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Phil. Trans. R. Soc. Lond. B 1978 **284**, 3-21
doi: 10.1098/rstb.1978.0050

Phil. Trans. R. Soc. Lond. B. **284**, 3–21 (1978) [3]
Printed in Great Britain

Ribbon reefs of the Northern Region

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[Plates 1–4]

Ribbon reef is a general term applied to most of the shelf-edge reefs of the Northern Region. The principal morphological characters of these reefs are described from aerial photographs. Their position in relation to the Queensland Trench is described from direct observation with the use of Scuba and from soundings. The depth and position of major reef zones and their substrates and dominant biota are described from transects of Tijou and Great Detached reefs.

Introduction

Of the many well defined reef systems within the Great Barrier Reef (G.B.R.) province, the northern shelf edge reefs are by far the most inaccessible. They are remote from any port or township and for most of the year are pounded by heavy seas driven by the SE trade winds. Thus they have remained unstudied and are almost completely undescribed. However, they form one of the major physiographic units of the G.B.R. province and are potentially one of the most important to the understanding of the G.B.R.'s complex morphology, structure and evolution.

Maxwell (1968) divided the G.B.R. into three regions on the basis of bathymetry and geomorphic changes and correlated these with differences in reef density, morphology and development. The Northern Region, north of 16 °S, is characterized by shallow water, the presence of an outer reef system and prolific reef growth across the shelf, induced by the proximity of a steep continental slope. This paper, the first of a series of three, summarizes aspects of the physical environment of the Northern Region that are relevant to the development of the shelf edge system, gives a general description of that system up to the northern limit of the 'ribbon reefs' (Figure 1) and gives the results of a study of two ribbon reefs, Tijou Reef and Great Detached Reef. The second paper (Veron 1978*a*, this volume) describes the shelf edge reefs north of the ribbon reefs, the 'deltaic' reefs and the 'dissected' reefs (Figure 1) while the third (Veron 1978*b*, this volume) gives an account of the evolutionary history of the latter, far northern reefs.

Methods

Field work with the use of the following methods was carried out from R.V. *James Kirby* (a modified 17 m steel trawler) during Phase III of the 1973 expedition and during a second northern voyage in November 1974.

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(*a*) *Aerial photography*

Physiographic features of the outer edge ribbon reefs were assessed from Commonwealth aerial photographs covering the outer reefs from their southern limit north to 12° 35′ S. A further series of three runs cover part of the northern deltaic reefs. R.A.A.F. aerial photographs of a greatly reduced quality are available for most far northern reefs.

Specific areas of study in the vicinity of Tijou Reef were photographed from a chartered aircraft by using 35 mm and Polaroid cameras.

Zonation patterns are clearly discernible in aerial photographs, as for example illustrated in figure 2, plate 1.

(*b*) *Bathymetry*

Detailed data on reef profiles were obtained by Scuba divers using depth gauges and underwater measuring lines laid perpendicular to reef faces.

Bathymetric data in the vicinity of reefs were obtained from R.V. *James Kirby* using a Furuno F850 mark III sounder. Positions of the vessel relative to reefs were measured directly by a measuring line for distances of 200 m or less and by radar from a reflector mounted in a dinghy for greater distances.

Bathymetric data at greater distance from reefs were obtained from the Hydrographic Office of the Royal Australian Navy and from R.A.N. and British Admiralty charts.

Off-reef bathymetric profiles were positioned so as to be continuous with the reef transects (see below).

(*c*) *Reef transects*

Rope transect lines laid perpendicular to the reef front were used by Scuba divers to measure the width of major reef zones. The depth, nature of the substrate, dominant biota and percentage cover of dead and living coral were estimated every few metres. These transects were continued across the reef flat and down the outer slope (eastern side) and reef back slope (western side).

(*d*) *Sampling*

Detailed collections of corals were made at the position of each quantitative transect (see below) and at all well defined biotopes studied. The results of these collections are included in Veron & Pichon (1976) and subsequent monographs in the series *Scleractinia of eastern Australia*.

Dominant species of all other biota were collected along reef transects.

Samples of the substrate along reef transects were collected by divers. At greater depths, substrate and coral samples were collected by using custom-made anchor dredges.

(*e*) *Quantitative transects*

Quantitative measurements were made at Tijou and Great Detached Reefs of the percentage area cover of dominant biota and substrate types, as well as of the percentage area cover of dominant coral species, by use of a 30 m measuring line laid parallel to the reef and transverse to the transects. Measurements were recorded as percentages of the 30 m line.

(*f*) *Supplementary surveys*

Each locality studied was selected on the basis that it was representative of a large area of reef. Selection was made according to data obtained from aerial photographs, aerial surveys, and surveys by Scuba divers towed behind small boats.

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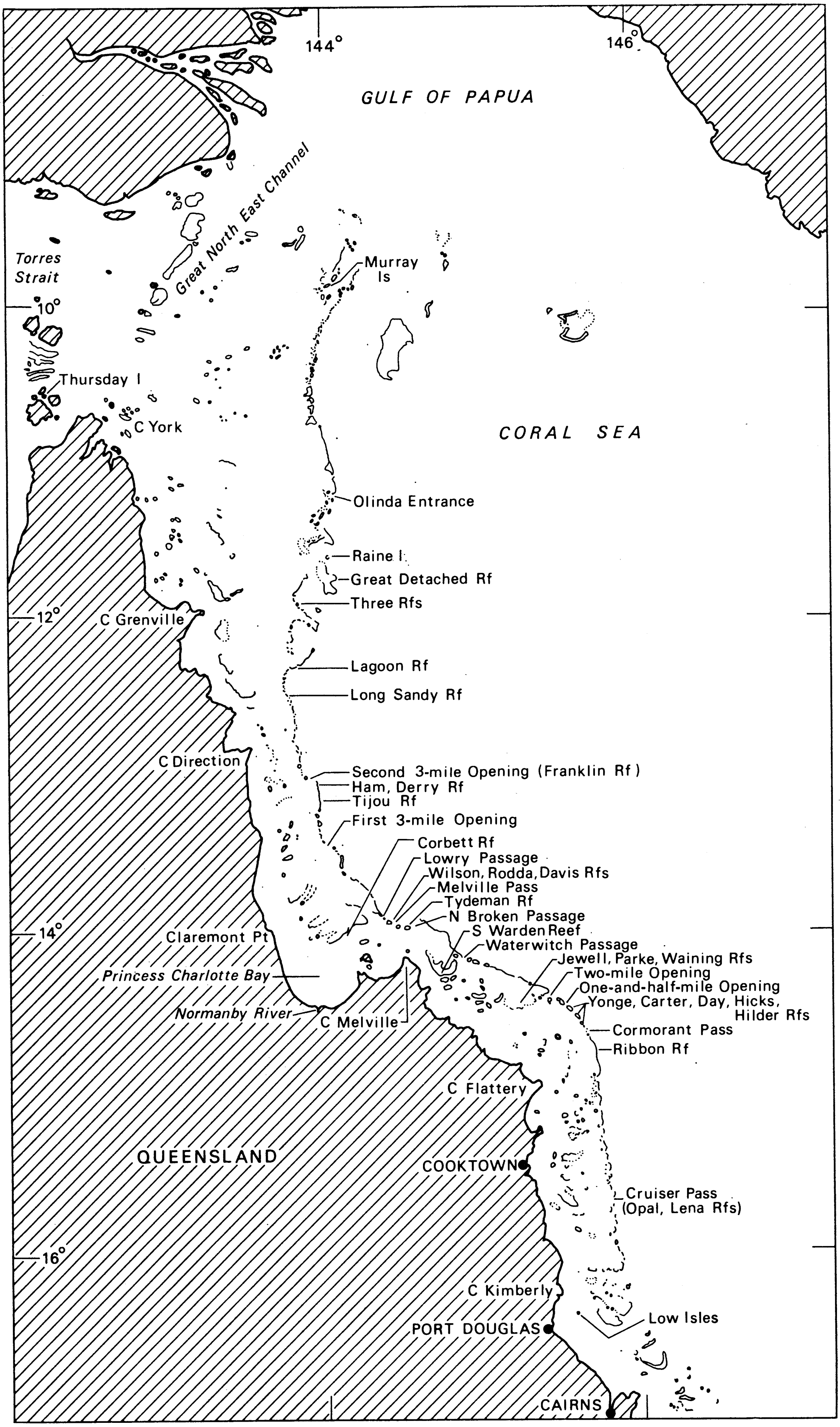

Figure 1. The northern Great Barrier Reefs, showing place names used in the text and the extent of the barrier reef system.

Other localities were selected for brief survey because they differed greatly from the main study localities.

Any other supplementary methods used are indicated in the text.

The ribbon reefs

General characters of the northern shelf edge reefs

In the south, the line of shelf edge reefs starts 43 km offshore from Cape Kimberley (16° 17′ S) and continues north approximately parallel with the coast. Off Cape Melville the reef curves closer to the mainland than at any other point in its entire length (25 km). The reef then curves northwards away from the coast, past Princess Charlotte Bay, to be some 65 km off Claremont Point. Coast and reef once again converge to be 28 km apart off Cape Direction, then diverge increasingly until the reef terminates 205 km northeast of Cape York, just north of the Murray Islands.

Table 1. Width (metres) of the channels between the outer reefs in the Northern Region of the Great Barrier Reef between latitude 15° 39′ S and latitude 12° 23′ S (excluding the channels between rear reef plug reefs).

