THE ALGAL RIDGES AND CORAL REEFS
OF ST. CROIX

their structure and Holocene development

by Walter H. Adey

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ABSTRACT

The shallow coral reef and algal ridge systems on the eastern shelf of St. Croix are described and mapped in some detail. Based on present reef morphology, a section through the barrier reef in a ship channel, numerous sand probes and C^{14} dating, Holocene growth patterns of the reefs are determined and a model of Holocene evolution developed. Based on many drill cores through the algal ridges, C^{14} dating and paleoecology relative to modern ridge and reef surfaces on St. Croix, growth patterns during the late Holocene are also developed for the algal ridges.

Lithophyllum congestum, Porolithon pachydermum, and several Neogoniolithon species are the primary algal ridge builders on St. Croix. L. congestum requires turbulent water and high light intensity to achieve the branching form which characterizes its occurrence in the algal ridges. Also, coralline accretion rates of 3-6 mm/year necessary for ridge construction are achieved only if intensive parrot fish and Diadema grazing are prevented by consistent and intensive wave action. A dead coral surface or pavement at a depth of 0 to 2 m, will be colonized by crustose corallines and in turbulent water, can develop progressively by coralline algal accretion into an incipient mound, a high boiler and eventually by boiler fusion, into a linear algal ridge.

Off open, easterly shores in St. Croix, coral reefs, on building to the surface, develop algal ridges. The present morphology of the ridge-reef complex has developed primarily as a result of the control exerted by pre-existing shelf and bench levels and changing rates of Holocene sea level rise on coral-coralline and grazer ecology. Special emphasis is placed here on the importance of pre-existing shelf level in determining the form and developmental stage of ridge-reef systems.

INTRODUCTION

The massive, wave-beaten, intertidal algal ridges of the Pacific atolls have been briefly described by numerous authors, largely beginning in the 1950's (see e.g., Emery, Tracey and Ladd, 1954; Munk and Sargent, 1954; Tracey et al., 1964; Wiens, 1962). More recently, Chevalier et al. (1968) and Littler and Doty (1974) have described the morphology of these ridges and their crustose coralline components in further detail. Elsewhere in the Indo-Pacific, the ridges are generally more weakly developed and often called algal rims (Maxwell, 1968, Great Barrier Reef; Stoddart and Yonge, 1971, Indian Ocean). Setchell (1926) emphasized the importance of crustose corallines in general on Pacific reefs.

Especially during the last 25 years, many borings have been made through the limestone caps of Pacific atolls, and some of these have also reported coralline algae as the dominant structural elements (see e.g., Gross et al., 1969-Midway). However, none of these have surficially penetrated an algal ridge. Easton and Olson (1968, 1973, in ms.) have drilled through an algal rim and dominantly coralline algal reef of Holocene age in Hanauma Bay, Oahu, Hawaii. However, this rim is apparently not intertidal and the coralline algae themselves were not studied. Some authors (Fairbridge, 1968) have considered the Pacific algal ridges as only thin algal veneers over older dominantly coral reef structures. This interpretation is probably not generally correct, but only extensive coring will settle the question.

Although relatively small coralline and coralline-vermetid frameworks, called boilers, cup reefs or microatolls have also been described for the Caribbean and tropical Atlantic (Boyd et al., 1963; Kempf and Laborel, 1968; Gessner, 1970; Ginsburg and Schroeder, 1973), "true" algal ridges have generally been considered as lacking (though see Ottmann, 1963; Rigby and McIntyre, 1966 and Glynn, 1973). More recently, Adey and Burke (1975) have described the distribution and morphology of a series of algal ridges and the associated reefs in the eastern Caribbean from the Virgin Is., Anguilla and Barbuda in the north to Grenada in the south.

The algal ridges of St. Croix are Holocene in development. They are truly algal ridges in that they are built above mean low water and not only is their upper carbonate framework dominantly crustose coralline, but their upper surfaces often support a rich fleshy algal flora of high biomass and productivity. Connor and Adey (1975) have described the non-crustose coralline algal flora of the ridges and its diversity and ecology in terms of standing crop. Adey and Vassar (1975) have examined the crustose coralline succession patterns and their growth and accretion rates, and Steneck and Adey (1975) have studied in detail Lithophyllum congestum, the chief builder of the ridges. In this paper, I describe the distribution, morphology and geological structure of the algal ridges and the relationship of these to the coral reefs and to bedrock geology and shelf or bench levels as well as tide levels and meteorological conditions.

The crustose corallines are the chief builders of the Caribbean algal ridges. On St. Croix, Lithophyllum congestum is the primary element, although in specialized situations Porolithon pachydermum and a complex

of _Neogoniolithon_ species are also important. On the generic level, most
of the ridge components can be identified using the keys of Adey and
Macintyre (1973). However, at the species level, of the dozen that are
important in ridge construction, nearly half are new species. In the
older literature, a large percentage of the described species are syno-
nyms of _Lithophyllum_ _congestum_ and _Neogoniolithon_ _strictum_. I am pres-
ently preparing a biosystematic study of the crustose corallines of the
Caribbean Sea. The new taxa used here are briefly described by Adey and
Vassar (1975) and will be described in detail in the biosystematic
treatment.

METHODS

    The maps appearing in this paper were all constructed from aerial
photographs taken from a single-engined, high-winged plane flying at alti-
tudes of 20 to 200 meters. Best results were obtained by removing the
photographer's door for better visibility and ease of camera handling, and
the most useful shots were high angle obliques (60-80°). Rollie and
Hasselblad cameras were used for the large negative size. Generally, shots
were taken at 1/500th of a second and with ektachrome-x color or sometimes
plus x, black and white. The color slides were most useful and initial
mapping was accomplished on Mylar (plastic drawing paper) by projecting
the color slides on a properly-oriented mapping board. Scale and angle
were controlled using the 1/210,000 scale high altitude black and white
verticals of Mark Hurd Aerial Surveys. Best results were obtained by
photographing during the short and more or less rare periods of norther
calms. Some of the high altitude commercial photographs were also taken
during norther calms and were especially useful in determining the limits
of the deeper reefs.

    The base maps were drawn with india ink in Mylar which could then be
taken underwater on a drawing board for interpretation and detail. Most

underwater mapping work was accomplished by using snorkel gear although
SCUBA was occasionally employed. The Boiler Bay maps (Figs. 29-37) were
completed first, and with approximately 150 man hours in the water are
the most accurate. Not as much time per ridge was available for the south
shore algal ridges (Figs. 16, 20, 22, 25), and especially as some of them
are considerably larger than the Boiler Bay ridge, the accuracy is less.
Areas not actually visited underwater are left blank. The Beach algal
ridge was the last ridge mapped. With the least time available for work
on that ridge, it is the least accurate in detail.

Intertidal and upper subtidal ridge elevations were estimated using
a standard eye-level and stadia rod. The base of the rod was placed in a
plastic tube with only a 2 mm hole for water flow to dampen wave action,
the rod being set in the quieter back reef area. Tide levels were deter-
mined at the West Indies Lab dock in Tague Bay. Two, four to five hour
parallel tidal measurements were made at Boiler Bay and at the Fancy-Robin
area on the south shore to see if a difference in tide time existed. No
difference was found. The tides are discussed in detail below.

Drilling on the algal ridges was accomplished using a gasoline-
driven hand held Acker Drill Company "pack-sack" and both diamond and
carbide bits. Most of the cores taken on the south shore algal ridges
were 29 mm in diam.; most of those taken in Boiler Bay were 20 mm in diam.
Flushing water was obtained with a 3 hp, gasoline-driven pump and holes
were not cased.

Two people could operate the drill on a ridge with some difficulty,
but three or preferably four were required for an efficient operation.
Usually a platform about two meters square and 1-1/2 meters high was set
up on the ridge to hold the core boxes, rods, pump, gasoline, tools etc.,
and drilling was accomplished standing on the ridge itself. Quiet days
were usually chosen for drilling, though on the larger ridges some hazard
to equipment and personnel remained on all but exceptionally calm days.
Once the platform was set up and the hole started, the drillers had some-
thing to hold onto and there was usually not a major problem with the
waves. The most difficult times were setting up and breaking down. On
several occasions all of the gear was dumped in the water and the operation
had to be suspended until the engines could be thoroughly serviced. Also
occasionally a wave would catch one of us off balance and the resulting
bounce on the ridge would result in a few scratches and Echinometra spines.

In the Boiler Bay algal ridge, we drilled 32 holes, 13 through to the
underlying basement at 2 to 4 meters. On the more difficult south shore
ridges, we drilled 7 holes, two of which went through to basement at 8 to
9 meters. Once the platform was set up there was usually little difficulty
in drilling in the upper 3 meters. Core recovery varied widely from 80
to 90% in solid coralline to nothing for as much as 3 meters in sand-
filled cavities. On the other hand below 6 meters increasing difficulty
was encountered, and we often spent as much as a whole day retrieving our
bit from one meter of drilling in the 6-9 meter range. A more powerful
water pump and an A-frame or tower with a block and tackle would probably
alleviate this problem.

Interpretation of the cores was achieved with 20 μm thick ground sections. In coralline cores the following four elements were determined in slides Lithophyllum congestum, Porolithon pachydermum, Neogoniolithon spp. and Tenarea sp. More detail could have been obtained in identification, but this was not considered necessary at this point in the study. Coral species were usually determined from the hand specimens of cores. Both cores and sections are housed in the coralline collection at the National Museum of Natural History in Washington, D.C.

Surficial blocks of ridge material 30-50 cm on a side were often obtained, sometimes with considerable difficulty, using a crowbar and large chisels. In Shark Reef in Boiler Bay we created a slot in the front of the ridge about 0.6 meters wide, 1.6 meters into the ridge and one meter in depth using a combination of chopping and drilling. The slabbing of these blocks on a rock saw helped considerably in our interpretation of the cores.

Twenty-eight C^{14} dates were obtained, 17 on coral and 11 on coralline. Although all but one of the coral dates are consistent with each other and the interpretation presented here, the oldest being 4360 years B.P. $\pm$ 90, the coralline dates are irregularly young. However, these ages all occur below the envelope for the Bermuda sea level curve of Neumann, as discussed below. A single Acropora palmata date from Boiler Bay at 4900 years B.P. placed several feet above the sea level standard. However, a careful check of this specimen showed that the gray-darkening characteristic of subaerially-weathered coral was present. We have interpreted this specimen as part of a supra-tidal storm berm such as are quite common on eastern St. Croix today. The position of sea level in the ridge cores was determined by our sea level indicator Lithophyllum congestum (see Steneck and Adey, 1975).

Through the courtesy of the Hess Oil Refinery in St. Croix, we were able to dive and take many subsurface samples of Long Reef, seaward of the refinery, where the 19-meter deep ship channel sections the reef and extends 6 meters into the basement. C^{14} dating of large coral samples from this section forms the basis for our time interpretation of the coral reefs.

Our 41-foot, ketch-rigged, motor-sailor trimaran "Corallina", with a relatively large central lab and bunks for six served as our home, field transportation and base of operations during the course of this study.

PHYSICAL ENVIRONMENT

All of the known algal ridges on St. Croix occur east of Canegarden Bay (Fig. 1), where the bed rock is mostly weakly metamorphosed, upper Cretaceous, deep water sand and mud stone of the Caledonia Formation. Whetten (1966) describes this formation in some detail. The westernmost ridge, at Vagthus Point, on the south shore we have not studied in any detail. Apparently it lies on a limestone member of the Judith Fancy Formation. We have also seen a small ridge off Spring Bay from the air,
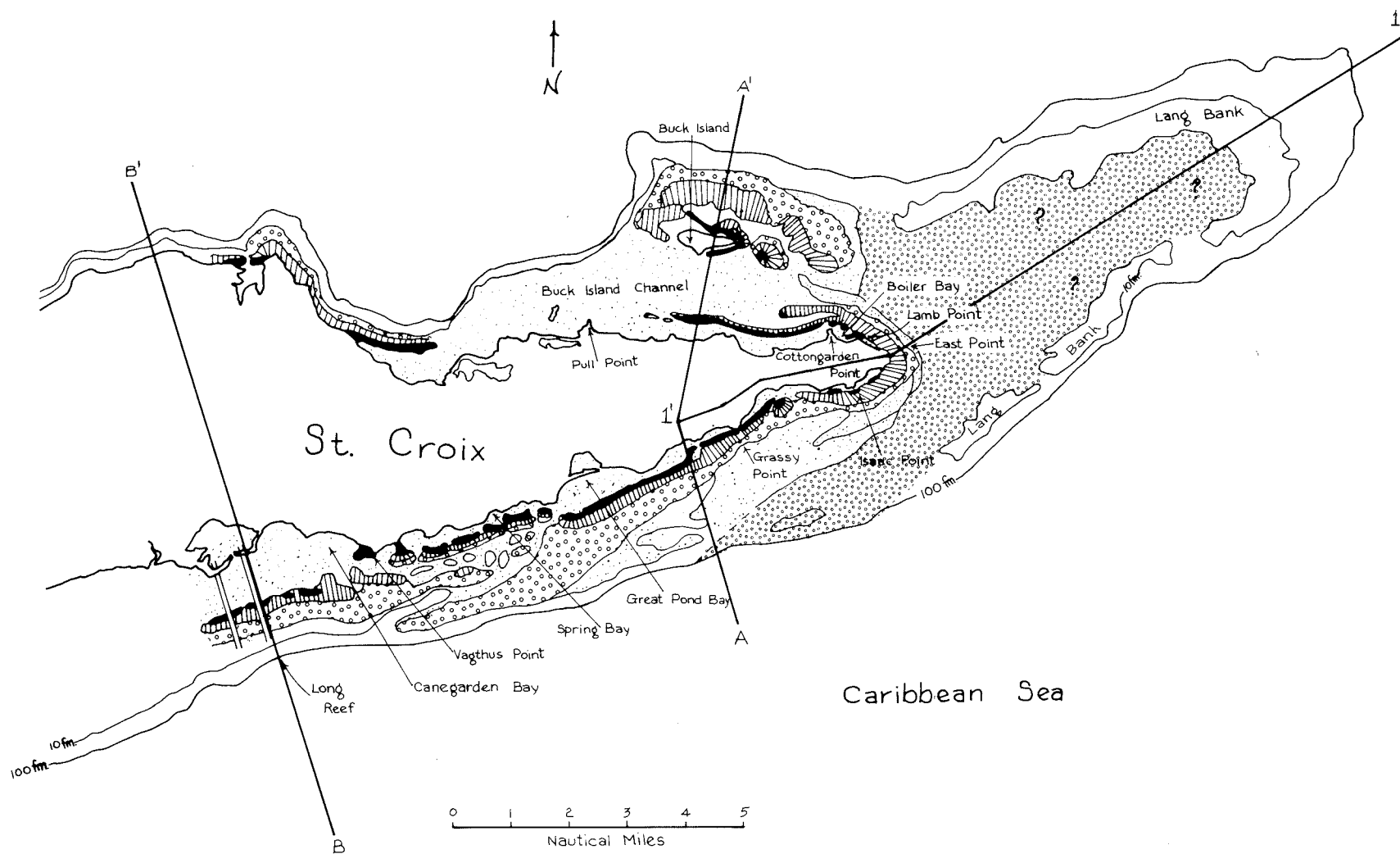
Fig. 1. Major reef-ridge environments on eastern St. Croix and positions of "shelf" sections. ▮▮▮ reef flat or algal ridge, +0.5 m to -1 m; ▦ dominantly Acropora palmata upper fore reef; ⬚ dominantly Montastrea annularis and Diploria spp., deeper fore reef; ⬚ Meandrina hard ground; ⬚ sediments, dominantly sand size and bioclastic.

but have not visited this ridge. The remaining ridges lie east of Great Pond Bay. The smallest of these, one at East End Bay (Fig. 4), and another north of Buck Island, lie close to exposures of the Caledonia Formation, but the nature and depth of their immediate basement is unknown.

Three of the large south shore ridges, Fancy, Robin and Isaac and the incipient ridge at Hughes Point (Fig. 4), lie off exposures of the point-forming East End Member of the Caledonia Formation (Whetten, 1966). All of these ridges are apparently developed on hard shelves cut in the bed-rock at the minus 8-12 meter level. The fourth major south shore ridge, Beach ridge, apparently lies on a similar bench cut on a fault scarp. Adey and Burke (1975) discuss in detail the control exerted by bedrock geology on shelf level and consequently algal ridge distribution in the eastern Caribbean. This is discussed further below in terms of ridge placement on St. Croix.

The algal ridge in Boiler Bay is unusual in several respects. A small part of it is apparently developed on ridges of the Caledonia Formation. However, the major lobes of the ridge are less than 3 meters thick and they are formed on a bench of Caledonia boulders. These boulders are the lag deposit or remains of a rapid-flow or colluvium derived from the Caledonia probably during the last 100,000 years of the late Pleistocene.

Formal meteorological data were not taken at any locality on the east end of St. Croix during 1973-74. However, "Corallina" has both an anemometer and a wind direction indicator. During our stay on St. Croix from late 1972 to early 1974, at least some members of our group had occasion to be in the field virtually every day of the period, and usu-ally we were concerned with both wind direction and strength. The following wind and sea description is based to some extent on this subjective familiarity.

The easterly trade wind is markedly constant on eastern St. Croix and during our stay it blew at 10-20 knots from ENE to ESE better than 95% of the time. According to the U.S. Navy Marine Climatic Atlas of the World (1955), this part of the Caribbean experiences two peaks of wind velocity, one in June and July and the other in December and January. This was roughly true during our stay, though the autumn of 1973 was extraordinarily windy. During the spring and autumn, continental fronts or northers sometimes reach St. Croix. Usually, this results in a shift of the wind into the north or northeast, where it blows at 10-15 knots, rarely 20 knots, for about a day. After this the wind often falls to light and variable for a day or two before picking up to a strong easter again. During the autumn of 1972 and then again in the spring of 1973, 3-4 northers followed this pattern. On the other hand, in the autumn of 1973 and then again in the early spring of 1974, there were few northers and for those that did pass through, the wind merely shifted from E to NE and back without markedly changing in intensity. During this latter period the wind was also occasionally well into the SE. However, in late April 1974, a strong front passed which caused the wind to blow from due north for one day at about 15-20 knots, and a second at 10-15 knots. This two-day norther was then followed by four days north to east winds at about 5-10 knots. Perhaps there is also a diurnal cycle, relatively

light during the night, and stronger during the day, but this is not marked on eastern St. Croix. It was often my impression that the wind on the exposed south shore was lightest from about 1600-1800, picking up again to mid-day strength by 2100-2200.

The constant offshore sea resulting from this wind pattern is short and steep and mostly from 1-2 meters in height. Pollers, the large swells resulting from intense northers in the southeast Atlantic and often experienced on the northern coasts of the northern Virgin Islands did not occur during our stay in St. Croix. They are apparently largely blocked and dissipated by the northern Virgin Islands. Even during the calm periods with low mid-day tides, the ridges at heights of 30-50 cm above mean sea level would take at least a wetting sea every few minutes. It is possible that an extended calm, like that experienced in April 1974, in conjunction with a period of daytime low water springs might result in serious desiccation and kill-off of algae and coral on the ridges and reefs. However, this did not happen on the algal ridges during the autumn of 1972 to the spring of 1974 period.

Water clarity around the ridges and reefs is usually largely dependent on the intensity of wave action and the resulting suspension of fine carbonate sediment. During rough periods, visibility is only 4-6 meters, while after a few quiet days it can be 15-20 meters. The quantity of plankton in the water appears to be highest in the summer and, as this is often a relatively rough time, the visibility tends to be particularly poor.

During the period that we were mapping and leveling the ridges (early April to late June, 1973), we kept a continuous record of tide at the West Indies Lab dock by simply reading sea level on a meter stick attached to the dock. This was read every one to two hours during the day and every 3-4 hours at night throughout April and May. The reading was more desultory during June, but by late June, John Adams and Jay Kunin of the Laboratory had installed a computerized guage at the dock. This record was not continuous, largely because of other computer use and technical problems, but in conjunction with our continuous reading in May and June, it provides a fairly complete picture of tidal patterns during July and later in December and early January.

During spring tides, which roughly correspond with the full and new moons, the tidal pattern is markedly diurnal and usually has a range of 30-35 cm. The neap tides, with a range of about 10-15 cm, are sometimes clearly semidiurnal. More often, however, the neaps are rather irregular with one high and one low strongly dominating the other. The period of neaps is often rather sharply begun as a "no tide day", with the low part of the diurnal cycle being clipped-off at or slightly below mean tide level and then remaining within a range of 2-3 cm for 10 to 12 hours. Our ridge leveling was based on a position for mean low water springs established from our data for April and May. A long term record might require some adjustment of this value, but it is probably correct to within ± 2 cm, which is likely as good as our accuracy of ridge leveling. Figure 2A shows a typical springs to neaps cycle from 1973, along with the relative positions of the higher parts of several algal ridges.
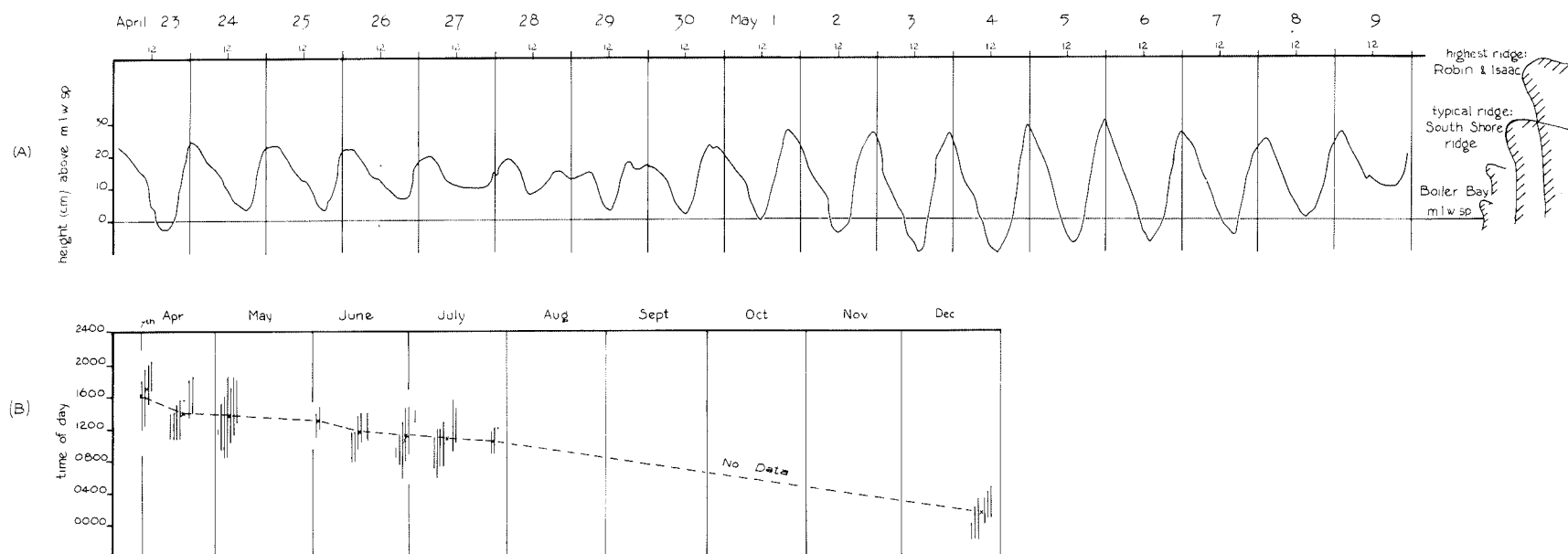
Fig. 2.   Typical tide patterns on eastern St. Croix.   (A) Bi-monthly cycle at West Indies Laboratory dock
for late April and early May 1973.   Level of mean low water springs based on tides for April to
June, 1973.   (B) Times of occurrence of tide levels at or below mean low water springs.   April-
December, 1973.

The degenerating Boiler Bay ridge crests range from about 17 cm above mean low water springs to mean tide levels. The larger, south shore ridges have crests that range from about the position of mean sea level to levels of mean high water springs. The very active Isaac and Robin ridges have many of their crests at or above mean high water springs and their highest crests are about 20 cm above that level or nearly 10 cm above the highest tide level recorded in this study. (Adey and Burke (1975) describe ridges in the Lesser Antilles ranging up to about one meter above mean low water.)

In April 1973 the period of low water springs was centered about mid-afternoon, with the early part of the 7-day phase being centered about early afternoon and the later days being centered about 1800 (Fig. 2B). By June, low water springs were centered around noon, by mid-July, they had migrated to about 1000, and finally in late December they were centered about 0300. Thus, at the present time at least, low water springs occur in mid-day during the early summer and during mid-night in the winter. Glynn (1968) discusses the effects of a similar tidal pattern on mass mortalities of reef organisms in rather protected environments in Puerto Rico.

According to the World Atlas of Sea Surface Temperatures, Navy Hydrographic Office (1944), the offshore sea surface temperatures in the vicinity of St. Croix range from 25° C in February to 28° C in July. Behind the reefs and ridges, especially during quiet weather, these values are often modified and the lagoon normal maximum range especially near shore is about 23-30° C.

The east end of St. Croix is rather dry with a yearly rainfall of about 30 inches, much of this being concentrated in the rainy season from June to December. Occasional very heavy rains may reduce the salinity below 35°/oo near shore where intermittent streams enter the lagoons. In the vicinity of the reefs and ridges, salinities probably only very rarely go below 34°/oo.

