ATOLL RESEARCH BULLETIN

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9. The Coral Reefs of Arno Atoll, Marshall Islands

Issued by

THE PACIFIC SCIENCE BOARD

National Academy of Sciences - National Research Council

Washington, D. C.

December 15, 1951

THE CORAL REEFS OF ARNO ATOLL,

MARSHALL ISLANDS

SCIENTIFIC INVESTIGATIONS IN MICRONESIA - Pacific Science Board

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An atoll has a top that's flat
And featureless extremely.
Corals and algae make a mat
Where mountains are not seemly.

(R.H.F., 1949)

John W. Wells
Cornell University
December 1951

ACKNOWLEDGMENTS

The author of this report participated in the 1950 SIM (Scientific Investigations in Micronesia) Project of the Pacific Science Board of the National Research Council. This project was supported by funds granted to the National Academy of Sciences by the Office of Naval Research, and the field work was carried out with the active assistance of the Navy Department, the Military Air Transport Service, and the officials of the Civil Administrative Staff of the Trust Territory (Navy).

To all of the above who helped to make possible the research described in this report I wish to express my gratitude and appreciation.

Special thanks are due to Mr. Donald F. Squires (Cornell '50) without whose able assistance in the field much less would have been accomplished.

CONTENTS

FIGURES

I. Field Work

A. Reefs

The coral reefs were the main object of study during the field period, and all types of reefs represented at Arno were investigated in more or less detail:

Ine Island - Seaward-leeward reef; windward-lagoon reef. A three-mile stretch on either side of Ine Village was mapped in detail on a scale of 1:8000.

Takleb Island - Seaward-windward reef; leeward-lagoon reef. Mapped.

Aotle and associated islets - Seaward-windward reef; lagoon reef. Mapped.

East Horn (Malel to Lonar I.) - Seaward-windward reef; lagoon reef (enclosed lagoon). Mapped.

North Horn (Eneman-Bikarej-Namwi) - Seaward-windward reef; seaward-leeward reef; enclosed lagoon reef; reef "dam" at north end. Mapped.

Studies were made of the water temperature fluctuations on the reef tract on the seaward side of Ine Village.

B. Lagoon

Following the arrival on 19 July of dredging gear from Washington, dredging was carried out nearly every day until 1 August, when the gear was re-packed for shipment. Earlier attempts to dredge with a crude dredge made from material at hand produced results, but were less than satisfactory. The regular dredges were more successful, but the great difficulties in operating from sailing outrigger canoes emphasize that systematic dredging, a necessary part of any scientific study of an atoll, is possible only from a sizeable powered boat. Nevertheless, as a result of Mr. Squires' persistence, a number of bottom samples and zoological specimens were obtained from some 25 hauls in the lagoon, even though nearly half of them were dry runs.

C. Collections

Corals. About 600 specimens, mostly cured, of reef and lagoon corals were collected.

Other. Insofar as possible, with only 2 gallons of alcohol, specimens of mollusca, echinoderms, alcyonarians, foraminifera, crustaceans, etc., were collected for the U.S. National Museum, as well as some dried material. A number of specimens were preserved but later had to be discarded or dried because of lack of sufficient preservative. Ten gallons of alcohol requested from Majuro late in June was finally delivered at Majuro on the return journey.

Some was added to the one tank, but the rest by that time was of no use and was returned.

In all/18 wooden packing cases were filled, weighing about 1000 pounds and shipped back by surface transport. The corals are still being studied, and a complete list at this time is impractical, but it is estimated that over 100 species representing about 45 genera of scleractinian and hydrozoan corals were procured, with ecological data. A list of these genera is appended.

About 350 photographs (Kodachrome) were taken, mostly of reef phenomena, including a number of underwater views. Five hundred feet of 16-mm. color motion picture film were exposed, again mostly of reef features above and below water, with unexpectedly good results. The motion picture camera and tripod were a loan from the Navy through the Honolulu office of the Pacific Science Board, and grateful acknowledgment of this is here made.

II. Structure and Physical Processes

A. General Statement

Arno Atoll, in the southern Marshall Islands at approximately 172 deg. E. and 7 deg. N., lies in the northeast trade wind belt and in the north equatorial current. The latter is deflected northwards during the summer months by the equatorial counter current. It is in that part of the Pacific where the surface water temperatures do not fluctuate more than 1 deg. above or below 28 deg. C. - the warmest part of the Pacific. The temperature, clarity, and agitation of the surface are at the optimum for reef coral development, but the planktonic food supply, on the other hand, despite the seasonal reversal of oceanic currents, is lower than in areas farther to the southwest and coral growth is below the maximum.

Arno, like many atolls, departs from the common idea of circular atoll shape, being roughly rectangular with two extensions or "horns", one extending to the north about 5 miles from the north corner of the rectangle ("North Horn"). The other extends about 7 miles northeastward from the east corner ("East Horn") (Figs. 1 and 2). Both horns are peculiar in that each encloses near its tip a small secondary lagoon separated from the main atoll lagoon. The total area enclosed by the seaward reefs and lagoons is about 147 sq. mi. The surface reefs cover about 16 sq. mi. and on them 133 islands and islets form about 5 sq. mi. of dry land. The main lagoon encloses about 125 sq. mi., the secondary lagoon in the East Horn about 4.5 sq. mi., while the little enclosed lagoon of the North Horn has an area of only 1.5 sq. mi. (Fig. 4). The seaward reefs extend continuously around the entire atoll, except where they are broken by Tutu and Takleb Passes, which have threshold depths (15-25 fms.) nearly equal to the lagoon depth, three shallow (4 fms or less) passes east from Takleb and one shallow pass into the northwest part of the East Horn lagoon. The total peripheral extent of the seaward reefs is about 65 miles, and except for minor pass into the East Horn lagoon, all breaks in the reef are in the 6-mile windward stretch of the northeastern face of the atoll extending southeasterly from Tutu Pass toward Namej Island.

The seaward slopes (Fig. 3) of the outer reefs are steeper to leeward than to windward. No precise data are available, but it is obvious from an inspection of aerial photographs of Arno, and indicated by H.O. Chart 6005, that there is a decided difference. At Ine Anchorage a depth of 200 meters is reached about 150 meters out from the reef margin, a slope of 55 deg. At 1700 meters the depth is 1000 meters, about 27 deg. Thus the profile from reef edge seaward is concave and steeper near the reefs, and gentler with increasing depth. On the seaward side to windward off Takleb Island the depth 400 meters out from the reef edge is only 40 meters, a 7 deg. slope. In the next 350 meters the depth increases to 200 meters, a slope of 25 deg., nearly the same as the downward slope from 200 meters on the leeward side. At 3500 meters from the reef margin a depth of 1000 meters is reached, a slope of 19 deg. from 750 meters. This slope is essentially convex near the reefs, thence gently concave. The presence or absence of a 10-fathom terrace like that at Bikini is not determined, but comparison of aerial photographs of corresponding parts of the two atolls suggests strongly that it is developed on the windward side of Arno.

The material of which the reef and islands of Arno is composed is wholly coral reef limestone and its derivatives: boulders, cobbles, pebbles, sand, and finer silt-size particles. Small patches of phosphatic limestone occur in the interior of a few of the larger islands, but rock material other than limestone is very rare and accidental. Early in the 19th Century Chamisso noted that the natives in the Radack chain (eastern Marshalls) searched the beaches for stranded tree trunks with tough rocks tangled in their roots, for tools. Stranded trunks from North America are actually not uncommon on the Arno beaches, presumably carried in by the California and North Equatorial Currents. Two in particular were noted in 1950, one a huge cut fir log 5 x 55 feet, the other a redwood trunk in the roots of which were several sizeable chunks of a tough quartzitic grey-green sandstone. The only other stray "foreign" rocks on Arno are bits of pumice ranging in size from small pebbles to rounded pieces the size of one's head, found both high on seaward and lagoon beaches and inland.

B. Structure of the atoll islands. (Fig. 5).

The beaches of the seaward sides of the atoll are everywhere bordered, with very few exceptions such as Ine Anchorage and stretches of low reef tract on which islands are not yet developed, by boulder ramparts. These are ridges of boulders and cobbles of water-worn coral carried by storm waves from the outer slope and ridge of the reef over the reef flat. The rampart is 6 or 7 feet high on leeward sides of the atoll, but to windward it is often as much as 10 or 12 feet.

Boulder ramparts or ridges are the first stage in the development of islands. In their lee accumulate finer materials, stray boulders, pebbles and sand, carried over the ramparts and around their crescentiform ends, spread out on a gentle slope toward the lagoon. Where the rampart is fairly stable, chinks between the larger pieces become filled in with sand and pebbles from the beach zone, and between tide-marks it may be consolidated by cementation into solid strata of beach conglomerate with initial dip toward the reef flat to which it is welded. Beach conglomerate is often exposed where a slight shift in wave approach removes loose surface material and stands with the rampart as the second line of defence behind the reef margin.

Where the seaward reef flat is broad the inner part near shore may be covered by a rubble tract or sheet of large irregular coral blocks to a thickness of as much as 3 or 4 feet. Since they lie between tide marks, these sheets may here and there be consolidated into a tough horizontal stratum. All gradations from fresh, more or less angular rubble through rubble conglomerate to old conglomerate, corroded and decayed to the point of being mere remanants more or less stoutly welded to the reef flat, can be seen.

The beaches around islands are relatively narrow, 3 to 4 feet high, and lie between low tide level and the highest point ordinarily reached by the waves at high tide. Their slope is adjusted to the normal wave action in their area. On seaward side of islands they are steep and narrow, with slopes up to 20°. On lagoon sides they are wider with slopes of 5°-10°. A few inches beneath the surfaces of most sand beaches bordering the lagoon are patches of beach sandstone with initial dip corresponding to the beach slope, developed as a result of cementation between tide marks, and often welded by their lower edges to the reef flat. Beach sandstone, like beach conglomerate, is an important factor in anchoring islands to the reef.

Another structural feature is the sand dunes developed on the lagoon sides of some islands where there is a sand beach facing the wind. The strong trades sweep over the beaches exposed at low tide and move particles of sand 0.2-0.7 mm. in size up the beach and drop them at the top, in much the same manner as dune are built on other windward shores elsewhere. The dune sand is composed of more uniformly-sized particles than beach sand. The dunes form more or less continuous ridges 2 to 5 feet above the top of the beach. Behind them the island surface slopes gently toward the interior of the island where the wind-carried sand mingles with the material spread in the opposite direction from the boulder rampart. Such a dune ridge extends almost continuously the length of Ine Island. In places it is double, the outer one being lower and newer than the inner one. At one point, about a mile east of Ine Village, the ridge is nearly 15 feet above the beach (Arno's mountain) and 50-100 feet broad.

The interiors of islands are 6 or 7 feet above low tide level, and consist of more or less horizontal layers of material derived from the seaward boulder rampart and lagoonward dune ridge or beach, often more or less consolidated into island or cay sandstone.

Figure 5 shows a generalized cross-section of an island on the lee side of Arno Atoll.

In summary: the islands and islets represent constructional work of wind and wave with materials derived from the living reefs. They are accumulations of loose material partly held together by a patchwork "endoskeleton" or framework of beach conglomerate to seaward, beach sandstone lagoonward, and interior island sandstone. They are seen in all stages of development on Arno, from lonely little bits of rampart with a single sprouting coconut to broad islands sufficiently old to have small patches of phosphatic limestone in their interiors. They are not, at least on Arno, as some would have us believe, the remains of old reef flats raised above sea-level by the more or less recent 5 or 6-foot lowering of sea-level coincident with the accumulation of the Greenland and Antarctic icecaps. Evidence of this eustatic shift is supposed to be widespread in the Pacific but no features at Arno need be ascribed to it. Speculation that the old reef surface elevated by eustatic change has been completely planed away at Arno seem unnecessary. Emphasis by some observers that isolated masses of reef rock welded to the present reef flat is evidence of an older, now elevated reef flat overlooks the possibility suggested here that they are remnants of old cemented rubble tracts.