A from lat. 15° 39′ S to lat. 14° 55′ S (from Lena to Ribbon Reef)	B from lat. 14° 41′ S to lat. 14° 13′ S	C from lat. 13° 27′ S to lat. 13° 15′ S	D from lat. 13° 2′ S to lat. 12° 23′ S	
1180	950	340	850	380
1500	820	85	300	410
1810	820	340	890	680
770	1300	340	260	850
2150	1210	210	70	340
1630	430	470	270	640
820	610	470	470	510
2150	1340	810	420	760
1940	1340	380	380	550
1810	260		300	
1120			740	
1430			260	
av. = 1526	av. = 908	av. = 383	av. = 491	
s.d. = ± 475	s.d. = ± 391	s.d. = ± 201	s.d. = ± 232	

From Opal Reef up to the northern limit of Lagoon Reef (12° 23′ S) is a total distance of 555.5 km. Within this distance there are 117 reefs ranging from small plug reefs to long ribbon reefs, which collectively present approximately 536 km of reef front to oceanic conditions. (Small plug reefs situated just behind the main reef line do not contribute to the length of exposed reef front in this context.) Water moves between the reefs through 86 well defined channels, which together account for 116 km of the total length of the outer edge (table 1).

Detailed information concerning the bathymetry of the continental shelf in the area immediately behind the reefs, and even more so of the continental slope on their seaward side, is lacking. Available bathymetric charts of the Coral Sea show that the reefs are situated near the edge of the continental shelf from Cruiser Pass (15° 40′ S) northwards, orientated with their axes parallel to the edge. The outer edge of the reefs descends abruptly to great depths, although the average slope is only 4° (Maxwell 1968). The outer face of Hicks Reef (14° 27′ S) descends to 400 m within about 300 m of the reef edge.

In the back reef area, the depth of the water is variable and, while it does not generally exceed 36 m, it is more commonly in the order of 28 m.

Southwards from Cruiser Pass, between Lena Reef and Opal Reef, the reefs occur increasingly close to shore and further from the edge of the continental shelf. They are not orientated with respect to the continental margin, but in a generally southeast direction. There appears to be a plateau at about 55 m between the outer limit of these reefs and the continental slope, probably a remnant of the 58 m (32 fathoms) strand line (Maxwell 1968). The sea floor shows a distinct declination eastwards to the outer reefs and, in the back-reef area, is deeper than that found further north. The depth of water is now greater than 36 m and it is possible to distinguish the 'Marginal Shelf' in Maxwell's terminology, as defined by the 36 and 92 m (20 and 50 fathom) contours.

The depth of water in the channels between the reefs is largely unknown. Where data are available, the depth would appear to be similar to, or greater than, that of the back reef area. Marked exceptions occur where strong currents flow and where former rivers have scoured deep channels, as for example in Lowry Passage between Wilson and Rodda Reefs (13° 57′ S). The ends of the reefs normally descend very abruptly.

North of Olinda Entrance (11° 14′ S), the appearance of the outer reefs changes greatly, from 'ribbon' reefs into 'deltaic' reefs, and then into 'dissected' reefs. The term 'ribbon' reef is used in this paper in its most generalized sense to include all the elongate shelf edge and detached reefs of the Northern Region south of the deltaic reefs.

Morphological characteristics of ribbon reefs

The enormous variability in shape, size and development of reefs within the G.B.R. province has been classified by Maxwell (1968) into a scheme which associates the present surface appearance of reefs with developmental stages. These stages appear to be well established, at least in principle, and the scheme thus appears to have a general, functional application.

The stages of reef development indicated by Maxwell represent the results of an interplay of all the factors, past and present, which influence the reef. In localities where these influences are approximately uniform all round, a symmetrical platform reef is formed. Continued expansion ultimately leads to the formation of a shallow lagoon, as conditions in the centre of the reef fall below those necessary to maintain coral and algal growth. In other localities where, for example, the bathymetry is limiting, reef expansion can occur only in certain directions. If this occurs along a drop-off contour, the asymmetrical elongate reefs variously known as 'wall', 'linear' or 'ribbon' reefs are formed. These reefs change, and are changed by, patterns of water movement. Strong currents flowing around the ends cause those ends to curve back, and may lead to prong and buttress formation in the back reef slope. Eventually the arms of the reef may join to form a lagoon. A number of other growth forms are described by Maxwell. As a result of continued growth, hydrological and biological conditions can change to such an extent that an adjacent reef or reefs may 'resorb' or degenerate by one process or another.

The shelf edge reefs are mostly elongate. They occur in an almost continuous series, separated by channels of varying widths as described below. The considerable variation in size and surface shape found amongst these reefs is indicated by the ten distinguishable types (elaborating on Maxwell's scheme) illustrated in figure 3. They range from simple ribbon reefs (types A and B) to closed ring reefs (type G), a variety of plug reefs (types H, J and K), and finally to a few reefs that show 'resorption' (type L). Such a classification does have limitations, however, as reef forms with intermediate features common to two or more types are frequently found. With the exception of the plug reefs (type J only) the different reef morphologies all appear to be derived initially from a basic building unit: the short wall reef (type A). Plug reefs develop in the openings between reefs or are remnants of earlier existing reefs. Coral growth occurs parallel with the current and so leads to the formation of a triangular reef with the apex directed upstream.

FIGURE 3. Morphological variation in outer edge reefs, elaborating Maxwell's (1968) classification (see text).

The following descriptions of reefs are best read with relevant navigational charts. However, most of the information given here has been obtained from aerial photographs and is not usually obtainable from the charts.

The reefs lying between and including Opal Reef at the southern limit of the region and Cruiser Pass (15° 41′ S) represent the transition from the scattered platform reef development, so characteristic of the Central Region, to the linear reefs that typify the Northern Region.

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Within this section the reefs are generally crescentic with, in some cases, considerable secondary coral growth in the back reef area. They appear, however, to be undergoing 'resorption' and are thus of type L. Their orientation would appear to be determined more by the influence of the SE trade winds than the direction of the continental shelf edge.

North of Cruiser Pass the outer reefs are orientated along the very edge of the continental shelf. Consequently they face in any direction between north and southeast; they are not aligned according to dominant wind direction.

Several natural divisions occur in the line of reefs that mark recognizable changes in the pattern of reef development. These divisions correspond roughly with the five major water exchange sites referred to above. The line of reefs extending north from Cruiser Pass to Ribbon Reef consist of a series of elongate reefs, mainly type D, showing thickening of the ends and some infilling of the back reef area with secondary coral growth. The average length of these reefs is 7930 m (range: 14190–2750 m). The width at their narrowest central part ranges from 950 to 470 m (mean: 720 m). Ribbon Reef itself is a type C reef. It is extremely long (35030 m) but only 1300–610 m wide. One, two or three plug reefs (type J) are located in almost every channel between the linear reefs, some distance behind the reef front. A group of three plug reefs is located radially behind the channel at the south end of Ribbon Reef. The occurrence of these reefs is indicative of strong currents, especially to the north and south of Ribbon Reef which inhibits E–W water flow by its great length. Between Lena Reef and the south end of Ribbon Reef, the ratio between the length of exposed reef front and the width of the channels between the outer reefs is 4.8 : 1.

The groups of reefs, which includes Yonge, Carter, Day, Hicks and Hilder Reefs, between Ribbon Reef and Two-mile Opening are type E, with two exceptions. Hilder Reef, situated between Two-mile and One-and-half-mile Openings, is a large advanced plug reef, type H. The small reef in Cormorant Pass is a small plug reef, type J. Type E and H morphologies are relatively unusual in the reef line, being found nowhere as well differentiated as in this section. The marked curving of the ends of these reefs and the extensive back reef margin are indicative of good water circulation. The 'Open Ring' formation, in Maxwell's terminology, develops progressively as one proceeds northwards in this section, suggesting that this region is one of the major sites for water exchange between the inner reef and oceanic waters and that the major currents pass through Two-mile and One-and-half-mile Openings. The possible influence of the southeast trade winds is seen in the greater coral growth in the southern recurved arms. The reef flats are 780–600 m wide and reefs appear similar to the simple wall type. Their average length is 6630 m (range: 3460–8650 m). The ratio between length of reef front and channel width from Yonge Reef to Hilder Reef is 5.4 : 1.

North of Two-mile Opening the reef continues as a series of narrow ribbon reefs, types C and D, to Waterwitch Passage (14° 12′ S). The strong currents at the southern end of this section and the long fetch over unobstructed water in the inner reef region for the prevailing southeast trade winds, appear to have led to the inward extension of Jewell Reef and its continuation in a line traversing the inner shelf by Parke Reef and Waining Reef. These appear very similar to the linear reefs, type A and type B respectively, of the outer edge. That strong currents flow in a northwesterly direction between these inner reefs is indicated by the presence of sand levees. A kite-shaped plug reef (type J) occurs as an outer reef off the northern end of Jewell Reef. It is followed by four elongate reefs, 3780–13580 m (mean: 8050 m) in length with an average breadth of 900 m (range: 690–1150 m).

A single large irregular type C reef, 49050 m in length with an extremely variable width of 1340–3370 m, separates Waterwitch Passage from the group of Passes from North-Broken Passage to Lowry Passage (collectively referred to as Melville Pass). This is the longest and widest reef in the Northern Region. Two reefs similar to ribbon reefs, of which the innermost is S. Warden Reef, have developed across the shelf off the southern end of this reef. Sand levees have formed behind and to the sides of the channels between them. The development of the narrow inner shelf reefs, the presence of sand levees, the line of back-reef development, and the breadth of the outer reef all indicate that strong currents flow northwesterly on the inside of this reef towards Melville Pass.

The three reefs situated in Waterwitch Passage and the six reefs in Melville Pass are characteristic of areas subject to strong currents, where conditions favourable to growth are good but not symmetrical. Thus the central reef in Waterwitch Passage and Wilson Reef in Melville Pass are of the closed ring type where the ends of the reef have grown around to enclose a lagoon (type G). Apart from the obvious plug reefs present in both passes, Tydeman, Davie and Rodda Reefs in Melville Pass, and the northernmost reef in Waterwitch Pass, all appear to be derived from short linear reefs (type A), modified by considerable back reef development, either in the form of thickening along the entire axis as seen in Tydeman Reef, or by prolongation of the back reef to form a triangular reef with its base seawards (type K). All these reefs have sand banks or unvegetated cays at their northwesterly ends.