DISTRIBUTION OF ALGAL RIDGES AND CORAL REEFS

The locations and depth profiles of the major reef and ridge environments on the shelf of eastern St. Croix are shown in figures 1, 3, 4. We have only visited a single locality on Lang Bank, and it consisted largely of a rubble-covered carbonate pavement with only scattered head corals and very few Acropora palmata. As I will elaborate below, it would appear that Lang Bank, now at 9-18 meters depth, was constructed on the shelf edge at 25-30 meters during the Holocene. We have only seen the western parts of the Meandrina pavement on the eastern shelf (Fig. 9), and its extension over the whole shelf remains to be examined. The two channels that were cut across Long Reef on the south coast (Fig. 1) extend into the industrial complex that now occupies Krause Lagoon. The eastern channel which enters the Hess Refinery, exposes the entire Holocene, the Holocene-Pleistocene contact, and the uppermost 7 meters of the Pleistocene. Much of our time-frame and stratigraphic interpretation of the coral reef system on St. Croix is based on this section.
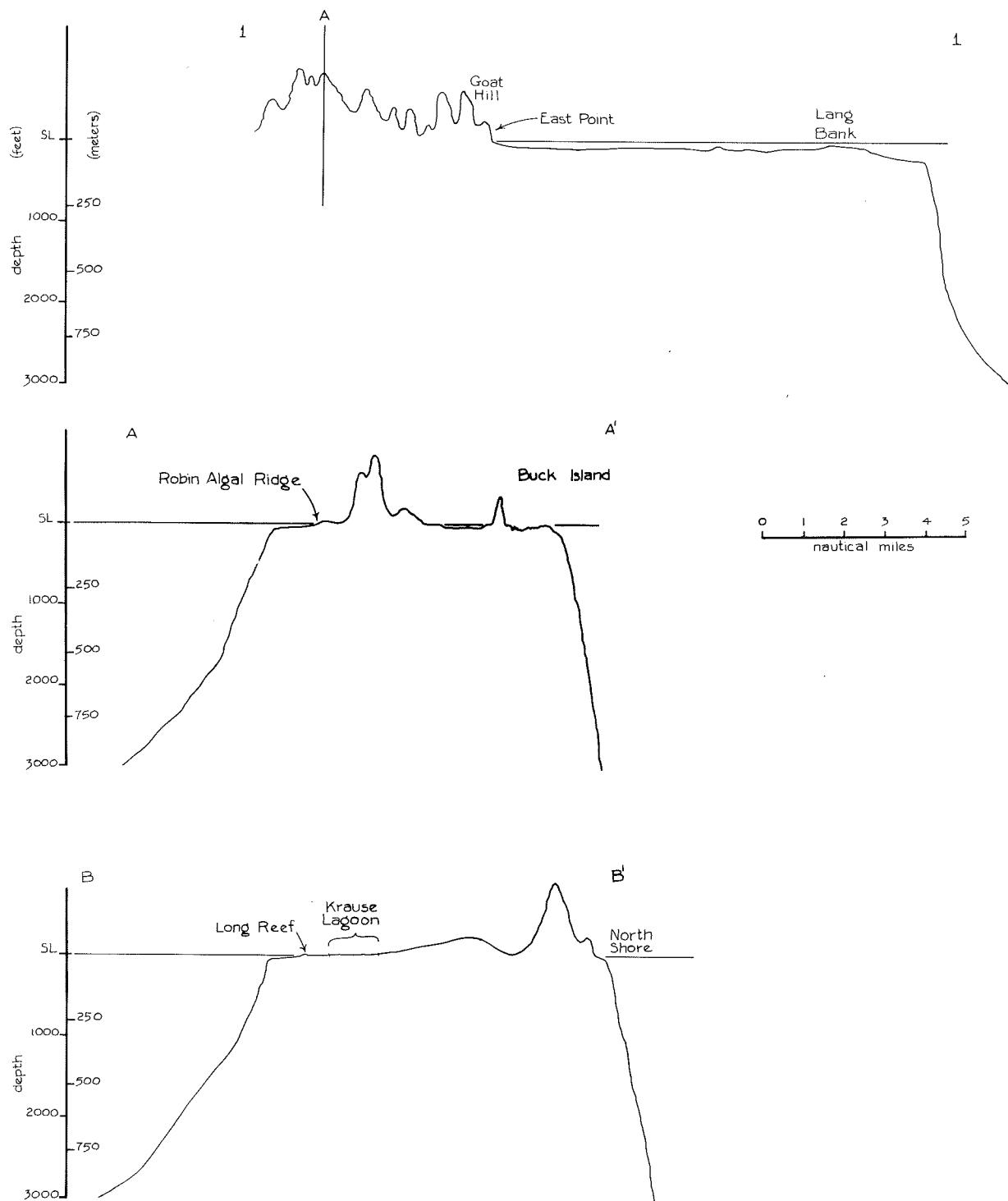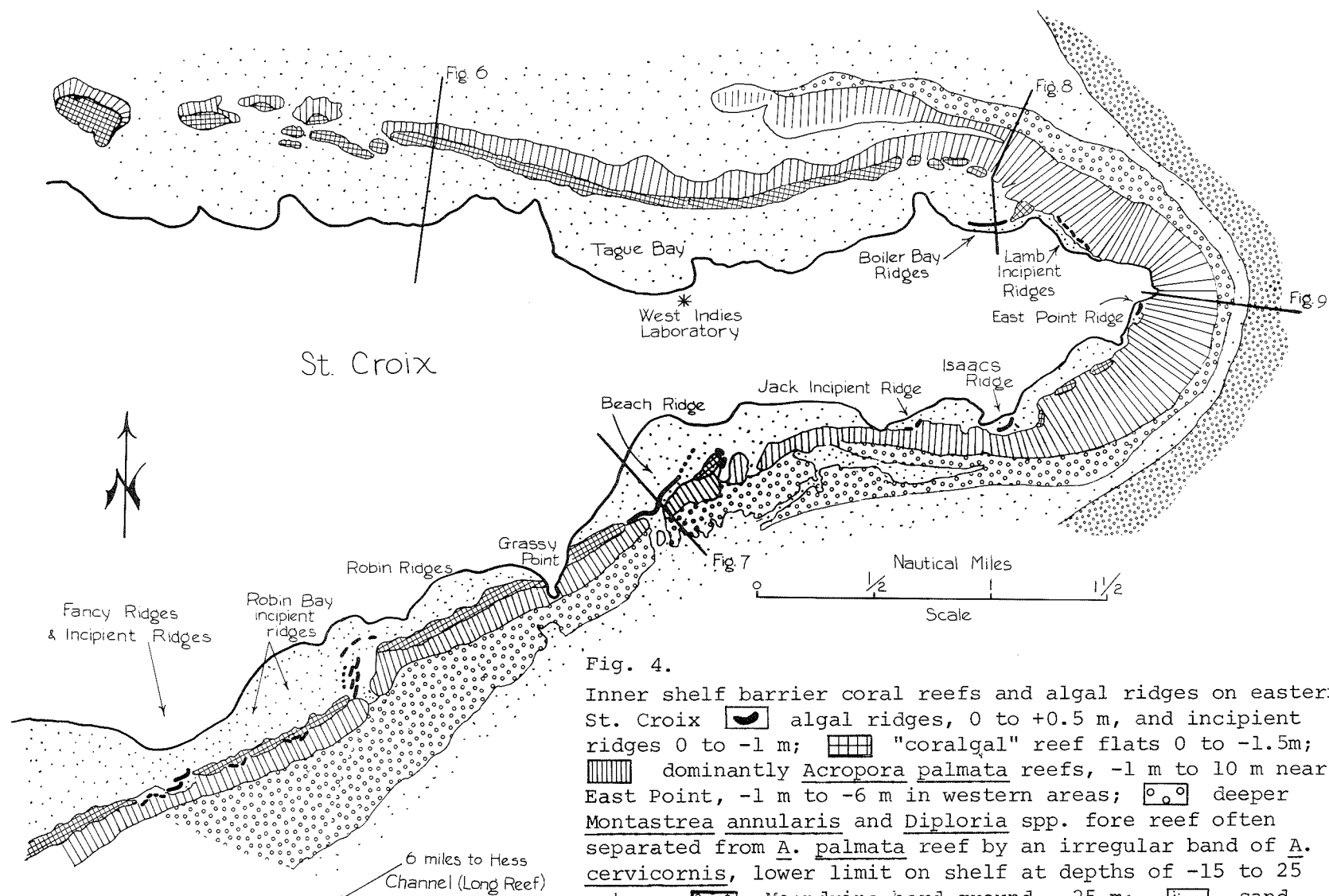
Fig. 3. "Shelf" sections on eastern St. Croix, see figure 1 for locations.
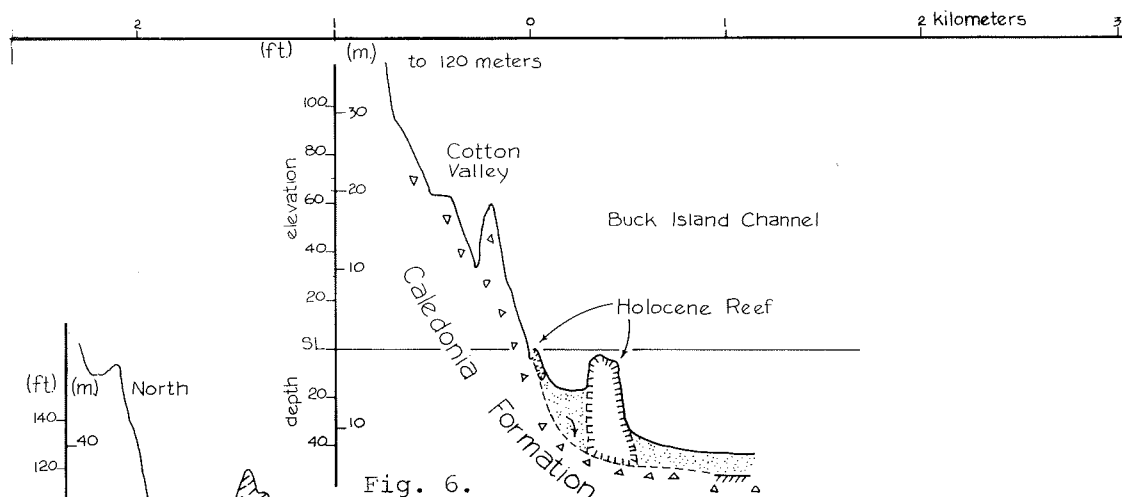
Fig 6

Fig 8

Fig 9

Tague Bay

Boiler Bay
Ridges

Lamb
Incipient
Ridges

East Point Ridge

West Indies
Laboratory

St. Croix

Isaacs
Ridge

Jack Incipient Ridge

Beach Ridge

Grassy
Point

Robin Ridges

Fig 7

Nautical Miles

Fancy Ridges
& Incipient Ridges

Robin Bay
incipient
ridges

0   1/2   1   1 1/2

Scale

6 miles to Hess
Channel (Long Reef)

Fig. 4.

Inner shelf barrier coral reefs and algal ridges on eastern
St. Croix ▰ algal ridges, 0 to +0.5 m, and incipient
ridges 0 to -1 m; ▦ "coralgal" reef flats 0 to -1.5m;
▥ dominantly Acropora palmata reefs, -1 m to 10 m near
East Point, -1 m to -6 m in western areas; ☷ deeper
Montastrea annularis and Diploria spp. fore reef often
separated from A. palmata reef by an irregular band of A.
cervicornis, lower limit on shelf at depths of -15 to 25
meters; ☷ Meandrina hard ground, -25 m; ▦ sand,
-2 to -6 meters in lagoon, -15 to -25 meters on shelf.

Fig. 6.
Section through northern barrier reef as shown in Fig. 4.
Sediment depths in lagoon and Buck Island channel (and
in Figs. 7-9) are based on probes.
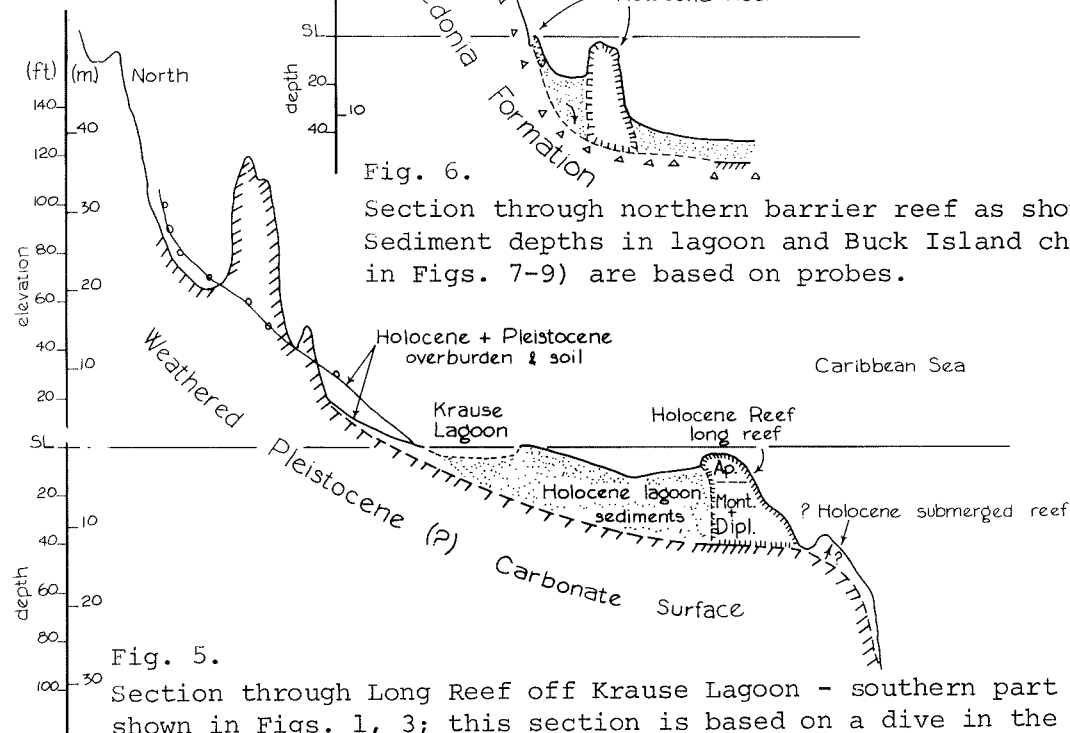
Fig. 5.
Section through Long Reef off Krause Lagoon - southern part of BB'
shown in Figs. 1, 3; this section is based on a dive in the
60-foot deep ship channel through the reef. Elevations, depths
and scale are based on the USGS topographic sheets and C&GS chart
905. In this and the following figures: ⊤⊤⊤⊤ verified basement;
⊤⊤⊤⊤⊤ assumed basement or interface.
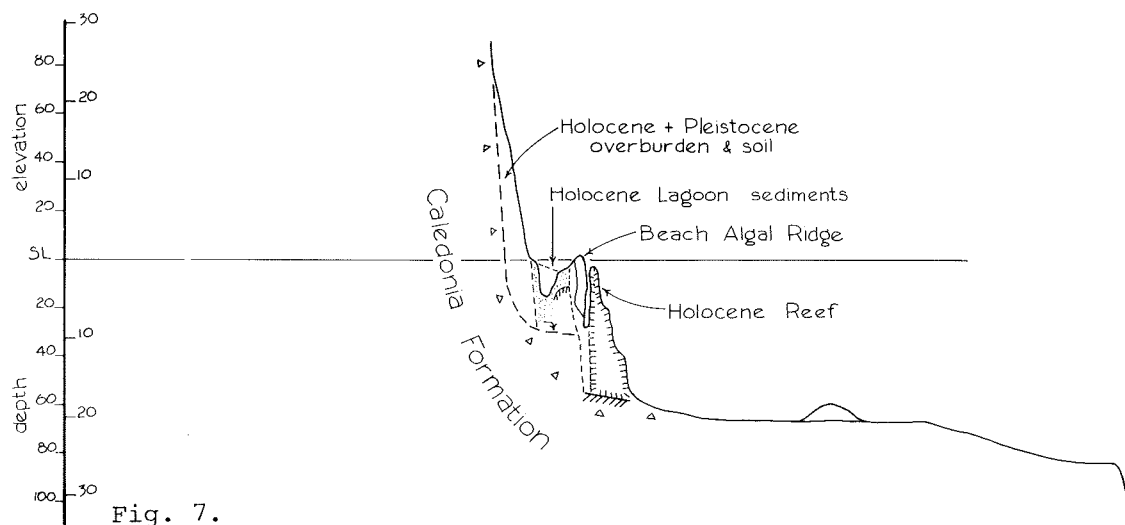
Fig. 7.
Section through barrier reef and Beach algal ridge just east of
Grassy Point (Fig. 4). Sediment depths between reef and ridge
based on probes; ⊤ indicates hard basement > greater depth shown.

Under Long Reef the shelf is about 12 meters deep, and just outside the reef it is about 13 meters deep (Figs. 5, 12). No raised platform, raised terrace or raised biohermal structure is evident beneath this reef. Elsewhere, where information was obtained on basement depths inside and outside, but not directly beneath the reef structure (see e.g., the reef sections shown in figures 6-9), I have assumed that the reef structure is lying on a more or less gently-sloping pre-Holocene topography and not on ridge or mound like reef or aeolian structures.

The shelf itself is relatively shallow (10-15 m) at its western ends both in the western Buck Island Channel on the north (Fig. 6) and along the south shore from Krause lagoon west. Further east, around Grassy Point (Fig. 4) the shelf lies at about 15-18 meters under the reef and about 20 meters outside (Fig. 7), while to the north off Boiler Bay, a shallow shelf in the Bay slopes to about 20 meters just offshore and has given rise to a triple-reef complex (Fig. 8). At East Point, outside the reef, the shelf is about 24 meters in depth and, although there is no direct evidence, presumably it is 18-20 meters under the reef itself (Fig. 9). The reefs lying on the inner shelf from Pull Point in the north and Long Reef in the south eastward to East Point show a general pattern of decreasing maturity. In the west the reef flats are relatively broad; they decrease in width eastward and off Boiler Bay in the north and Grapetree Bay in the south they become fragmented. From Isaac Point around East Point to Lamb Point, reef flats are virtually absent.

Thus it appears to be shelf depth (i.e., position of the pre-Holocene surface relative to Holocene sea levels) that has influenced the rate and pattern of development of the inner shelf barrier reef system on St. Croix. The pattern of development in Long Reef (discussed below), as shown by C^{14} dating and coral paleoecology, indicates why this has happened. The reason for the west to east shelf slope may lie in carbonate sedimentation patterns, i.e., a general east to west reduction in energy along with increased carbonate sediment load, at high sea level stands during the later Pleistocene, though structural control is also possible. The immediate shelf surface probably is an age equivalent to the massive very shallow marine formation at about 2 meters height from Hamm's Bluff to Cane Bay on the northwest shore of St. Croix. We have two coral dates on that formation both at 20,000 years B.P. However, these are probably both "dead", affected by more recent carbon, and are likely about 120,000 years B.P. in age. As I discuss below, higher sea level stands probably would not have allowed the development of massive Holocene reef systems on this shelf, much as the present situation in the southeastern part of the northern Virgin Island shelf (see Adey and Burke, 1975).

The positions of the coral reefs as well as the major algal ridges and the larger sublittoral or "incipient" algal ridges are shown in figure 4. As was pointed out above, there are small ridges on the north side of Buck Island and on the south shore outside of Spring Bay and at Vagthus Point. These were not studied in detail and will receive only occasional reference here.
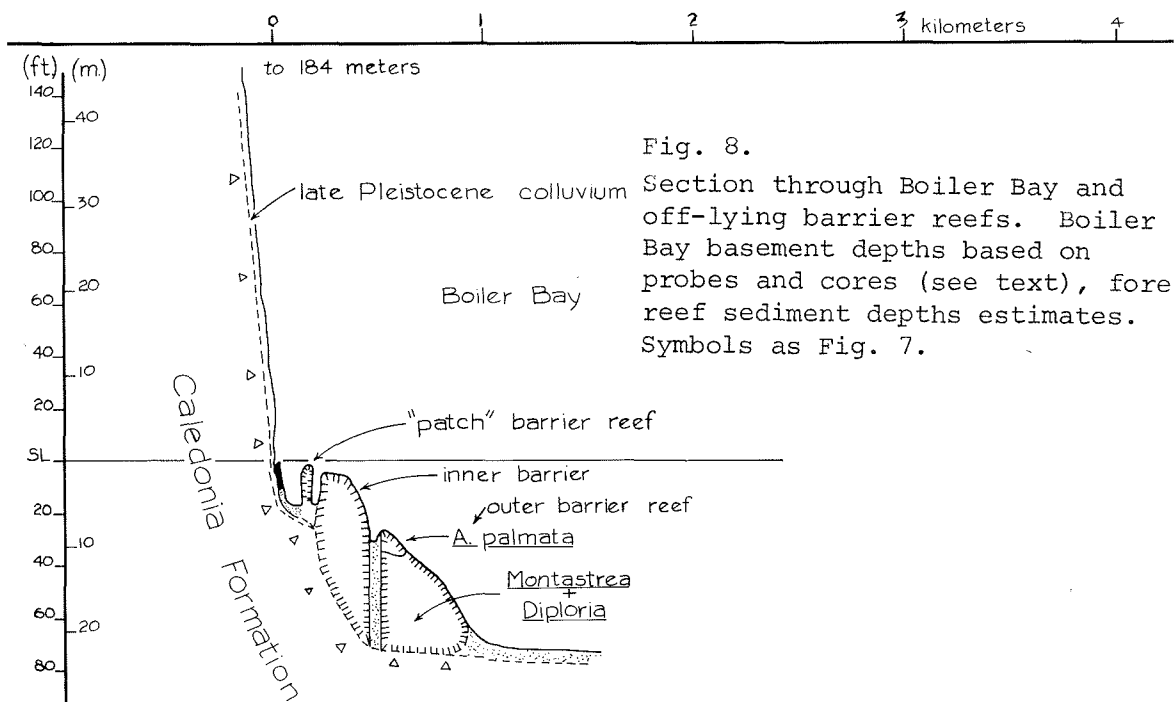
Fig. 8.
Section through Boiler Bay and off-lying barrier reefs. Boiler Bay basement depths based on probes and cores (see text), fore-reef sediment depths estimates. Symbols as Fig. 7.

Fig. 9.
Section through reef at East Point (Fig. 4). Basement depth estimated from previous sections. From -2 to -13 m, the reef is dominated by Acropora palmata on undercut blocks of A. palmata pavement separated by rubble-filled grooves and basins. A narrow rubble-sand band with gorgonians occurs at -13 m. The rather narrow deep fore-reef is characterized by Acropora cervicornis, Montastrea annularis and Diploria labrynthiformis alternating with a pavement occasionally having gorgonians and basket sponges. This zone degenerates to a rubble slope and then to a narrow sand channel at 23 m. The easterly limit of the Meandrina hard ground is not known.
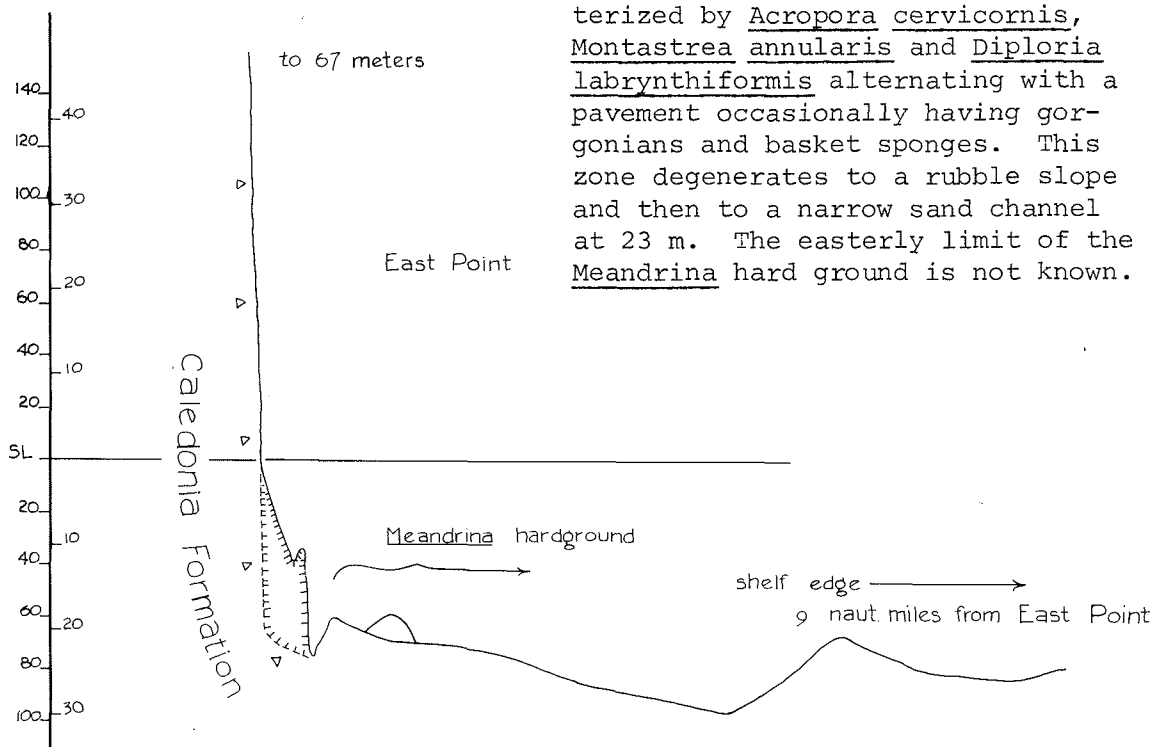
CORAL REEFS

The "reef flat" shown in figures 4, 10 and 27 is generally dominated by Acropora palmata. While some colonies of A. palmata are alive and extend to near mean low water springs, a large part of the flat or pavement surface at 0.5-1 m below mean low water is constructed of a matrix of dead arms of A. palmata coated with crustose coralline, especially Neogoniolithon megacarpum and to a lesser extent Neogoniolithon imbricatum and Porolithon pachydermum. The outer edge or crest of the flat also tends to have a high proportion of Millepora complanata, and the back flat sections, as they deepen into the lagoon (at 2-6 meters), frequently also have abundant Montastrea annularis, Diploria spp., Porites porites, and the small form of Acropora cervicornis. The Acropora palmata fore-reef is usually strongly dominated by that species. It extends to depths of about 13 meters at East Point, the lower boundary gradually rising to the west probably because of decreasing light due to turbidity and perhaps partly due to lessened wave action. Further west on the Tague Bay reef, on the south of the Buck Island Channel, and on the western parts of the south shore, the lower depth limit is 5-8 meters. The upper parts of the A. palmata fore reef, especially in highly turbulent areas, often consists of extensive dead areas or pavements, heavily coated with crustose corallines, mostly the same species dominating on the reef flats (Fig. 11). These pavements, which are essentially A. palmata frameworks extensively filled with crustose coralline and apparently without major amounts of submarine cementation, can give rise to the "incipient" algal ridges discussed below.

In the relatively quiet Buck Island Channel, an irregular band of Porites porites often extends from the base of the A. palmata fore reef to the sand channel floor at 10-12 meters. However, further east and on the south shore, this zone is usually occupied by Acropora cervicornis. The A. cervicornis band can be extensive, tens of meters wide, or on the other hand sometimes it exists only as scattered patches. From the lower end of the A. palmata fore reef to the sandy shelf, the dominant coral is usually Montastrea annularis, though Diploria spp. are common and scattered A. cervicornis, with an occasional A. palmata, also occur. Occasionally a marked spur and groove pattern occurs in the lower fore reef and sometimes it extends partly into the shallower A. palmata zone (see Fig. 27). The lower boundary of the deeper fore-reef is sometimes marked by a more or less abrupt drop of 1-2 meters to the sediment interface.

