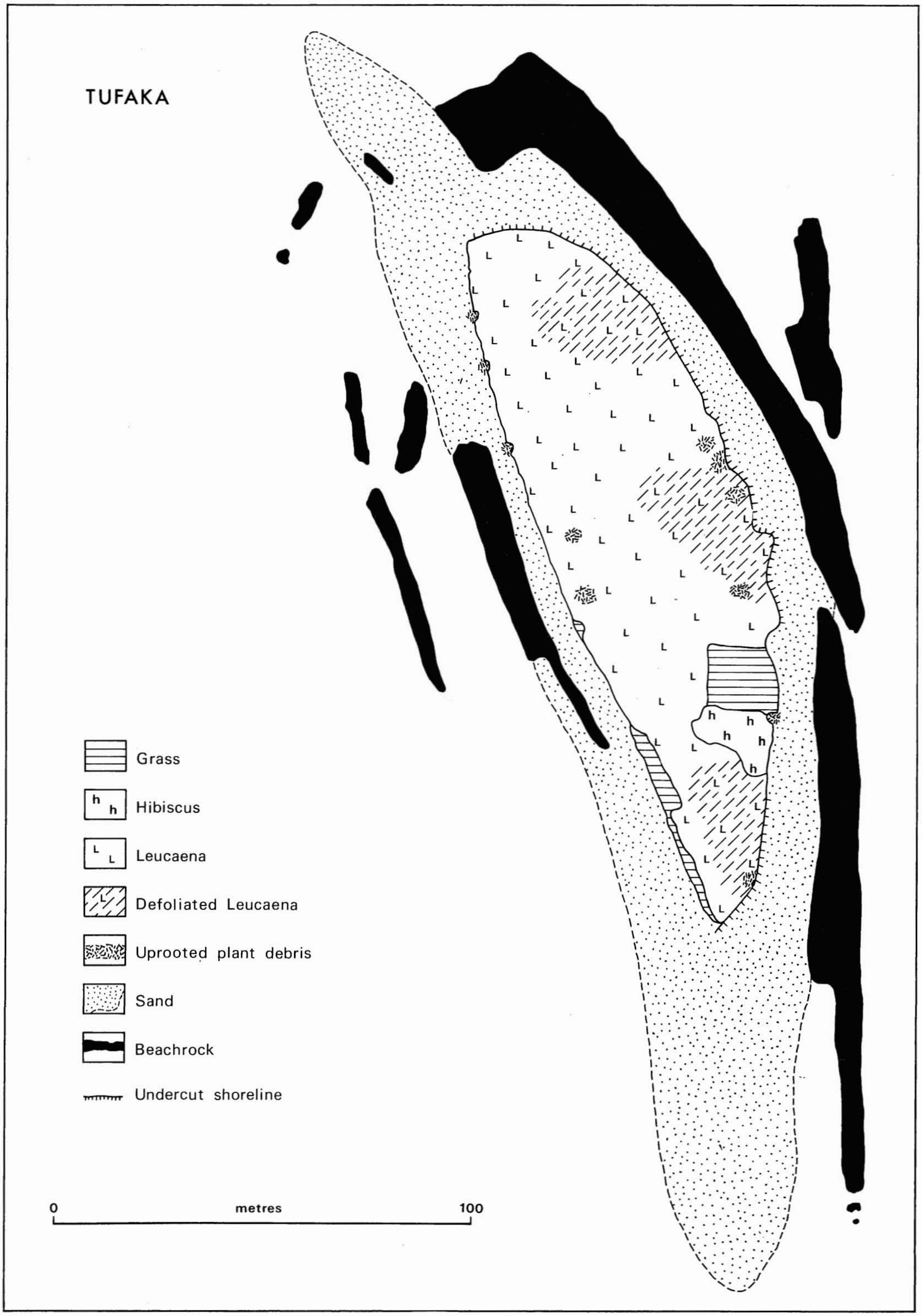

FIGURE 13. The island of Tufaka after Cyclone Isaac.

north. Outliers of beachrock to the northwest illustrate past changes in the size and configuration of the island. An undercut shoreline is present along most of the eastern shore, generally 1 m high and vegetated with *Leucaena*, reaching 1.2 m high to the southeast. The sand cliff is particularly distinct where there is beachrock at the foot of the beach. Plant debris consists of *Acacia* and *Pandanus* and is generally not widespread, as on Monuafe, because little of the vegetation is woody.

MALINOA: Malinoa is a small sand island, 285 m long by 100 m wide, which lies on an isolated reef flat more than 10 km north of Nuku'alofa. The most apparent result of Cyclone Isaac has been the deposition of sand on the eastern and southern shores, where a steep beach is found on which the sand has been undermined to leave a sand cliff 50 cm high. Sand, up to 1 m thick, has buried a stand of *Messerschmidia* leaving only the uppermost branches exposed, and partly buried adjacent scrub of *Suriana* and of *Scaevola* and *Acacia*.