C. Surface processes and changes.

Everywhere on Arno evidence can be seen of moderate change due to shoreline processes, and here and there vast changes due to occasional great typhoons. The former are more obvious on the lagoon side, the latter on both lagoon and seaward sides, and both are most apparent on the lee side of the atoll.

The thirteen-mile long lagoon shore of Ine Island has a nearly continuous sand beach. In places this beach is being aggraded, as at Ine Village. Some of the slow sand increment is carried in from the lagoon reef flat, and some is shifted along shore by waves from another part of the beach. From Ine Village westward for some miles stretches of gravel-cobble beach alternate with stretches of beach sand. The gravel beaches develop in places where waves are strong enough to degrade, leaving concentrations of coarse material. This alternation coincides with the alternately concave and convex parts of the reef and island with respect to the lagoon. Degradational gravel beaches occur along the salients, aggradational sand beaches in reentrants. The lagoon reef is not yet wide enough to stabilize the shoreline - the geomorphologists' Nirvana, a shoreline of equilibrium, is far from reached.

Active degradation of a sand beach is seen at the east end of Ine Island, where for the last few miles the beach is narrow and the dune ridge is strongly undercut so that turf overhangs the top of the beach. Coconut palms have toppled onto the beach in an almost even row and are slowly dying. About a quarter mile west of Ine Village, approaching a convexity in the island, undercutting has proceded so far inland that the dune ridge has almost disappeared and a 3-foot cliff of island sandstone is now being cut into. At this site the island is unusually narrow, less than 100 feet, and the initiation of the present slow undercutting is the result of washing away of most of the dune ridge and old beach sandstone by typhoon waves. The beach sandstone that lay under the old beach is now exposed at the water's edge at low tide.

More striking, however, than the normal shoreline changes, are the effects of the typhoons that strike the Southern Marshalls four or five times a century. Records are rare and older natives are the only source of eyewitness information, but their recollections are naturally vivid of such disasters and are confirmed by the physical traces of typhoon effects which can still be seen. One old man, Lijömmar, remembers four typhoons during his lifetime, those of 1905 and 1918 being the last two, as he related to Dr. E. L. Stone in 1950. These are remembered by others and their dates seem fairly certain. That of 1905 was the most violent.

Previous to 1905, according to Lijömmar and others, all of the islands now scattered along the reef from the eastern tip of Ine some 18 miles to L'Angar Island at the tip of the East Horn were one continuous island, with only one canoe passage (portage?) between the west end of Ine and L'Angar, apparently

apparently a mile or so north of the present east end of Ine (Fig. 7,A). The typhoon of 1905 swept away long stretches of this island (Fig. 7,B) so that where there was a single long island there are now about 40 (Fig. 7,C), the smaller ones having been built up since the typhoon, the larger ones being remnants of the original island. Confirmation of this extensive change is found on a small chart, corrected by officers of the old "Albatross" from a German hydrographic chart, published in 1903 by Alexander Agassiz (M.C.Z. Harvard, Mem., vol. 28, fig. 4, p. 228), which shows a continuous strip of land from L'Angar to the west end of Ine, broken by a pass near the present east end of Ine and another about 5 miles west of Ine Village. If these passes existed, they must have been merely canoe passes over the reef, or possibly portages, for no break in the reef can be seen at or near these places on aerial photographs, and Agassiz himself did not see them, saying "....there are said to be several boat passes on the southwestern face of the lagoon." At any rate, two years after the corrected chart was published, it was obsolete.

The destructive effects of typhoons on atoll islands can be seen at many places on the leeward side of Arno. Mention has been made of the washing away of a stretch of lagoon beach just west of Ine Village, exposing island and beach sandstone. About 2 miles farther west beyond Jab'u, the island narrows to less than a third of its normal width and in places is scarcely 30 feet wide (Fig. 8). For half a mile the dune ridge is very much lower and between it and the boulder ridge on the other side of the island the sand seems to have been scooped out into miniature box canyons with steep heads toward the rampart. About 50 feet from the beach remnants of the old beach sandstone can be seen at low tide on the lagoon reef flat, indicating the former greater width of the island. This change was the result of water piled up on the leeward side during the 1918 typhoon washing completely over the island into the lagoon, carrying away land, dune, and lagoon beach. Since then a new beach, underlain by freshly-formed beach sandstone, and a new dune ridge have developed. Similar washouts were seen at the east end of Kilange near the base of the East Horn. On the next island west, Malel, are large numbers of prostrate breadfruit trees, still alive, which were downed by the same storm.

Eastward from Ine Village extend two old paths bordered by beach sandstone slabs, one paralleling the lagoon beach, the other swinging south and paralleling the seaward shore just inside the boulder rampart. Beyond Stony Point, as one approaches the next "point", the beach swings inward crossing the trend of the path which ends abruptly as if cut off. For several hundred yards beyond, the southern part of the island has apparently been carried away by a typhoon to the extent that on the next point the old island sandstone core is now exposed at the edge of the reef flat.

The 1905 typhoon washed away parts of the former long island between L'Angar and Ine and left long stretches between with only the bare bones of former land, -- a low ridge of beach sandstone on the lagoon side, a rubbly band in the former island interior and a new seaward boulder rampart (Fig. 6). Over the lagoon reef opposite these places are strewn masses of rubble, now corroding, the finer materials having been bypassed into the lagoon. Dark lines of old beach sandstone, marking the site of former beaches and land, show well on aerial photographs and can be traced nearly continuously between islands from L'Angar almost to Ine. The amount of land lost during this typhoon on this part of the atoll was about 160 acres, only 5% of the total land on Arno now, but nearly 25% of the area of the former island.

Typhoons and destruction of land on Arno will occur again and again. The forces tending to construct new land are slowly but steadily operating, but in the 46 years since the last great storm, they have not replaced the land lost then. It has not been possible to determine how many of the small islands in the area of major destruction are remnants and how many are replacements, but certainly less than 10% of the lost acreage has been made up. The typhoon of 1918 probably destroyed part of the gain, and that of 1950 may have washed away still more. The long narrow islands of Arno invite typhoon damage, for they act as barriers to the heightened tides and waves of the storm, and the only egress for the piled-up waters is over the land.

From these observations it would appear that the windward side of atolls in the Southern Marshalls are safer and less susceptible to damage than the leeward. Typhoons in this region come from a southerly direction and the normally leeward side bears the brunt of the shock. The leeward reef, its islands, and the lagoon absorb and weaken the rush of water, and waves in the lagoon can hardly rise as high as the open sea waves. The windward islands suffer mainly from the high winds instead of being overwhelmed by water during a great storm. Unfortunately, most of the land on Arno is on the lee or typhoon weather side.

Little, if anything, can be done directly by man to lessen, much less prevent, loss of land or soil by typhoon damage. This should be kept in mind if attempts are ever made to increase soil productivity on atoll islands. Greater soil productivity leads not necessarily to higher or better standards of living, but to larger populations. Well-intentioned attempts to improve the lot of the native populations of atolls thus might well jeopardize more lives than ever when the inevitable typhoon sweeps in, and lead to appalling drops in population and lower living standards than now obtain for the survivors. True, the Indian Ocean atoll of Cocos-Keeling has been almost completely devastated several times in the last century by typhoons and still comfortably supports a very much denser population than any Pacific atoll. But Cocos has capital wealth obtained from other sources than the atoll soil and is populated by a highly energetic group of people under a strong patriarchy.

D. <u>Reef types</u>.

The seaward reefs at Bikini Atoll in the Northern Marshalls were recently classified by Tracey, Ladd, and Hoffmeister (1948, G.S.A. Bull., vol. 59, p. 870), largely on the basis of the character of the reef margins, as follows:

I. Strongly grooved.

   A. Lithothamnion ridge low, uncut by grooves.
   B. Lithothamnion ridge prominent, cut by grooves.
      1. Room and pillar structure developed.
      2. Algal mounds and blowholes developed.

II. Grooves weak or absent.

   A. Margin smoothly scalloped.
   B. Margins made irregular by erosion.
      (two subtypes)

The distribution of these types at Bikini is shown on Figure 3 of the paper cited. Application of this classification to the Arno reefs is shown in Figure 2 of this report. Comparison of the two shows one striking difference and a number of similarities. The difference is the almost complete absence of reefs of Type II, in which the grooves down the upper part of the slope are weak or absent, at Arno, whereas at Bikini they are characteristic of the leeward stretches. According to Tracey, Ladd, and Hoffmeister, where reefs of this type are developed there is no evidence of a terrace. At Arno there is no evidence of a terrace on the leeward slopes, but a strongly grooved, steeply sloping reef margin of Type IA, with low algal ridge, is developed. A typical profile of such a leeward reef of this type at Arno is shown in Fig. 9.

Reefs of Type IB_2, with strongly developed algal ridge, are found at corresponding windward sites at both atolls, alternating with Type IA which is developed on stretches less exposed to the northeasterly and easterly trades. At Arno there does not appear to be the close relation between islands and Type IB reefs and stretches between islands and Type IA, observed at Bikini. In areas where there are islands or islets on the reef, open spaces between islands are narrow and water flow across the flat is impeded by rubble.

At only one site at Arno is a reef of Type II (grooves weak or absent) developed. A stretch of about 300 meters northwestward from Stony Point on the seaward leeward side at Ine Anchorage in a shallow bay between two crescentiform swellings of Ine Island best fits Type IIA. Grooves are absent and the margin slopes very steeply, practically vertically at first, less so below about 10 meters, with an average slope of 55 deg. to 200 meters. There are more or less regular re-entrants 3 to 10 meters deep, 2 to 10 meters wide, with sandy or rocky floors. One or two of these are interconnected by open channels, isolating flat-topped pillars, but there is no evidence of collapse due to erosion. Wind waves are negligible at this site and the strong swells from the east are reduced by the projection of Stony Point.

E. <u>Lagoon Reefs</u>

The lagoon reefs are not so continuously developed as the seaward reefs although banks on which reefs might exist are continuous. They are best developed along the windward lagoon side of the west, south, and north sides, where there is little or no wash of sand and other detritus from the seaward reefs. The only development of leeward lagoon reefs on the windward side of the atoll is in the vicinity of the two threshold passes, Tutu and Takleb. The sand banks developed on the lagoon side of the windward reefs from wash from these reefs are rapidly extending into the lagoon. They slope steeply downward toward the lagoon floor at about 35 deg., the normal angle of repose.

In the enclosed lagoons of the North and East Horns the reefs are distributed as in the main lagoon but again coral growth is patchy owing to the sand cover of the flats and lagoon slopes.