The flat, sandy shelf is found directly below the Montastrea-Diploria deep fore reef and this generally extends almost to the shelf margin. Off East Point, however, as shown in figure 4, the sand band is narrow, and the shelf beyond is coated with a pavement or hard ground. The dominant coral on the hard ground is Meandrina meandrites, although Montastrea cavernosa, Siderastrea siderea, Diploria strigosa, Dichocoenia stokesii and Zoanthus spp. also occur. Approximately 75% of the surface is a coral-bare pavement with abundant gorgonians and sponges. The subsurface nature of the hard ground was not studied. The wrapped-back westward-curving pattern of the hard ground and sand boundary seen in figure 4 suggests that wave and current action on the shelf gradually moves much of the carbonate sediment produced on the hard ground westward.
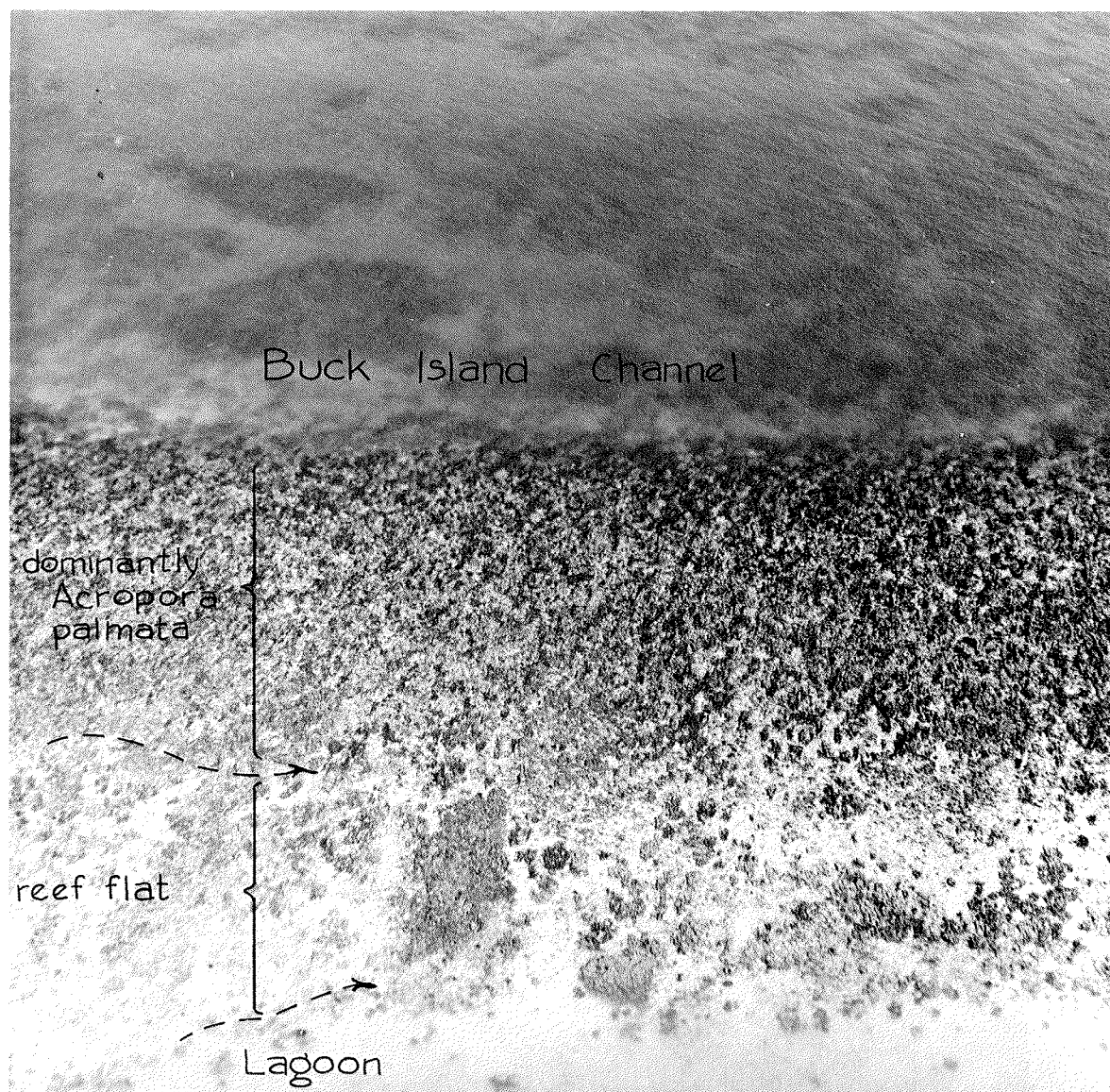
Fig. 10. Northern barrier reef off western Tague Bay (see Fig. 4).
          This aerial photograph was taken looking north towards Buck
          Island channel at an angle of 60-80° from horizontal. A
          section through this area was described by Ogden et al. 1972.
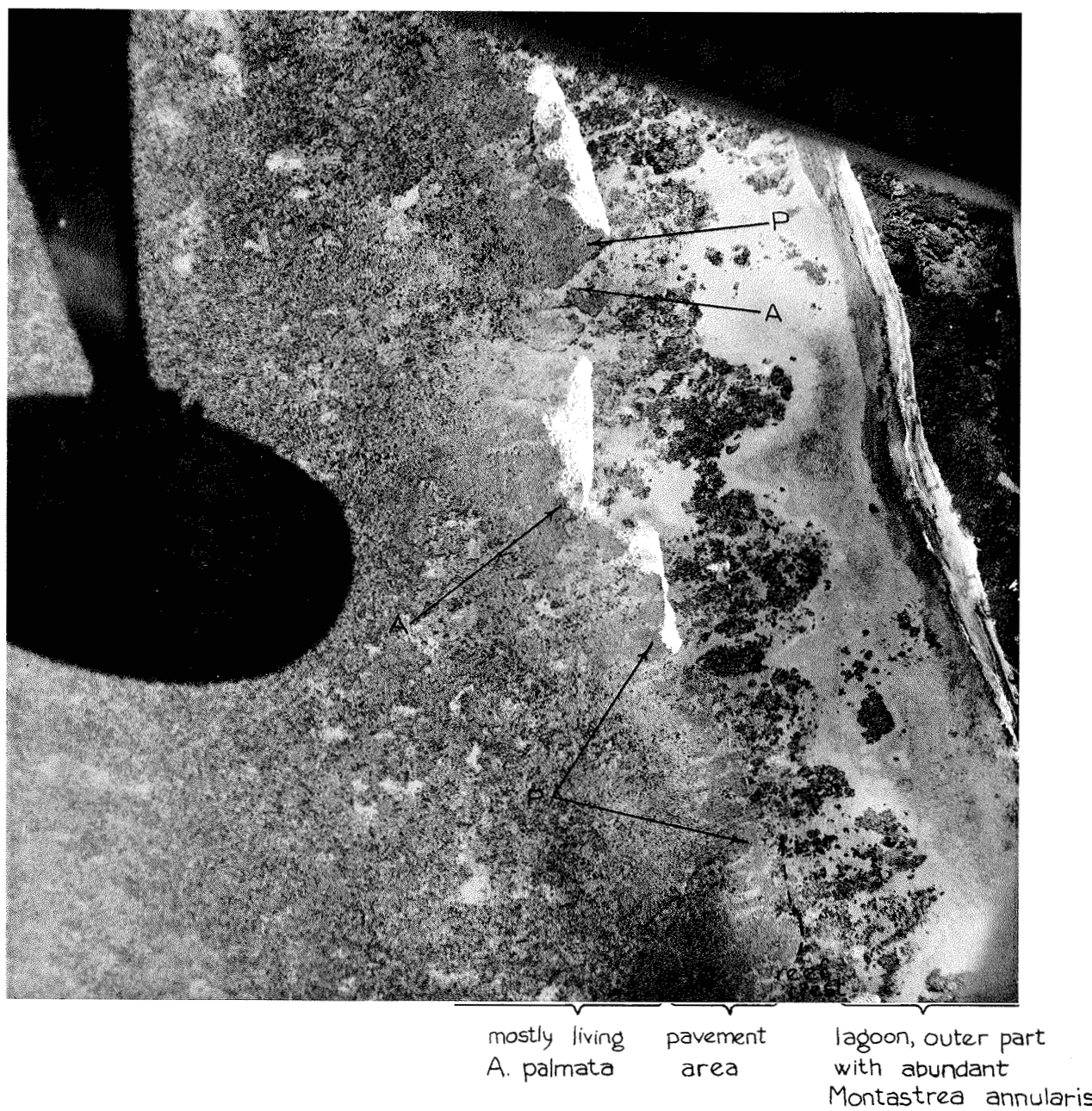   The reef is about 140 m wide here.

mostly living   pavement   lagoon, outer part
A. palmata   area   with abundant
                              Montastrea annularis

Fig. 11.   Aerial photograph of Lamb Incipient algal ridge. P extensive
            Acropora palmata pavements. A small incipient algal ridge
            lobe. No well-defined reef flat exists in this area.

When this combines with the probably much greater quantity of sediment pouring off the A. palmata and Montastrea reef, formation of a hard ground is prevented by an excessive "bed-load" of carbonate sand and silt. Thus, the westward-widening sand channel off East Point (Fig. 4). The Meandrina hard ground is especially interesting and in need of extended study because of its possible importance to shelf-building in the Antilles.

A detail of the Hess channel section through Long Reef is shown in figure 12. This reef appeared to be a rather loose aggregation of coral fragments, although this might have resulted from blasting in the channel. In the upper part of the section, the coral was frequently coated with up to 1 cm of coralline algae and Homotrema, however, there was no evidence of either inter-fragment connection of crusts or of secondary cementation. In the lower section, there was no evidence of encrustation on the coral, while a considerable amount of surface boring was present. The dates shown were taken from the quite "clean" centers of large coral pieces.

The upper part of the underlying carbonate basement is well cemented and consists of coralline-coated Porites porites and mollusc shell fragments in a matrix of fine-grained carbonate. The upper surface immediately below the reef is blackened to a depth of 5-10 mm and pitted much like weathered carbonate surfaces subaerially exposed on St. Croix. Ian Macintyre (Smithsonian Institution) ran an x-ray diffraction analysis on a blackened Porites porites fragment from this crust finding no aragonite and with low-magnesium calcite dominant, further indicating that is is a subaerially weathered Pleistocene surface. This Porites-shell member grades downward into a poorly indurated carbonate clay with scattered small shell fragments having a trace of intermixed non-carbonate minerals.

The c^{14} ages shown in figure 12 are plotted as a function of depth below present sea level in figure 13. The Neumann sea-level curve for Bermuda (Neumann, in ms.) is also plotted for reference, assuming negligible tectonic activity on St. Croix during the Holocene. This reef was apparently not initiated until about 2500 years after sea level rose over its foundation, probably the time required to clear the Wisconsin regolith from the shelf surface and move it west beyond Krause lagoon. At this point, 4400 years B.P., the water depth would have been about 7 meters, and at this relatively turbid location the dominant corals would be Montastrea and Diploria spp. For about 1400 years thereafter, sea level rose at 2.4 mm/year exceeding the rate of reef growth, and the average water depth from 3000 to 4000 years B.P. was increased to about 9 meters. The resulting rate of reef growth for this interval 1.3 mm/yr, is close to that obtained by Goreau and Land (1973) for reef growth at 25 m on the north coast of Jamaica. At about 3000 years B.P., sea level rise slowed to about 0.4 mm/year and continued reef accumulation shallowed water depths over the reef. At about 1000 years B.P. Acropora palmata became established on Long Reef at a depth of about 4.5 meters, reef upward growth became quite rapid (15 mm/year) and depths close to the present reef flat (-1 meter) would have been reached at about 500 years B.P. Reef flat accumulation at this relatively quite turbid, westerly location, with new reefs forming to the east, is probably very slow as shown in figure 13.
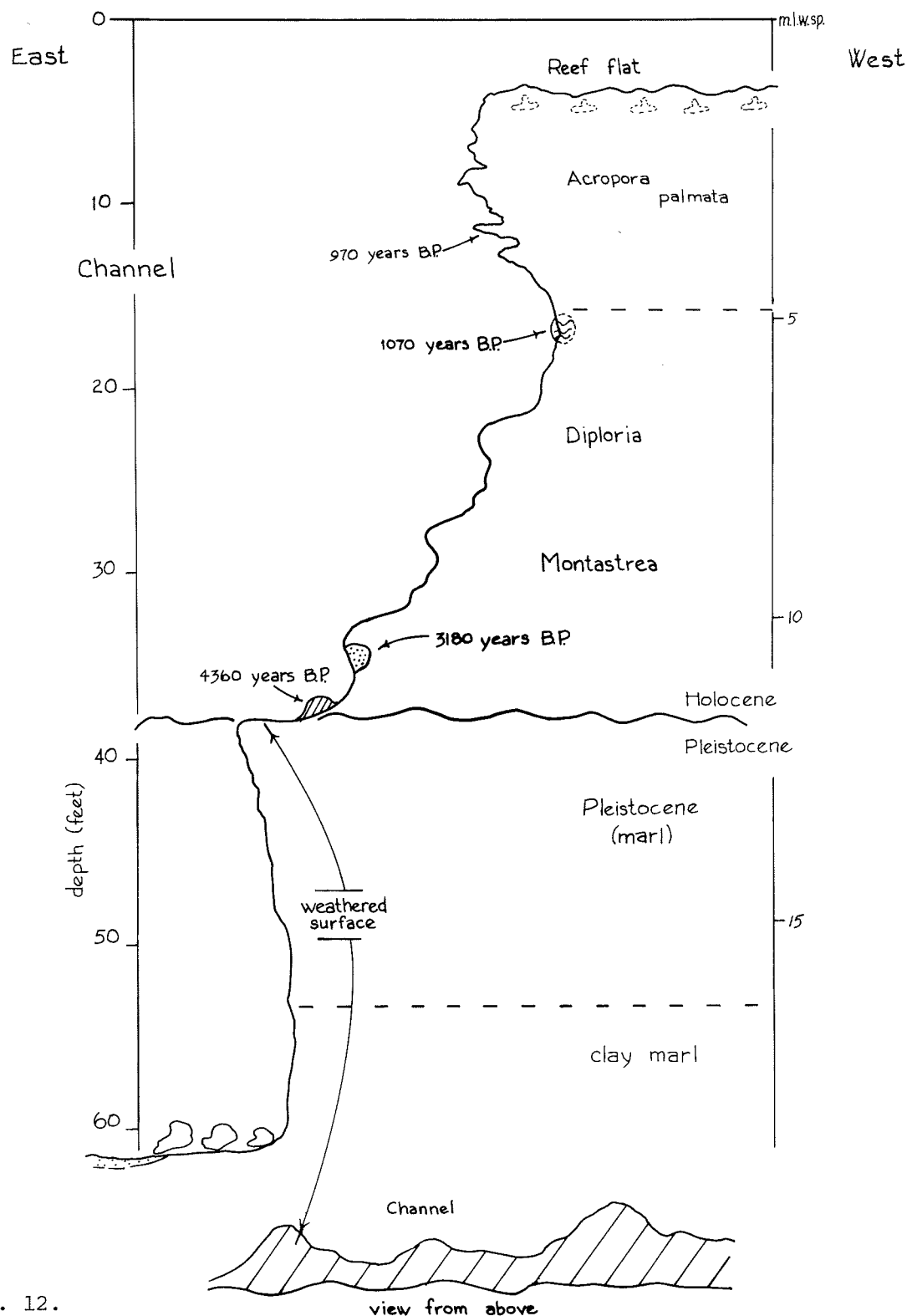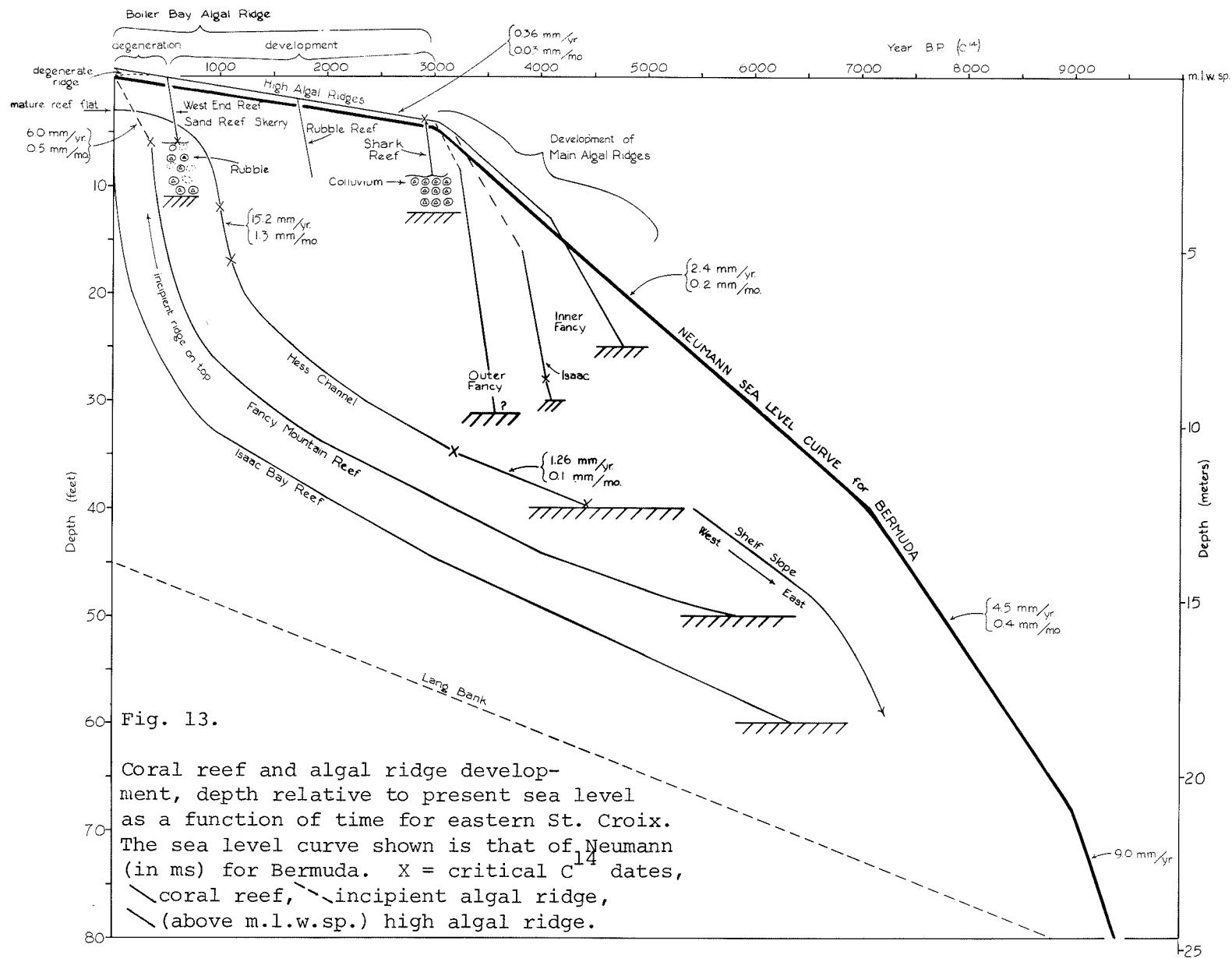
Fig. 12.
West wall of the ship channel cut through Long Reef off the Hess Oil Refine
at Krause Lagoon. Collections were made independently by four divers and
pooled later. Almost all samples taken from 4.5-13 m were Diploria (▯▯▯▯▯)
and Montastrea (▧▧▧▧). One Siderastrea siderea (▨▨) was collected. Most
of the samples taken above 4.5 m were Acropora palmata.

As discussed above, the inshore pre-Holocene shelf on southern and eastern St. Croix slopes irregularly eastward. Even allowing less time for reef establishment on these more easterly shores, but considering the more rapid rise of sea level prior to 7000 years B.P. at -12 meters, these reefs, at the same growth rates, would have been slower to reach the surface than those to the west. Thus, the general pattern of reef morphology, more mature to the west and less mature eastward.

Applying the same reasoning to the easternmost margin of the shelf and assuming no marginal pre-Holocene ridge, the shelf edge at about -25 meters would have been covered by a rapidly rising sea level at about 9500 years B.P. Taking the average depth of Lang Bank as about 45 feet and using a rate of 1.3 mm/year, the Bank could have been developed in its present proportions by beginning its Holocene reef growth within a few hundred years after being placed in the marine environment. This is in agreement with the conclusion reached by Macintyre (1972) that the submerged (or marginal shelf) reefs of the eastern Caribbean are Holocene (or latest Pleistocene). These relations also indicate that if sea level remains near its present level for another 4-5000 years that a shelf edge reef will form at Lang Bank, thereby depriving the inner reefs and ridges of wave action.

Adey and Burke (1975) have indicated that pre-Holocene shelf depth is one of the primary factors controlling reef presence and placement in the eastern Caribbean. Barrier reefs only occur where shelf depths are less than 25 meters and the most mature systems where shelf depths are less than 15 meters. When adversely comparing Pacific atoll reefs with those of the Caribbean, this should be borne in mind. For example (Lalou, et al., 1966) showed that the pre-Holocene topography under Muroroa reef islands was only at 6-10 meters, and Wiens (1962) cites fore-reef terrace depths of less than 20 meters for Bikini, Eniwetok, Rongelap, Zohhoiiyoro and Raroia. This suggests that perhaps major differences between Pacific and Caribbean reef development are not Holocene biological or climatic problems but Pleistocene geological problems, i.e., that the eastern Caribbean pre-Holocene shelves are relatively deep when compared to those of Pacific atolls.

Several patch reefs northeast of Buck Island rising from a sandy shelf at about 10 to 12 meters appear to be anastomosing thickets of massive Acropora palmata from bottom to top. Also, recently Macintyre and Glynn (1974) drilled an intertidal reef flat off Caribbean Panama and found up to 11 meters of Acropora palmata most of which accumulated from 6000 to 2000 years B.P. The top 0.5-3 meters of this reef was younger reef flat dominated by Millepora, Agaricia agaricites, Porites furcata and coralline algal accumulation. This indicates that given proper shelf depths, perhaps 5-15 meters, and favorable environmental conditions, that extensive growth of A. palmata can start shortly after submergence and develop reef structures dominantly of this coral.

Boiler Bay Algal Ridge

degeneration   development

$\begin{cases} 0.36 \text{ mm/yr} \\ 0.03 \text{ mm/mo} \end{cases}$

Year B.P. (C[14])

degenerate ridge

1000   2000   3000   4000   5000   6000   7000   8000   9000   m.l.w.sp.

mature reef flat

High Algal Ridges

West End Reef

$\begin{cases} 6.0 \text{ mm/yr} \\ 0.5 \text{ mm/mo} \end{cases}$

Sand Reef Skerry

Rubble Reef

Shark Reef

Development of Main Algal Ridges

Rubble

Colluvium

10

$\begin{cases} 15.2 \text{ mm/yr} \\ 1.3 \text{ mm/mo} \end{cases}$

$\begin{cases} 2.4 \text{ mm/yr} \\ 0.2 \text{ mm/mo} \end{cases}$

5

incipient ridge on top

20

Inner Fancy

Hess Channel

Outer Fancy

Isaac

30

Fancy Mountain Reef

Isaac Bay Reef

$\begin{cases} 1.26 \text{ mm/yr} \\ 0.1 \text{ mm/mo} \end{cases}$

NEUMANN SEA LEVEL CURVE for BERMUDA

10

40

West Shelf Slope East

Depth (feet)

50

$\begin{cases} 4.5 \text{ mm/yr} \\ 0.4 \text{ mm/mo} \end{cases}$

15

Lang Bank

Depth (meters)

60

Fig. 13.

Coral reef and algal ridge develop-
ment, depth relative to present sea level
as a function of time for eastern St. Croix.
The sea level curve shown is that of Neumann
(in ms) for Bermuda. X = critical C[14] dates,
＼coral reef, ＼incipient algal ridge,
＼(above m.l.w.sp.) high algal ridge.

70

9.0 mm/yr

20

80

25

ALGAL RIDGES

In turbulent areas open to the easterly trade wind sea, the upper-
most Acropora palmata fore reef, at depths of 0 to -2 m, is frequently
an irregular coralline-encrusted pavement (Fig. 11). Sometimes the
original outline of the A. palmata is obvious and a broken branch will
show a coralline accretion of a few mm to many cm on the dead coral. In
other cases, even though a vague outline of the original A. palmata arms
is still present, one can break off projection after projection and find
only coralline. In many of these areas, e.g., off Fancy Mountain (Fig.
22), Robin Bay, western Jack Bay, Isaac Point (Fig. 19) and in Lamb Cove,
just shoreward of these pavements, the A. palmata shapes gradually dis-
appear to be replaced by an irregular coralline pavement which slopes
up to about low water levels.

Several Neogoniolithon species are important on these pavements and
Porolithon pachydermum is sometimes conspicuous. If the pavement extends
to near low water levels, Lithophyllum congestum may be abundant, build-
ing small irregular heads extending above mean low water. Under over-
hangs, and in the abundant holes Lithothamnium ruptile, Mesophyllum
syntrophicum and sometimes Archeolithothamnium dimotum along with
Homotrema are also responsible for considerable carbonate accretion.

We have cored two of these coralline-A. palmata pavements or
"incipient algal ridges" near their crests at about mean low water
springs. During the first, at Jack Incipient Ridge, our drill trans-
mission failed at 80 cm of nearly solid coralline crust with about 50%
recovery. The upper part of the core is quite fresh in appearance.
Further down, although crust corallines are still dominant, much boring,
and re-fill of cavities by sediment and mineralization has altered the
cores. The alteration and mineralization of these algal structures
appears to be similar to that described for the Bermudian cup reefs by
Ginsburg and Schroeder (1973), and I have not carried out a detailed
examination of these processes in the Cruzan ridges. The incipient algal
ridge drilled was on the outer reef south of Fancy Mountain (Fig. 22).
Here we drilled through almost 2 meters of little-altered coralline, with
a little Lithophyllum present, but mostly crust species with scattered
Homotrema. Although occasionally the vermetid Dendropoma is important
in these algal structures, incipient as well as high ridges, it is more
often absent or a very minor element. This differs rather markedly from
the Ginsburg and Schroeder (l.c.) description of the Bermudian cup reefs.
From 2 to 3 meters in the Fancy incipient hole, with only about 10% re-
covery only coral was found. This was dominantly Acropora palmata
although Diploria species and some Porites astreoides also occurred.
Immediately below the coralline cap, a C^{14} date of 355 years B.P. was
obtained in a large, clean core of A. palmata, thus providing an accretion
rate in this incipient algal ridge of 5.6 mm/year. Adey and Vassar (1975)
have studied crustose coralline accretion rates on plates in reef and
ridge environments on St. Croix, finding values of up to 5.2 mm/year.
They attribute high accretion rates in turbulent environments to reduced
grazing action especially by parrot fish, and show that in quiet areas
where these fish can operate effectively net coralline accretion can be
reduced to 0.5 to 1 mm/year.

Once an incipient ridge builds to elevations near mean low water, branching Lithophyllum congestum often becomes dominant, as it has on some of the incipient knobs off Lamb Cove. Steneck and Adey (1975) have shown this plant to dominate highly in turbulent areas at $\pm$ 10 cm of m.l.w. springs and to achieve average branch tip growth rates of 8 mm/year and accretion rates of 4 mm/year. Within 10-15 cm of the surface of a Lithophyllum congestum head, the interstitial space between the branches is often filled with wave-driven sediment that is subsequently cemented by high magnesium calcite into a hammer-ringing hard limestone. Except around holes or channels, Lithophyllum congestum is replaced by Porolithon pachydermum at ridge elevations above about 20 cm above mean low water springs. In areas of especially high turbulence, the latter plant is capable of building the ridge to levels of about 50 cm above m.l.w.sp., i. e., about 20 cm above mean high water springs (see Fig. 2). (Adey and Burke (1975) have reported other algal ridges in the considerably rougher Martinique-Guadeloupe area that reach heights of one meter above m.l.w.sp., approximately the height of the higher Pacific atoll ridges.)

In the small, open cove just to the south of East Point, the irregular Acropora palmata pavement blocks at depths of 2 meters fuse into lobed coralline pavements that extend to elevations of up to about 30 cm above m.l.w.sp. These lobes, dominated by Lithophyllum congestum, with raised rims and weakly-developed bowls behind and separated by rubble channels 1-2 meters deep, have not developed extensive overhangs or interlobe fusions. Although we have no subsurface information on this small algal ridge, its surface configuration as compared to the well-developed ridges and the immaturity of the offlying A. palmata reef suggests that it is the youngest of the Cruzan ridges with a thickness of only 2-4 meters and has existed as a high ridge for only a few hundred years. Since this ridge provides an intermediate developmental stage between the incipient ridge condition now fairly abundant on the maturing A. palmata reefs at the eastern end of St. Croix and the older high algal ridges, it would be especially desirable to core it. It is quite rough however, and it would probably be necessary to construct a large, high platform from which the drilling could be undertaken.