The position and curvature of Corbett Reef on the inner shelf and the backward northwesterly directed extension of the southern end of the first reef north of Rodda Reef indicate that there are still strong currents flowing northwards inside the reef. North of this point, however, these currents appear to dissipate. The contours of the channels between the reefs up to First Three-mile Opening and the extent of coral development in the back reef areas suggest that some portion of the northerly current exists through the reefs here. In addition, there is substantial water flow through First Three-mile Opening and another channel to its south, that has enhanced back reef growth of the reefs immediately to their south. As a result, these reefs have developed type F morphologies.

The line of reefs extending north from Rodda Reef to First Three-mile Opening consist of types A, D, E, F and K. The influence of currents flowing on the inside of these reefs is seen

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Description of plate 1

Figure 2. Wilson Reef (13° 15′ S), illustrating comparisons between zones visible in aerial photographs and those observed on the reef. These zones are: (A) Sandy ocean floor with large clumps of broken reef-rock. Coral cover approximately 10%, dominated by *Millepora tenera*. (B) Approximately 50% cover of ramose *Acropora*, dominated by *A. intermedia* and *A. formosa*. (C) Flat, consolidated limestone with much filamentous algae and approximately 1% coral cover of many species. (D) Flat, consolidated limestone with sand and rubble; no coral. (E) Mostly sand with approximately 5% coral cover, mostly ramose *Acroporas*. (F) The lagoon, extending to a depth of approximately 5 m. The substrate was clean, white, calcareous sand with occasional outcrops of ramose *Acropora* and *Porites*. (G) Clean, white calcareous sand. (H) A mixture of sand and *Acropora* debris with irregular patches of ramose *Acropora*. (I) Cemented *Acropora* rubble. The outer edge of this zone was bordered by a 5 m wide strip of actively growing *Acropora* sp., the same species which comprises most of the cemented rubble. (J) Flat, limestone covered by filamentous algae and some sand. This is the zone of maximum wave action. (K) Coral cover increased was approximately 30% and was dominated by *A. hyacinthus*, *A. humilis* and *A. palifera*. The latter species became very dominant at depths greater than 3 m. The whole zone was characterized by spur and groove formations, with the grooves up to 3 m deep. Vertical exaggeration in lower part of figure is 1 : 20.

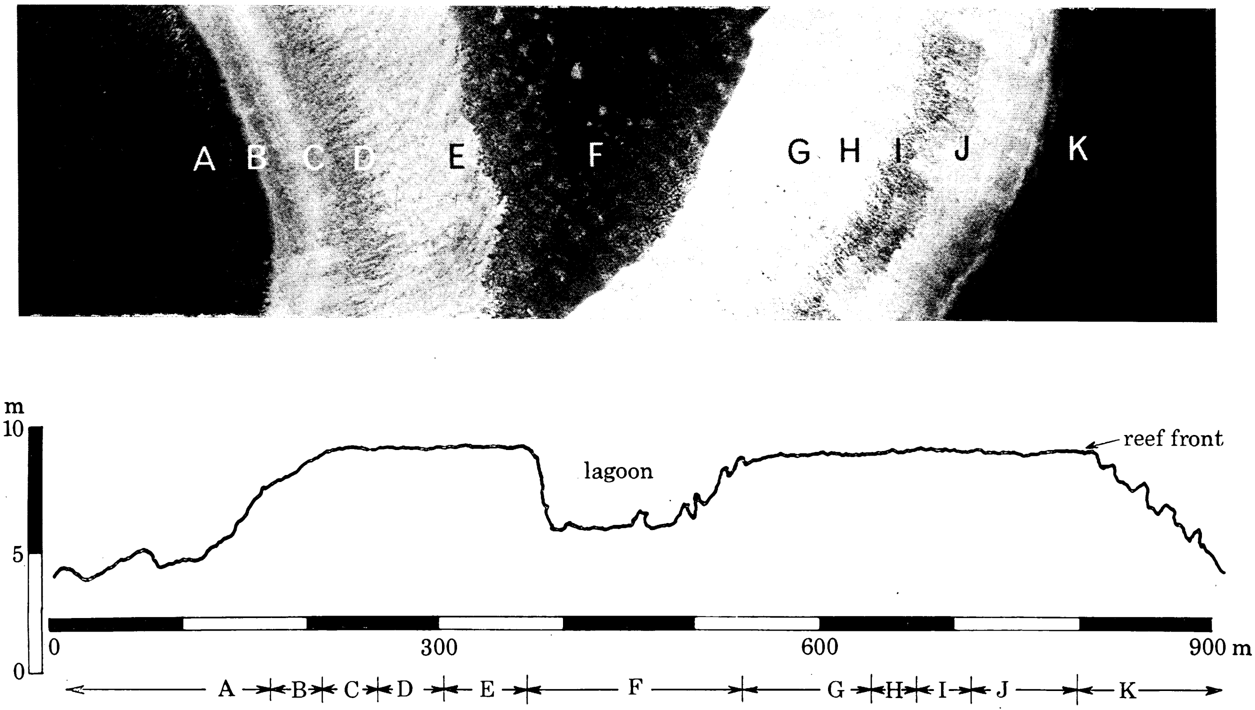

FIGURE 2. For description see opposite.

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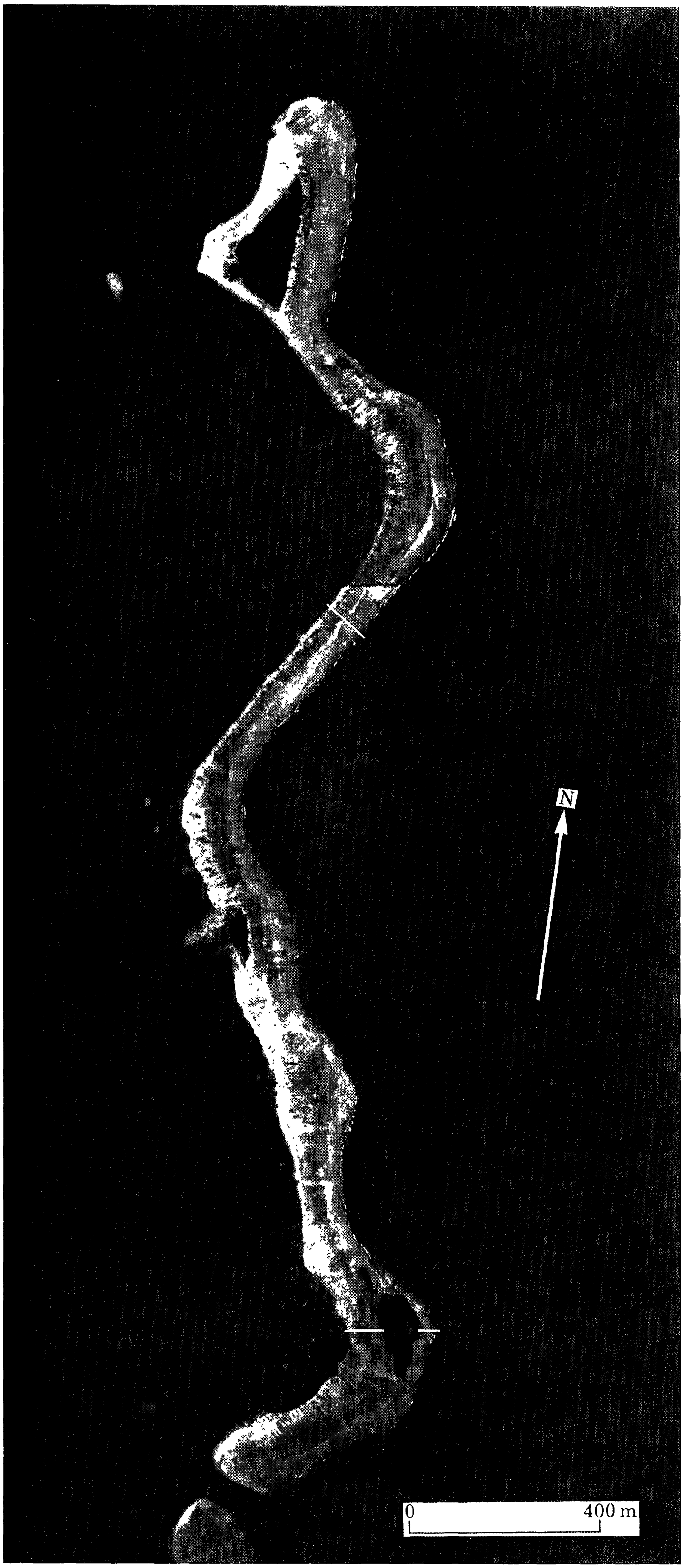

FIGURE 4. Tijou Reef. The positions of the reef transects (figures 6 and 7) are indicated.