In the North Horn (Fig. 4), which has no pass whatever to seaward a special situation has developed. On all sides except the north, the seaward reef flats are built up either with islands or thick rubble to a level above low tide level. On the eastern side the rubble areas between islands are penetrated by sand-floored channels from the lagoon side, usually with a moderately rich growth of corals, but about halfway to the seaward margin they become very shoal and choked by rubble which often is more or less cemented. Except to the north this rim is 1 to 2 feet above low tide level, but is 2 to 3 feet below high tide level. When tide level falls below the rim level the excess water flows northward and part of it escapes over the lower rim between the ends of the windward and leeward reefs. The rest of it flows outward through the channels onto the seaward reef flats. Formerly most of the excess flowed out by the northern outlet, which was covered or crossed by a reef flat built to within about a foot of low tide level. This rapidly moving water, however, supported a profuse growth of corals and calcareous algae which have now grown up across the opening, forming a low, broad, convex rampart, one edge of which slopes steeply into the lagoon, the other gently down into the scattered microatolls around the embayment in the northern end of the horn. At present this dam has a uniform crest of at least 2 feet above low tide level on the seaward side, and over its entire surface there is a steady but diminishing outflow of water as the tide ebbs. Coral growth is rich but the depth of water on the spillway slope at each low tide is now hardly more than an inch and broad stretches are exposed, and coral colonies are low and spreading. Thus the water level in the enclosed North Horn lagoon never falls as low as the level reached at low tide on the seaward reefs.

This enclosed North Horn lagoon is much shallower than the main lagoon or the enclosed East Horn lagoon, and soundings shown on the H.O. chart indicate a maximum depth of 10 fathoms. Coral knolls are numerous, and the lagoon is probably filling rather rapidly. Because of the absence of even a shallow pass into this lagoon circulation of the lower levels of water in it must be restricted, but unfortunately it was not possible to obtain bottom samples bearing on this point.

F. Coral Knolls.

These characteristic structures of atoll lagoons, often loosely referred to as "coral heads", are abundant in all the Arno lagoons (Figure 1 shows only a very few of the knolls). Some of them are sufficiently developed as to be awash or even exposed 2 to 4 feet at low tide. In the main lagoon there are six areas where they are concentrated: 1) in the area at the base of the North Horn generally west of Eneweto Island, 2) a large cluster fanning out from the break in the reef south of Jarkul Island, 3) across the inner end of Tutu Pass, 4) halfway across the lagoon between Takleb Pass and Ine Village, 5) in the southeast corner of the lagoon, and 6) in the secondary embayment at the base of the East Horn.

The distribution of the knoll clusters seems less than fortuitous. Three are in corners of the lagoon, and two are associated with threshold passes. The remaining one, the large Jarkul cluster, is probably also of the second group. The broad break in the reef southeast of Jarkul (2 miles northwest of Tutu I.) suggests a filled-in threshold pass. The absence of a strong seaward reef at this point still enables the wind waves and swells to sweep in and transport large quantities of sand which are building a "delta" into the lagoon over the site of the former pass. Around this "delta", within a radius of about 1.25 miles there are at least 65 knolls visible on aerial photographs in addition to two large shoals. The cluster around Tutu Pass is smaller - 22 - and none is visible in the immediate vicinity of Takleb Pass. The latter is shallower than Tutu and less to windward, but the large cluster in the lagoon to the south, beginning about a mile from the pass, may be related to it. Are these knoll clusters related to the developmental stage of the passes with which they are associated?

A somewhat similar distribution of knolls may be found in the lagoon of Majuro Atoll, suggesting an interesting minor research problem.

III. Reef Zonation

A. Seaward Reefs

As indicated above, three reef types of the Tracey-Ladd-Hoffmeister classification are developed at Arno: IA, IB, and IIA.

1. Type IA.

This is the dominant type at Arno, and extends almost uninterruptedly from the west side of the North Horn southward around the lee side of the atoll to the eastern end of the East Horn. A typical section of this type of reef, strongly grooved with a low algal ridge uncut by the grooves, is shown in Figure 9. The broad rock flat, seemingly barren, supports no coral growth except in occasional depressions where small patches of Porites lichen and a few other forms grow feebly. At practically all sites, however, except on open stretches unbroken by development of islands (i.e., NE of Kilomon, E. of Takleb), there is an extensive overgrowth of a curly, disreputable-looking brown alga (Microdictyon okamurai) on the fronds of which live vast numbers of Calcarina. Associated with these are many individuals of the large, closely-adherent pelecypod Chama which resemble projections of rock about the size of one's fist. This is the Calcarina-Chama zone. This zone is truly barren only where there are prominent convexities in the reef (Fig. 8). Where this flat begins to slope gently down as the "algal ridge" toward the upper ends of the grooves, low and broadly adherent colonies of Pocillopora are usually dominant, (with fewer specimens of Acropora, Astreopora, Porites, etc.), on the weak encrustation of lithothamnion,- the Pocillopora zone, at the outer end of the waves of translation at low tide. Beyond this, in the surf zone, Pocillopora is replaced by Acropora (A. pectinata, A. digitifera, etc.), forming a zone extending well down into the upper part of the grooved area. Other common genera in the Acropora zone are: Astreopora, Porites, Millepora, Favites, etc.

2. Type IB.

This seaward reef type, with relatively high, prominent algal ridge, is characteristic of the exposed windward reef tracts, and is replaced by Type IA only where some protection is afforded by concavities in the reef margin. The usual zonation of this type is shown in the section, Figure 10. The rocky flat is usually less richly endowed with the alga-Calcarina-Chama association and the ridge is not a place of vigorous coral growth. The surge channels are usually shallow, rarely roofed over, and often partly filled with coarse boulders. Occasional small colonies of Acropora cuneata are found, but less commonly than in the corresponding zone on reefs of this type at Bikini. Nowhere is this reef as broad as at Bikini, and no trace of an inner Heliopora zone was noted.

3. Type IIA.

As previously noted, this type is found only in a limited area at Ine Anchorage (Fig. 8). It is distinctly zoned by corals as shown in the section, Figure 11. Following an inner barren zone, exposed for long periods at practicall every low tide, is a broad tract thickly settled by extensive colonies of Montipora ramosa, -- a nearly exclusive society, here and there replaced by patches of Acropora hebes or alcyoniid "soft corals"(Lobularia). Occasional colonies of Synaraea, Leptastrea, Porites (especially P. superfusa), and Pavona, also occur. At low tide the depth is from zero to about fifteen inches, and the water is practically undisturbed by swells or waves of translation. The outer limit of this zone is at about the inner extent of the ordinary low tide waves of translation, where it is succeeded by a zone dominated by Acropora, especially species of the corymbose A. pectinata type, which extends to the reef margin. Fungia scutaria is common in this zone. It is the zone of richest variety of corals and other reef animals. Calcareous algae are relatively very unimportant. Species of at least 33 genera of scleractinians and hydrozoans have been collected in the zone, but Acropora accounts for around 90% of all colonies. Over the reef edge and in the re-entrants along the edge the next zone, marked by the pedestal colonies of A. reticulata, begins about 6 feet below low tide level in water only slightly agitated by the constant but low swells, and extends down to about 30 feet, where coral growth becomes very sparse. Fungia scutaria, F. fungites, and F. concinna are very common.

B. Lagoon Reefs

Two main types of lagoon reefs may be distinguished at Arno. One is found on the leeward side of reef tracts on the windward side of the atoll, or on the leeward side on long stretches where islands are not yet developed. The other is developed on the windward side of the island-flecked reef tract on the leeward side of the atoll.

1. Leeward Type.

The first type is developed in the enclosed lagoons of the North and East Horns (Fig. 13), and in places along the sheltered leeward side of the reef tract between the horns (Fig. 12). The immediate substratum is primarily the sand washed into the lagoon margin from the outer reefs, either across the flats or around the passes. These sand tracts slope steeply (35 deg.) at their inner edges, which may be from a very few to several hundred feet out from the shore, down to the lagoon floor. On this insecure base luxuriant coral patches are scatteringly developed, rising with more or less abrupt sides from depths of a foot or so, often very close to the beach, to 12 or 15 feet. The spaces between them are flat and floored with sand on which few corals grow. The characteristic coral of this zone is Porites andrewsi, a ramose form found in the same environment at Bikini and other northern Marshall atolls. Also common in this zone is Acropora palifera which often forms huge colonies in shallower parts of the sandy interspaces. Fungia is common. The Acropora reticulata zone, found below about 6 feet on the Type IIA seaward reef, extends as might be expected on these protected lagoon reefs well into the P. andrewsi zone, in as little as 2 or 3 feet of water at low tide. It does not appear to extend downward much below about 20 feet.

2. Windward Type

The second type of lagoon reef at Arno, exemplified by the section, Figure 14, extends from near the southeastern corner of the lagoon along the windward southern side of the lagoon the entire length of Ine Island to Arno

Island, about 13 miles, and beyond. It is the broadest of Arno reefs of any type, averaging about 1500 feet from beach to margin. The flat consists of a patchy veneer of sand and silt on an uneven, corroded reef rock flat which lies from 6 inches to 3 feet below low tide level. It is shallower near shore, deepening to about 3 feet at the midpoint, then shoaling near the margin, which in a few places is exposed at low tide. Beyond this low ridge the rock surface, often quite bare of sediment, slopes gently at about 10 deg. to the sandy floor of the lagoon at 15 or 20 fathoms. Coral growth over this type of reef is sporadic and nowhere rich and flourishing. The width and depth of the tract enable the wind waves to proceed well in toward shore where they keep the sand and silt well stirred at high tide, inhibiting the growth of all but a few colonies of such hardy forms as Porites lutea and Pocillopora damicornis. Hippopus is common in this inner zone. In the deeper water beyond and nearly to the margin, Astreopora is abundant, forming massive heads up to 5 feet across. Many large dead colonies of Acropora palifera and A. gemmifera, occasional large Pocillopora, and discouraged Porites andrewsi also occur. On the bare, pitted and irregular marginal slope is found the widest variety of forms, but no one species appears dominant. Especially common are several species of soft alcyoniid corals (Lobularia and Lobophytum). Fungia is absent. Lithothamnion is only occasional and not flourishing. From a depth of about 5 feet down the slope, Acropora reticulata is dominant, often forming huge spreading brackets 3 to 8 feet across. This zone extends nearly to the lagoon floor into the Acropora formosa habitat.

A third type of lagoon reef, with an algal ridge and zonation similar to that of seaward reefs, is developed at Bikini around the western end of the lagoon, where wind waves developed over a fetch of about 20 miles produce a strong surf. This type is not found at Arno where nowhere do prevailing winds have a fetch of more than 10 miles.

IV. Reef Temperatures

For mid-Pacific reefs there is, so far as the writer is aware, only one detailed record of water temperature variations across a definite reef tract. In 1918, A. G. Meyer published (Carnegie Inst. Wash., Pub. 213, pp. 31-34, fig.9) an account of the temperatures on the Maer Island coral reef, Torres Straits,-- a fringing reef about 188 feet wide. In general he showed that while daily temperature changes at the seaward margin have a narrow range (3.5 deg. C.), the range increases toward shore to as much as 12.5 deg. (C.), and concluded that the high temperatures experienced during part of the year must be sufficient to kill all corals within 450 feet of the shore.

During the month of June, 1950, a number of temperature traverses were made across the Ine Anchorage Reef along the section line of Fig. 11, at various times of day and states of tide. The temperatures were measured at the height of coral growth, usually about a foot from the bottom, at 30-foot intervals across the 450-foot width of the reef. The results are summarized in the chart, Figure 15 and presented in the same form as Mayer's cited above. On the basis of Mayer's results and theoretical considerations, the results obtained at Arno might have been predicted. The least range is found at the seaward edge, the greatest nearest shore, regardless of the state of the tide. Coral growth on the reef is closely correlated with this. It is richest at the reef margin where the temperatures are more constant, and weakest or absent near shore where temperature ranges are greatest. This correlation, of course, is not exclusively due to temperature control. Agitation and water movements are greatest near the edge; salinity fluctuations due to heavy rainfall are greatest in the very shallow water near shore, among other controlling factors.