I will begin the discussion of the major high algal ridges on St. Croix with the complex off Robin Point on the south shore (Figs. 14-17). This ridge lies on a southwesterly projection of the reef system. It is open to the easterly sea, almost perpendicular to the direction of the wave train and is generally the roughest and most active of the Cruzan ridges.

In the outer line, there are some small individual boilers or cup reefs from 2 to 3 m in diameter with well-developed raised rims all around and marked central depressions. Other boilers range up to about 30 m in diameter with the highly raised rims being present only on the seaward margins. In the latter case, the central basins are often either open on the back or with a slight rim, and are relatively deep, about 1 m, often with large Diploria heads. These larger ridge elements are formed by series of fused individual boilers (Fig. 15). The largest of these, platform reef transected by section AA', is about 120 m long and

averages about 40 m in width. In places, the junction between fused boilers is marked by the still raised rims and by a conspicuous slot occasionally wide enough for an arm or pole. In other places, there is little direct surface evidence of the fusion, except for the obvious inward curving of the two boilers where they meet marginally. However, underneath in this case, there is usually a quite open channel wide enough for a diver to swim through. Many of these outer ridge elements are honeycombed with such caverns, the rounded walls being coated with many layers of shade coralline species as well as Homotrema and Squamariacea.

The waters immediately around the high algal ridges often are relatively deep, 3-6 meters, and in addition to rubble and sand patches, in some of the channels, the pavements often support a community of Diploria spp., Millepora and Montastrea annularis. In this environment, these corals tend to be scattered but quite large. In the deeper area at 5-6 m in front of Robin Ridge, some Diploria colonies 1-2 m in diameter extend nearly to the surface.

We were able to drill three holes on Robin Algal Ridge, but none of these extended to the basement. The deepest of these, on the outer part of the high ridge on section AA, broke out into an underlying cavern at about 3.5 meters and was terminated. The core in this case was dominated by branched heads of Lithophyllum congestum to a depth of about 2 meters with crust species and abundant Homotrema below. Using the Neumann sea level curve (Fig. 13), this indicates that this ridge has been growing at or near mean sea level at least since 3300 years B.P. The remaining two Robin cores are short, 1 m, and were placed in the back ridge area on section AA'. The surface of this "ridge" is now about one m below m.l.w.sp. and has little coralline on its surface. Diadema antillarum is abundant and the pitted, scraped and gray carbonate surface is obviously being removed by grazing. However, below several cm, the cores are dominantly crustose coralline. This suggests that this structure was once a high ridge, perhaps older than the outer series, that was subsequently blocked from the required wave action by the development of the younger outer series. Shoreward of this second line, there is a third series of ridge-like structures which may also be degenerating high ridges.

Presently, seaward and southeast of Robin Ridge an active Acropora palmata reef is developing. This is shown on both figures 14 and 16. The surface of this reef is still 2-4 meters below sea level and only occasionally do waves break on it. However, it has likely already reduced some of the wave energy delivered to the ridge complex and is probably partly responsible for the degeneration of the back ridge system. If this reef has a growth rate comparable to that of Long Reef, a well-developed reef flat will have formed within 6-800 years and Robin Ridge will be in full degeneration.

Isaac Algal Ridge off Isaac Point is, in area, one of the smallest high algal ridges. However, being quite exposed, it has rim heights, about 50 cm above m.l.w.sp., equal to any known on Robin Ridge. There are a few off-lying individual boilers in the southwestern part of the

Fig. 14. Aerial photograph of Robin algal ridge. Compare with map
(Fig. 16). Note A. palmata reef building everywhere seaward
of the ridge except in the narrow sand channel (mid-right).
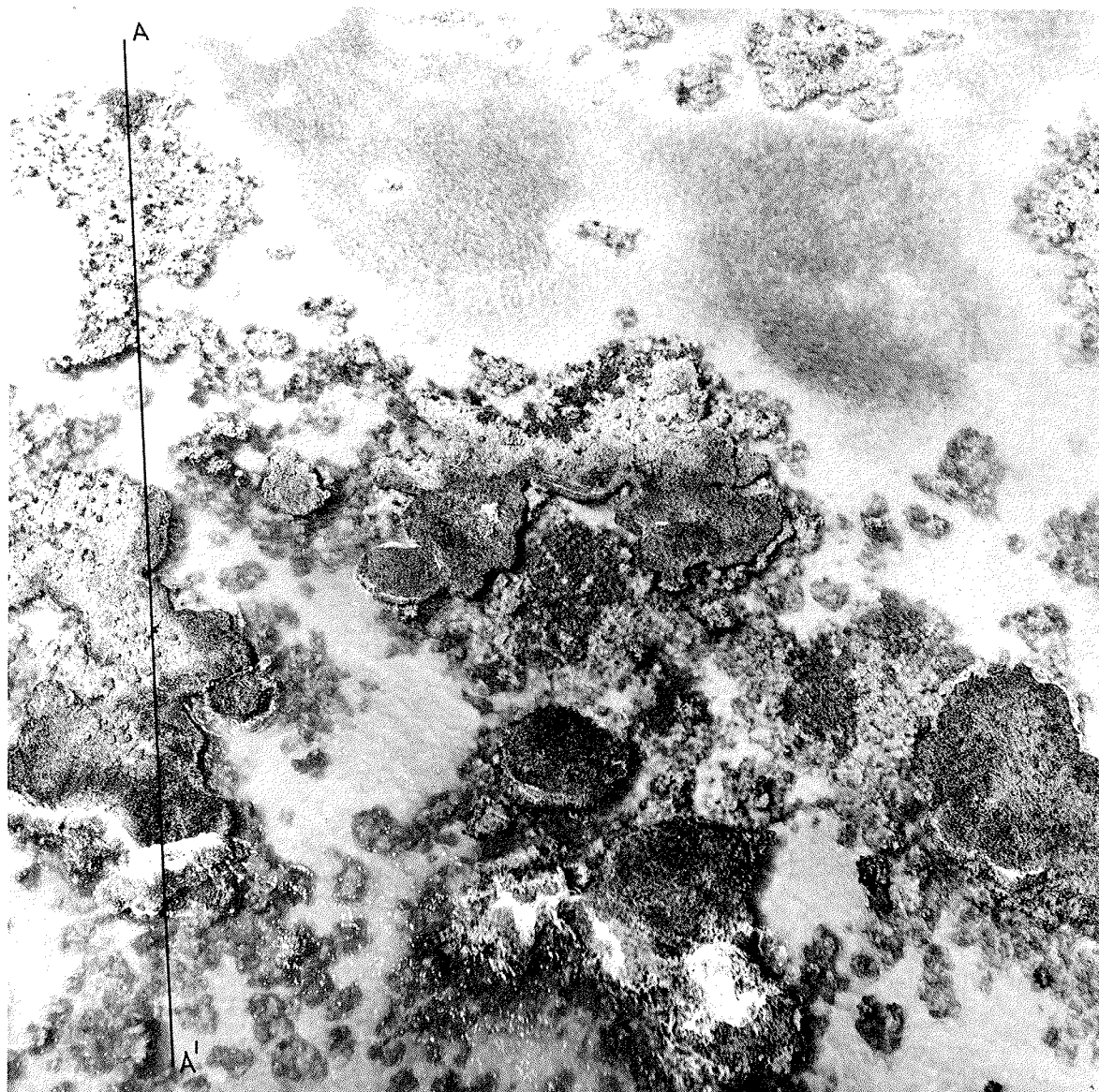
Fig. 15. Large scale aerial photo of the central section of Robin ridge.
(See Fig. 16 for location of AA'.) The fused "boiler" origin
of a large part of this ridge is evident here. See figure 17
for depths.

Reef, dominantly _Acropora palmata_

Reef flat

Robin Bay

access to south shore road

3 fm.

AB

Robin Point

N

dominant wave direction

Caribbean Sea

Figure 16

approx. position
3 fathom contour

A

B

Scale

(feet)
0   100   200   300   400   500
0   50   100   150
(meters)

Reef, dominantly _Acropora palmata_

Rod Bay

Mostly sandy lagoon

shore
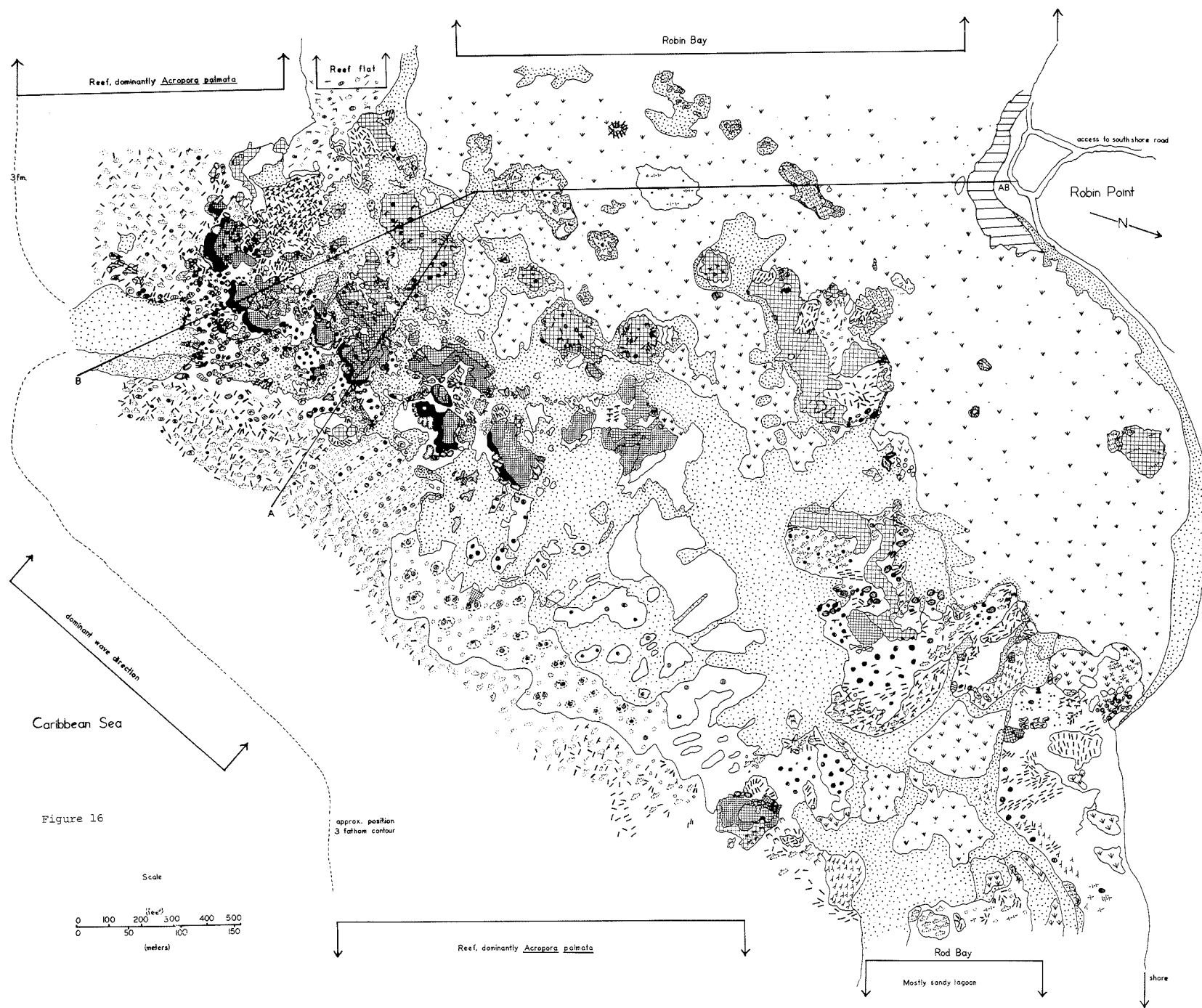
Fig. 16. Robin algal ridge complex and the surrounding coral communities. Indicated sections are shown in Figure 16. Ridge elevations relative to m.l.w.sp.: ▮ +15 to +50 cm, ▦ -10 to +15 cm, ▦ -100 to -10 cm, ▢ -200 to -100 cm. The following symbols are used on all of maps below:

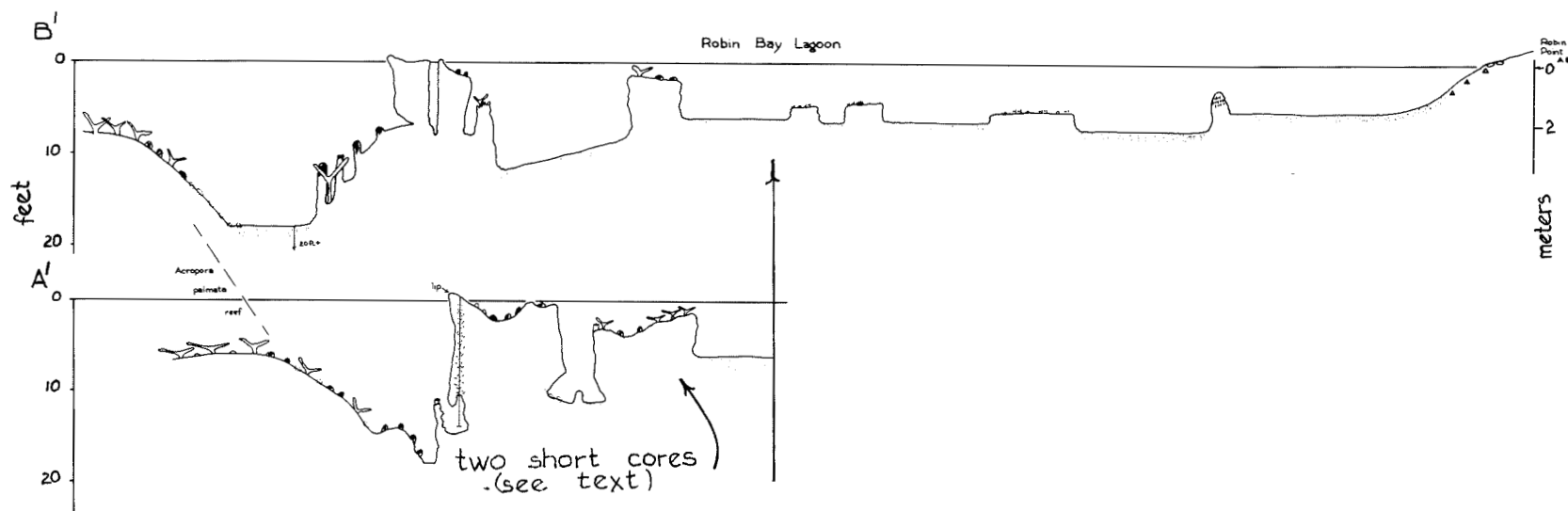|		
living Acropora palmata	living Porites porites	⊕ collapsed blocks of algal ridge
dead standing	dead or Porites pavement	
rubble	Y living Acropora cervicornis	Caledonia bedrock
pavement	Y dead	sand
	YYY pavement	
living Diploria spp.		beach rock
dead	○ Siderastrea siderea	
living Montastrea annularis	◯ Porites astreoides	V dominantly Thallassia grass
	dead	V dominantly Syringodium grass
living Millepora		
dead		

Fig. 17. Sections of Robin algal ridge complex shown in figures 14-16.

ridge system, and in the eastern corner only a partial fusion of several boilers has taken place (Figs. 18, 19). These have the typical high, fleshy algae covered rims, the uppermost sections being relatively smoothly encrusted with Porolithon pachydermum and the front or lower areas dominated by Lithophyllum congestum. The higher parts of rim and fore-ridge areas have few Echinometra and tend to be relatively smooth. However, the upper back ridge areas at approximately -20 to +20 cm are heavily infested with these echinoids and their burrows, making walking very difficult. The elongate main section of the ridge has developed by a fusion of boilers. This is quite apparent in the eastern section where one can still swim through some of the channels below. However, in the central and western sections, the only obvious evidence for the original boiler structure is the presence of scattered closed caves at least one of which extends back to the ridge "flat" as a very narrow slot. The result of boiler fusion over a long tract has been the exclusion of wave action from the back ridge areas, and a pronounced narrowing of the high ridge zone. The back ridge "flat" is now at about -1 m and is dominated by Porites porites and Porites astreoides.

It should be pointed out here that while the Pacific atoll algal reef margins are called ridges, they are more or less formed of boilers as described here. This is well shown by the massive, boiler built ridge system described for Muroroa by Chevalier et al. (1968) and as diagrammed by Emery, Tracey and Ladd (1954) in their classic treatment of the Bikini ridges.

The southeast corner of Isaac Ridge has a quite low rim, and the collapsed blocks just to the outside have apparently broken out of this position. On the eastern corner of this area, an unfused boiler has fallen over, with the upper surface now resting at about 45°. The upper portions of this conspicuous tilted boiler now project nearly a meter above low water and have the characteristic pitted surface of coastal subaerial eroding limestone (see Fig. 18). Just outside of this tilted block, a new boiler is developing, having reached the incipient stage just below m.l.w.sp. This incipient boiler can be traced seaward into the Acropora palmata pavement on which it is developing.

A single core hole has been placed in one of the eastern lobes of Isaac Ridge. The dominant elements encountered are shown in figure 21. At about 8 meters, a mixture of Caledonia and coral fragments were encountered which made drilling virtually impossible with our rig. I have interpreted this as a Caledonia bedrock surface, but it has not been established with certainty that it is not a weathered, Pleistocene reef surface with terrigenous pebbles and cobbles. A sand probe to the outside of the ridge, as shown, did not reach a hard surface at 15 meters, thus indicating that the basal structure of the algal ridge is formed on a raised bench structure at 9 meters, at least 6 meters and probably 8-10 meters above the offlying shelf. A date of 4040 years B.P. was obtained from a large, clean core of Acropora palmata taken a foot or two above the basement. Unfortunately, this hole was not placed on a major ridge lobe, but rather on a minor lobe connecting two boilers. Thus, only 2.5 meters of coralline, mostly L. congestum, was encountered here, and from 3.5-6 meters a single massive Diploria head, of the type
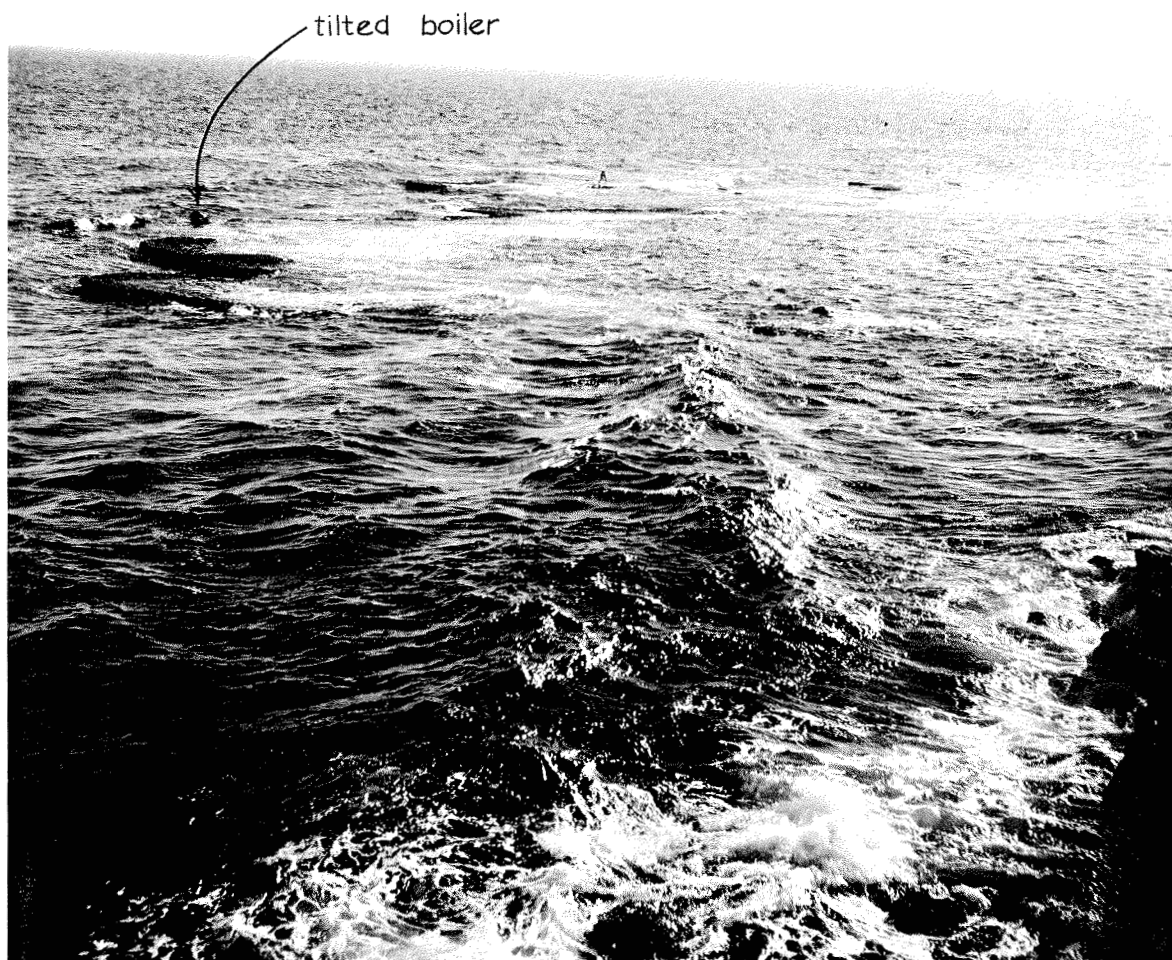
tilted boiler

Fig. 18. Photograph of Isaac Algal Ridge on a relatively quiet day with
a tide level of about +20 cm. Note figure standing (bent over)
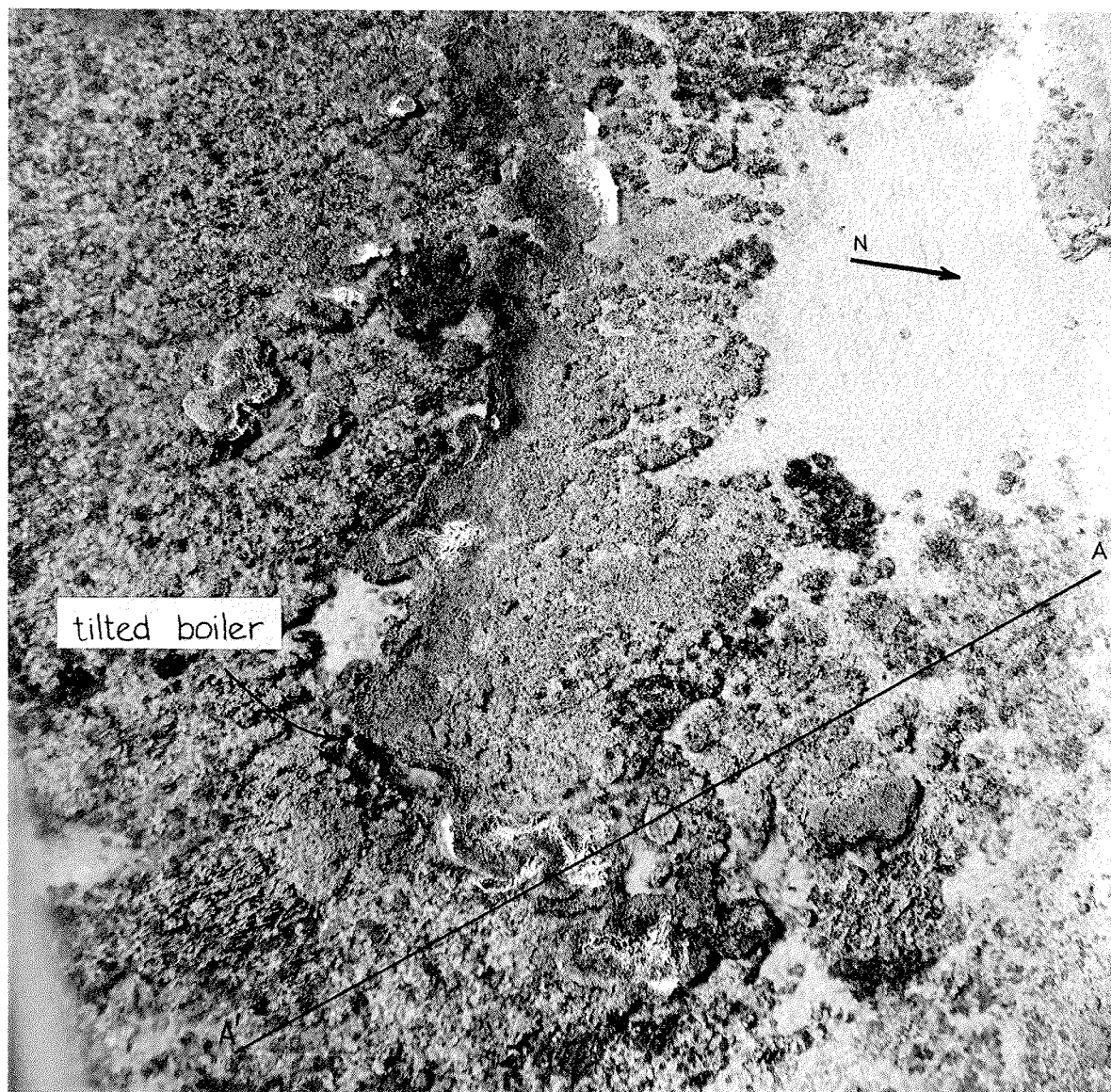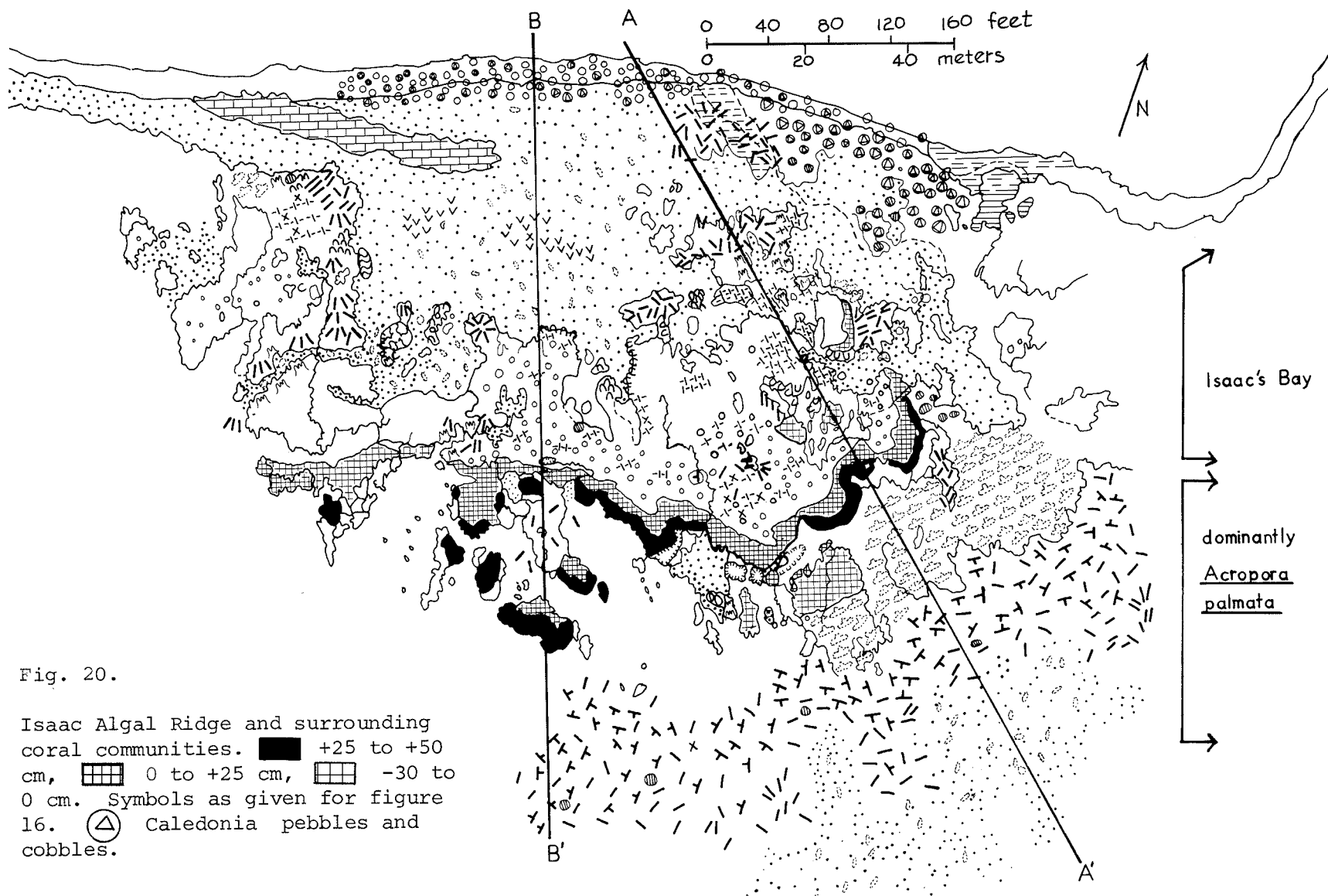near the center.