This island shows a greater diversity of vegetation types than seen on other islands to the south (Figure 14). Malinoa is the only island visited on which *Pisonia* is an important element, forming several stands along the western shore. The interior of the island has a coconut woodland fringed with stands of *Pandanus*, rarely more than 5 m tall; both show little evidence of storm damage.

Beachrock occurs around the western and northern shore of Malinoa, in a broad band generally 14 m wide, but exceptionally reaching 37 m wide. Undercutting has also occurred to the north of the island, and a sand cliff up to 1 m high was observed. Little plant debris was found on the coast of Malinoa which, despite being the closest of the islands to the center of the storm, has experienced deposition rather than erosion. Some trees of *Pandanus* have been toppled along the eastern shore.

DISCUSSION

One of the major effects of catastrophic storms on coral reefs and reef islands documented in studies elsewhere is the deposition on reef flats of coral rubble and storm blocks removed from the forereef and adjacent reef flat. Although Ostergaard noted that in 1926 reefs north of Nuku'alofa, and particularly those of Makaha'a, were "heavily littered with hurricane blocks" (Ostergaard 1935: 9), Cyclone Isaac appears to have moved little material of this size; little rubble was observed on reef flats and storm blocks were rare. Isolated boulders generally less than 1 m in diameter were recorded on the eastern reef flat of the Ha'apai barrier reef, but few were observed to have fresh faces on them and many were probably deposited before the passage of Cyclone Isaac. Rubble and boulders on the northern coast of Tongatapu also probably predate the cyclone, though some of the more delicate material may have been added recently. To the north of 'Uiha and Uoleva in the Ha'apai group it was noticed that several microatolls of coral had been detached from their growth position on the reef flat and either tilted and strewn on the reef flat or in many cases carried to the foot of the beach, where the coral polyps had died.

Not all storms move rubble, and the absence of rubble on the reef flats in Tonga might imply that Cyclone Isaac was not of sufficient magnitude to move such large fragments. Alternatively, absence of rubble may reflect the short supply of material of such size on the adjacent reef flats and offshore reefs but, as no underwater observations were made on the nature of the offshore reefs and no recent accounts of these exist, this cannot be verified. Conversely, rubble need not always be deposited on the reef flat. In Belize, Stoddart (1963) recorded that in many cases Hurricane Hattie had carried material entirely across the reef flat and deposited it in deeper water to leeward, and in the Lau Islands Hurricane Val deposited rubble in 20 m of water (Phipps and Preobrazhensky 1975). It may be that Cyclone Isaac has destroyed reefs around Tonga and deposited coral rubble on offshore terraces. It is interesting to note, however, that rubble ramparts are often found on islands in areas which experience hurricanes and are evidence that storm events can move material of considerable size and deposit it above water level (Hernandez-Avila, Roberts, and Rouse 1977).