The fluctuation is diurnal. Early in the morning, before the sun shines on the reef flat, temperatures across the reef are nearly uniform, usually a degree less nearer shore than the normal 28 deg. C. at the reef margin, but within a few hours temperatures near shore, even at high tide, are much higher than at the margin.

Of particular interest are the two sets of serial temperatures graphically analyzed in Figure 16. These were run at 50-foot intervals along a line 1000 feet long and parallel to the reef edge and about 200 feet from shore, approximately on the boundary between the *Acropora* and *Montipora* zones. At the east end this line cuts across the transverse section line of serial temperatures shown in Figure 15. At high tide (10:30 a.m., 24 June) the water along this line was about 3-4 feet deep, and little variation in temperature was expected or found. With this depth of water the swells are little impeded and broken by the reef margin and no cause for fluctuation is developed. But at low tide (4:00 p.m., 23 June) great variation was found: from 28.2 to 30.9 deg. at more or less regular intervals along the tract. The highs were about 200 feet apart and alternated with the lows. These represent wedges of cooler water extending into the shoreward band of warmer water, or contrawise. The separation of these wedges is striking. At one spot a temperature difference of 1.5 deg. was found in a distance of only 25 feet.

The explanation of these wedges of warm and cool water at low tide is not hard to find. There is a close correlation between the wedges and the re-entrant channels in the reef margin. The cooler water wedges are opposite the re-entrants, the warmer wedges extend outward opposite the salients. At low tide the constant swells from the southeast, refracted around the easterly side of the atoll from the northeast, are slowed by the salients but move undiminished into the re-entrants. A wave of translation forms at the head of a re-entrant and is reinforced by refracted swells from the salient on either side. This drives a mass of cooler water onto the reef flat at each re-entrant. Rip currents moving outward onto the salients then shift the displaced warmer water toward the salients.

V. Appendix: List of Coral Genera Occurring at Arno

A. Scleractinia

Acanthastrea
Acrhelia
Acropora
Alveopora
Anacropora
Astreopora
Coscinaraea
Culicia
Cyphastrea
Echinopora
Favia
Favites
Fungia
Goniastrea
Goniopora
Halomitra
Herpolitha
Hydrophora
Leptastrea
Leptoseris
Leptoria
Lobophyllia
Merulina
Montipora
Mycedium
Pavona
" (Polyastra)
" (Pseudocolumnastraea)
Platygyra
Plesiastrea
Pocillopora
Porites
" (Synaraea)
Psammocora
" (Plesioseris)
" (Stephanaria)
Seriatopora
Stylocoeniella
Stylophora
Symphyllia
Ulophyllia

B. Alcyonaria

Heliopora
Tubipora

C. Hydrozoa

Distichopora
Millepora
Stylaster

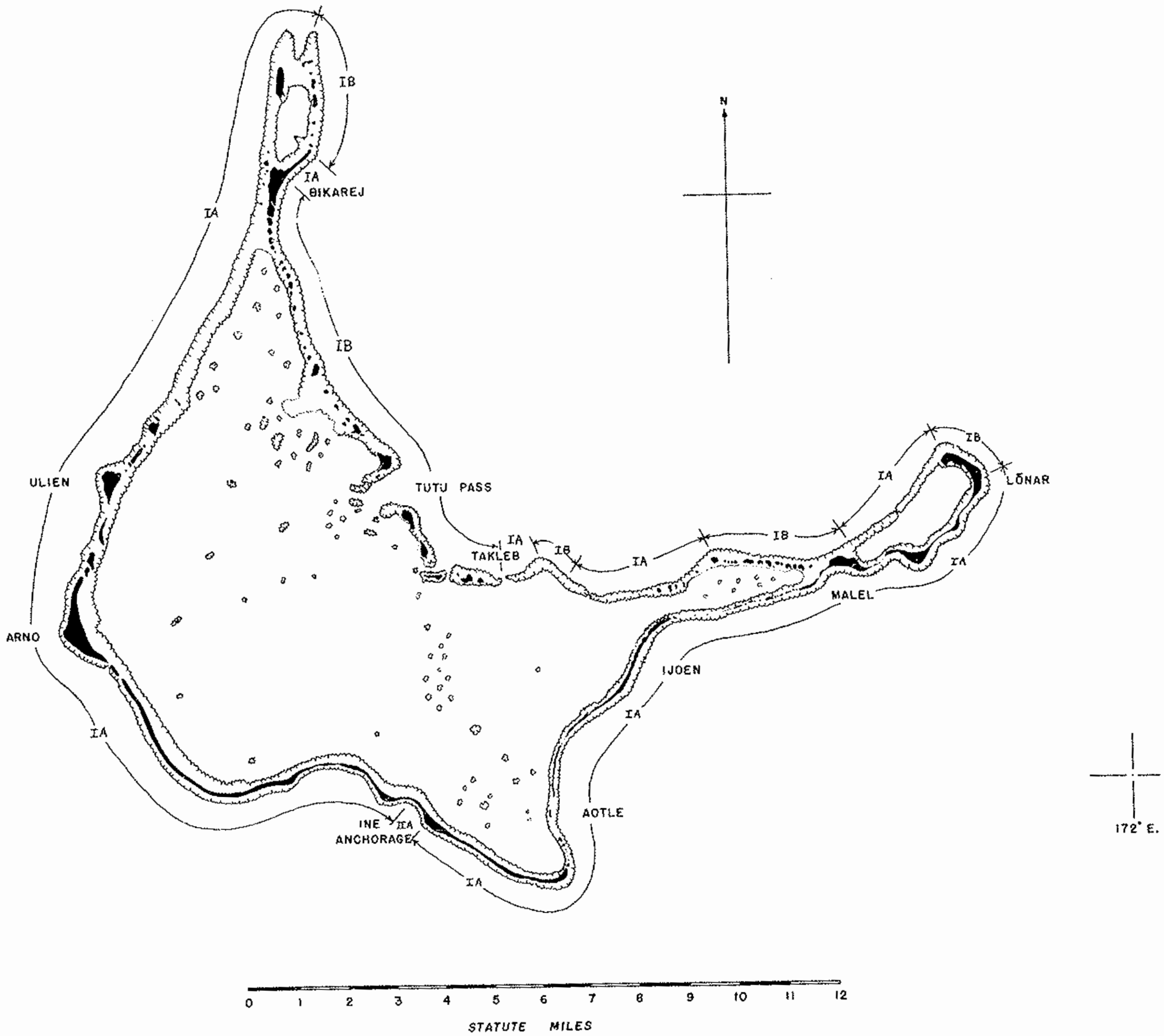


FIGURE 1. DISTRIBUTION OF REEF TYPES, ARNO.

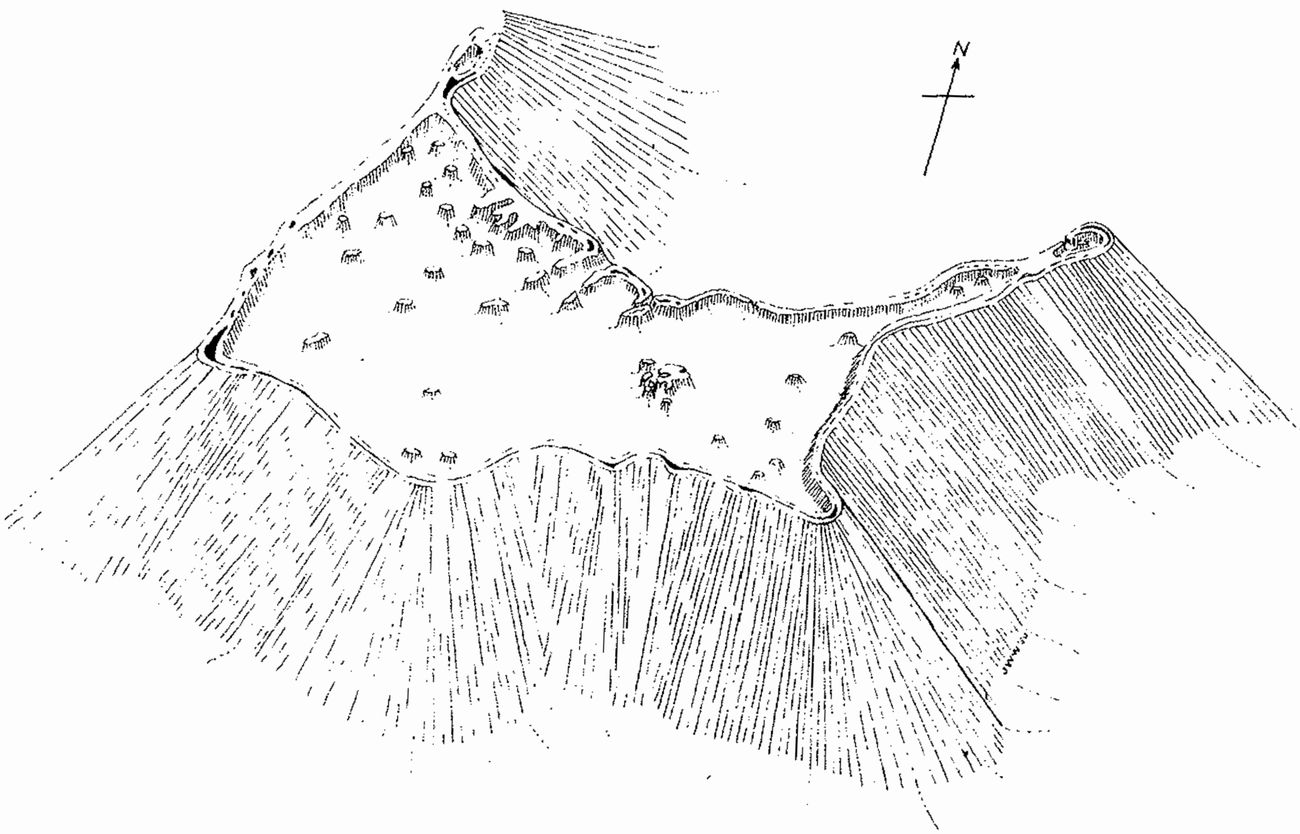


FIGURE 2. PHYSIOGRAPHIC DIAGRAM, ARNO ATOLL.