Fig. 19. Aerial photo of Isaac Algal Ridge taken at about 600 feet on an
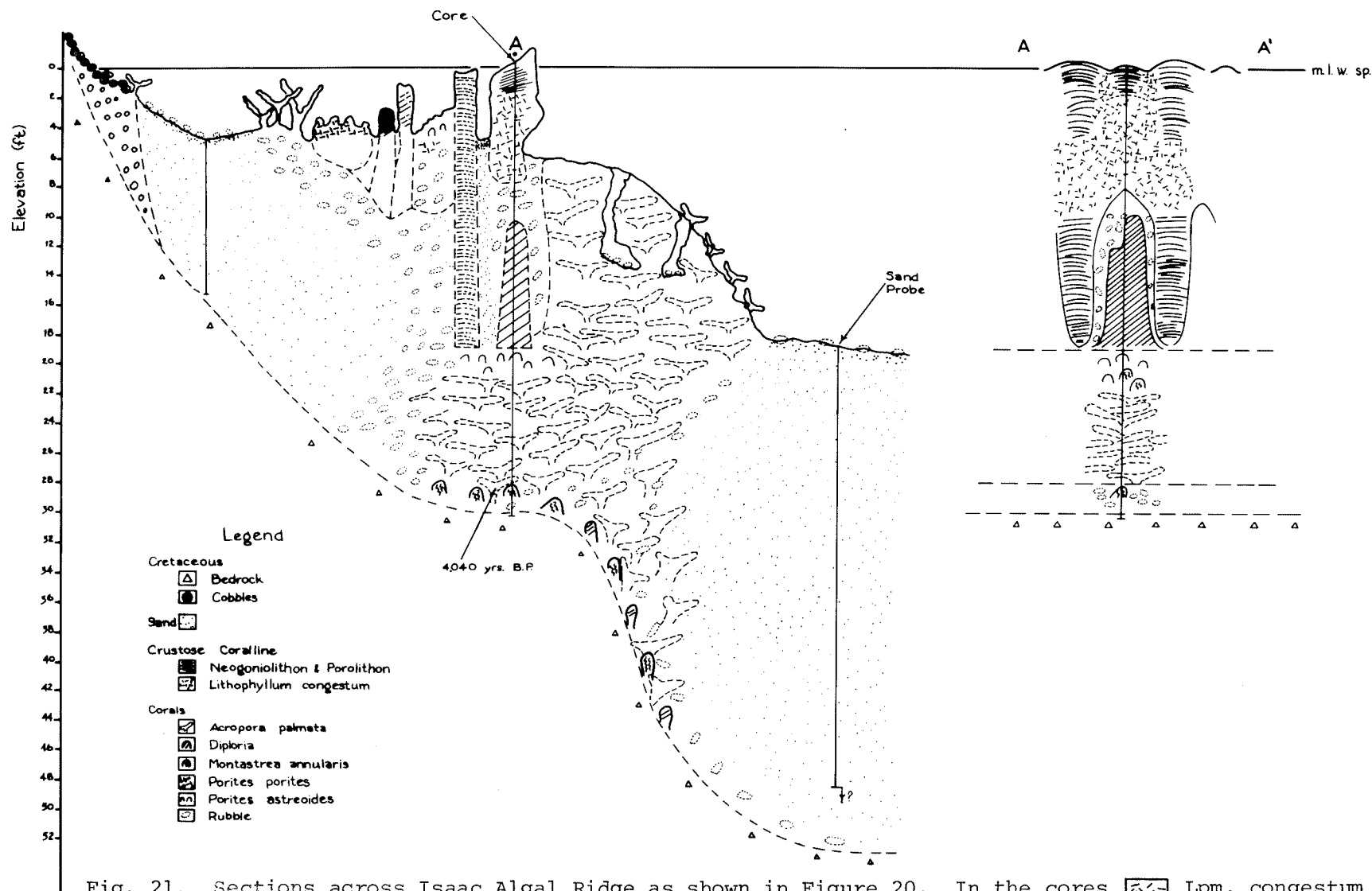extremely quiet day. See figure 20 for scale.

Fig. 20.

Isaac Algal Ridge and surrounding coral communities. ■ +25 to +50 cm, ▦ 0 to +25 cm, ▦ -30 to 0 cm. Symbols as given for figure 16. △ Caledonia pebbles and cobbles.

B

A

0   40   80   120   160 feet
0   20   40   meters

N

Isaac's Bay

dominantly Acropora palmata

B'

A'

Fig. 21. Sections across Isaac Algal Ridge as shown in Figure 20. In the cores [▨] Lpm. congestum, [▨] crust corallines, [▨] coral rubble. The section AA' is an interpretation based on the surface characteristics of the boilers making up this section of the reef.

normally encountered in deeper inter-boiler channels, was cored. Below 6.5 meters, the sub-ridge structure was dominantly A. palmata. Based on the surface plan of the ridge in this area, an interpretive section parallel to the ridge front (AA') is also shown in figure 21.

The depth-age relationships of Isaac Ridge are shown in figure 13 and interpreted as follows: Sea level rose over the raised beach off Isaac Point at about 5700 years B.P. About 1600 years was required to establish strong reef growth on this bench. Since sea level was only about 5 meters above the bench in the eastern area, Acropora palmata dominated and quickly built the reef to within 1.5 to 2 meters of sea level. There, crust type corallines built the ridge to sea level, as an incipient ridge, by about 3200 years B.P. (determined by position of Lithophyllum congestum in the core). From that time until about 1300 years B.P., the ridge was dominated by L. congestum in the area cored and probably had a height of 0-25 cm above m.l.w.sp. The last part of the ridge section consists of coralline crust species, indicating that since about 1300 years B.P., this part of the ridge has maintained its present height.

The developing A. palmata reef off Isaac Algal Ridge is still relatively deep, 3-4 meters, although directly to the east off Isaac Bay a section of reef is approaching the surface. Probably it will be more than 1000 years yet before Isaac ridge will be blocked to the point of serious degeneration.

Figures 22 and 23 show the algal ridge pair and its associated incipient ridges off Fancy Mountain. These ridges are both relatively low and degenerating due to wave-blocking by the A. palmata reef forming outside. The inner ridge being partly blocked by the outer ridge reaches maximum heights of only +26 cm above m.l.w.sp. having an average elevation of +10 to +17 cm. The outer ridge averages +17 to +23 cm.

The core hole in the inner ridge returned a clean, 8 cm section of Caledonia with parallel top and bottom fracture planes at 8 meters. The boring then broke into coral rubble and jammed with hard drilling at 9 meters. I have interpreted this as shown in figure 23. While here also the piece of Caledonia could have been a cobble on a weathered reef surface, there is no evidence of a rounded nature on either end of the core and bedrock seems the most likely interpretation. The crust coralline in the core begins at 6 meters, and L. congestum at 4 meters, indicating that the coral reef structure developed on the ledge shown at about 4800 years B.P. had become an incipient ridge by 4500 years B.P. and finally a high ridge by 4300 B.P. (Fig. 13).

The core in the outer ridge is dominated by L. congestum only in the upper 1.5 meters and becomes mixed with Millepora and then Montastrea at 2.5 meters. Thus, the outer ridge is considerably younger than the inner, starting at about 3000 years B.P. Its position in line with the present Acropora palmata reef crest and in the vicinity of a number of presently-forming incipient ridges suggests the presence of a secondary bench or series of benches, in elevation somewhere between the high bench with the inner ridge at 8 meters and the outer shelf at approximately 15 meters.
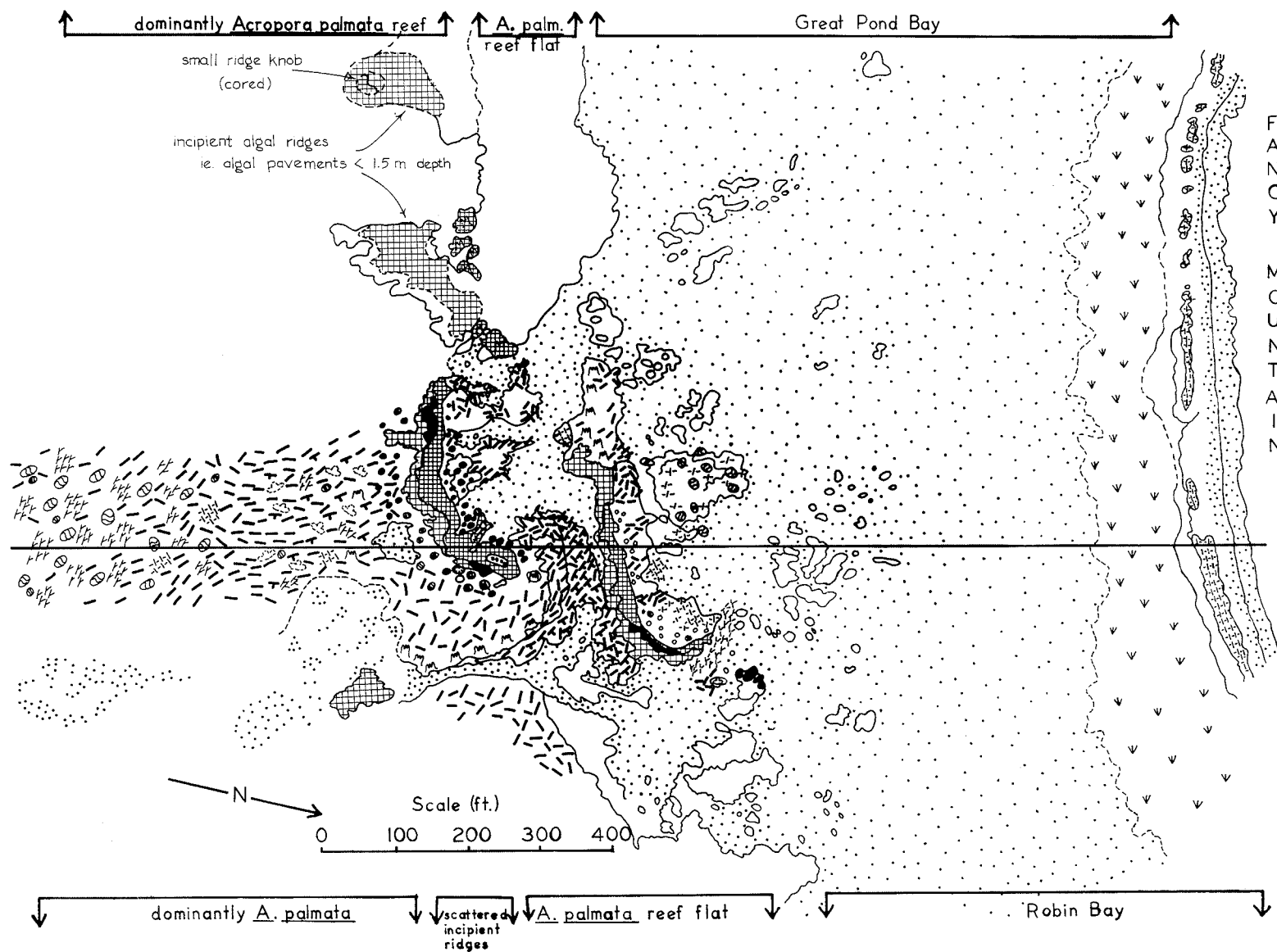
Fig. 22. Map of Fancy Mountain algal ridge pair and its associated incipient algal ridges and coral reef communities. Section shown in figure 23. ■ +15 to +30 cm above m.l.w.sp., ⊞ -10 to +15 cm, ⊞ -100 to -10 cm.
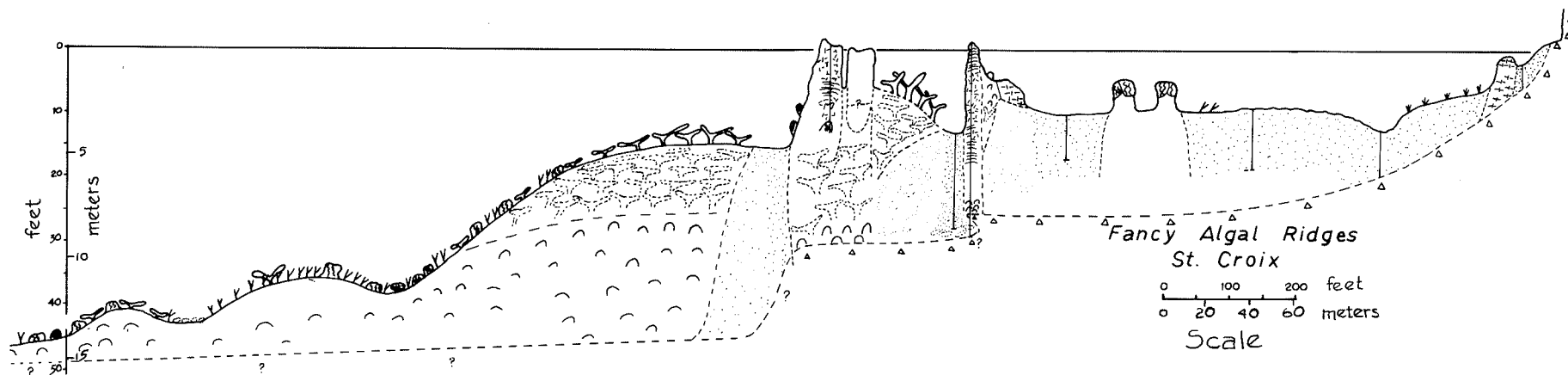
Fig. 23. Section from shore at Fancy Mountain, across Fancy algal ridges to the outer shelf. Symbols as previous figures. ⌐∩⌐ inferred head corals Diploria spp. and Montastrea annularis.

Beach Algal Ridge, between Grassy and Grapetree Points (Figs. 24-27) is the longest (over 0.5 km) and straightest ridge on St. Croix. Although some narrow caverns are present extending back into the ridge, there is little surface evidence of boiler amalgamation. It is probably the oldest Holocene ridge on eastern St. Croix, 5000 years or more, although we do not have a core to establish this. Beach Ridge is not high, the maximum elevation measured being 22 cm above m.l.w.sp., and it is also being blocked by an off-lying reef system. In the eastern part of the area the off-lying reef has already developed a reef flat and to the westward it gradually decreases in height. The algal ridge behind is inversely proportional in its height to that of the reef. Behind the reef flat areas, it has degenerated to subtidal levels.

Beach Algal Ridge apparently lies on a bench that is greater than about 8 meters in depth, but probably considerably less than the shelf depth here of about 19 meters. Unless reef growth was particularly favorable at this locale, which doesn't seem likely because of its embayed nature, the maximum bench depth would be 10-12 meters. This inferred bench is conspicuously aligned with an inferred fault scarp on the island (see Fig. 27). Beach Ridge also grades into an A. palmata-Millepora rich reef to the west. This could result from a sloping of the underlying bench to the west to merge with the shelf. The sand channel in front of Beach Ridge is quite deep and abrupt. It is mostly 8 to 10 meters in depth, but reaches 13 meters in its western sections. It is bigger and much better defined than any of other fore ridge channels known on St. Croix, perhaps because of the association with a pronounced scarp structure.

BOILER BAY ALGAL RIDGE

At the time of our arrival on St. Croix in mid-1972, the boilers or "cup reefs" of Boiler Bay were generally known to the considerable number of scientists who had worked on the eastern end of the island. The high algal ridges, although easily visible from the air, had not been noted, as they can be quite obscure to the swimmer especially with average wave conditions and without low water spring tides. Perhaps it is unfortunate that our work was begun in Boiler Bay, as this ridge is certainly the most atypical on the island. Some of the 32 holes drilled in Boiler Bay could perhaps have been more useful on the larger ridges.

Except for East Point algal ridge, the Boiler Bay ridge is the only one associated with the head of a bay. The former case does not even appear as much of an exception as the cove is quite shallow and faces due east. Most of the other algal ridges are associated with points, or in the case of Beach ridge an apparent fault scarp oriented almost normal to the wave train. Most of the high ridges are also associated with the point-forming East End Member of the Caledonia Formation suggesting development on benches cut at 10 to 12 meters, perhaps at the 30 to 40 thousand B.P high level sea stand.

The central boilers of the Boiler Bay ridge are resting on a 0.5 to 1.5 meter thick lag colluvial deposit (Fig. 28). The latter, a weakly
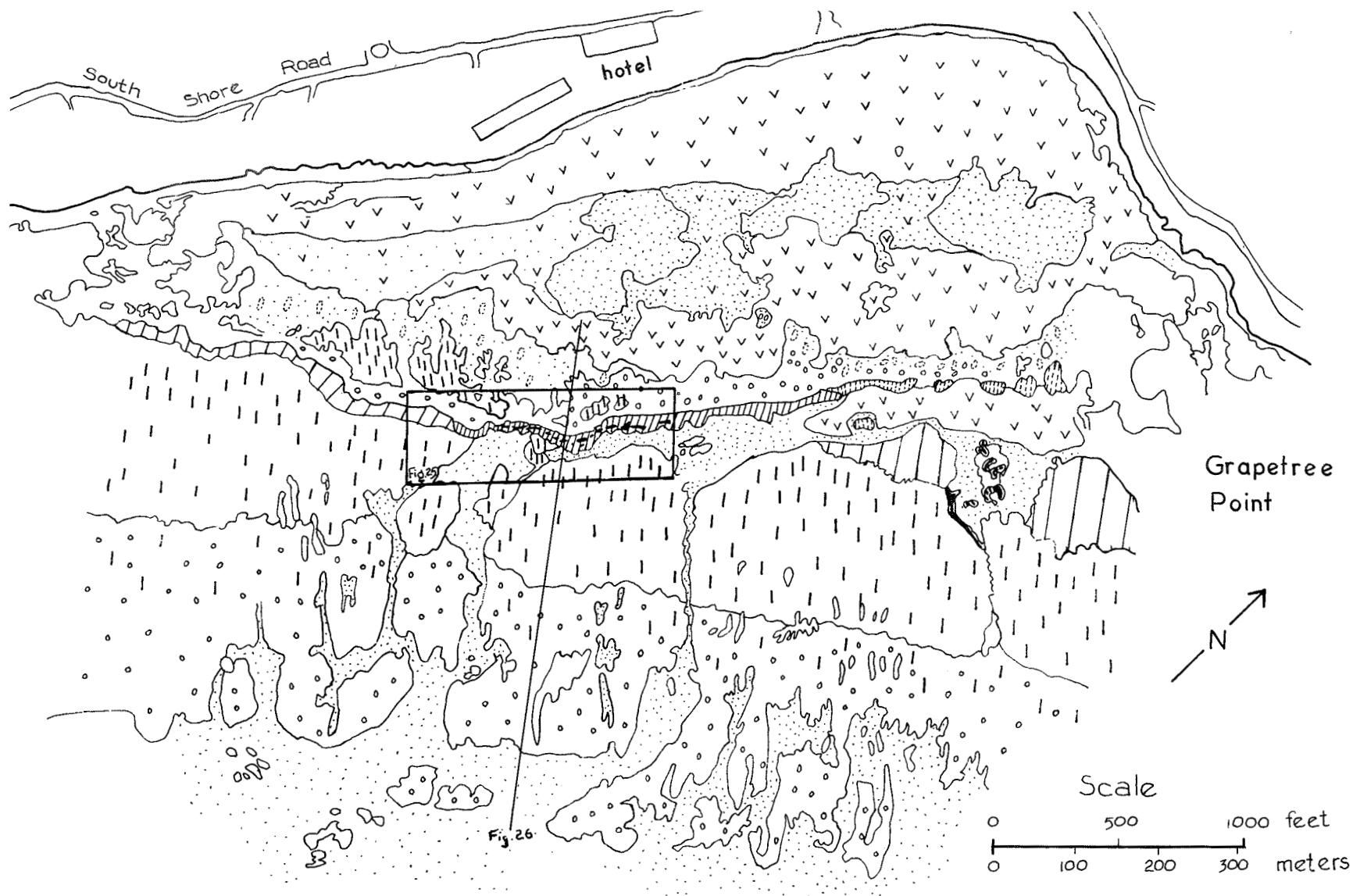
Fig. 24. Coral Reef and algal ridge complex between Grassy Point and Grapetree Point. ▮ high algal ridge, ⊞ reef flat, ⊪ algal ridge area, ⊡ Acropora palmata fore reef, ⊡ Diploria-Montastrea deep fore reef and back ridge, ⊡ sand, ⊡ grass. Section shown in figure 26.
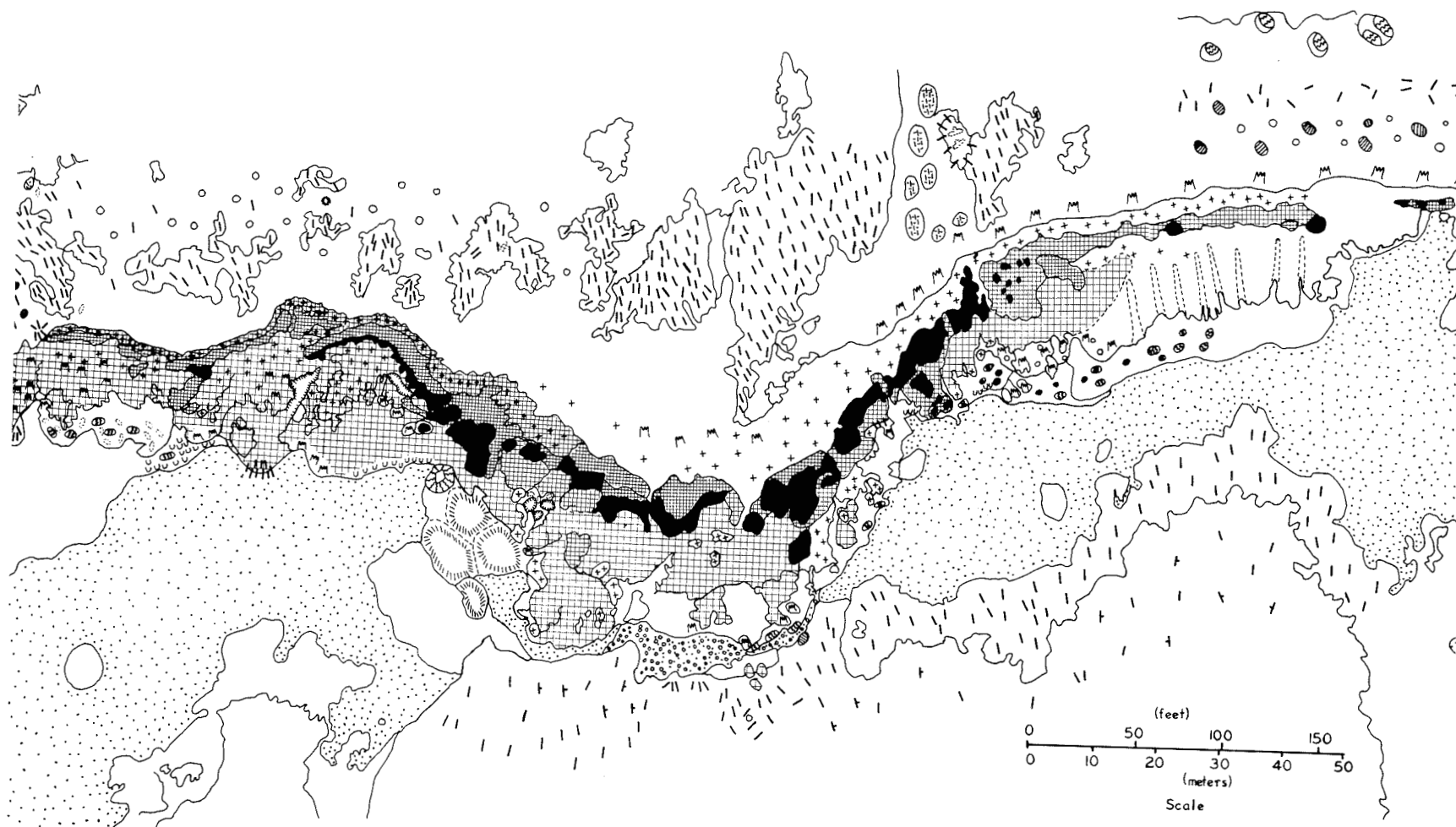
Fig. 25.   Beach Algal Ridge, area in inset of Fig. 24.   ■ 0 to +22 cm above m.l.w.sp., ⊞ -20 to 0 cm, ▦ -100 to -20 cm, ▭ -300 to -50 cm.   Otherwise symbols as previous diagrams.

main algal ridge

fore ridge coral area

m.l.w.sp.