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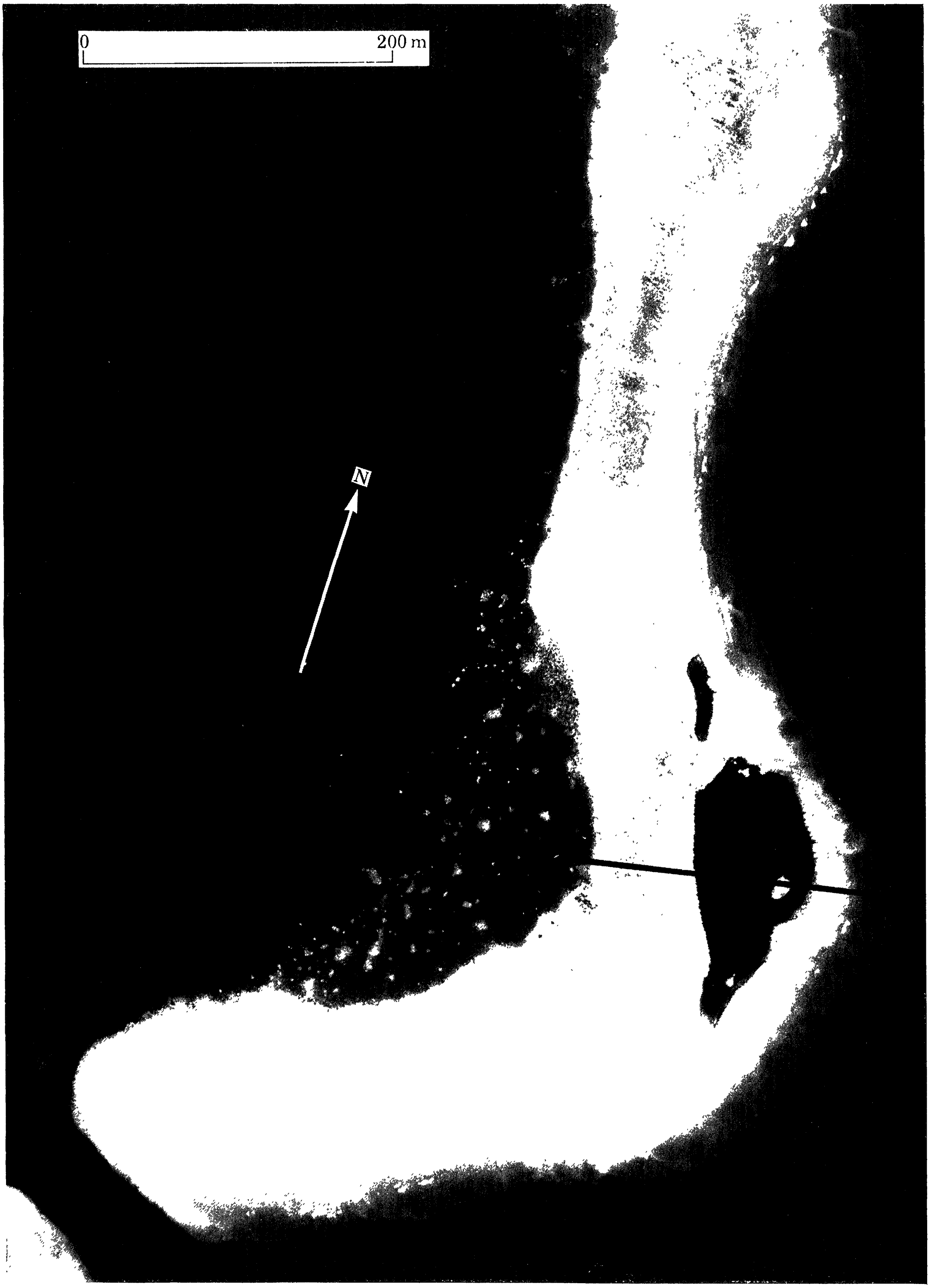

FIGURE 5. The south end of Tijou Reef. The position of the reef transect (figure 6) is indicated.

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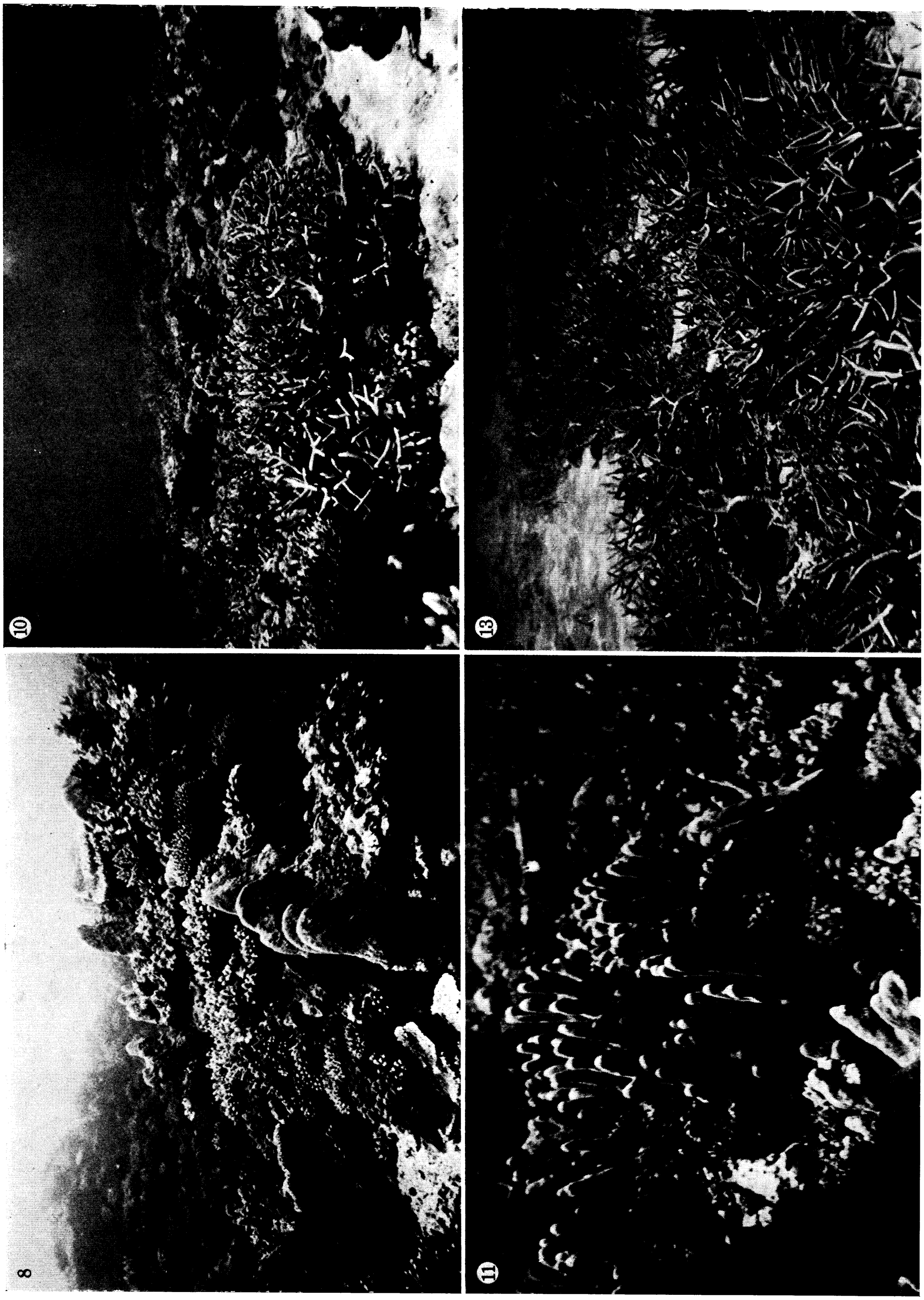

Figures 8, 10, 11 and 13. For description see opposite.

in the development of broad reef flats, varying between 1200 m and 2660 m wide. The development of these reefs compares with that of the long reef between Waterwitch and Melville Passes. Their average length (excluding type K reefs) is 8990 m, varying from type A, 3440 m long, to type D, 15310 m long.

North of First Three-mile Opening, the character of the outer reef changes again to become a long irregular line of reefs with similar breadths following closely one after another. The reefs are mostly of types A–D, interspersed with types J and K. The linear reefs are generally shorter, except for Tijou Reef (13° 8′ S) which is 27800 m long, and narrower than the reefs to the south. Excluding the various plug reefs and Tijou Reef, the average length of the linear reefs is 6600 m (range: 11510–3160 m) and their average minimum width 830 m (range: 1150–590 m). In addition to the above features, the channels between the reefs are significantly narrower than those of the southern sections. The reef back margin is markedly reduced.

Strong tidal currents occur in Second Three-mile Opening which interrupts the outer barrier to the north of Tijou Reef and is the only site of major exchange between reef and oceanic waters in this section. Strong currents also appear to occur in the narrow channels between the reefs. Two small type K reefs – one unnamed, the other Franklin Reef – are situated in Second Three-mile Opening. These reefs, in common with the two larger type K reefs (Ham and Derry) that continue the line north, have sand banks on their west or north-west sides. A number of small plug reefs (type J) have become established close to the rear margins of the reefs in the strong currents running through several narrow channels. These currents have in places led to marked but narrow rearward growth of the ends of some reefs, while in others the ends of the reefs have thickened. In some cases, e.g. Long Sandy Reef (12° 31′ S), the ends of the linear reefs remain unmodified. Presumably the currents around these reefs are slight. Several short linear reefs (type A) show overall thickening to create short, broad, rectangular reefs, similar in appearance to those described above in Melville Pass and Waterwitch Passage, although smaller. These reefs suggest that greater water movements and exchange occur in their vicinity.

In this section of the reef there appears to be a reduction in the total width of the channels penetrating the reef line. The ratio between the length of exposed reef front and the width of the channels is 9.1 : 1. Lagoon Reef at the northern limit of this section is unusual. It is approximately triangular, has reef front along two sides, and has a deep lagoon towards its apex which is open to the sea. In some respects it resembles a large, well developed plug reef, type H. However, it is at about this point that the long linear reefs give out and the outer reefs continue as a series of short reefs which cease to show strong affinities with the elongate linear reefs to the south.

Description of plate 4

Figure 8. The outer slope of Great Detached Reef at 15 m depth.

Figure 10. The inner reef flat of Great Detached Reef approximately 300 m from the front, along the line of the transect.

Figure 11. The back reef slope of Great Detached Reef, showing the characteristic growth form of *Acropora palifera*.

Figure 13. The reef flat of the far northern end of Great Detached Reef, showing the dominance of ramose *Acropora* species in a sandy substrate approximately 300 m from the reef front along the line of the transect.

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Tijou reef

Tijou Reef (figure 4, plate 2) is a long narrow reef with an exposed reef front 27800 m in length. The width of the solid reef mass varies from 1550 m at its maximum to 640 m at the narrowest part near the north end. The general orientation of the reef is north–south, but as the reef is very irregular in shape, different sections face in directions ranging from southeast to northeast.