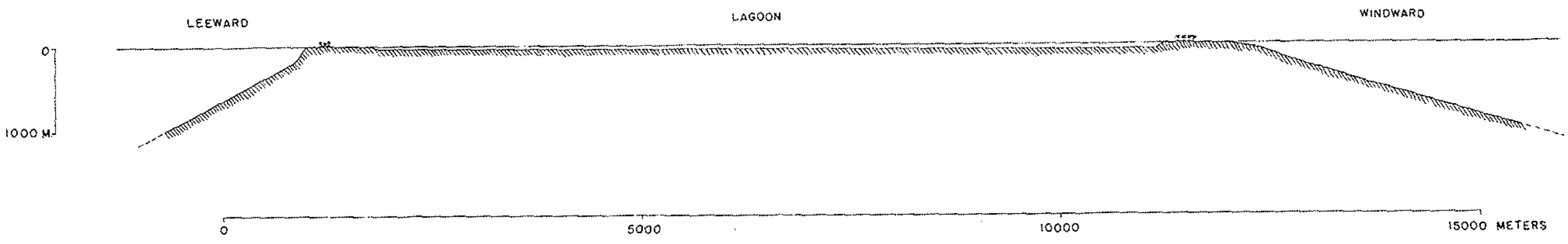
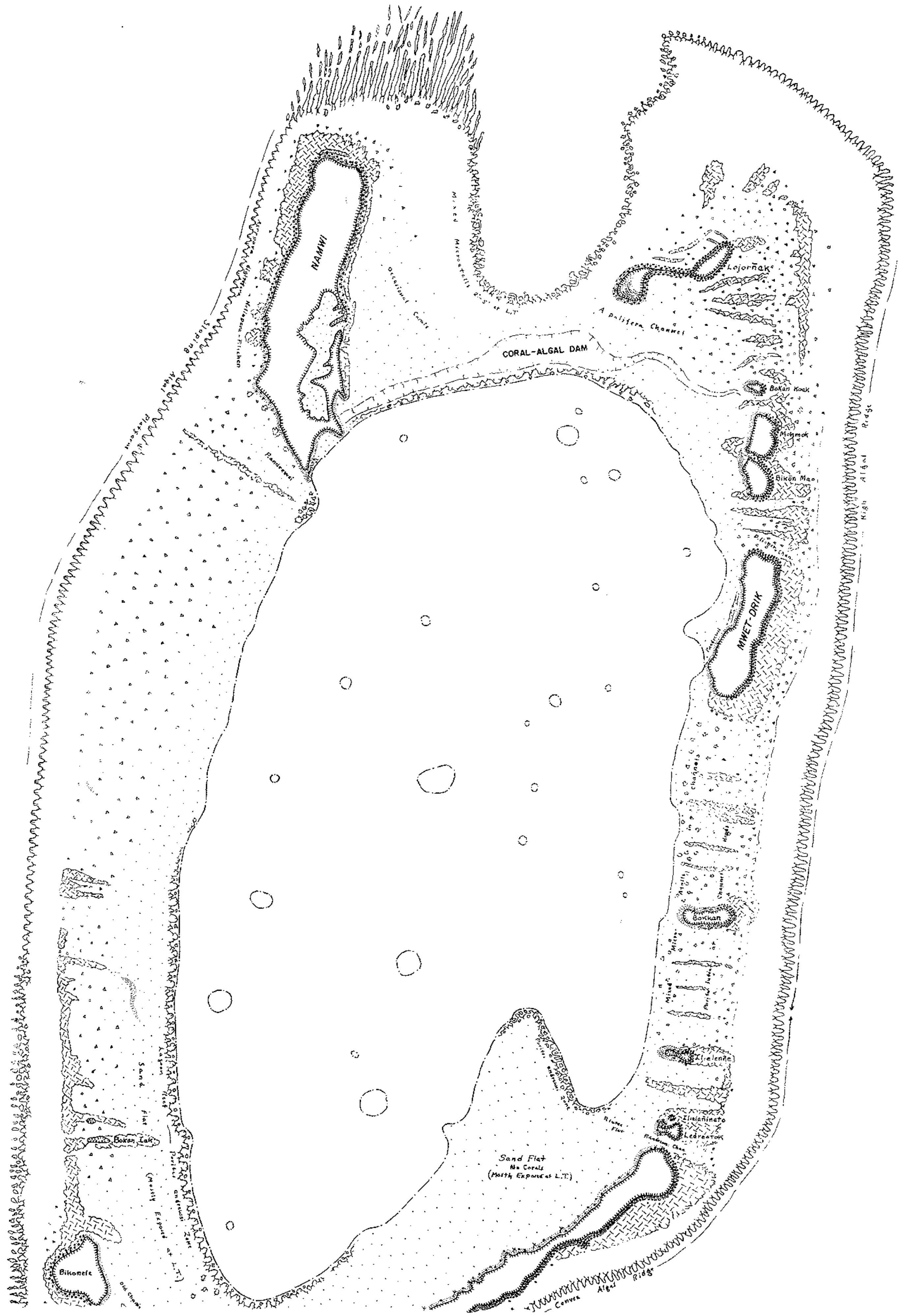


FIGURE 3. TRUE SCALE CROSS SECTION, ARNO ATOLL.


NAMWI
CORAL-ALGAL DAM
MWET-DRIK
Bokkan
Sand Flat
No Corals
(Mostly Exposed at L.T.)
Bikonele

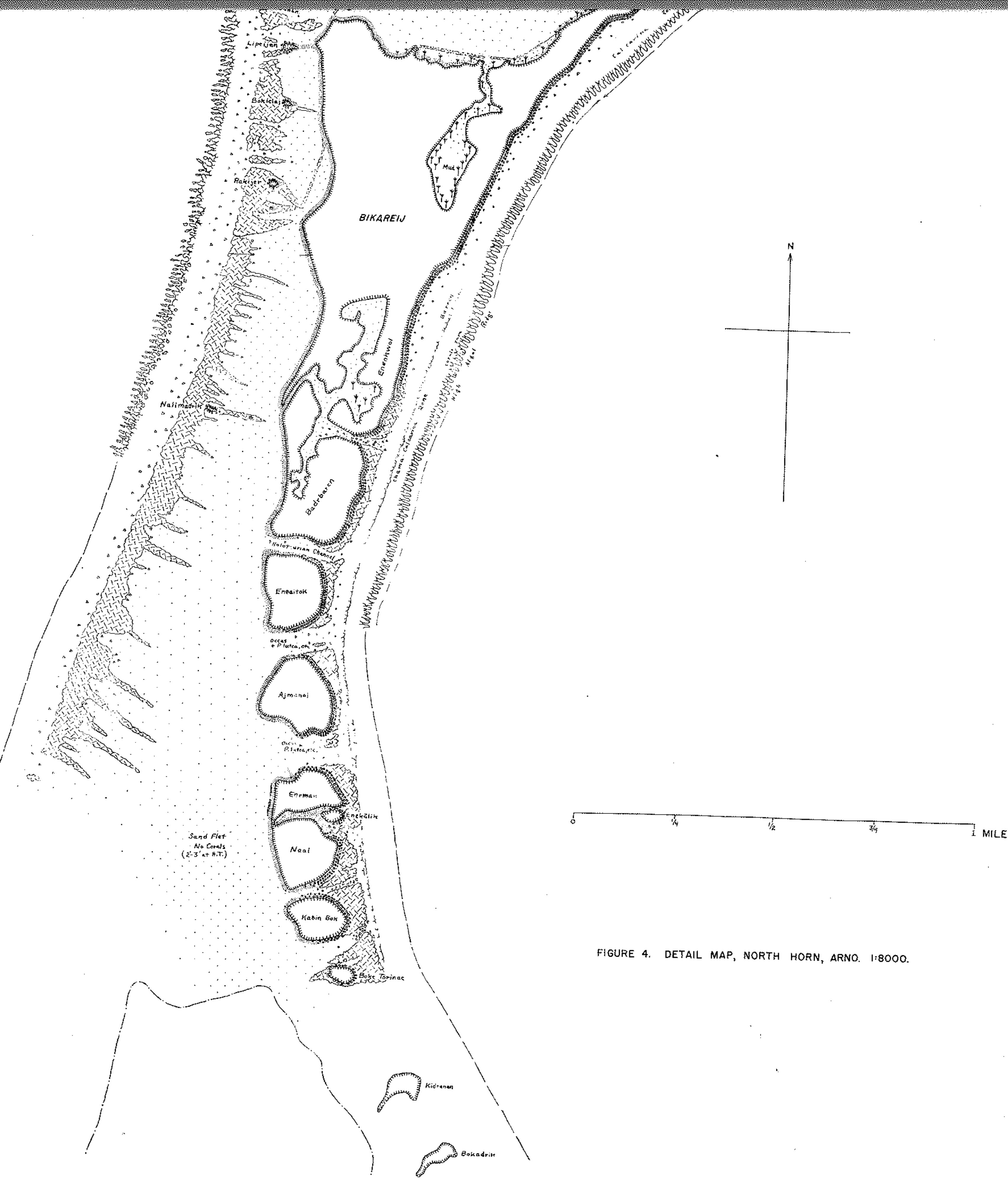


FIGURE 4. DETAIL MAP, NORTH HORN, ARNO. 1:8000.

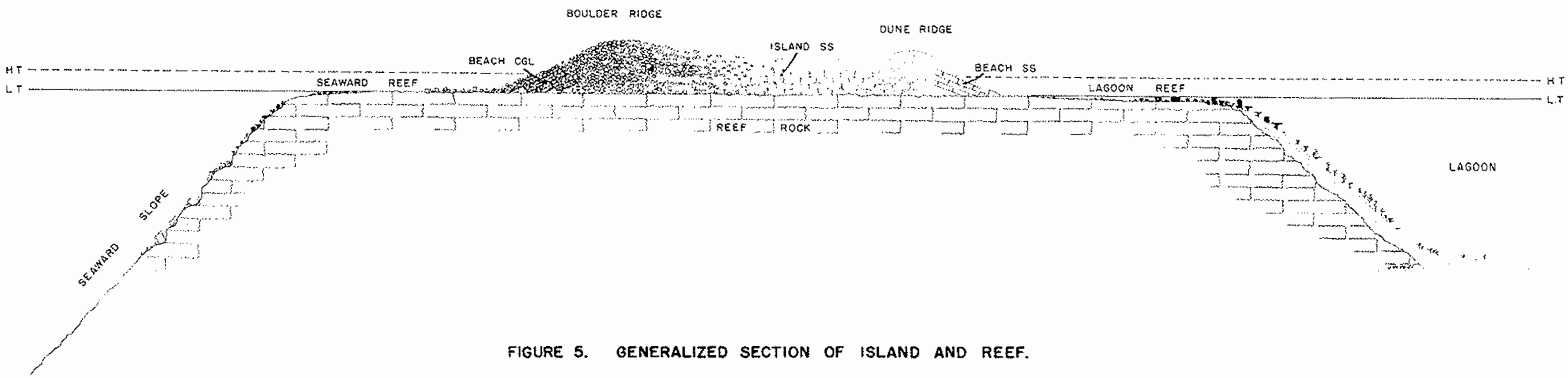


FIGURE 5. GENERALIZED SECTION OF ISLAND AND REEF.

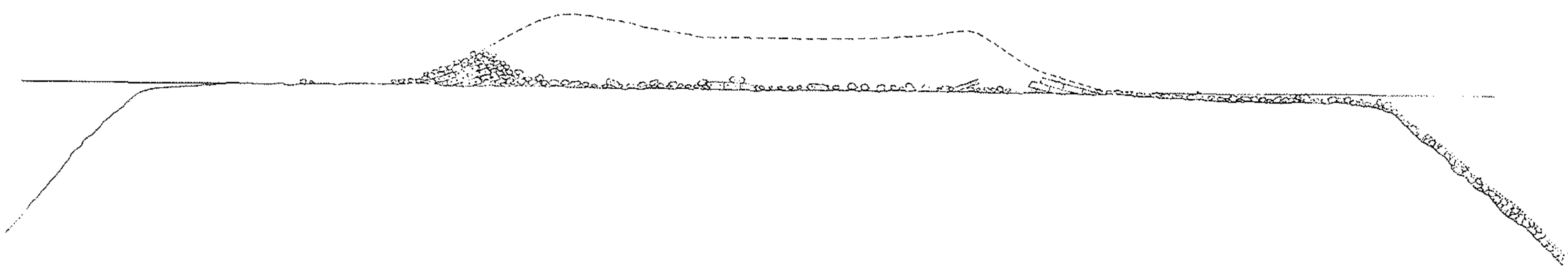


FIGURE 6. SECTION OF ISLAND SWEPT BY TYPHOON.