cavern

inferred
dom. A. palmata

spur & groove area

rubble
Diploria
Millopora

inferred
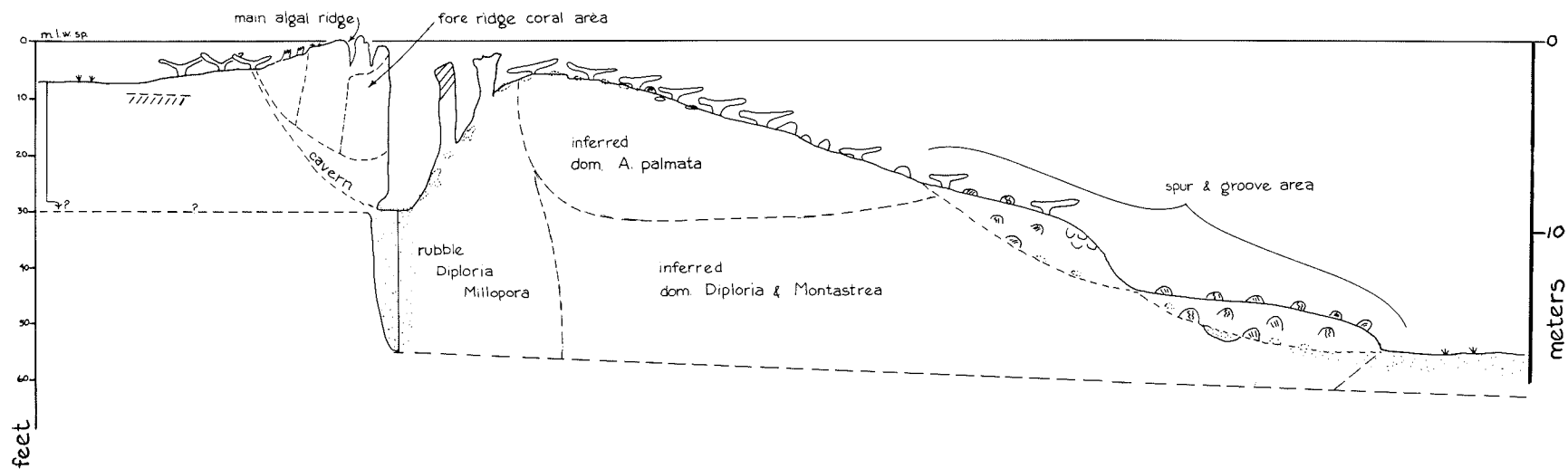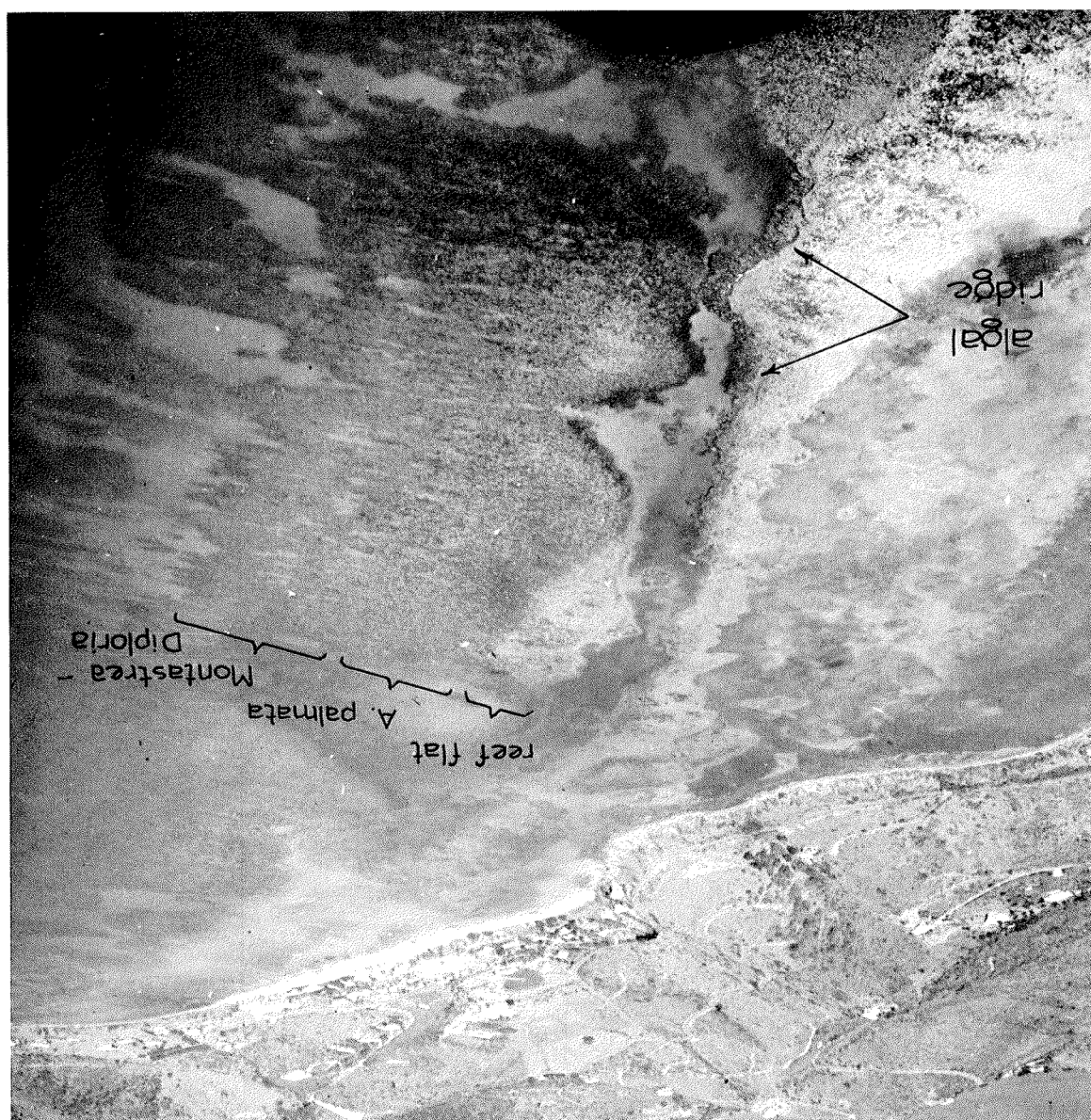dom. Diploria & Montastrea

feet

meters

Fig. 26. Section of Beach Algal Ridge and off-lying reef complex as shown in figure 24.

Fig. 27. Aerial photograph of Beach Algal Ridge area showing apparent continuity of inferred bench beneath ridge with inferred fault scarp on land.
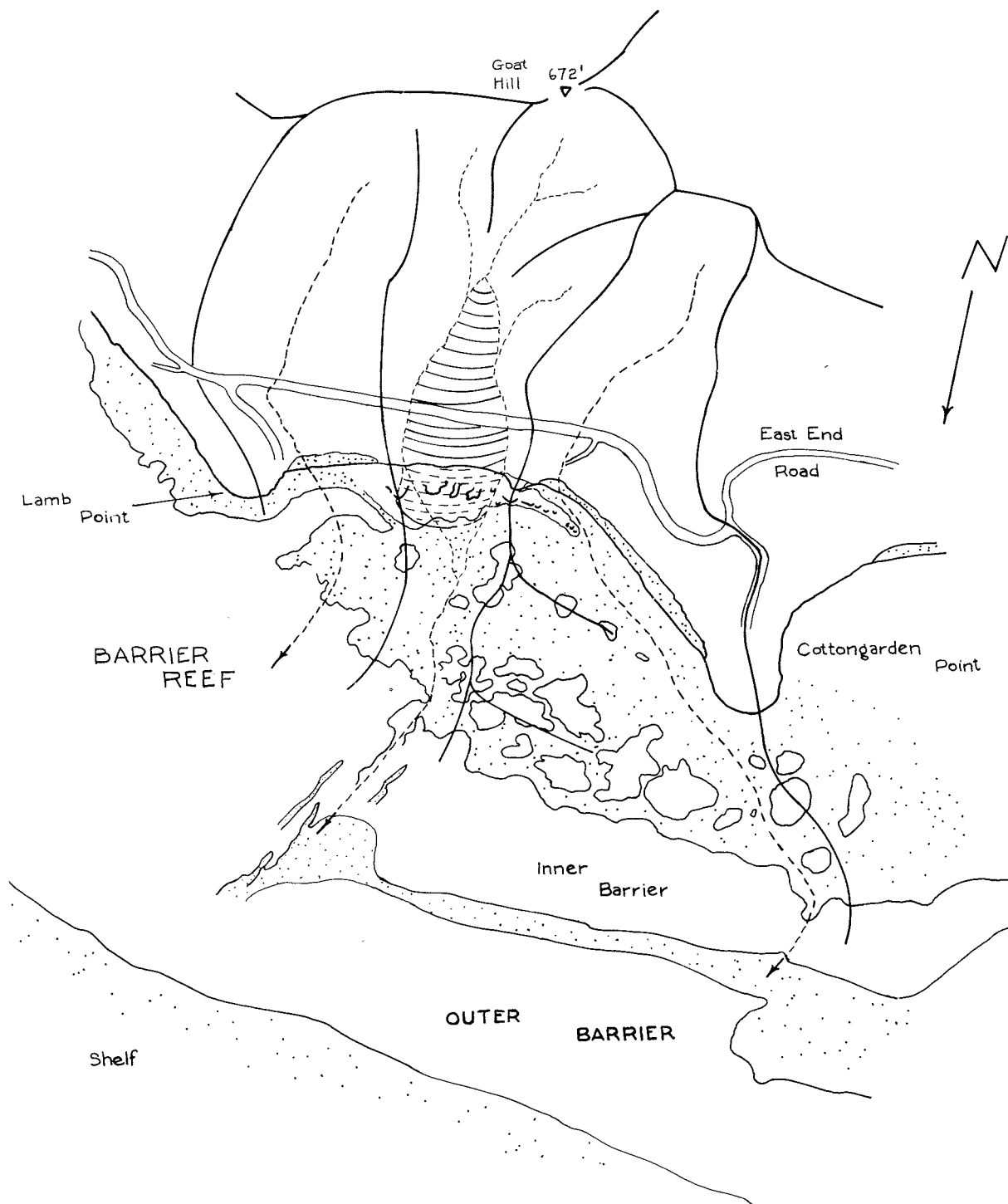
Fig. 28. Boiler Bay area (see Fig. 4) showing ridge crests ⌒ and drainage patterns ⌐⌐ , colluvial lobe ⌇ and offlying barrier reefs.

cemented probably Wisconsin rapid flow or colluvium consists of unsorted, angular Caledonia boulders, cobbles and pebbles in a silt-sand matrix. With late Holocene rise of sea level, this deposit was eroded rapidly, leaving a lag of boulders and cobbles, and now appears as a 10 meter high bluff, with a wave cut terrace behind the central ridge area. The boilers are stretched out across this boulder-pebble lag terrace between the two Caledonian ridges with a smaller set tailing out to the west probably on a pebble spit developed from the colluvium.

Details of the boiler-ridge area and the surrounding coral communities are shown in figures 29-37. Depths and subsurface data are given in figures 39-44, keyed as to locality in figure 38.

The surfaces and even the highest boiler rims in Boiler Bay are presently infested with Echinometra, their burrows occupying about 30% or more of the surface. Crustose corallines only occupy about 30% of the remaining surface, being intermixed with algal-bored, dead coralline, peyssonnelid crusts, Homotrema and the crusts or filamentous bases of the abundant fleshy-leafy algae. The latter develop a large and diverse standing crop and are discussed in detail by Connor and Adey (1975). The crustose corallines that are present are dominantly Neogoniolithon species, Porolithon pachydermum not being common and Lithophyllum congestum being quite rare. Tenarea bermudense, a shade species, can be a massive accreter on the undersides of overhanging lips. Even though wave action is presently insufficient in Boiler Bay to sustain effective growth of L. congestum, the borings at Shark Reef slot show that this plant was the major constructor of these ridges (Fig. 40) just as it was on the present high ridges. Adey and Vassar (1975) have shown that present coralline accretion rates on the crests of these ridges are reduced to 1-2 mm/year. This is apparently not sufficient to maintain the ridges in the face of the massive Echinometra boring.

Long, overhanging lips appear to be more characteristic of the fore-ridge in Boiler Bay than the larger ridges, perhaps because reduced wave strength allow them to reach larger size. In addition to overgrowing and fusing with each other, boilers apparently fuse with Millepora heads and (Figs. 39 and 40) probably occasionally A. palmata colonies. Most of the boilers in Boiler Bay are based on A. palmata and some, e.g., Rubble Reef and Sand Reef Skerry (Fig. 44), have coralline caps only 0.4-1 meter thick (dominantly of L. congestum) making them less than 2000 years old (see figure 11). A few of the drilled boilers were found to be based on Millepora, mostly those in the far west areas. A C^{14} date on coral under West End Reef at 2 meters gave 650 years B.P. However, Millepora appears to frequently lack the strength to support a boiler alone and several "exploded" Millepora-based boilers occur in the area (see Fig. 34). A single boiler was found with an apparent Diploria base (Fig. 43A).

In large areas around the Boiler Bay ridges a relatively bare pavement occurred at depths of 1-4 meters. These have only scattered corals, usually Siderastrea siderea and Porites astreoides and are named according to the dominant coral. Crustose corallines are relatively unimportant on these pavements occupying in some cases as much as 30%, but usually less than 10-15% of the surface. Several Neogoniolithon species,
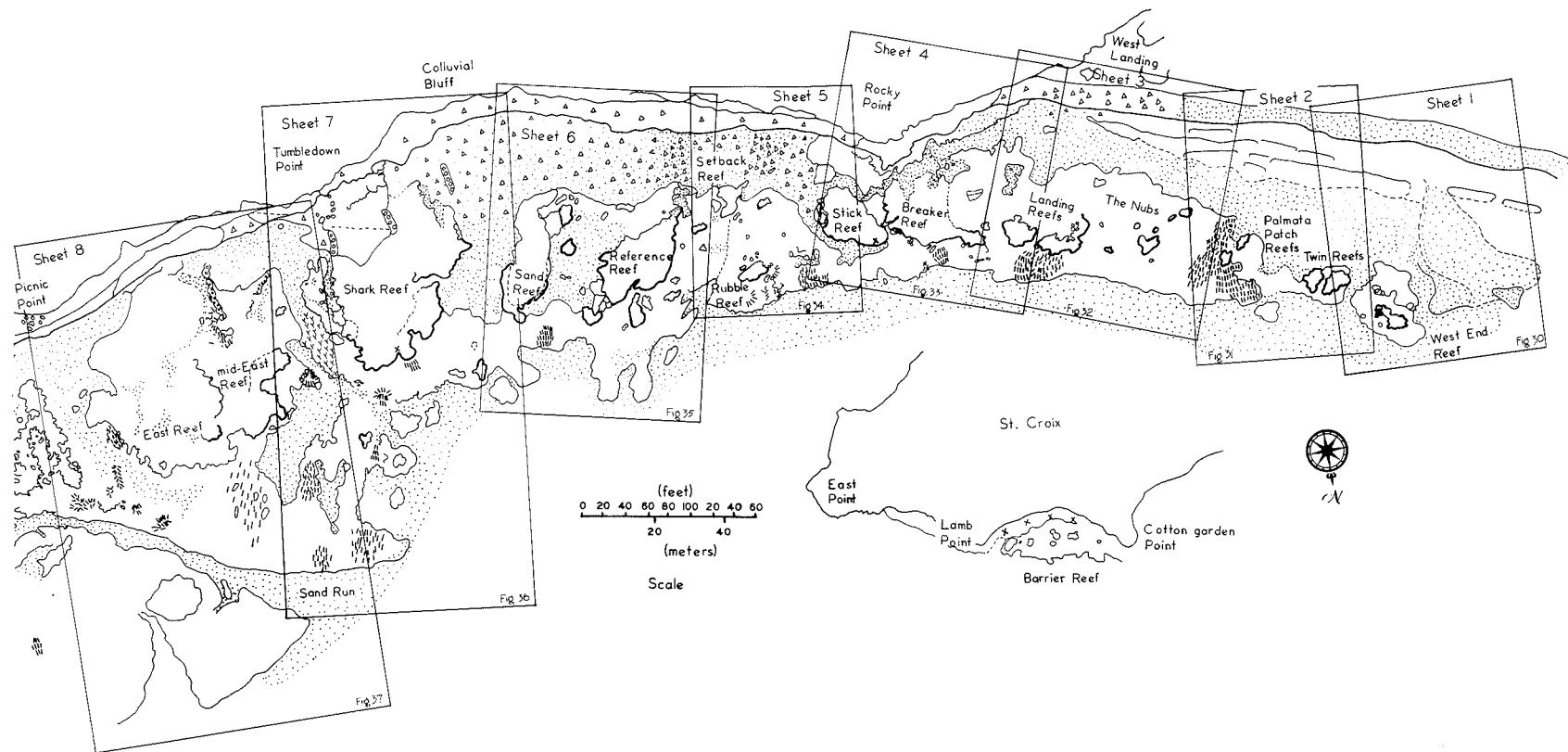
Fig. 29. Key map of boiler area of Boiler Bay showing the locations of large scale maps.
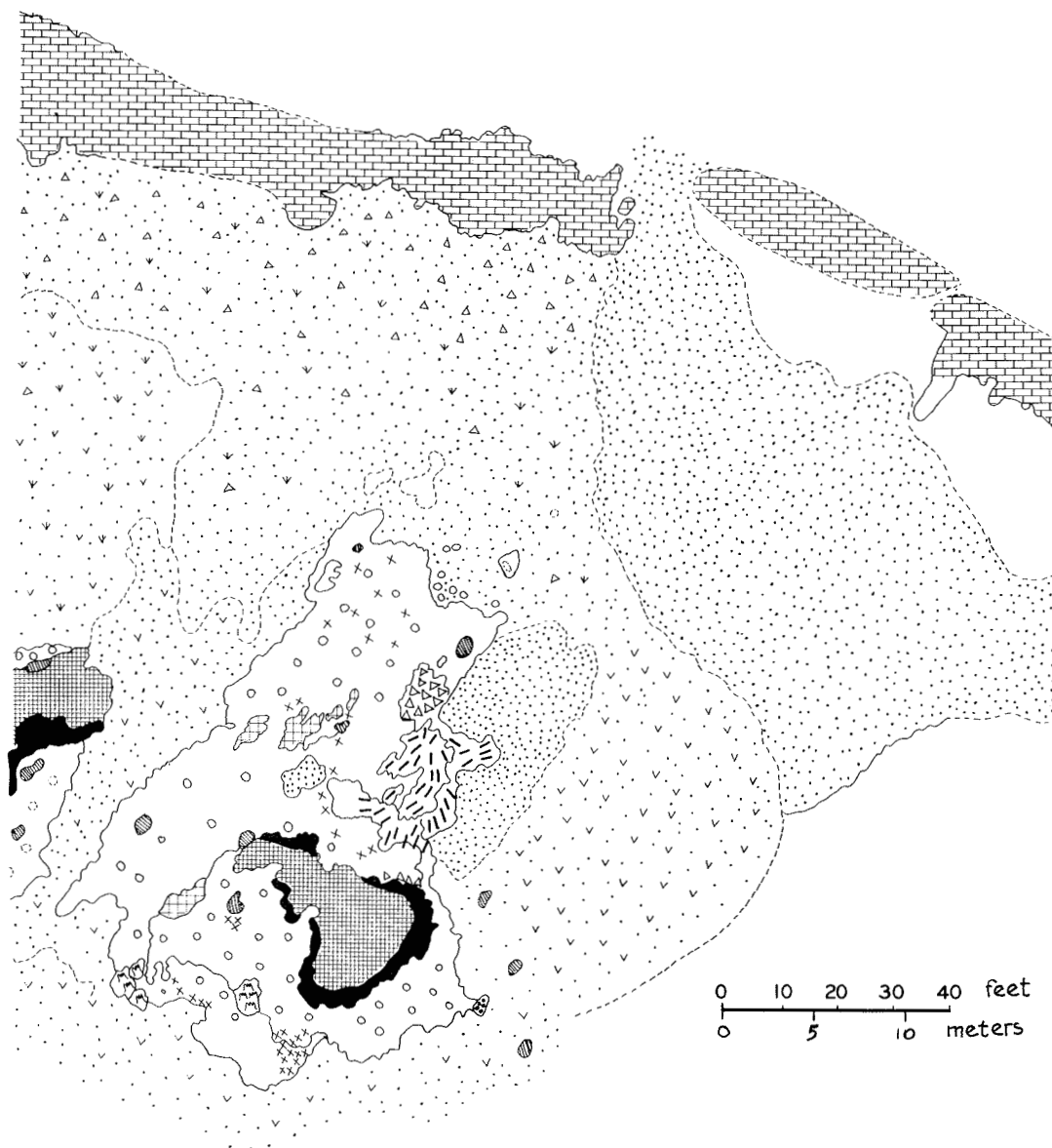
Fig. 30. Westernmost boiler, West End Reef. Algal ridge ▮ 0 to +17 cm above m.l.w.sp., ▦ −30 to 0 cm, ▦ −60 to −30 cm, ▢ pavement > 60 cm. Symbols otherwise as preceding maps. ✕ rhodoliths (coralline nodules), △ terrigenous pebbles. See figure 42C for depths.

Fig. 31.   Twin Reef and palmata patch boilers.   The _Acropora_ _palmata_
           patch is the largest presently live area of _A._ _palmata_ in the
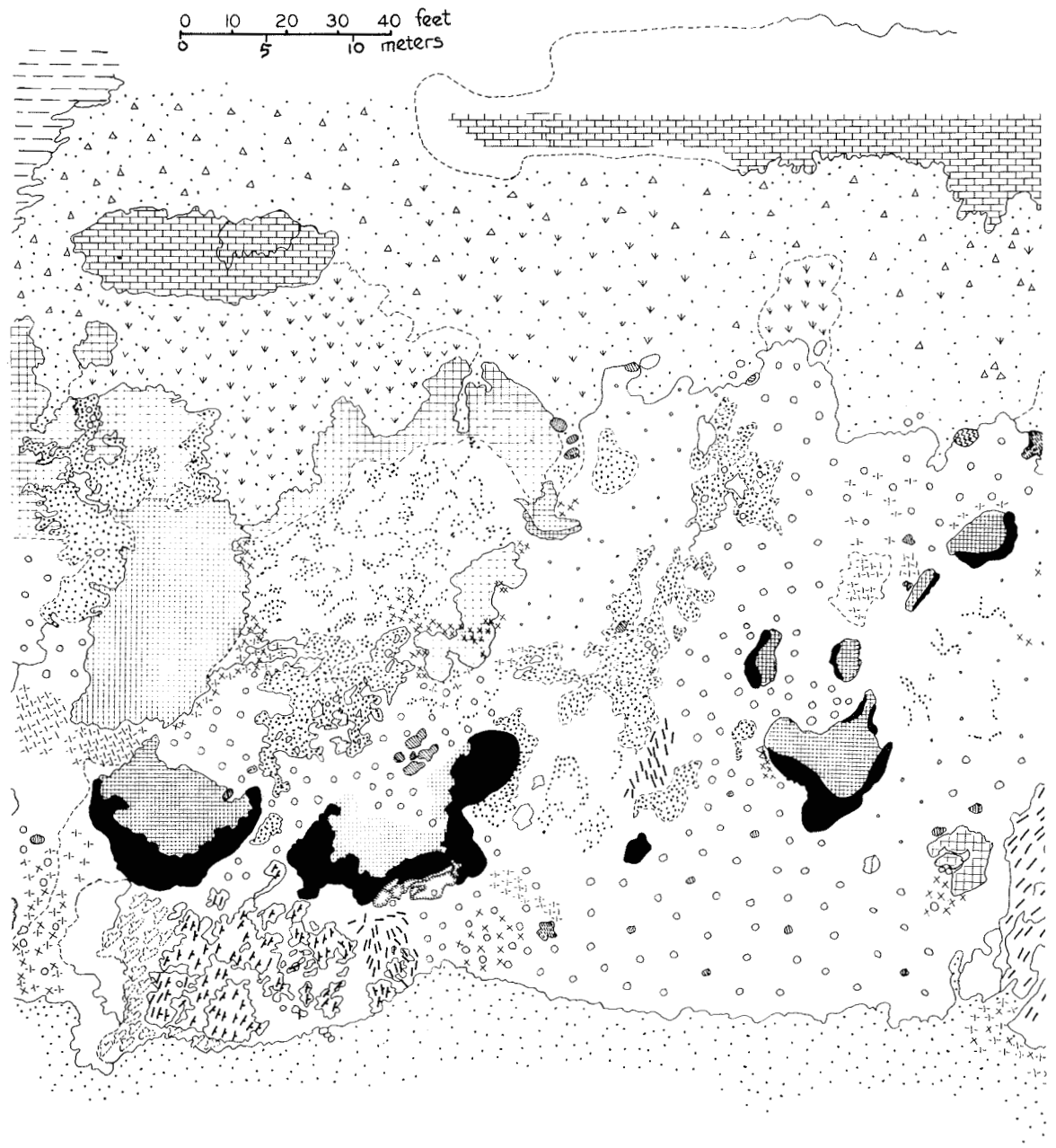   boiler-pavement area.   See figure 43B for depths.

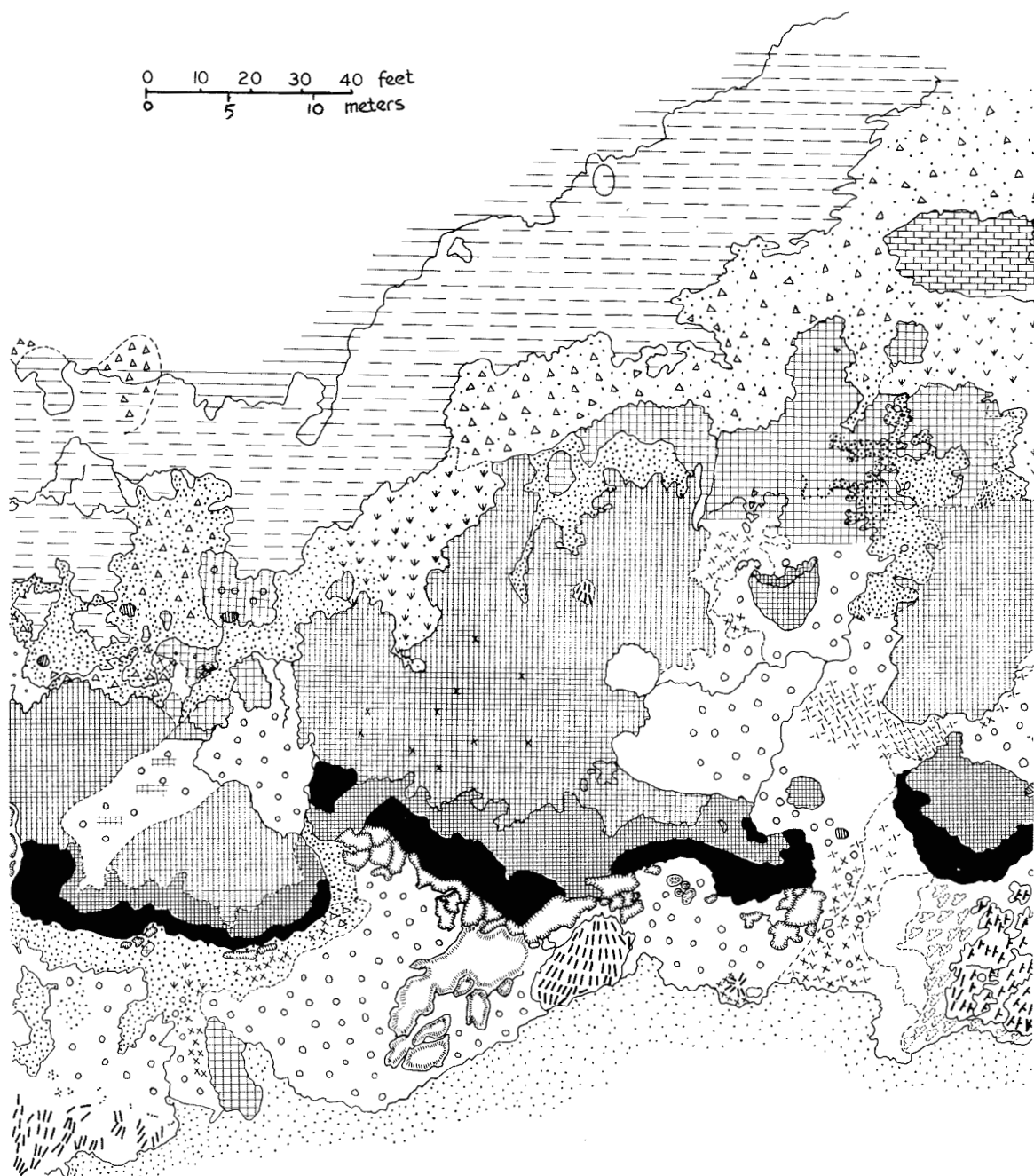Fig. 32. Landing Reef and Nub boilers. See figures 43B & C for depths.