In terms of the reef types illustrated in figure 3, Tijou Reef combines features of types B, C and F. At the northern end, the strong currents in Second Three-mile Opening appear to have induced the formation of a lagoon studded with large coral heads (type F). From this lagoon south to the approximate midpoint of the reef, it is basically type B, being almost uniformly narrow (about 680 m) and having little secondary coral growth in the back reef area. The southern half of the reef is type C. It is more variable in width and secondary coral growth has occurred along the rear margin, particularly in the protected angle where the reef curves through to the southwest, and in the region of the obtuse curve of the reef at about the midpoint. The southern end is not thickened in any significant way.

Tijou Reef, south end

The south end of Tijou Reef is characterized by an enclosed deep lagoon (figure 5, plate 3). The principal surface features of the reef and lagoon are illustrated in figure 6.

The outer slope

The outer slope was not examined in detail by divers. The seaward margin is dominated by deep spur and groove formations that penetrate the reef front at an oblique angle. At their seaward end, the grooves are up to 7 m deep and 10 m wide.

The reef flat and lagoon

The principal features of the reef flat and lagoon are indicated in figure 6. The eastern side was dominated by deep spur and groove formations running obliquely to the reef front. At their seaward end the grooves were up to 7 m deep and 10 m wide. The reef margin was penetrated for distances of up to 80 m by grooves that gradually diminished in size. The dominant corals were *Acropora humilis* (Dana) and *A. palifera* (Lamarck). A wide diversity of Alcyonaria was present in similar abundance. Green filamentous algae and hydroids dominated the wave-battered reef flat between the spur and groove zone and the edge of the lagoon.

The reef flat up to 100 m east of the lagoon was mostly composed of partly cemented rubble and sand. A narrow band of rubble sloped steeply into the lagoon and was replaced by loose calcareous sand grading into mud in the lagoon itself.

The small reef patch in the lagoon shown in figures 5 and 6 had irregular, vertical or undercut walls of limestone to approximately 5 m depth which became buried in steeply sloping, soft, muddy sand. The western edge of the lagoon also had an irregular vertical wall to about 15 m, where it merged into a soft sandy floor. The extraordinarily great depth of the lagoon, 43 m, was measured by lead-line at four positions along the line of the transect.

The reef flat was dominated by Alcyonaria and coralline algae up to 70 m west of the lagoon, and thereafter by very irregular patches of ramose *Acropora* species, interspersed by patches of sand, dead coral and rubble.

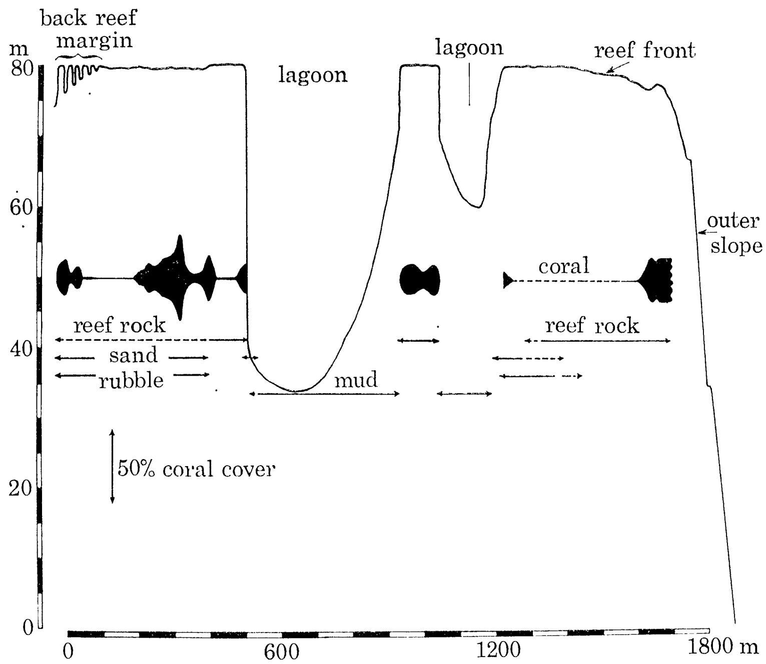

FIGURE 6. Profile of Tijou Reef, south end, showing the distribution of substrate types and estimated percentage cover of coral. The position of this profile is indicated in figures 4 and 5. Vertical exaggeration is 1 : 20.

The back reef margin

As indicated in figure 6, the back reef margin consisted of an extensive area of secondary coral development. A brief examination showed these to be similar to the back reef margin of the northern end of Tijou Reef, described below.

TIJOU REEF, NORTH END

The principal surface features of the north end of Tijou Reef at the position indicated in figure 4 are summarized in figure 7.

The outer slope

The outer slope below the spur and groove zone declined at an average angle of approximately 45°, reaching a depth of 70 m at a distance of 80 m from the front. Beyond that the reef descended more steeply, reaching a depth of 127 m at 100 m from the front.

Coral cover was between 50 and 100 % over most of the outer slope, to a depth of at least 45 m. At approximately 5 m depth, *Acropora humilis* (Dana), *A. palifera*, *Pocillopora verrucosa* (Ellis and Solander) and an unidentified *Acropora* were dominant. *Porites lichen* (Dana) also became dominant at 10 m. At 30 m, *P. lichen*, *A. palifera* and *Tubipora musica* (Linnaeus) shared approximately equal dominance. At greater depths, species diversity greatly increased and no species showed marked dominance.

The reef flat

Coral cover in the spur and groove zone (indicated in figure 7) averaged approximately 30 %, being greatest on the spurs and least in the grooves which are approximately 1–$1\frac{1}{2}$ m deep. At approximately 20 m west of the well defined front, the coral cover decreased to approximately 5 %, then to less than 1 % at 40 m. *Acropora humilis* and *A. pyramidalis* Klunzinger are markedly dominant.

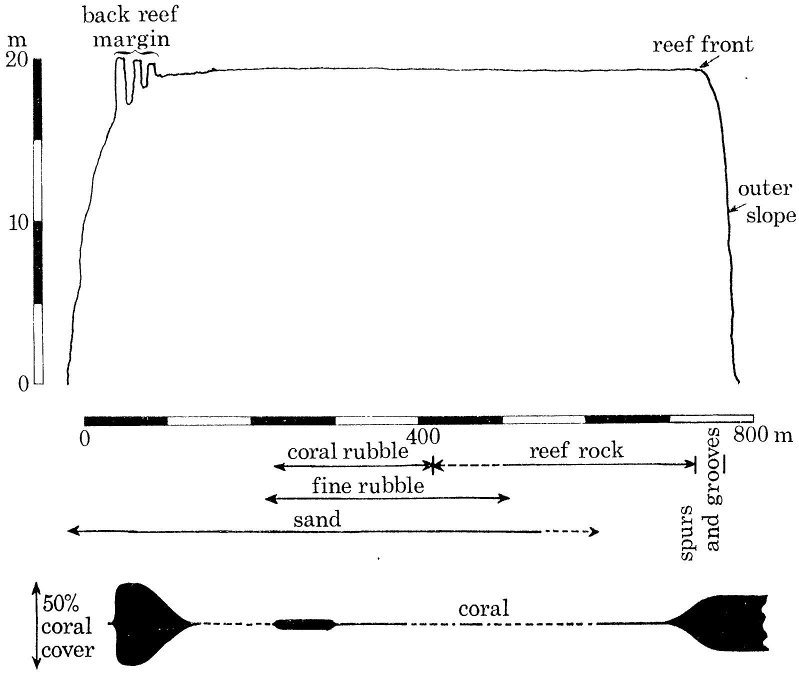

FIGURE 7. Profile of Tijou Reef, north end, showing the distribution of substrate type and estimated percentage cover of coral. The position of the profile is indicated in figure 4. Vertical exaggeration is 1 : 20.

TABLE 2. PERCENTAGE OF TOTAL AREA COVERED BY THE BIOTA AND SUBSTRATES (INDICATED) OF REEF SURFACE, AT THE POSITIONS INDICATED, AS DETERMINED BY 30 m TRANSECTS LAID PARALLEL TO THE REEF FRONT, NORTH END OF TIJOU REEF.

Position of 30 m transect	dead coral (consolidated and loose)	sand	Scleractinia	Alcyonaria	hydroids	sponges	filamentous algae	coralline algae
5 m depth, reef front	66.4	—	32.8	0.8	—	—	—	—
10 m depth, reef front	30.7	—	62.9	5.9	—	0.5	—	—
15 m depth, reef front	34.2	—	50.8	13.5	0.2	1.3	—	—
200 m behind crest	6.2	64.1	21.5	—	—	0.8	5.5	1.9
300 m behind crest	93.6	—	6.4	—	—	—	—	—
450 m behind crest	77.8	—	16.0	2.8	—	3.4	—	—
600 m behind crest	7.2	87.8	3.5	—	—	1.5	—	—

Very little coral occurred over the rest of the reef flat. Limestone, rubble and sand zones can be readily identified in aerial photographs. Hydroids are common to 140 m in from the front. Massive species of corals, mostly Faviidae, form an ill defined zone 560–630 m from the front. At 660 m from the front, *Acropora humilis* became markedly dominant again and remained the major reef-building species up to the reef back margin.

Table 2 summarizes the results of quantitative (30 m) transects, run parallel to the reef front, at three depths down the outer slope and at increasing distances west of the front, on the reef flat. There is a marked discrepancy between the results obtained by this method and those obtained from visual estimations by the authors (cf. figure 7). In view of the patchiness of coral distribution and the limited nature of such quantitative samples, it is concluded that 30 m transects of this type are inadequate for assessing the cover of biota and substrates of these reefs. Analysis of data from many hundreds of metres (each requiring perhaps a day's work) would appear necessary for each transect.