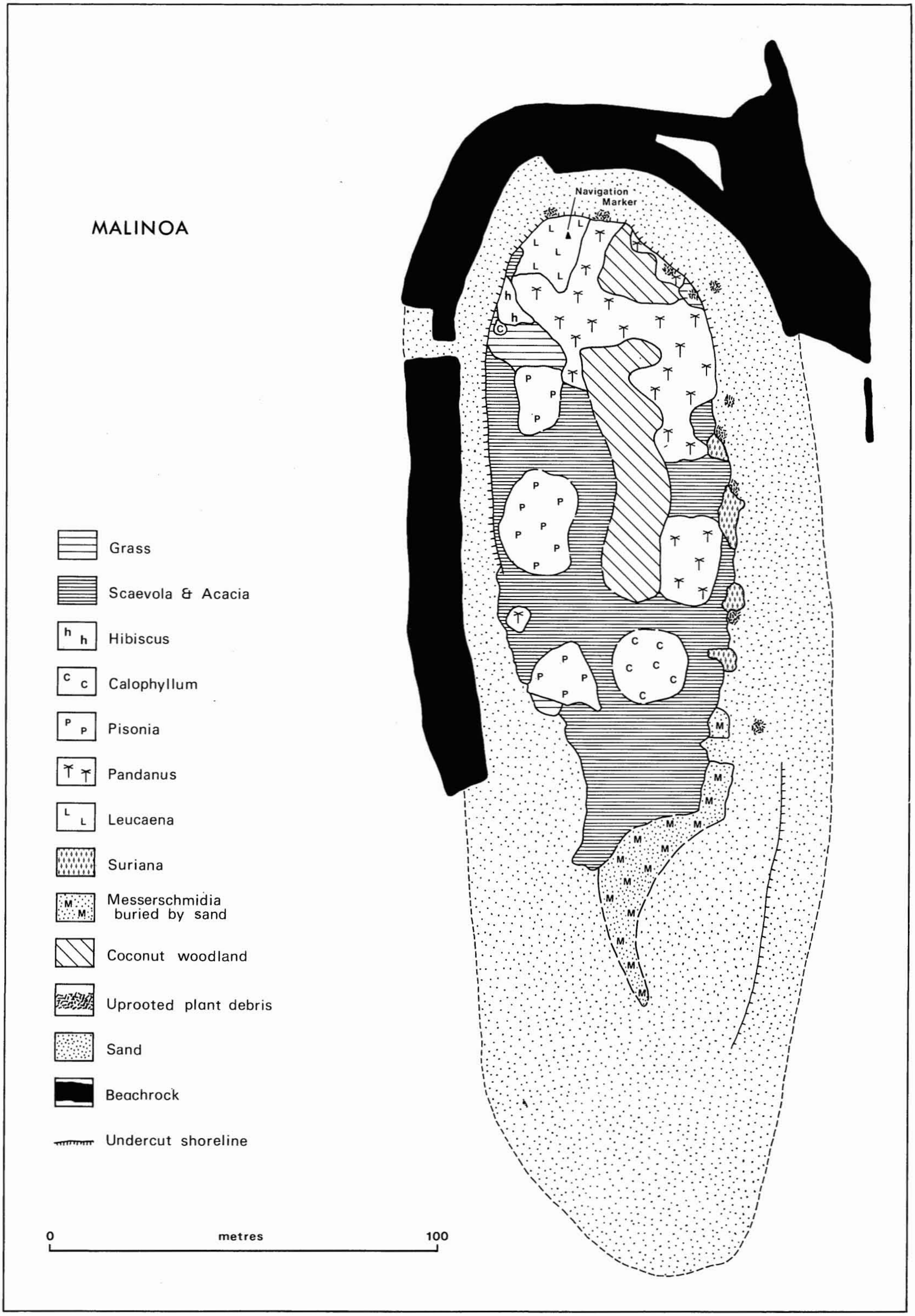

FIGURE 14. The island of Malinoa after Cyclone Isaac.

Similar coastal deposits are found in the Lau group despite the observation that rubble deposition by Hurricane Val occurred predominantly on offshore terraces. Rubble deposits are not prominent landforms on the coast of any of the islands visited in Tonga, and there is as yet no indication that they are extensive offshore. As Cyclone Isaac was probably the most severe storm experienced in the southern Tonga islands in 100 years or more, it is implied that storms rarely deposit rubble-sized material on the reef flat or on the coast in Tonga and are not major factors determining island topography.

The raised reefal limestone coasts underwent little morphological change as a result of the storm, except for the detachment of blocks from the upper part of the wave-cut notch on Ha'ano. Both erosion and deposition occurred along the pocket beaches of these raised reefal limestone coasts, with erosion prominent on the smaller beaches and deposition on the upper part of the longer beaches. Beach changes were comparable to those previously reported after storms from pocket beaches on Mauritius (McIntire and Walker 1964) and on Guam (Emery 1962), and the volume of 28 m^3 per meter of beach face for sand removed from the beach at the site of profile 2a on Lifuka is within the range 25–32 m^3 per m reported for other beaches under storm conditions (Morton 1976, Ogg and Koslow 1978, Simpson and Riehl 1981). Deposition of sand had taken place on eastern beaches facing the open water, over reef flats of 100–500 m width, and had resulted in steep lower beaches 7–8°, a prominent berm at high-tide level, and deposition on the upper beach with variable angles of slope.

The greatest coastal change resulting from Cyclone Isaac was observed on the sand islands. In the Ha'apai group Uoleva, sheltered in the lee of Lifuka, underwent little change, but Tatafa was perhaps the worst affected island in Tonga. It had completely lost more than 200 m of sand shoreline from the southern end of the island, with a further channel scoured through the southern part of the island. There was extensive undercutting, and water overtopping the island had scoured holes in the leeward side like the scour holes reported from Jaluit and from the Belize cays (McKee 1959, Stoddart 1963). The changes on the sand cays off the north coast of Tongatapu were less pronounced than on Tatafa. The four islands nearest to the shore, Oneata, Manima, Pangaimotu, and Makaha'a, had changed by different amounts since the survey in 1969 (Stoddart 1975), with greater change on the smaller islands of Manima and Makaha'a, which both showed aggradation to the west. Some retreat had occurred on the eastern shore of each of these islands, though not all of this retreat necessarily resulted from Cyclone Isaac. There was direct evidence of scour during Isaac, the retreat of the foreshore having left individuals of *Excoecaria* and to a lesser extent *Thespesia* outstanding, indicating as much as 8 m of recession on Oneata and Pangaimotu, or, where stumps of coconut palms remained on the reef flat, indicating up to 12 m of retreat on Manima.