Fig. 33. Stick Reef and Breaker Reef. These are boiler-fused ridges,
Stick Reef having some caverns, but the original boiler pattern
is not obvious. Considerable collapse has occurred on the
front of Breaker. See figure 41 for depths.
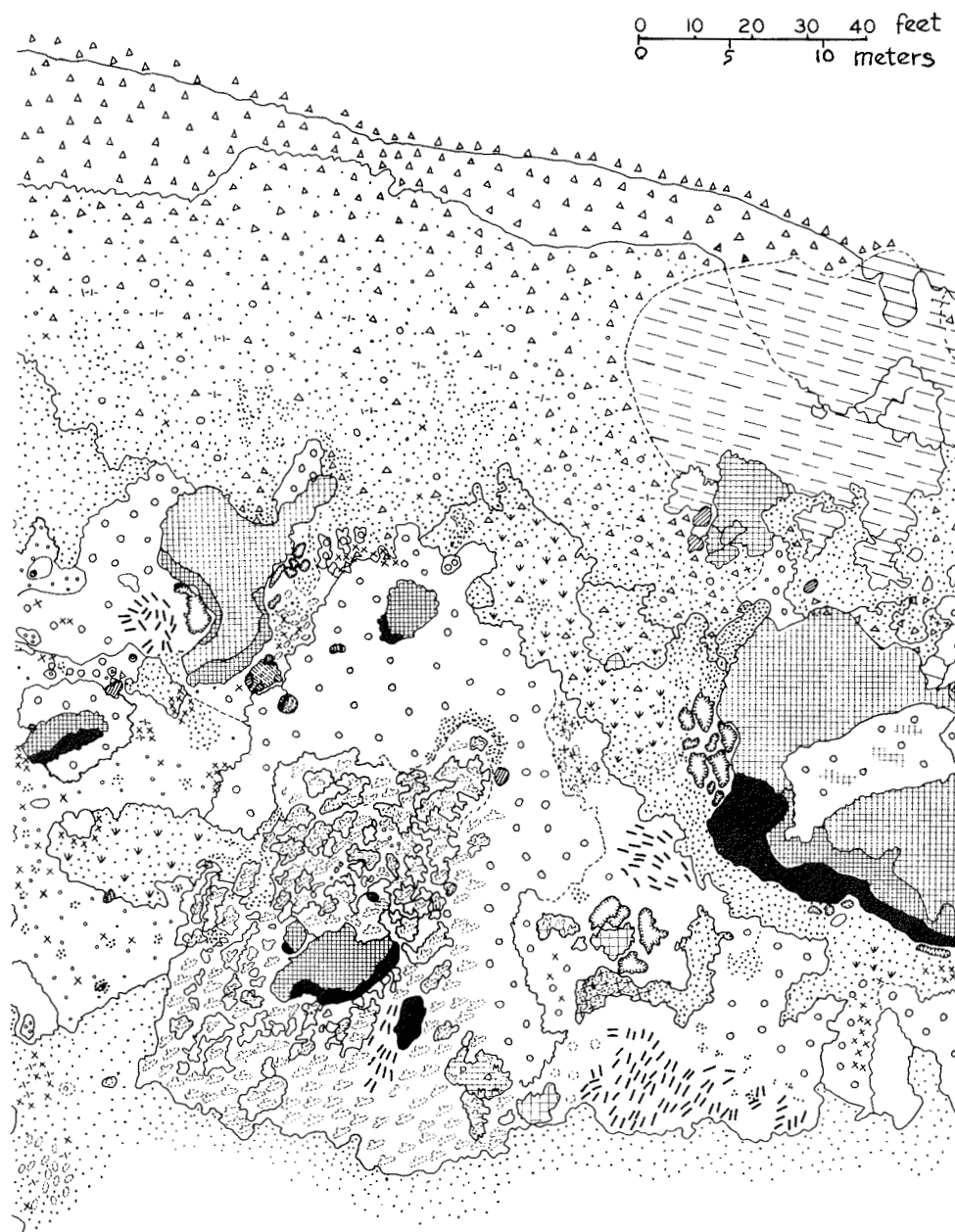
Fig. 34. Rubble and Setback Reef areas. Rubble reef is a young boiler
          developed on a massive recent A. palmata pavement. Halfway
          between Rubble and Stick is a Millepore-based boiler that has
          collapsed in a ring of broken blocks. See figure 44B for
          depths.
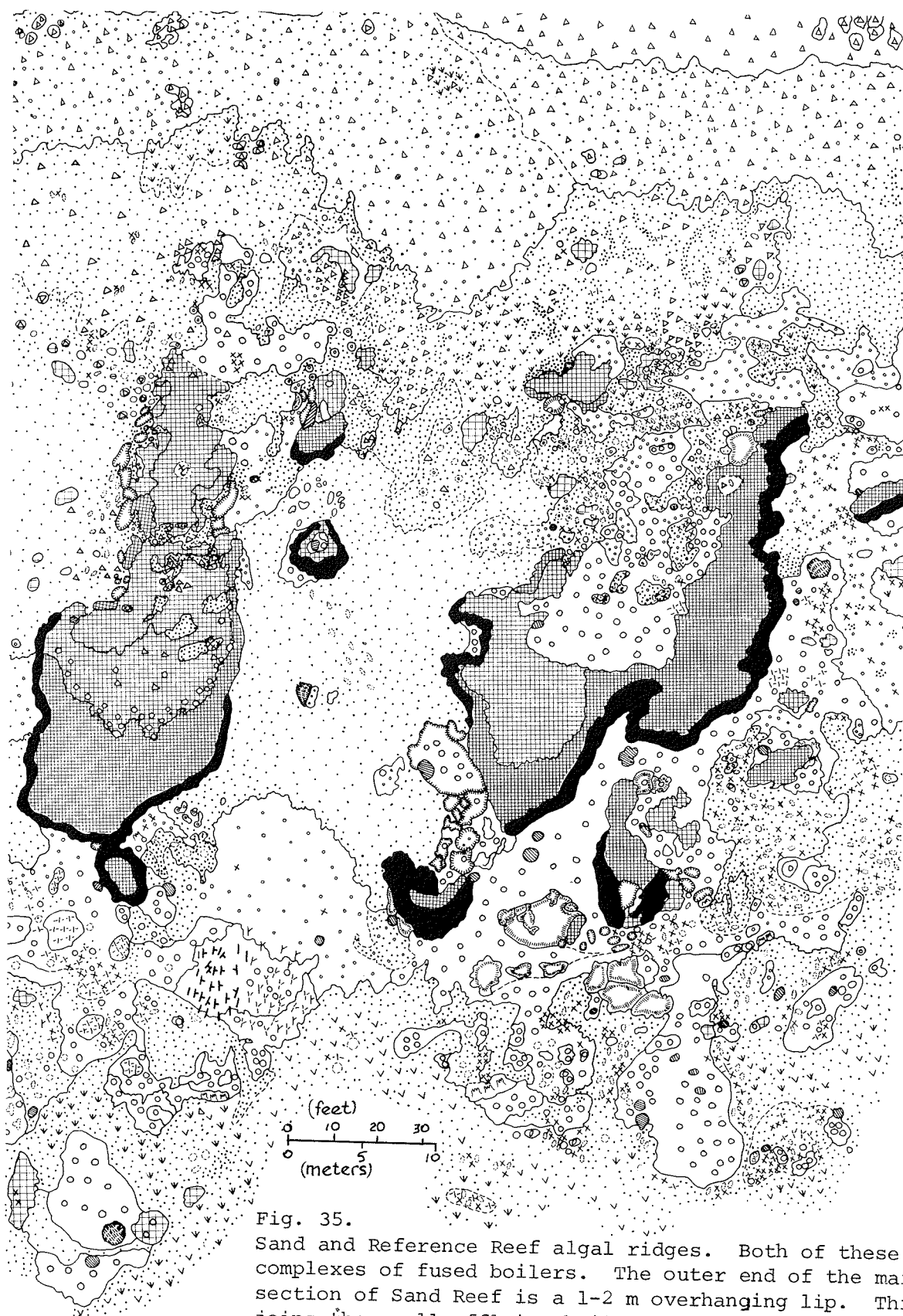
Fig. 35.
Sand and Reference Reef algal ridges. Both of these are
complexes of fused boilers. The outer end of the main
section of Sand Reef is a 1-2 m overhanging lip. This
joins the small offlying boiler to form a short tunnel.
Considerable roof collapse has occurred on the outer
part of Reference Reef. For depths see Fig. 42B.
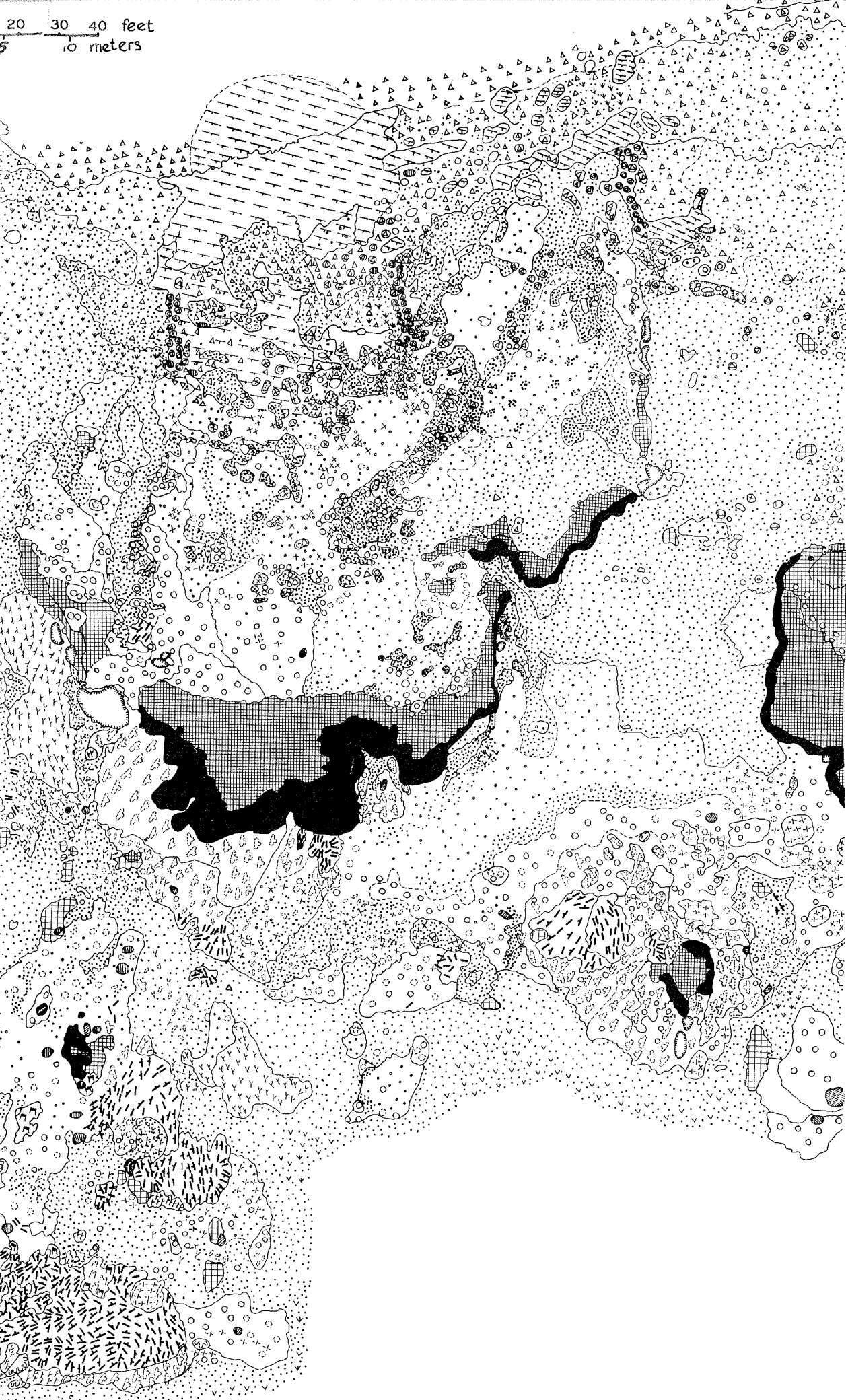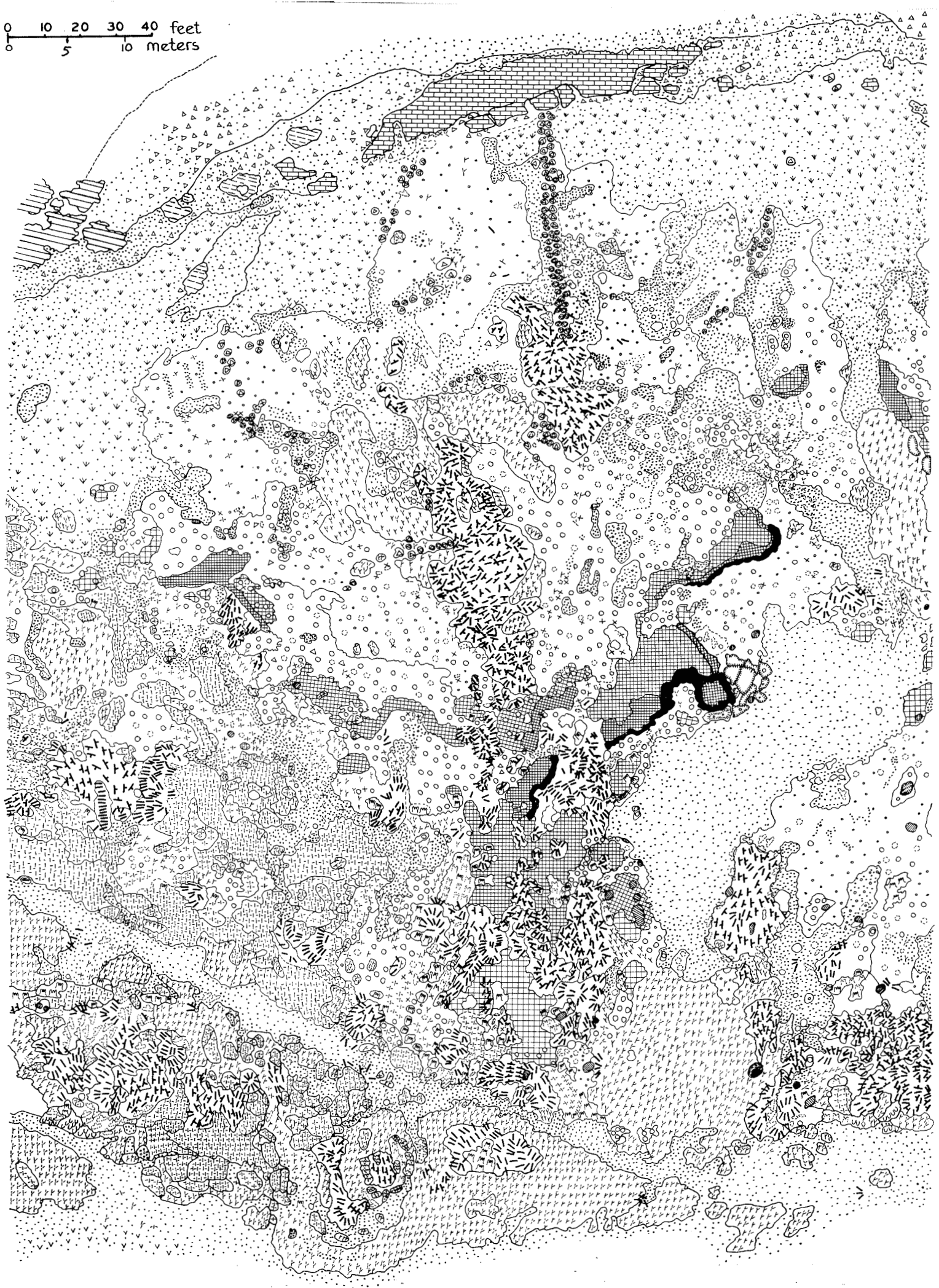
Fig. 37. East Reefs. This partly fused complex of boilers began to degenerate before completion of ridge formation. For depths see figure 42A.
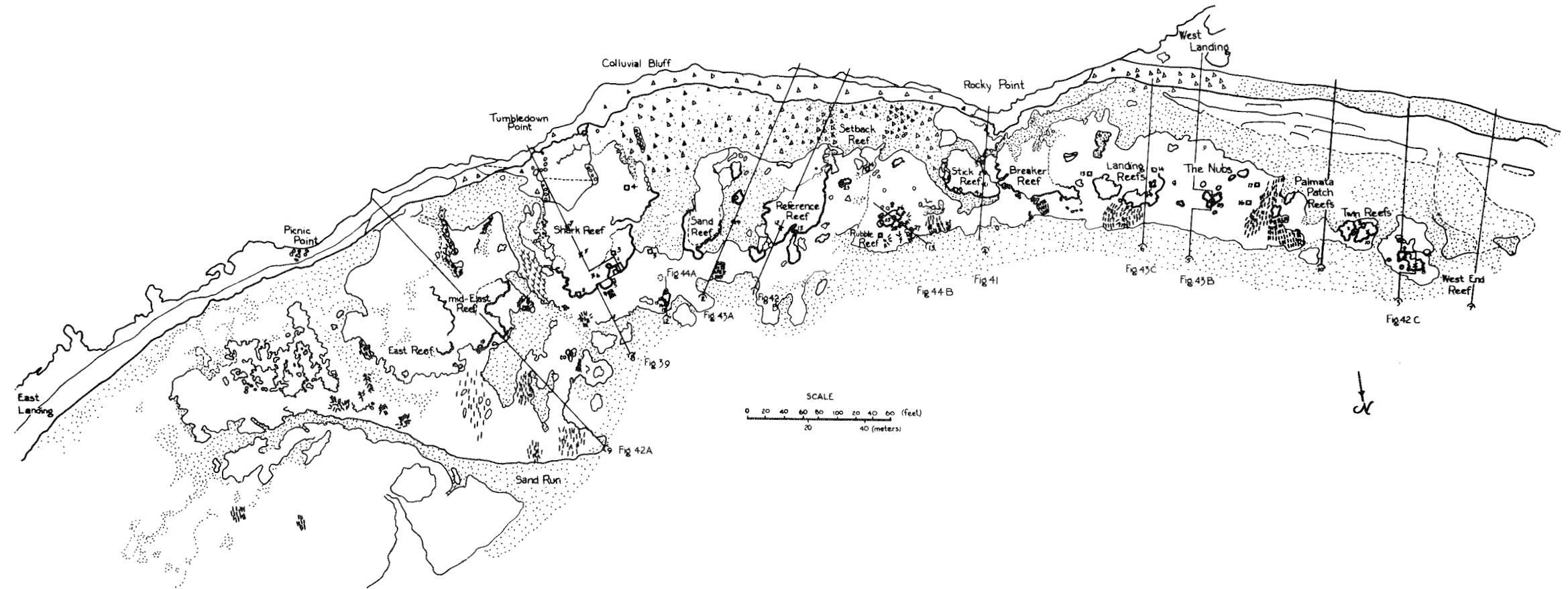
Fig. 38. Locations of transects, drill cores and collected ridge or pavement blocks in Boiler Bay.
Transect 1 - Fig. 42B, Transect 2 - Fig. 43A, Transect 3 - Fig. 42C, Transect 4 - Fig. 41,
Transect 5 - Fig. 43B, Transect 6 - Fig. 43C, Transect 8 - Fig. 39, Transect 9 - Fig. 42A,
Transect 12 - Fig. 44A, Transect 13 - Fig. 44B.
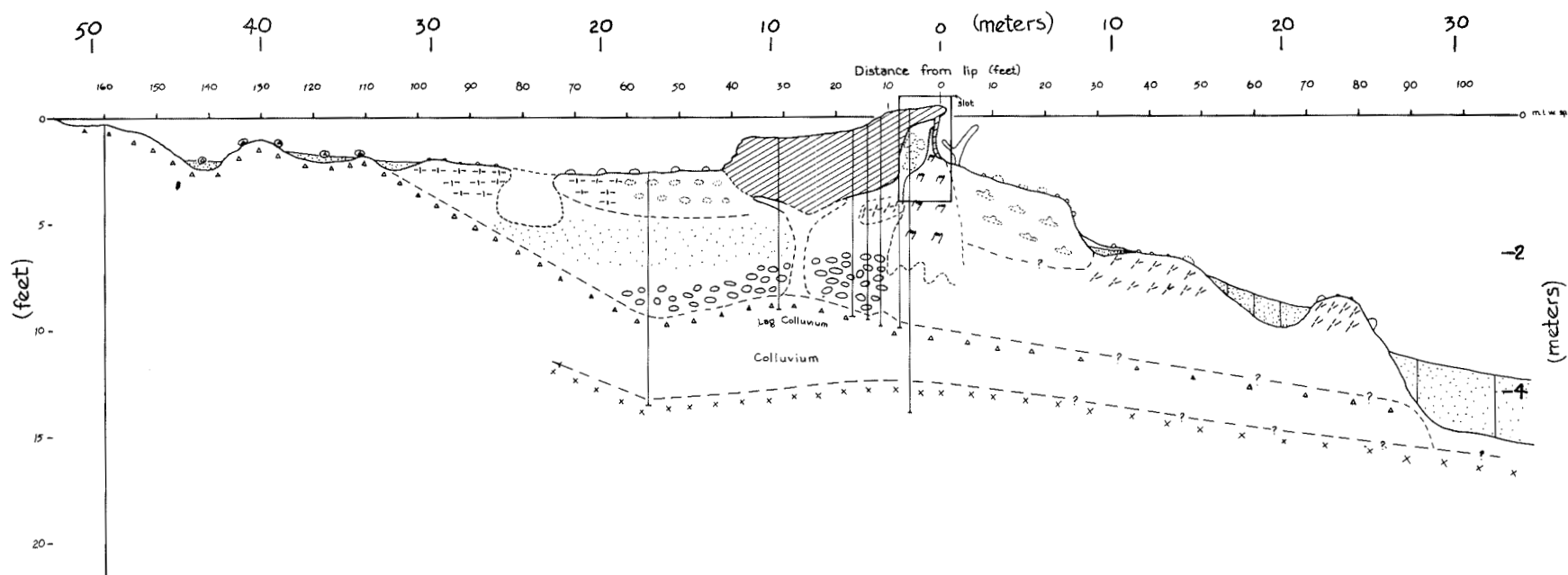
Fig. 39. Section through Shark Reef algal ridge. The details of the nose area are based on a 60 cm wide slot chiseled out of the ridge front (Fig. 40). The _A_. palmata immediately underlying the coralline cap was dated at 2900 years B.P. (see Fig. 13). ▨ crustose coralline cap.

Feet from lip

m.l.w. sp.