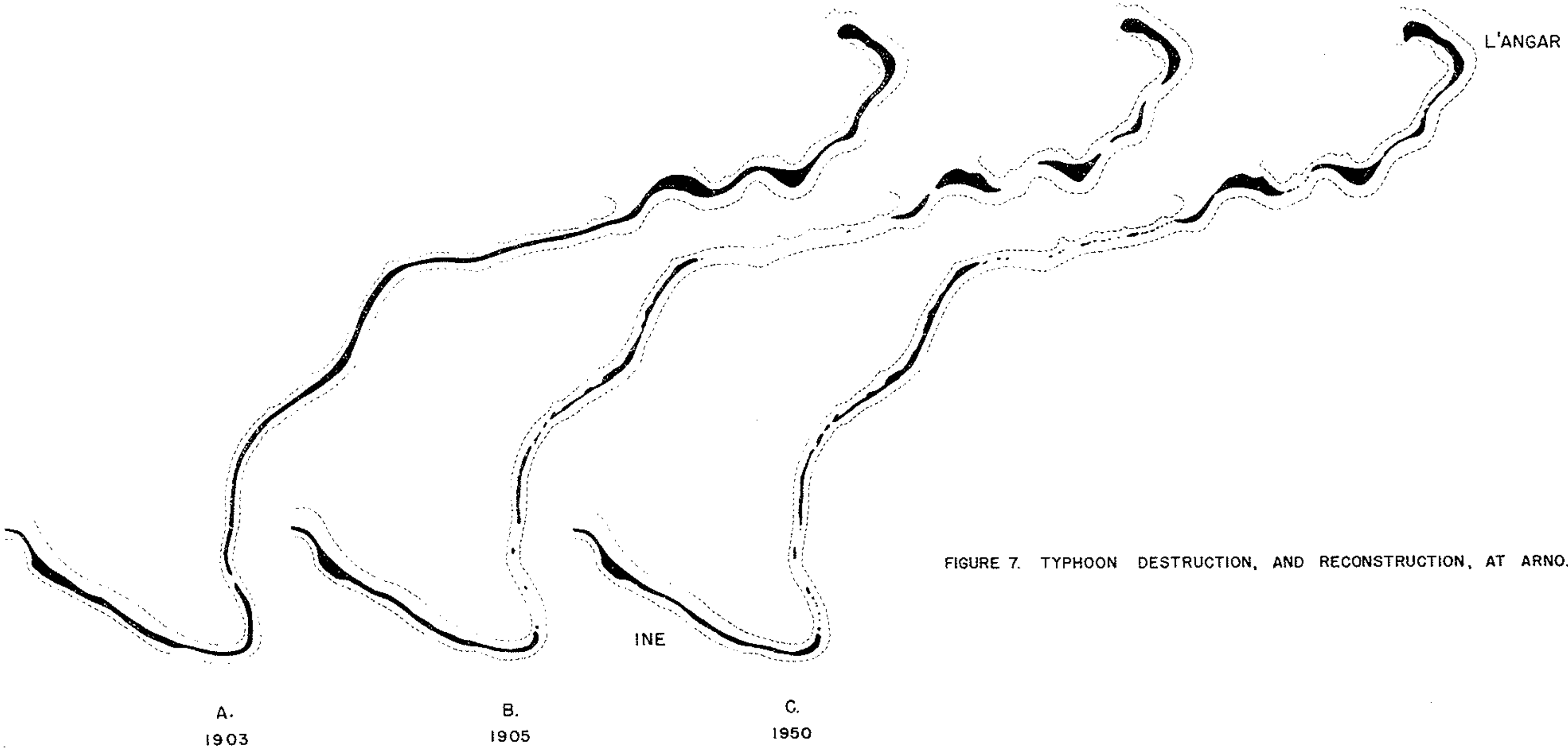


FIGURE 7. TYPHOON DESTRUCTION, AND RECONSTRUCTION, AT ARNO.

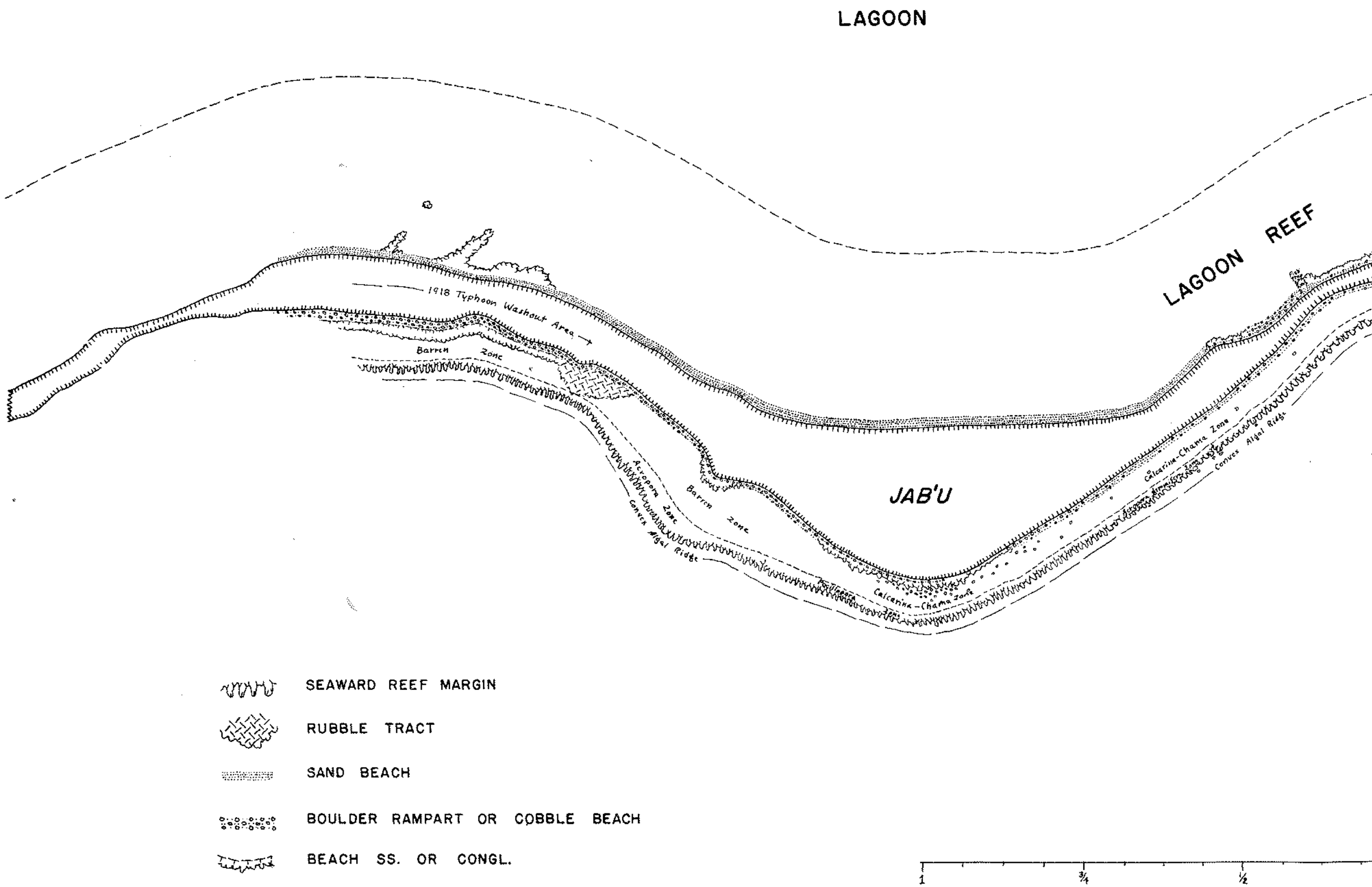
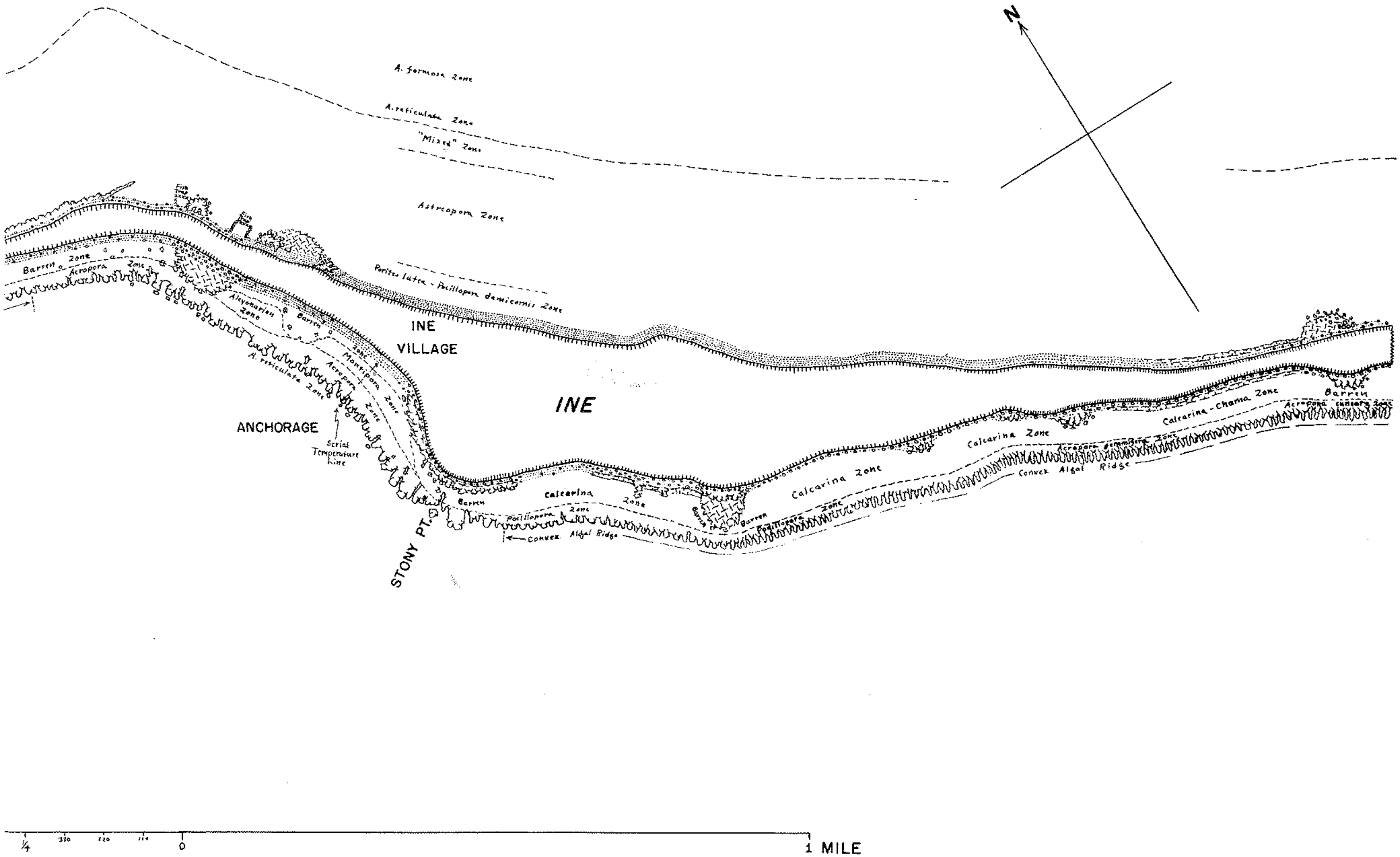


FIGURE 8. DETAI



L MAP, PART OF INE I., ARNO. 1:8000.