Table 3. Percentage surface area cover of live coral, dead coral and sand on the front of Great Detached Reef at the three depths indicated (see text).

depth below reef front/m	*Acropora palifera*	*Acropora* sp.	*Stylophora pistillata*	*Acropora pyramidalis*	*Porites lichen*	*Pocillopora damicornis*	*Pocillopora verrucosa*	other Scler-actinia	total coral cover	dead coral	sand
5	10.5	1.8	1.3	2.3	—	—	1.7	10.1	27.7	64.3	7.6
10	16.2	11.0	3.8	—	—	2.7	—	12.2	45.9	50.3	0
15	1.8	0.7	3.5	—	4.0	—	—	14.6	24.6	62.0	10.2

The back reef margin and back reef slope

Echo soundings west of the back reef margin indicated an even sandy floor sloping gently from a depth of 5 m at a distance of 20 m, to 30 m depth at 100 m distance and then to 34 m depth at a distance of 200 m.

The reef back margin was composed of a well defined line of deeply and irregularly dissected limestone hillocks and ridges which were penetrated by sand to varying degrees and which supported a lush and varied coral growth, especially on their sides.

Species diversity was very great, and no species was conspicuously dominant. A single 25 m transect across the top and down the side of one such dissected hillock 3 m high, gave area covers (including overlapping) for dead coral of 47.0 %, live coral 43.3 %, coralline algae 40.0 %, Alcyonaria 8.3 %, and sand 1 %. Average coral cover on the side (alone) was 63 %, with reduced areas of dead coral (22.5 %) and coralline algae (17.5 %).

Great Detached Reef

The Great Detached Reef is one of the northernmost, and one of the longest, of the ribbon reefs. The reef front is approximately 30000 m long and forms the eastern wall of a sandy plateau 175 km^2 in area that is detached from the continental shelf by a 6–7 km wide trench. The depth of this trench is unknown, but is at least 280 m. It is bounded on both sides by distinct lines of small reefs and sand banks which respectively compose the western edge of Great Detached Reef and the eastern limit of the continental shelf. The latter reefs and sand banks are a continuation of the more southerly ribbon reefs, including Three Reefs. The trench curves around the northern limit of Great Detached Reef to form the deep Raine Island Entrance.

The outer slope

At depths below approximately 5 m, the substrate consists of poorly cemented coral rubble interspersed with irregular pockets of *Halimeda* sand. The coral cover was approximately 50 % and (as is perhaps indicated in table 3) was irregular both in species composition and density.

In most areas *A. palifera* were dominant to depths of approximately 15 m (figure 8, plate 4), after which *Porites lichen* became markedly dominant to about 30 m depth. No species were clearly dominant below 30 m.

At depths of less than approximately 5 m, the substrate consisted of increasingly well cemented limestone carved into irregular spurs and grooves up to 2 m deep. This spur and groove zone was approximately 30 m wide, the grooves becoming gradually shallower with decreasing depth. *Acropora palifera*, *A. humilis* and *A.* cf. *pyramidalis* were dominant, all with the extremely flattened growth forms indicative of areas exposed to extreme wave action.

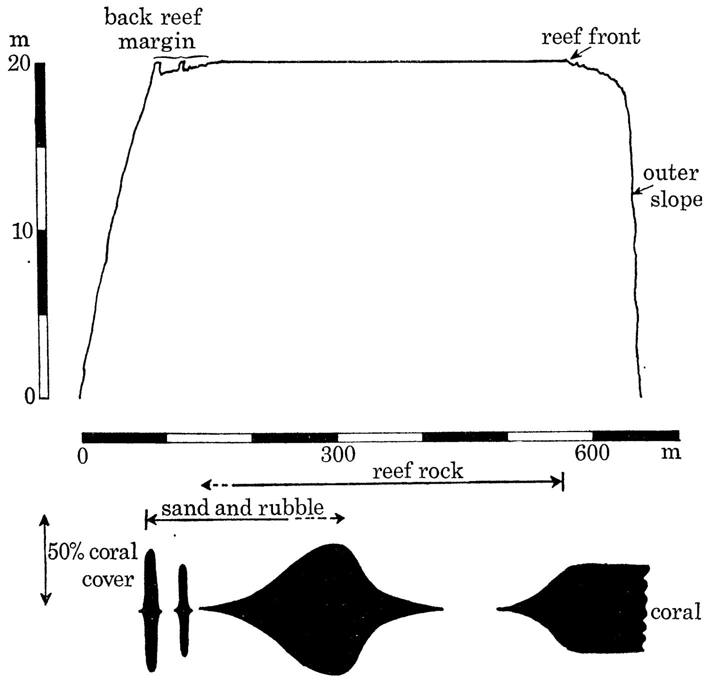

Figure 9. Profile of Great Detached Reef, showing the distribution of substrate type and estimated percentage cover of coral. Vertical exaggeration is 1 : 20.

The reef flat

The principal features of the reef flat indicated in figure 9 are probably generally representative of most northern ribbon reef flats orientated in a north–south direction, which are exposed to prevailing winds and which are uncomplicated by close proximity of channels, other reefs, etc.

Coral cover decreased rapidly behind the spur and groove zone and became completely absent 100 m behind the reef front. In this region the substrate consisted of flat, very hard limestone sparsely covered with green filamentous algae and hydroids.

Corals first reappeared approximately 180 m behind the reef front and continued to increase in density to form a zone of coral growth which is distinctly visible in aerial photographs of many northern ribbon reefs. In this area, *A. formosa* (Dana) was markedly dominant, although brief inspection of neighbouring areas indicated that several different species of ramose *Acropora* may dominate this zone.

Coral cover steadily decreased beyond about 300 m from the reef front and tabular and subtabular species and growth forms of species (especially *A. hyacinthus* (Dana) and *A. humilis*) became increasingly dominant (figure 10, plate 4). There is a narrow zone of massive species, composed primarily of Faviidae, at the very back of the coral zone.

Beyond 450 m behind the reef front, the now poorly consolidated limestone surface became increasingly replaced by meandering valleys with sandy floors which increased gradually in depth and width towards the back reef margin.

The back reef margin and back reef slope

The back reef margin (figure 11, plate 4) was composed of a well defined line of irregularly dissected limestone standing above a substrate of calcareous sand. West of the back reef margin, the sand sloped relatively steeply to approximately 27 m depth, then gently to reach a constant depth of 34 m, 180 m from the reef back.

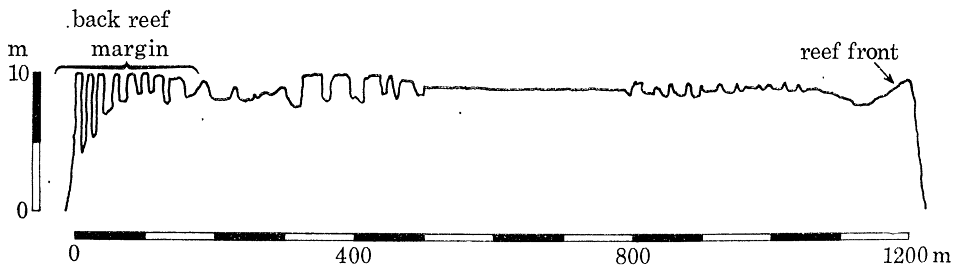

FIGURE 12. Profile of Great Detached Reef, far northern end. Vertical exaggeration is 1 : 20.

The north end of Great Detached reef

The north end of Great Detached Reef, shown in profile in figure 12, is well protected from the prevailing seas but is adjacent to the deep water of Raine Island Entrance. The reef front had a dense coral cover, mainly of *A. humilis* and *A. pyramidalis*. This decreased abruptly till, 20 m behind the front, the cover was about 1 %. The substrate was mostly loose rubble. At a distance of 80 m behind the front, *A. palifera* became dominant, with individual colonies growing to over 1 m in height. Sand was the main substrate from 100 m onwards behind the front, with *A. palifera* remaining dominant until at 210–250 m, it was replaced by ramose *Acropora* species (figure 13, plate 4). *Acropora palifera* again became dominant at 300 m and remained so over the rest of the reef, in most areas showing extremely lush growth, with individual colonies sometimes reaching 1 m in height.

Three Reefs

The profile of Three Reefs differs greatly from all other ribbon reefs observed (figure 14). The reef surface consisted almost entirely of limestone with deep spur and groove formations on the eastern side. These grooves extended across to the western side of the reef flat, decreasing gradually in depth. Corals and calcareous algae were nowhere abundant.

These reefs appear to be in the path of strong tidal currents; they are also exposed to very strong wave action. Perhaps as a consequence, the depth of water over the reef was approximately 1 m greater than that over the main transect of Great Detached Reef, itself approximately 0.5 m deeper than corresponding areas of the protected north end of Great Detached Reef.

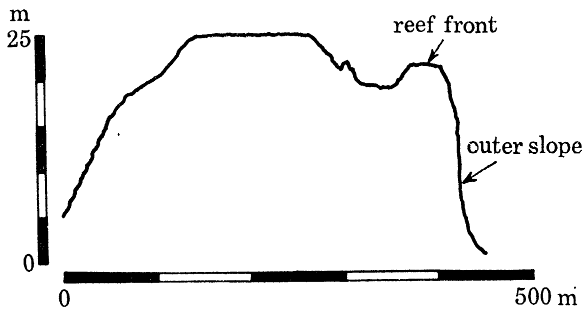

FIGURE 14. Three Reefs, shown in profile. Vertical exaggeration is 1 : 20.

DISCUSSION

The northern outer reefs of the G.B.R. have remained largely undescribed by reason of their remote and inaccessible position. Hence, their omission from the discussions of earlier writers on the theory of reef evolution (see Veron 1978*b*, this volume) and even from more recent accounts of the G.B.R. itself (notably Dakin 1963; Maxwell 1968; Bennett 1971).