Some undercutting of the shoreline had taken place on most cays, and sand cliffs reached up to 2 m high on Fafa and Makaha'a. However, this undercutting was in most cases related to the occurrence of beachrock around the island, and while the cliff provides evidence of removal of sand, the presence of beachrock at the foot of a generally narrow beach implies that little retreat of the shoreline occurred. It is true that the beachrock may have been formed several decades ago, and could subsequently have been buried and exhumed by the storm, as found to the south of Tatafa and reported from Belize by Stoddart (1963), but this is unlikely to have happened in many cases, and has not been a trend observed on those islands mapped in both 1969 and 1982. Presumably the beachrock is resistant to scouring by the water (McIntire and Walker 1964), but it also appears to concentrate that scouring up the beach. The ineffectiveness of shoreline undercutting as a means of shoreline retreat is further indicated by the apparently "fossil" sand cliff on Makaha'a which shows little change in plan with respect to the beachrock from that mapped by Stoddart, and which has *Hibiscus* growing to seaward of it.

Patterns of change on the northern sand cays off Tongatapu are more variable. Fafa shows recession of the shoreline of the eastern and northeastern shore, but in addition has retreated on the southern shore, presumably a function of the reef flat configuration. The degree of change on Monuafe and Tufaka is harder to reconstruct because the vegetation is not so woody and little evidence of the former shape of the islands exists. Malinoa, the island closest to the path of Cyclone Isaac, has experienced deposition rather than erosion with sand deposited on the upper beach to the southeast. This pattern of accumulation resembles that on the eastern beaches of the islands of the Ha'apai barrier reef and of Tongatapu, and presumably reflects the relative isolation of Malinoa, the narrow reef flat, and the open and deeper water to the east, from where the sand may have been derived.

While the effects of Cyclone Isaac on coastal landforms were not as far-reaching as experienced on isolated atolls, coastal vegetation was in some cases as severely devastated. Coconut palms were badly damaged on many islands, many were felled, others snapped off, and of those remaining standing most had had their crowns damaged and lost nuts and inflorescences. Other introduced economic trees, such as breadfruit and mango, also suffered, especially in the center of the larger islands, with many big trees uprooted by the wind. *Casuarina* was also noted to have been particularly susceptible to windfall, as noted on Mauritius (Sauer 1962) and to a lesser extent on Jaluit (Fosberg 1961).

Around the sand islands much coastal woodland and scrub was removed by scouring, or in other places buried by sand. *Hibiscus* was severely hit, but on many shorelines, as on Tatafa, it was showing signs of recovery and regrowth from the broken stumps. *Messerschmidia* was in many cases buried on the eastern beaches, as on Malinoa and eastern Lifuka, and it too was showing regrowth from the stumps. Big trees such as *Hernandia* and *Calophyllum* were undercut on the coast, and where these had partly fallen they were obviously going to continue to grow in this position. Scouring of coastal vegetation had left deep-rooted individuals of *Excoecaria*, otherwise not a conspicuous element of the scrub, isolated on the foreshore. *Leucaena* was partially defoliated on the smaller islands.

Damage to coastal scrub on the raised reefal limestone shores directly exposed to Cyclone Isaac, on the northeastern shores of the islands of the Ha'apai barrier reef and of Tongatapu, was largely by wind, though erosion of soil and deposition of coral gravel were evidence of high water levels on these coasts. Much of the vegetation was snapped off, and *Pandanus* in particular was conspicuously broken generally just above the prop roots. Regrowth of several shrubs, notably *Messerschmidia*, though also of *Hibiscus* and *Bikkia*, was occurring from the stumps.

CONCLUSIONS

Evidence of past storms is not preserved conspicuously on the coast of Tonga. Cyclone Isaac was one of the most severe storms to strike the southern islands of Tonga during the time for which records are available and caused extensive destruction to property and to crops. It had relatively little impact on the morphology of the raised reefal limestone coasts and deposited little rubble-sized material on the reef flats or beaches. Its effect on sand cays was most devastating on those directly in its path, such as Tatafa, while both deposition and erosion occurred on those off the north coast of Tongatapu, depending upon the configuration of, and shelter provided by, the reef flat. Deposition occurred both on sand cays and on the longer beaches exposed to the east or protected by only a narrow reef flat. While many of the changes to coastal landforms were relatively minor and will be rapidly obscured, destruction of the coastal vegetation was more extensive, particularly on the raised reefal limestone coasts. Regrowth, especially from the stumps of the dominant coastal shrubs, has been rapid, but changes in species composition which have resulted from the storm will be longer lasting. Nevertheless, storms of hurricane force would appear to be a much less important factor in shaping coastal landforms and coastal vegetation communities on raised limestone and sand islands in Tonga than on more isolated atolls elsewhere in the Pacific.

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