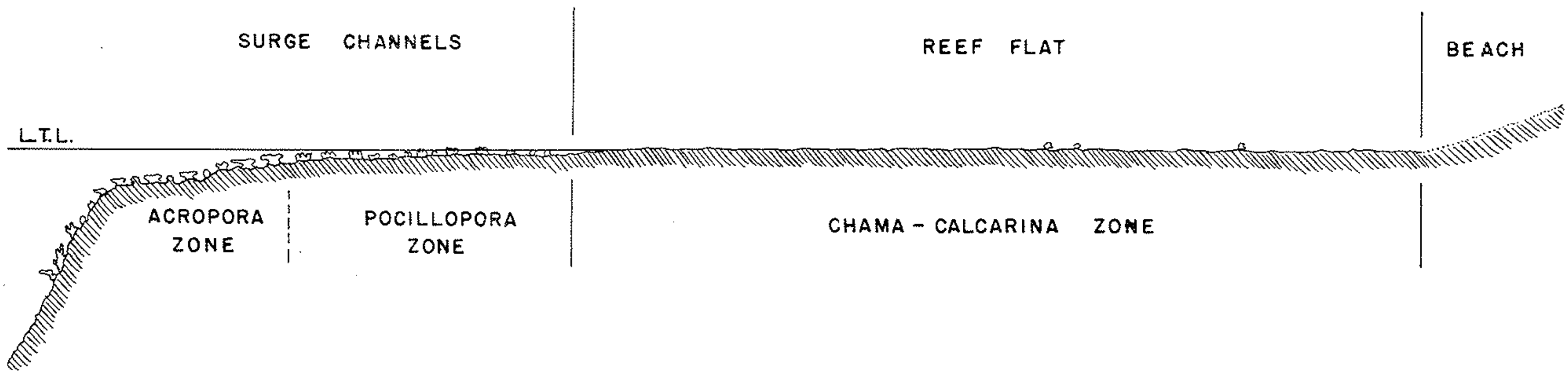


FIGURE 9. SEAWARD REEF, TYPE IA, INE I.

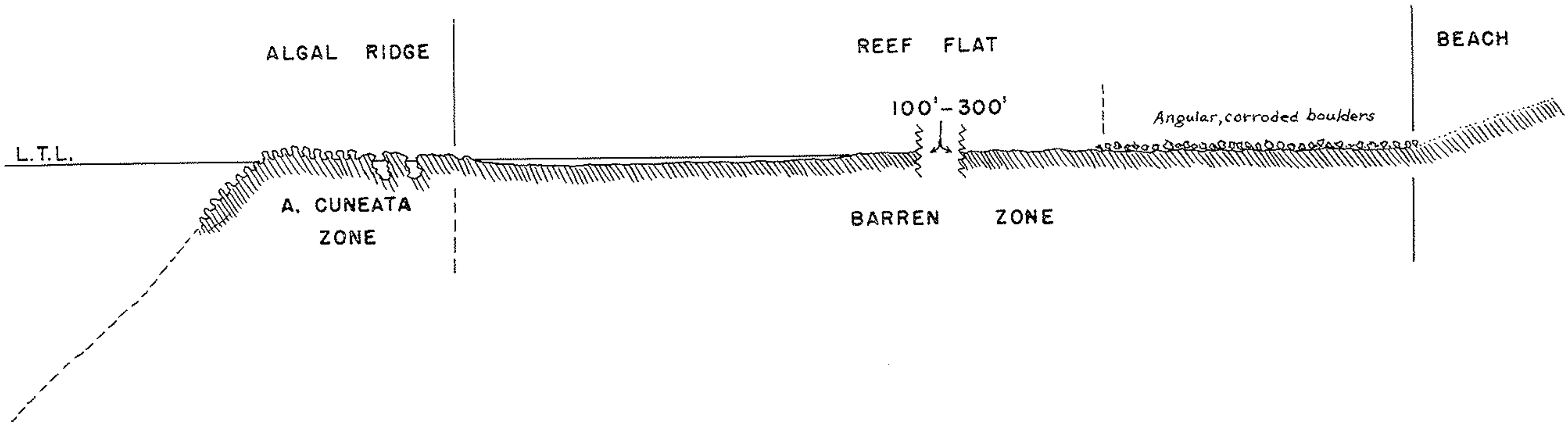


FIGURE 10. SEAWARD REEF, TYPE 1B, TAKLEB 1.

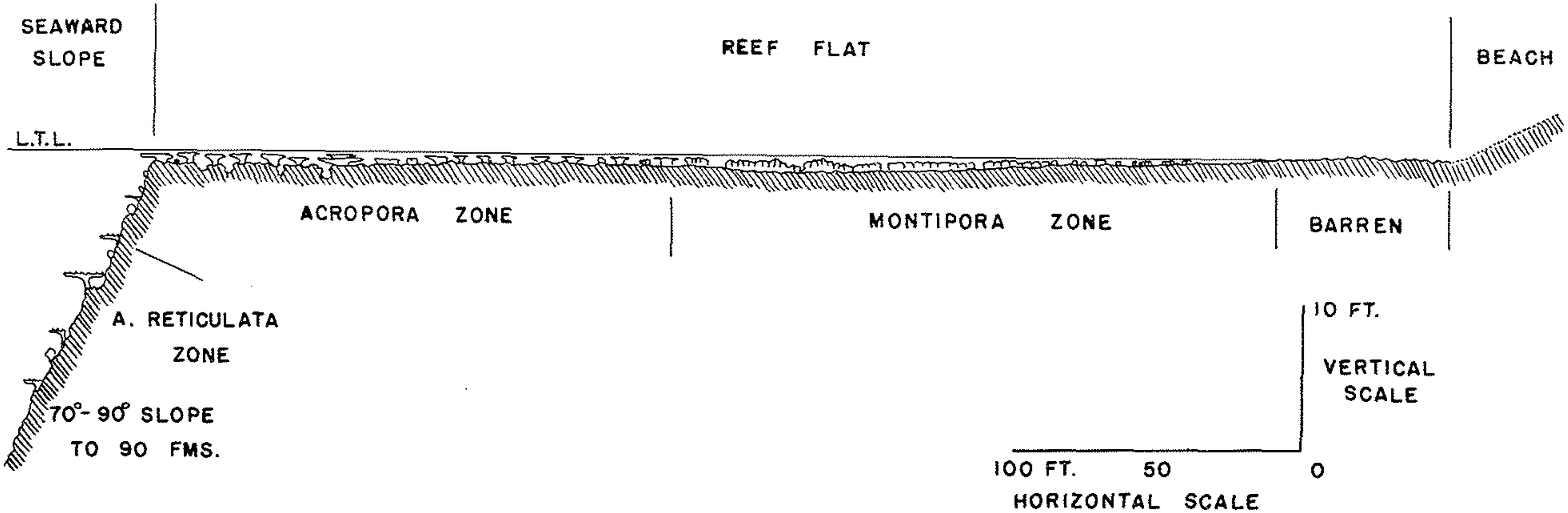


FIGURE 11. SEAWARD REEF, TYPE II A, INE ANCHORAGE.

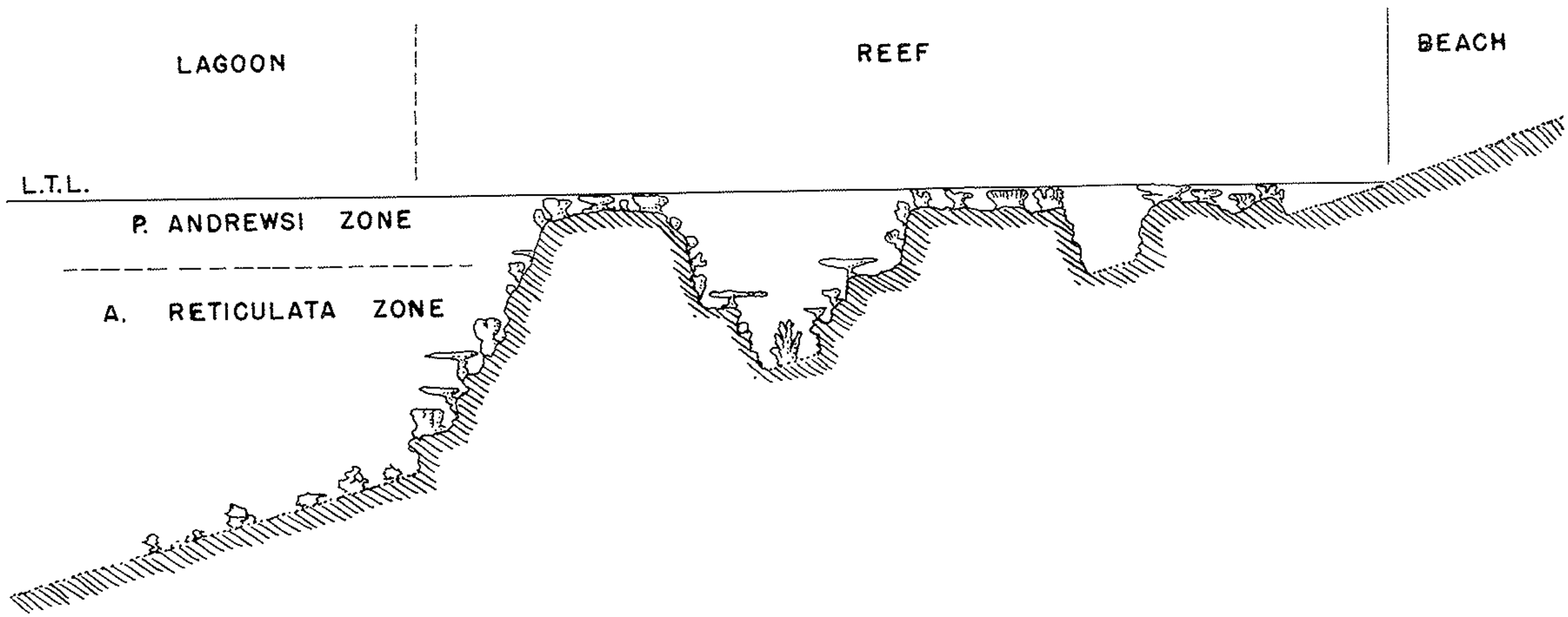


FIGURE 12. LAGOON REEF, LEEWARD TYPE, TAKLEB I.

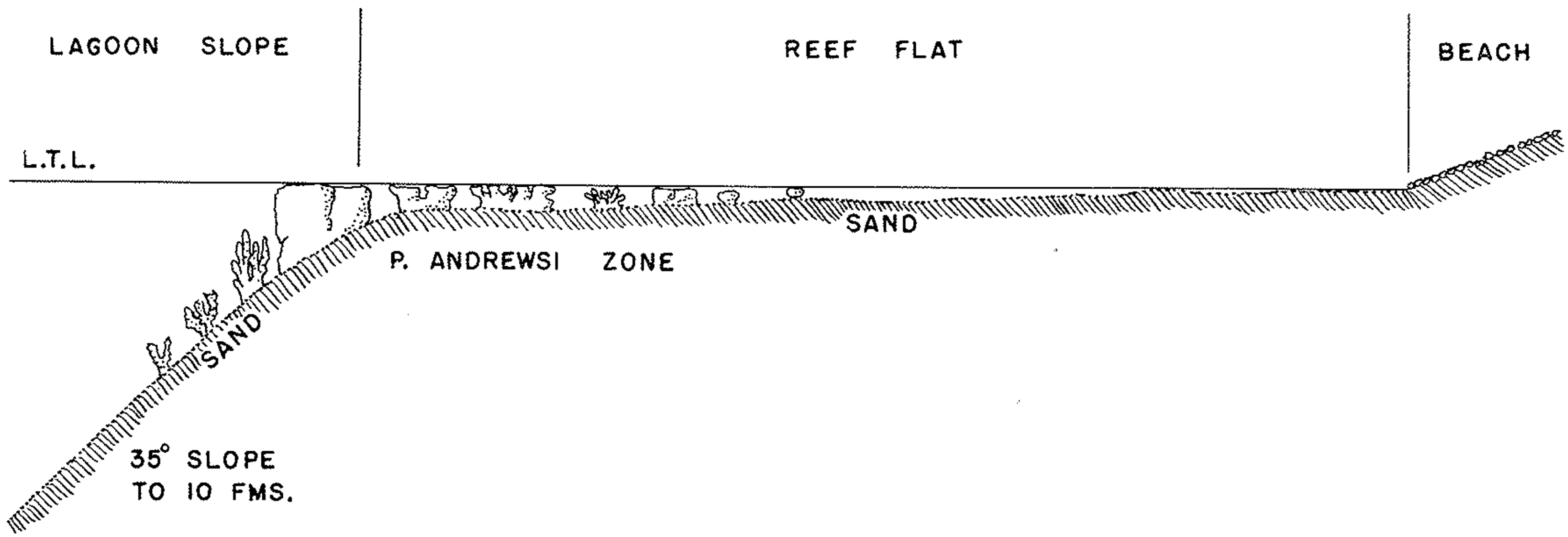


FIGURE 13. LAGOON REEF, ENCLOSED LAGOON, NORTH HORN.