Darwin himself (1842) mostly restricted his comments on the G.B.R. to the brief observation that '... if instead of an island, the shore of a continent fringed by a reef were to subside, a great barrier reef, like that of NE Australia would be the necessary result'. Darwin's concepts of reef development have indirectly influenced many subsequent attempts to define and categorize reef systems within the G.B.R. province. The most recent classification (Maxwell 1968) is generally applicable to the G.B.R. (and probably to other shelf reef systems, as distinct from Darwin's oceanic reefs). Maxwell divided the G.B.R. into the three regions already noted, and each region into six more-or-less bathymetrically defined, semi-meridional zones. Of these, the outermost is the 'marginal shelf' zone which is bordered by the 'shelf edge' reefs. These occur in the Southern Region as the outer reefs of the 'Pompey Complex' (discussed in Veron 1978*a*, this volume), in the Northern Region as the ribbon reefs, and in the far north as the deltaic and dissected reefs.

These reefs are, in a sense, 'barrier' reefs. Certainly they form a barrier to the interchange of water between the continental shelf and the open ocean. However, the term 'barrier reef', used in the Darwinian sense, essentially means a line of reefs separated from the mainland by a lagoon. Such barrier reef–lagoon combinations are well known and form a large proportion of the world's coral reefs. In most cases the lagoons are shallow and contain platform reefs of various types. In these respects the whole Northern Region could be considered as an extremely large lagoon, and the shelf-edge reefs as Darwinian barrier reefs. The difference is primarily one of size and complexity. As with other shelf reef systems, the G.B.R.'s origins are associated with tectonic subsidence of the continental margin. As with many other barrier reefs, the shelf edge reefs of the Northern Region are situated on, and are orientated to, the edge of the continental shelf and form an actively growing barrier to oceanic waters. As with many other large reef lagoons, the inter-reef areas of the Northern Region have substrates of soft mud or sand, with a very low density of sedentary fauna and flora.

The unproductive, lagoon-like qualities of the Northern Region are best developed behind the shelf edge reefs where there is a 10–25 km wide expanse of open, mostly reef-free water with an extremely sparse sedentary fauna. They are least developed in the far north, where major exchange of water occurs through Torres Strait and also at the principal sites of exchange of oceanic water (described above) where reefs tend to border or invade the deep ocean passes. Away from areas of oceanic input, major reefs develop only where the north–south setting tidal currents are strong or in areas of very shallow water around islands etc.

Thus, much of the reef development in the Northern Region is associated with currents, either those of the distant past which have led to the establishment of the present bathymetric elevations and associated reef developments, or those of the present, which transport oceanic waters of a suitable quality for reef growth into the region. As yet, little is known about those aspects of water quality which affect or govern reef growth. Inorganic nutrient enriched waters associated with upwelling at the edge of the continental slope, high levels of organic nutrient transport from the open ocean and current-induced sediment removal have each been suggested to play a part in stimulating coral growth.

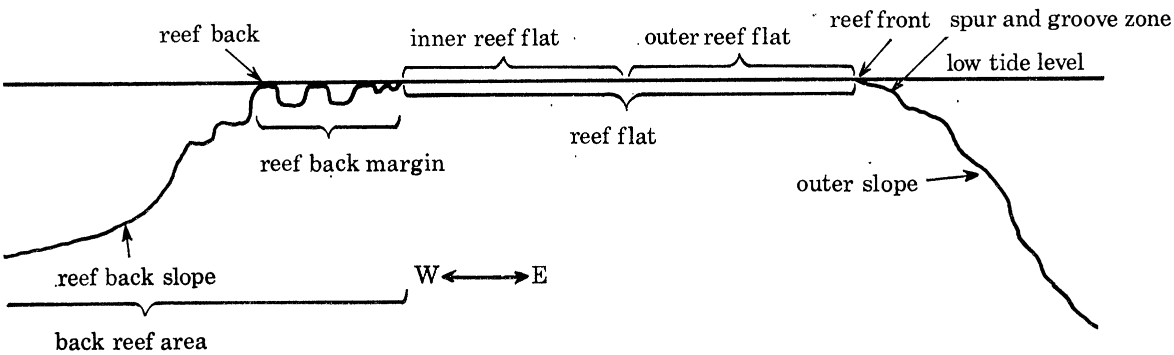

FIGURE 15. Diagrammatic profile of a ribbon reef, showing the principal morphological zones and indicating the terminology used in the text.

Ribbon reefs differ substantially from other reefs within the G.B.R. province. Their position and general shape is determined bathymetrically, but is modified by hydrodynamic influences which are mostly of their own making. Their surface features are further modified by climatic factors, dominated by the SE trade winds which generate a heavy oceanic swell for approximately 8 months of the year.

Figure 15 indicates the principal morphological zones of ribbon reefs and the terminology applied to them in this study. The outer slope and the reef back margin both support a dense coral growth usually dominated by *A. palifera*. This one extremely polymorphic species forms much of the consolidated substrate of the reef and probably much of its volume also. At the top of the outer slope there is usually a well defined zone of spur and groove formations, orientated to the direction of the prevailing winds. The grooves penetrate the reef flat, often for long distances, as 'drainage grooves'.

The wave-pounded reef front of most ribbon reefs is sparsely covered by a thin layer of corals and calcareous algae. In some areas the algae are dominant over the corals but nowhere do they form hard, smooth, pavement-like 'algal ridges', 'algal ramps' or 'algal platforms', such as have been described on many outer Indo-Pacific Reefs (e.g. Tracey, Ladd & Hoffmeister, 1948; Chevalier 1973; Stoddart 1973; Pichon 1979). The zone of maximum wave action is, however, situated well behind the reef front. Waves build up over the front and break on the outer reef flat, an area of hard, flat, denuded limestone which appears to be characteristic of all shelf edge reefs of the Northern Region which are exposed to the ocean swell. This zone on

Yonge Reef has been termed the 'reef crest' by Stephenson, Stephenson, Tandy & Spender (1931), and appropriately described by them as 'A pavement of solid coral rock, swept clear of coral debris, over 3 miles [*ca.* 5 km] in length and over 160 yards [*ca.* 145 m] in breadth'. This type of outer reef flat, or its close equivalent, has also been described from exposed reefs from other parts of the world where they are frequently termed algal ramps or algal platforms. A similar zone (from the exposed reefs of Tuléar, Madagascar) has been termed 'reef glacis' by Clausade *et al.* (1971). This is perhaps the least ambiguous of the established terms for it.

The seaward edge of the outer reef flat may show 'moats' or other irregularities in height which vary from reef to reef but which appear to be associated with the degree and type of exposure to wave action. Maximum wave action occurs closest to the reef front in reefs which face the prevailing winds and which have a steep outer slope. Where the outer slope is gentle, wave build-up is gradual and wave energy is dissipated over a greater area. Thus the 'inner and outer moats' and 'outer ridge' described by Stephenson *et al.* (1931) are products of the pattern of wave action peculiar to Yonge Reef. This pattern varies greatly from reef to reef and so therefore do the outer reef flat contours.

The inner reef flat is the most variable morphological zone of the ribbon reefs, partly because it accommodates most of the variation in the width of the ribbon reefs and partly because it contains sub-zones which vary greatly from one reef, or part of a reef, to the next. The junction between the inner and outer reef flats is normally clear in aerial photographs and is due to the replacement of the solid limestone substrate of the outer reef flat by a substrate of rubble or sand and rubble. The sub-zones of the inner reef flat are usually the result of change in the nature of the substrate. This frequently alters the depth of water over the substrate and the biota contained on it.

Yonge Reef, one of the southern ribbon reefs and the only one to have been previously described (Stephenson *et al.* 1931), has been re-studied by the authors and others and will be re-described in detail elsewhere. The second paper of this series (Veron 1978*a*) describes the shelf edge reefs north of the ribbon reefs, the deltaic and the dissected reefs.

The authors wish to thank Mr L. D. Zell for assistance in all aspects of this work, Mr L. Brady for preparing the figures, Miss A. Addison the text and Mr J. Amess for library assistance. Comments on the manuscript from Professor W. G. H. Maxwell and Professor M. Pichon are gratefully acknowledged. Field work was partly assisted by members of the expedition, especially Mr J. D. Collins and the crew of R.V. *James Kirby*.

This project was supported by the Royal Society, James Cook University, the Australian Research Grants Committee and the Australian Institute of Marine Science.

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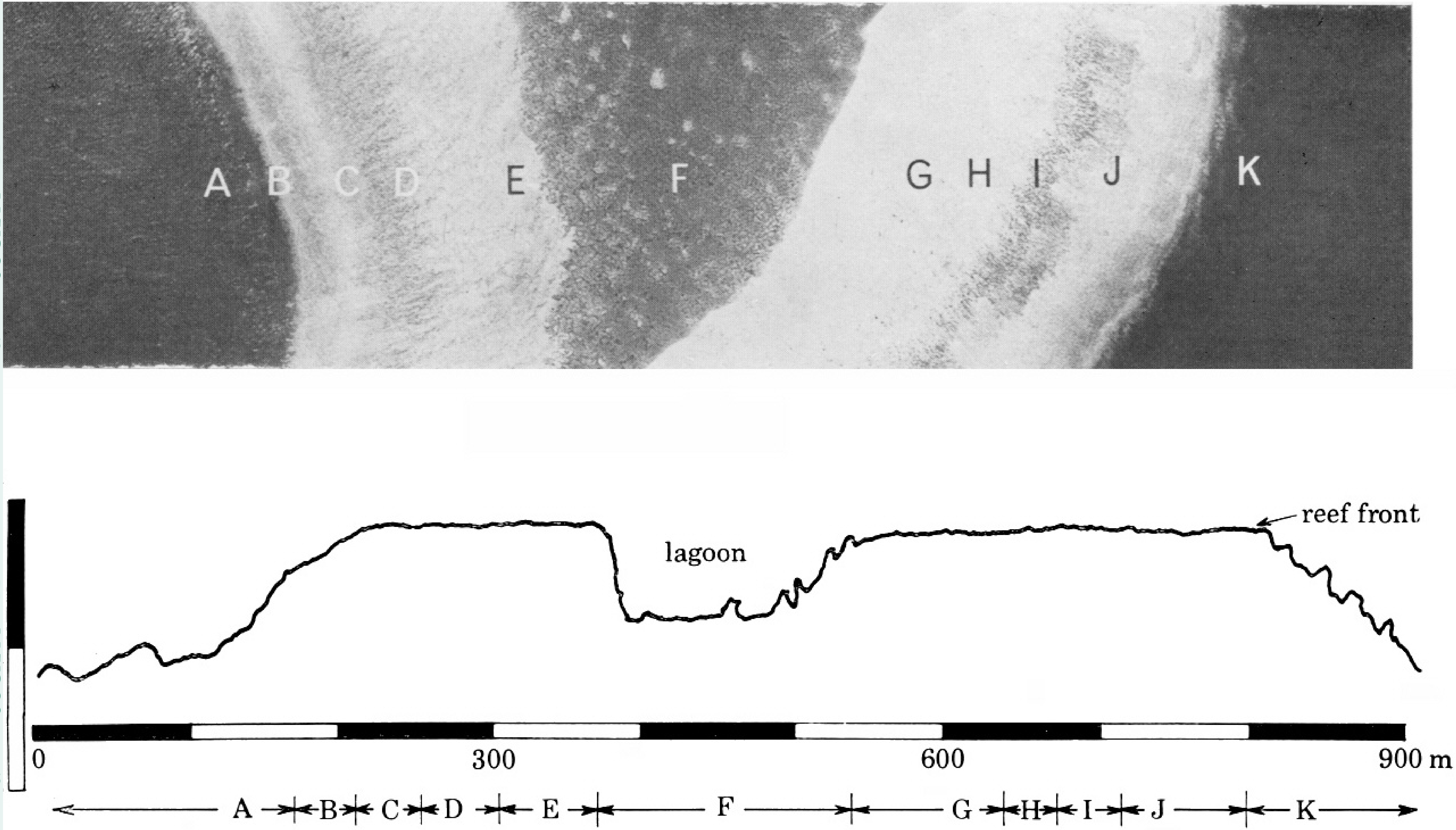