Feet below m.l.w. sp.
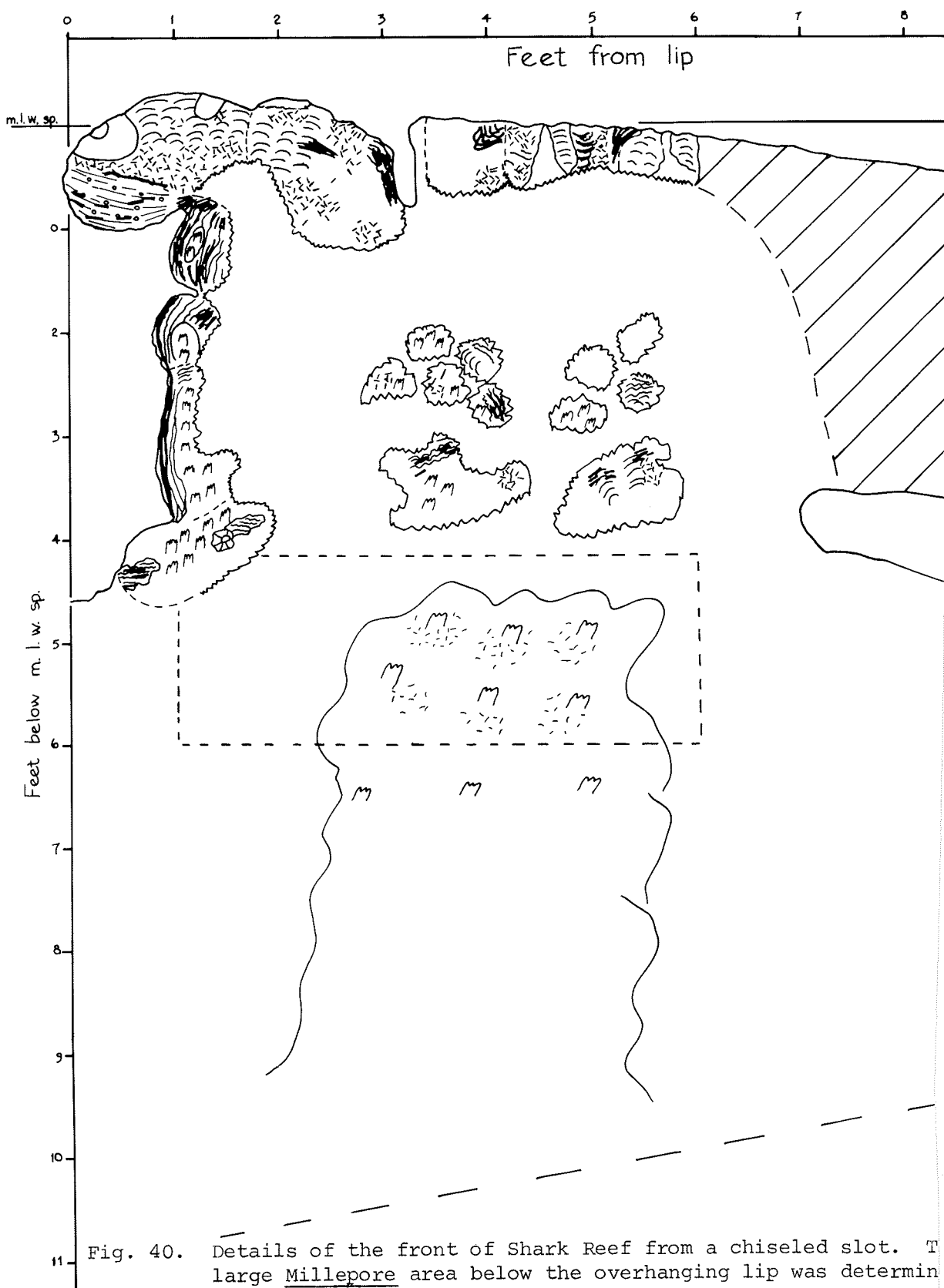
Fig. 40.   Details of the front of Shark Reef from a chiseled slot. T
large Millepore area below the overhanging lip was determin
by repeated core-drilling. [M] Lpm. congestum, [≈] crust
species, mostly Neogoniolithon and Porolithon above, Tenare
bermudense below lips, [SS] Homotrema, [M] Millepore.
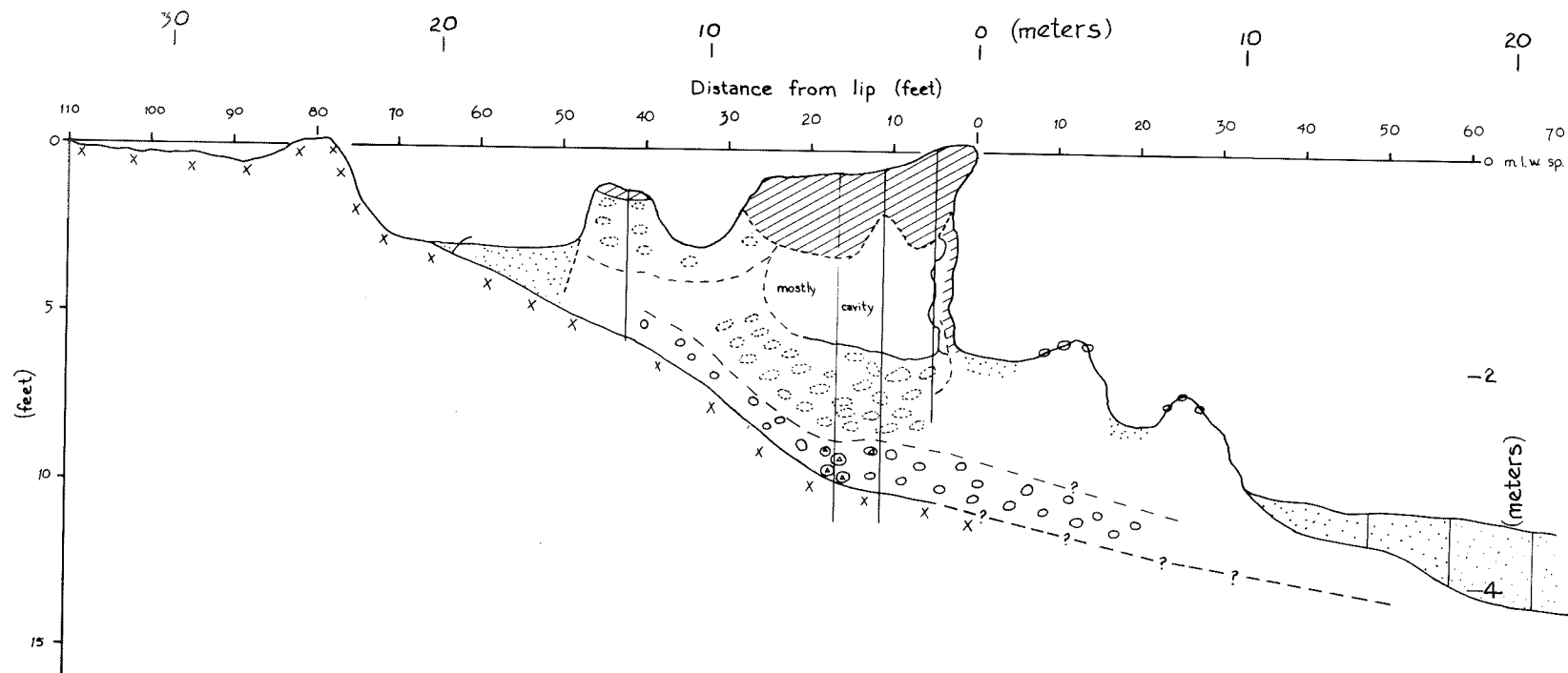
Fig. 41. Section through Stick Reef. This ridge has an obvious lobate character and our cores have apparently penetrated the cavernous junction of several boilers. No standing large coral species were found beneath the coralline cap in these cores. Caledonia pebbles and cobbles, perhaps primarily derived from colluvium, overlie the Caledonia basement under this ridge.
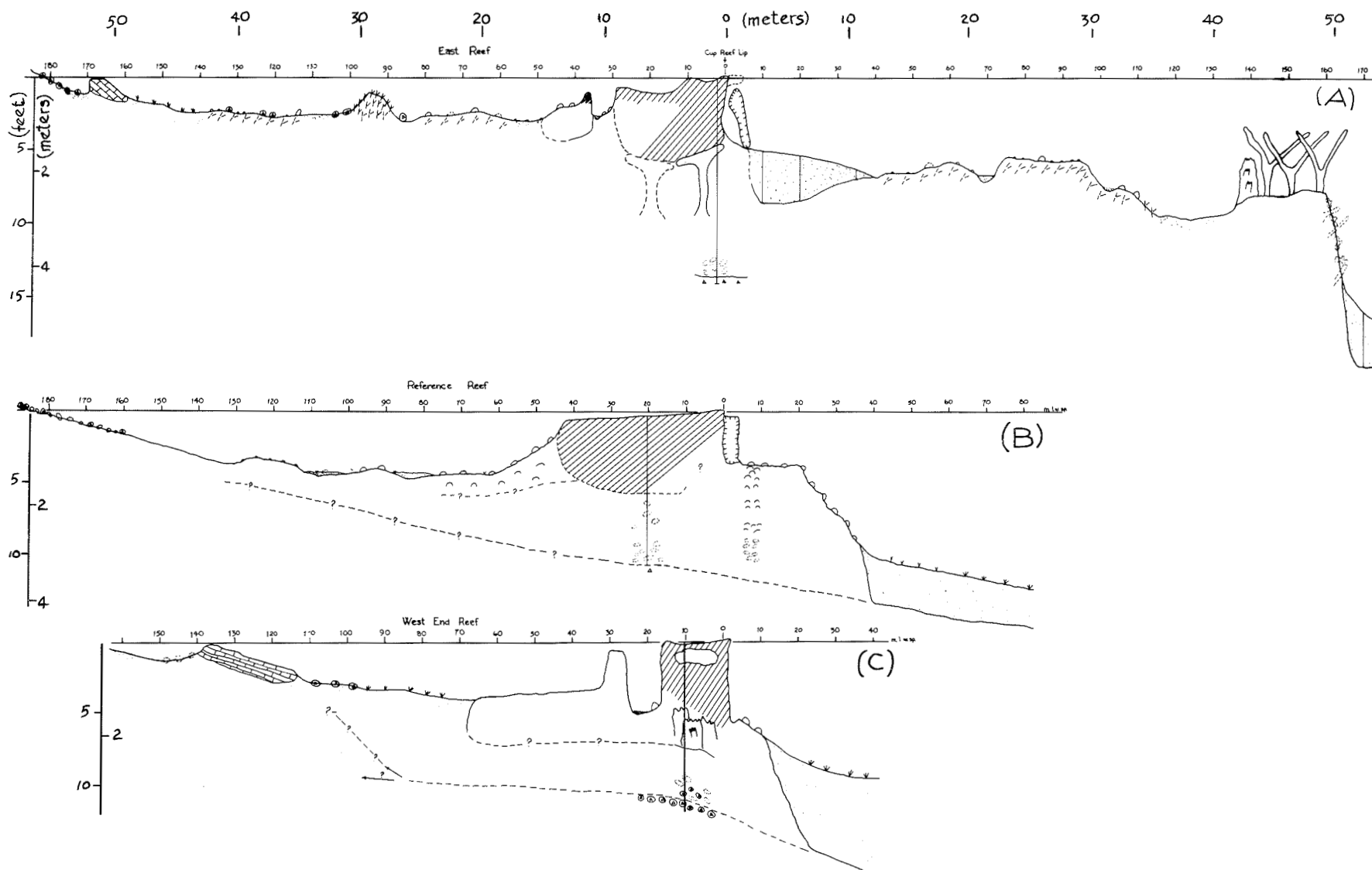
Fig. 42. Sections through East, Reference and West End Reefs. The small westernmost boilers appear to be _Millepore_-based, the _Millepore_ having developed on a spit of pebbles extending down-current from the colluvial lobe.

50   40   30   20   10   0 (meters) 10   20

Clean Cut and Diploma Cup

Projection
Hole #2

(A)

(feet) (meters)

Big Nub and Nub-Landing Channel

(B)

West Landing

(C)
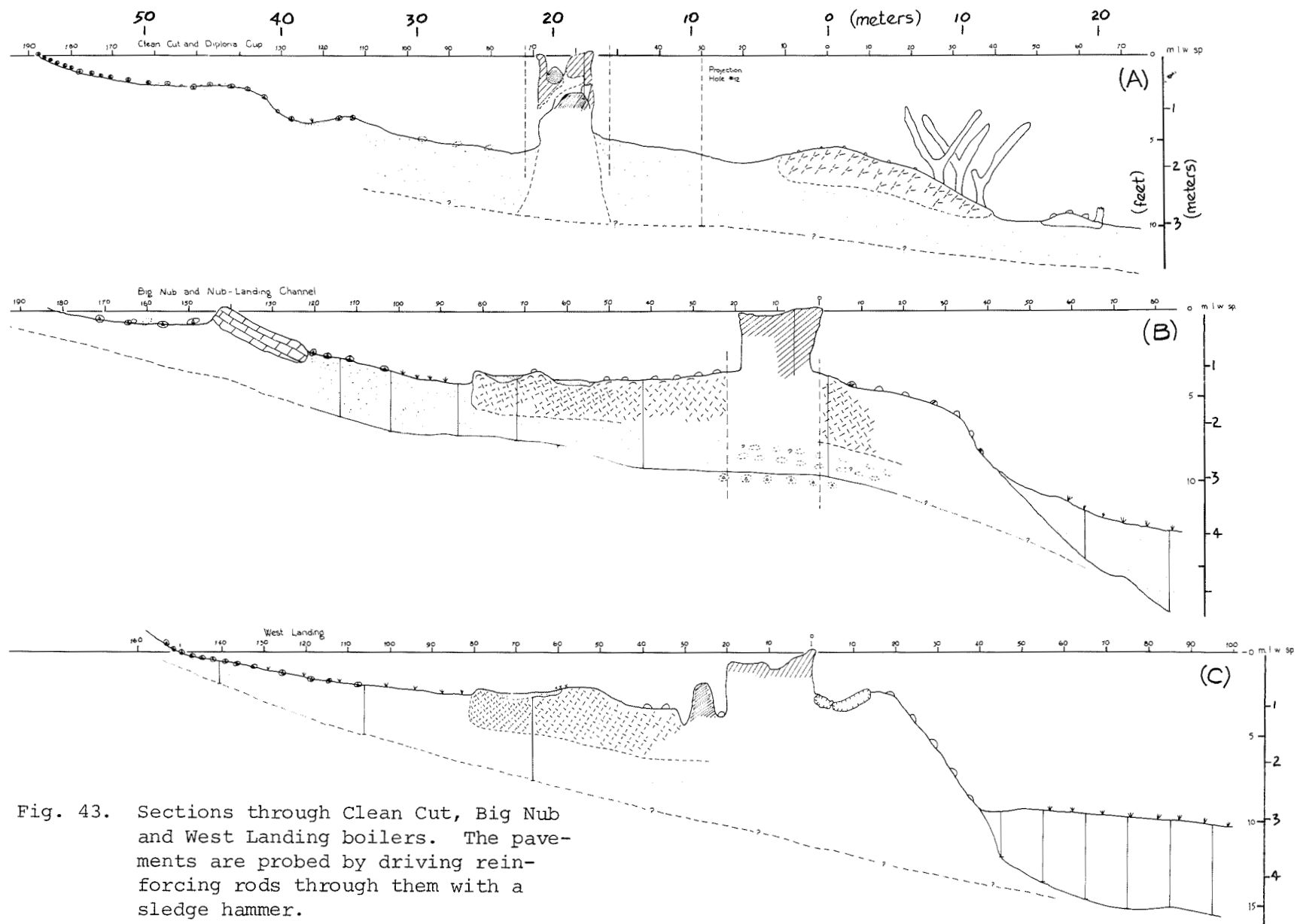
Fig. 43.   Sections through Clean Cut, Big Nub
and West Landing boilers. The pave-
ments are probed by driving rein-
forcing rods through them with a
sledge hammer.

Sand Reef Skerry

10   5   0   outer   5 (meters)
                                  lip
m.l.w.sp. 40   30   20   10   0   10   20 (feet)

A

1

5

2

(feet) (meters)

10   3

V V V

Rubble Reef Complex

20   15   10   5   0 (meters)   5

m.l.w.sp. 60   50   40   30   20   10   0 (feet)   10   20

B

5

(feet)

10
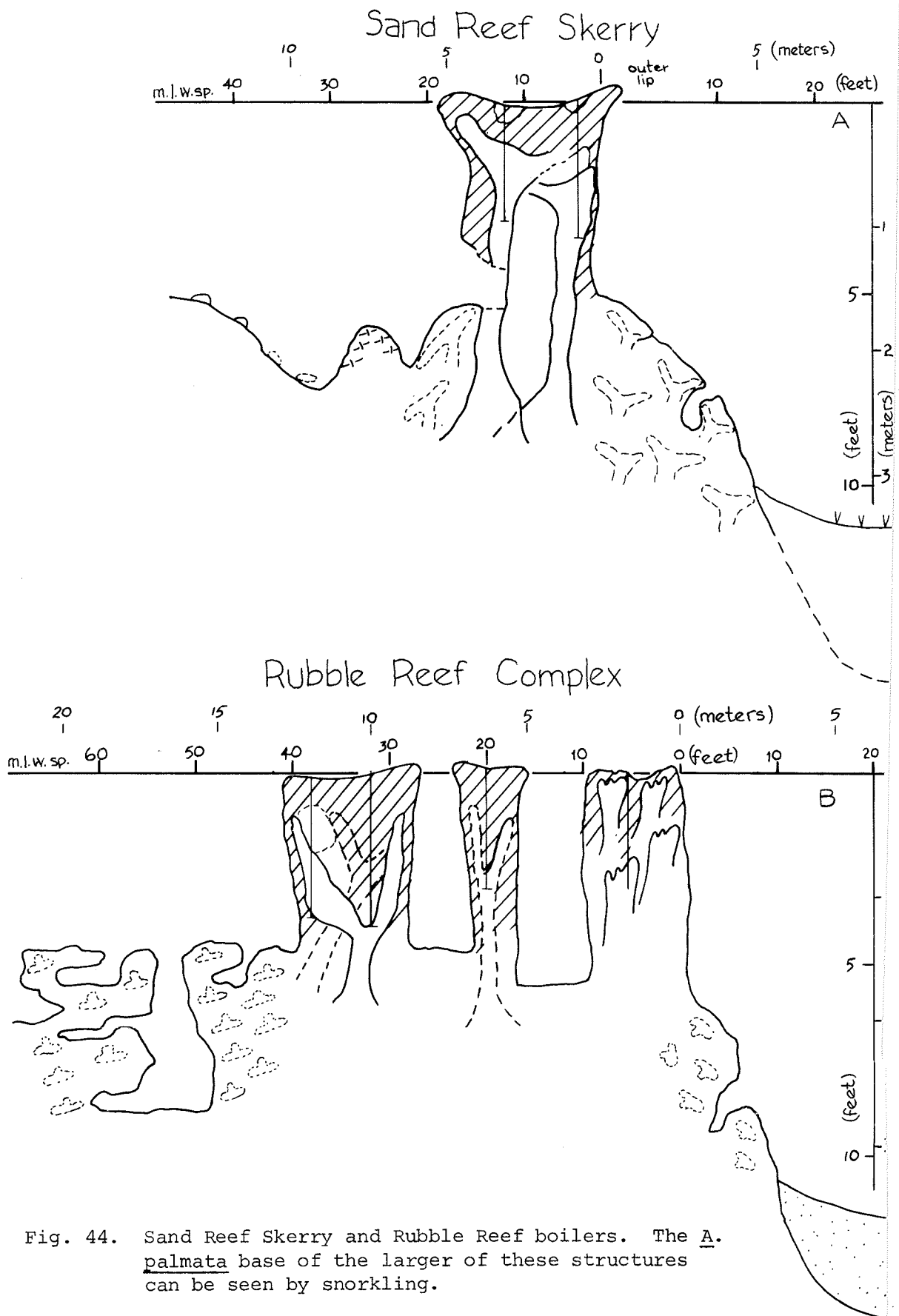
Fig. 44.   Sand Reef Skerry and Rubble Reef boilers.   The A.
           palmata base of the larger of these structures
           can be seen by snorkling.

Fig. 45. Generalized surface structure of algal ridge area in Boiler Bay. ▮▮▮ coralline-constructed al-
gal ridges; ⊞ coral pavements, mostly Porites porites and Acropora cervicornis (small
variety), some A. palmata; ⊟ living A. palmata colonies; ▨ dominantly live coral, mostly
P. porites and A. cervicornis areas.

especially shade types, and a small brancher N. westindianum occur on the pavements, but Hydrolithon børgesenii is also often conspicuous. Much of the surface is apparently "dead" and occupied by green or red boring algae (see Adey and Boykins, 1975 - Hawaii).

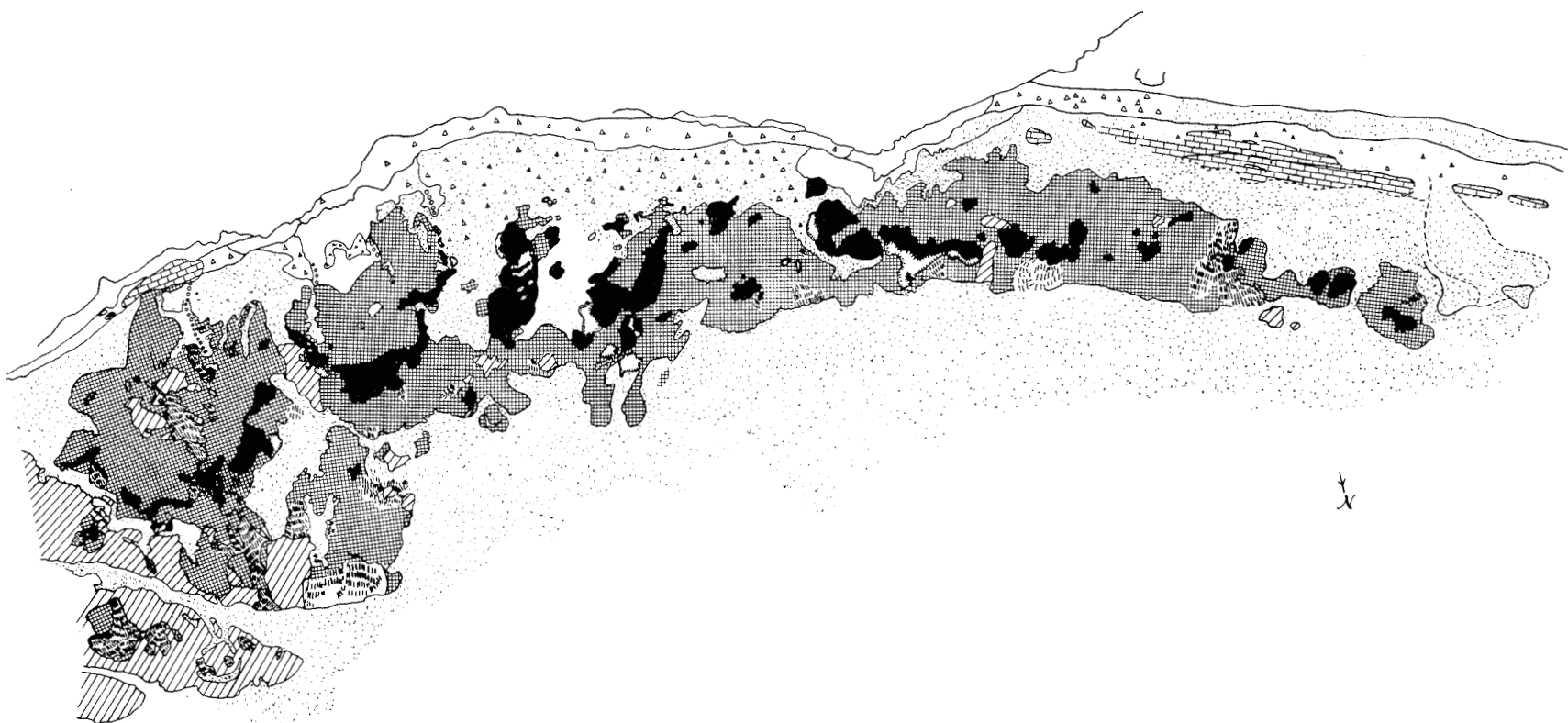We have removed several blocks from these pavements in inter and back ridge areas (Fig. 38), and in all cases, the framework was found to be either Porites porites or Acropora cervicornis with considerable Homotrema, secondary cement and perhaps 10-40% porosity. Two ages on coral were obtained on these pavements, one at 640 and the other at 940 years B.P. Apparently prior to 600-900 years B.P. most of the boiler area was densely-covered with a coral thicket much like that presently existing in far eastern areas (Fig. 37). The pavements are more or less easily probed using reinforcing rod and were cored in some cases (Figs. 39, 43B and C). Fore ridge pavements have not been cored or probed and some are A. palmata frameworks.

In some areas the back-ridge pavements support scattered rhodoliths, coralline encrusted nodules with cores of coral, terrigenous pebbles or shell. These are being studied separately.

In summary, the barrier reef in front of Boiler Bay has effectively begun to block wave action into the bay only during the past 300-500 years. Prior to that time the bay was quite open. About 4000 years B.P. rising sea level encountered the Boiler Bay colluvium. Within 1000 years, wave and current action had removed much of the weakly-consolidated colluvium leaving a lag conglomerate of Caledonia cobbles and pebbles. With the partial protection of the bay, coral colonies especially A. palmata were soon flourishing, and by 3000 years B.P. incipient algal ridges and high boilers had begun to form. This process continued up to about 500 years B.P. with numerous small boilers developing on Millepora and A. palmata colonies along with fusion of the major ridges. Apparently about 1500 to 2000 years B.P. wave action had begun to be reduced around the boilers and dense thickets of the finger corals began to develop. The richest period, in terms of coral and coralline algae development in Boiler Bay, must have been about 1000 years B.P. Since that time and especially during the past 500 years, degeneration, mostly as a result of wave blockage by the outer barrier, has become progressively more serious.

SUMMARY AND DISCUSSION

On the eastern shelf areas of St. Croix, Acropora palmata dominates shallow, turbulent water, reef communities at depths of from 1 to 6 and up to 12 meters depending probably primarily on water clarity. Once established this coral is capable of verticle reef building at rates of up to 15 mm/year, quite sufficient to match the rate of sea level rise having occurred at any time during the Holocene. However, as sea level rose over the shelf areas, A. palmata communities were not immediately established, perhaps due to wave removal of the sediments of the Pleistocene regolith. By the time coral colonies were established on the outer shelf at depths of 25-30 meters, sea levels were from 8-10 meters

above the developing reefs and the deeper and much slower-growing (1-2 mm/year) Diploria-Montastrea reefs could not keep up with sea level rise rates of from 2-5 mm/year. At shallower depths, 12-20 meters, on the inner parts of the shelves development followed the same pattern.

The siltstones and sandstones of the Cretaceous Caledonia Formation form most of the basement rock of eastern St. Croix. These weakly meta-morphosed rocks of deep water volcanic origin probably underlie the car-bonate shelf, and they rise rather abruptly from under the shelf near the present shoreline. Especially off modern points, narrow benches, prob-ably of Pleistocene origin, appear to be cut in this Formation. Since the benches because of their relative elevation were probably quickly cleared of sediment as sea level rose over them 5000-3000 years B.P., coral colo-nies were soon established. These were early dominated by Acropora palmata and rapidly built to within 1-2 meters of the existing sea level.

Typical A. palmata colonies have a large proportion of their surface at any one time in the dead but standing condition, perhaps due to grazing or disease. This dead surface, in water less than 1-2 meters is quickly occupied by crustose coralline, and if major grazers of coralline, especially parrot fish and Diadema, cannot operate effectively due to continuous water turbulence, the crusts will accrete at rates of up to 6 mm/year. This accretion would soon develop an "A. palmata pavement", and at rates of sea level rise of the last 6000 years would build an incipient algal mound or ridge to about mean low water.

Lithophyllum congestum is a rapidly growing, branched coralline that appears to be confined, in its massively branched form, to quite turbulent areas near low water levels. A shallow subsurface algal mound colonized by L. congestum would develop quickly into the typical, inter-tidal, cup-shaped boiler. A group of these boilers occurring together on a bench because of their outward growing lips would tend to fuse with each other and with the surrounding coral structures. Fusion results in a reduction of wave activity on the lee side of the boilers, greater grazing in the back area and a narrowing of the fused boilers to eventually form a ridge type structure.

From about 5000 to 2000 B.P., a series of these high algal ridges developed on favorably situated benches on the eastern end of St. Croix. Massive shallow barrier type reefs were not yet developed, and the inner shelf at this time had only relatively deep coral reefs. In Boiler Bay on the northeast corner of St. Croix, a rather unusual Pleistocene col-luvium, or rapid flow, of poorly consolodated boulders to pebbles in a silty matrix became exposed to wave action about 3500 years B.P. Within 500-600 years, an A. palmata community, followed by algal boilers and ridges developed on the lag cobbles from this colluvium.

Beginning about 1000 years B.P. the deeper water coral reefs on the inner shelf were reaching close enough to the surface to develop A. palmata communities. These in turn have built rapidly at rates of about 15 mm/year to near present sea levels. Due to a general west to east slope of the shelf the more westerly reefs matured first and with gener-ally less wave action have tended to form broad reef flats. In more eastern areas, the reefs have just reached levels of -1 to -3 meters,

a few small reef flats have formed, and in some places, where sufficient
wave action is present, incipient and young algal ridges are forming on
the barrier reef. This barrier system is blocking wave action to the
older algal ridges resulting in their destruction by grazing and
burrowing organisms.

If sea level remains nearly constant for another 5000 to 6000 years,
the shelf edge reefs should reach the surface and develop new barrier
reefs and algal ridges. The present barrier reef and its developing
ridges will then also be deprived of the required wave action and face
gradual destruction by boring, burrowing and grazing organisms.

Adey and Burke (1975) describe the distribution of barrier reefs
and algal ridges in the eastern Caribbean. Also, they discuss in some
detail the major factors that have controlled the Holocene development
of these reefs and ridges and compare their development with the equiva-
lent structures of several of the better known Pacific islands. There
is perhaps no reason to repeat that discussion in detail, but I will try
to cover the salient points.

Relatively flat carbonate shelves have developed during the late
Tertiary and Pleistocene to the north, east and south of most eastern
Caribbean islands. While the depth of the surface of these shelves
relative to present sea level is quite variable, the average depth,
inshore and near the islands, is 12-20 meters. Within this range, as
discussed above for St. Croix, many extensive barrier reefs have de-
veloped. These are presently reaching sea level and to various degrees
are forming reef flats. Areas with a generally shallower shelf (e.g.,
the Grenadines) have an extensive mature reef development. Other areas
(such as the southeastern part of the northern group of the Virgin
Islands) have deeper shelves and have very few mature reefs. In areas
of considerable turbulence, algal ridges, the equivalent of the incipient
ridges on St. Croix, are forming on these barriers.

However, at depths shallower than 15 meters, relatively small benches
are also locally cut into the island bedrock. These are especially
strongly developed on limestone capped islands, but occur on late Tertiary
volcanics as well as Cretaceous metamorphics. These benches, probably
developed at high sea level stands during the late Pleistocene, are
effectively local, shallow shelves and have a more mature reef system.
Especially in the high wave energy St. Eustatius to Barbuda to Martinique
area of the lesser Antilles, large algal ridges, to greater than 1 meter
in height are developed on these shallow benches. These ridges, although
limited in length, are quite analogous to the extensive algal ridge sys-
tems developed on the margins of Pacific atolls where in the cored and
better known cases the pre-Holocene topography also occurs at depths of
6-10 meters.

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