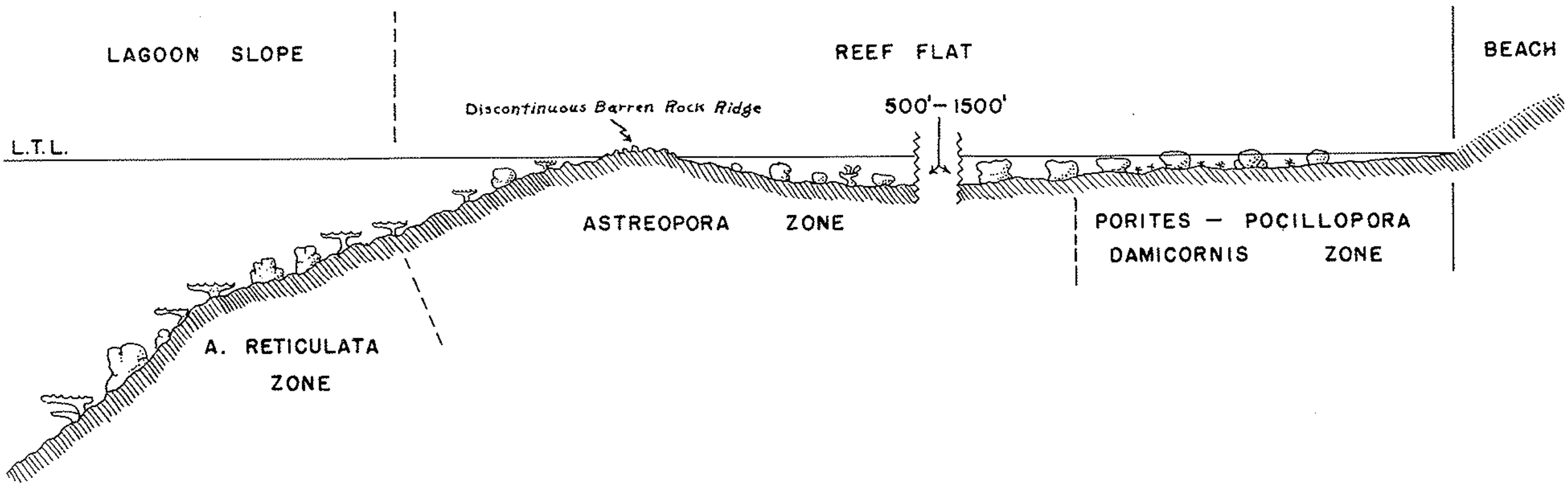


FIGURE 14. LAGOON REEF, WINDWARD TYPE, INE 1.

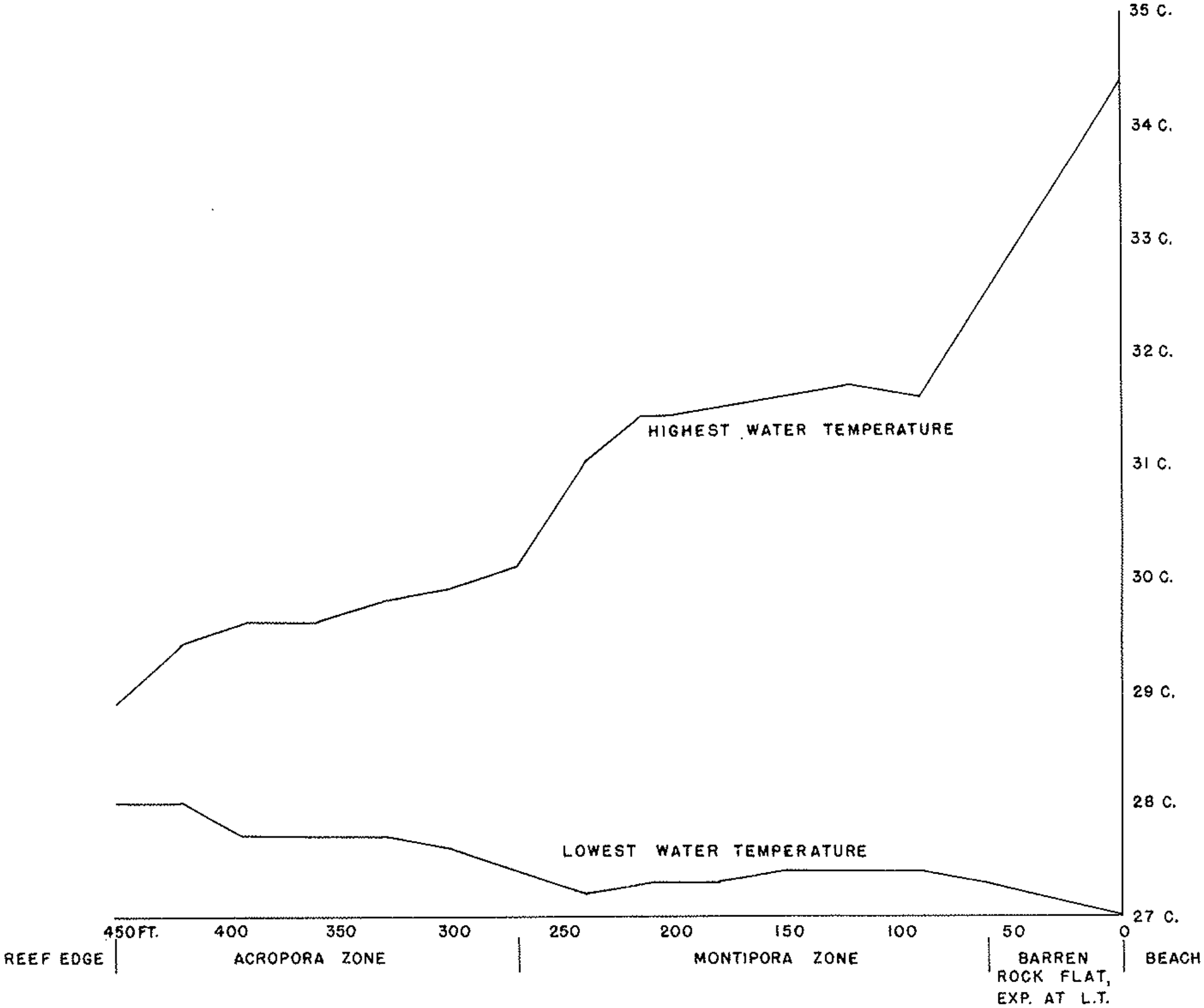


FIGURE 15. WATER TEMPERATURES ACROSS INE ANCHORAGE REEF, JUNE, 1950.

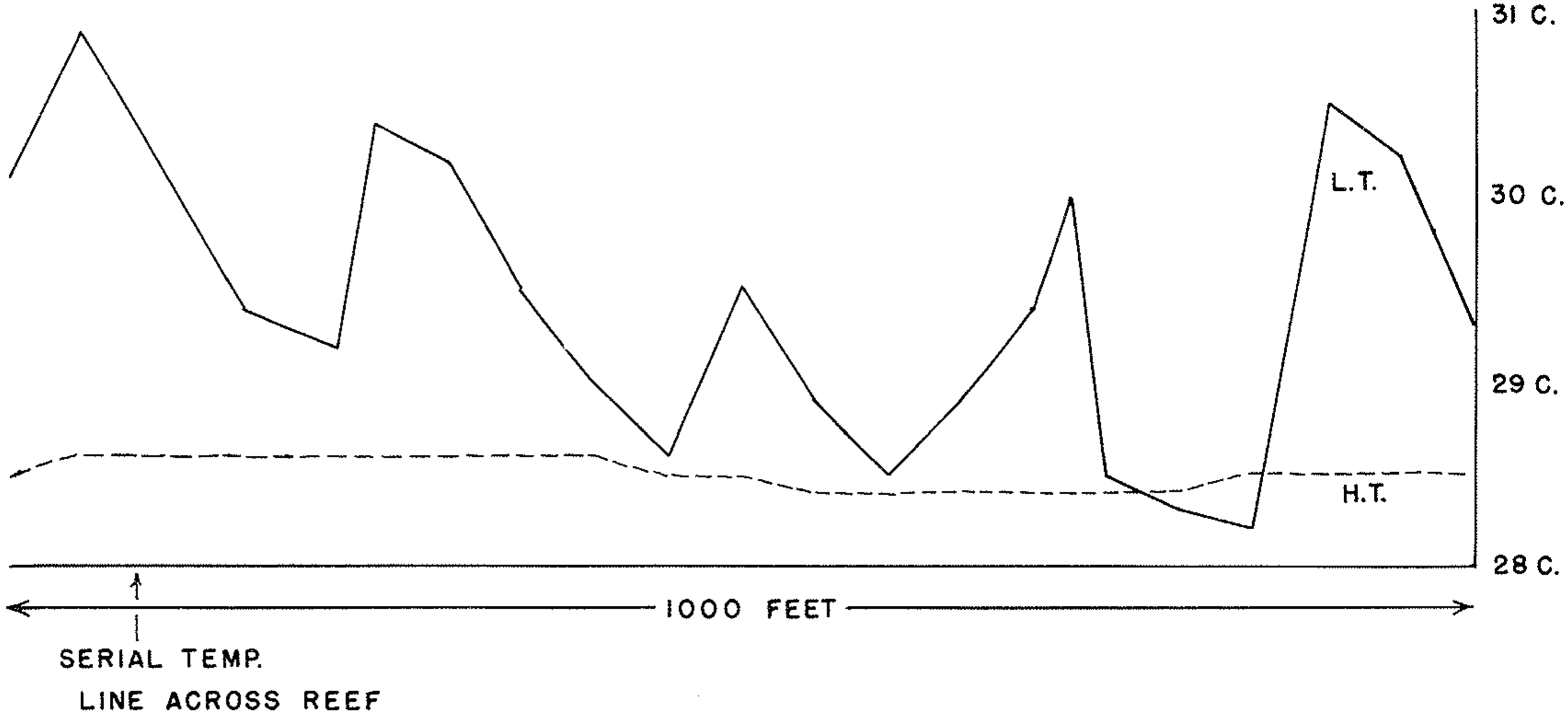


FIGURE 16. WATER TEMPERATURES ALONG INE ANCHORAGE REEF, INNER EDGE OF ACROPORA ZONE.