FIGURE 2. For description see opposite.

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FIGURE 4. Tijou Reef. The positions of the reef transects (figures 6 and 7) are indicated.

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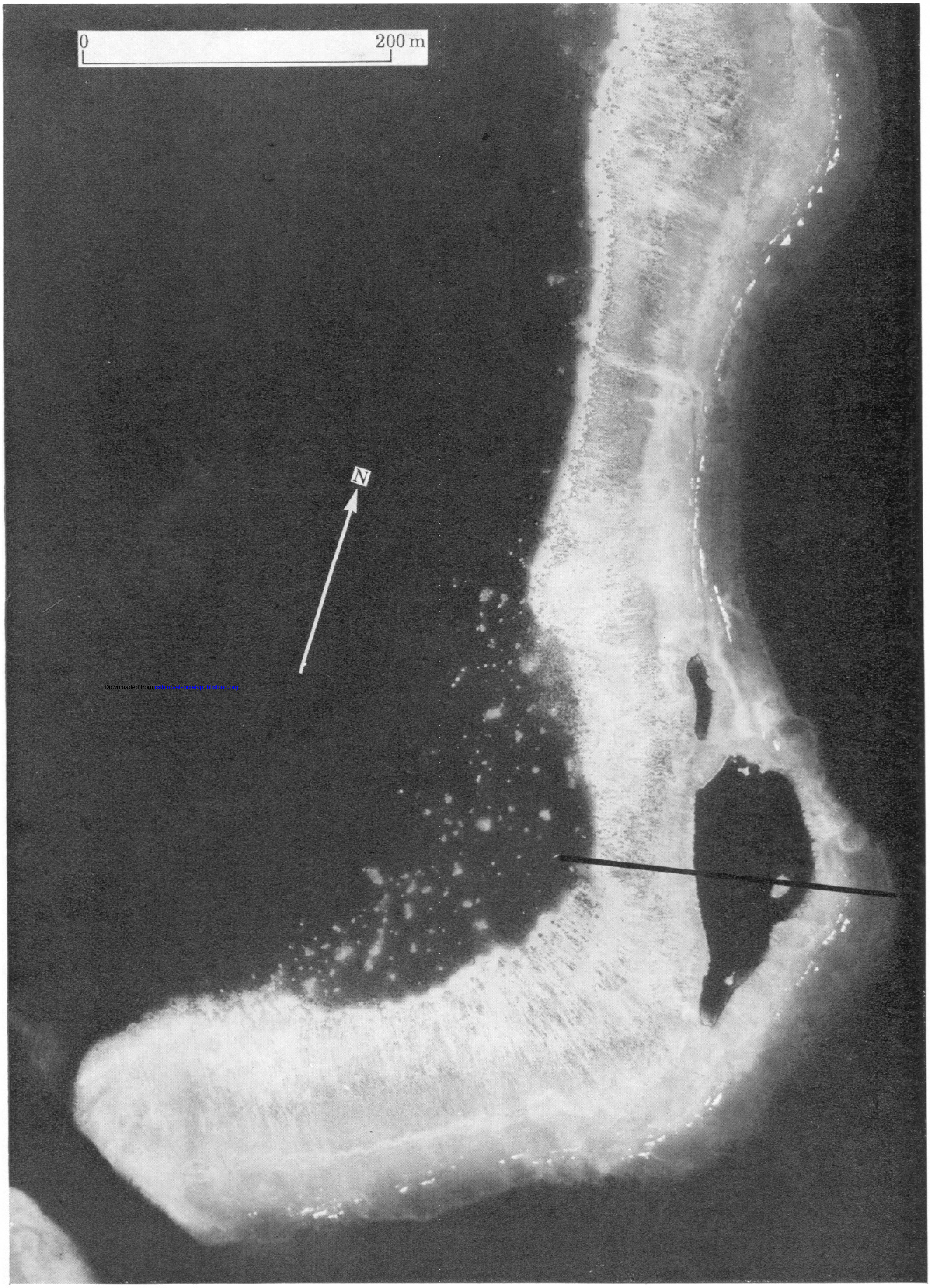

FIGURE 5. The south end of Tijou Reef. The position of the reef transect (figure 6) is indicated.

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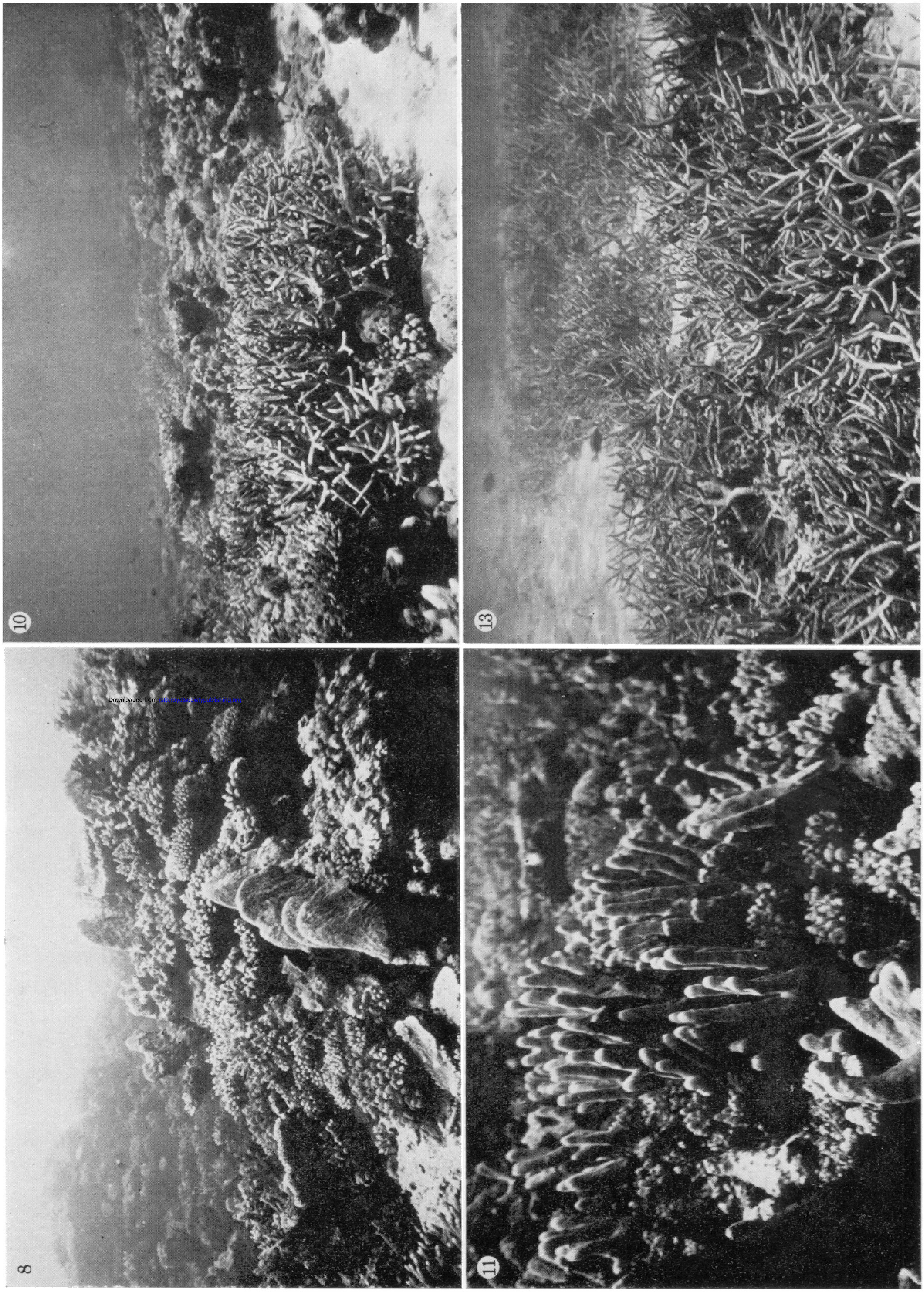

FIGURES 8, 10, 11 AND 13. For description see opposite.