The Recent Development of the Reefs in the Northern Province of the Great Barrier Reef

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Phil. Trans. R. Soc. Lond. B 1978 **284**, 129-139
doi: 10.1098/rstb.1978.0057

Phil. Trans. R. Soc. Lond. B. **284**, 129–139 (1978) [129]
Printed in Great Britain

The Recent development of the reefs in the Northern Province of the Great Barrier Reef

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[Plates 1–3]

Geophysical and well data suggest that the Recent reef growth on the exposed northern Great Barrier Reefs forms only a thin veneer on earlier reef limestones. Reef framework growth up to sea level is principally from local prominences which supply sediment of unstable coral branches to neighbouring valleys. Once a large area of a reef reaches sea level, the SE winds play an important rôle in further development by causing the major lateral growth to be to leeward and characteristic intertidal deposits to accumulate. Leeward sand cays form during prevailing conditions on reefs across the shelf and may be eroded during storms but windward rampart deposits form during storms and are eroded during prevailing conditions on those reefs exposed to heavy surf. The ramparts on the inner-shelf reefs are stabilized by mangroves and cements resulting in a progressive elevation of the surfaces of reefs towards the mainland.

1. PRE-HOLOCENE

In this province the earliest unambiguously described subsurface reef rock is very early Pleistocene, though Miocene and Pliocene carbonates may well be of reef detritus (Hill 1974). During the Pleistocene, polar ice sheets expanded and retreated such that world sea level fell and rose with an amplitude of 100 m or more for at least 2 Ma (Stoddart 1973). During times of high sea level, reefs, if not too deeply drowned, would grow up to the sea surface and then expand laterally; during times of low sea level any exposed reef limestone would be eroded at the perimeter by marine erosion and at central elevated parts by freshwater solution. If exposure was for a long period the reef surface would be truncated at about sea level. Later growth would start from this surface and a discontinuity would exist between the two reef deposits. Geophysical evidence (Orme, Webb, Kelland & Sargent 1978, part A of this Discussion) indicates the existence of several discontinuity surfaces beneath the northern Great Barrier Reefs. The samples recovered from the borehole at Bewick (Thom, Orme & Polach 1978, part A of this Discussion) indicate that the last major advance of the sea covered a discontinuity surface on the reef at 4 m depth below present low water of spring tides (l.w.s.t.) at about 6300 a B.P. (Polach, McLean, Caldwell & Thom 1978, part A of this Discussion). Presumably very shortly after this the sea first reached its present level during the last major transgression, for the oldest in-place intertidal corals on the reef flats of nearby reefs are 5850 years old (Polach *et al.* 1978).

In this region the living reefs project from a shelf seabed that is about 30 m deep, so borehole evidence suggests that a maximum of only about one-eighth of the reefs' vertical thickness resulted from the growth during the last transgression of the sea. Consequently the major form of the reefs had developed long before the present sequence of continuous reef-top growth commenced.

2. HOLOCENE

2.1. *Introduction*

In the Northern Province of the Great Barrier Reef, reefs near to sea level grow in two distinctly separate environments. One is at the shelf edge where long 'ribbon' reefs grow on the crest of a steep slope facing the open Pacific Ocean, the other is in the shelter of the barrier where individual reefs grow in roughly equidimensional planimetric proportions from a shelf floor of 20–40 m depth. The logistics of the expedition necessitated that most study should be given to the inner-shelf reefs and the results presented here relate principally to these. Our conclusions are drawn from a range of observations made during one visit to the region. These observations include aerial surveys, subsea surveys by SCUBA diving, land surveys including drilling, and geophysical surveys.

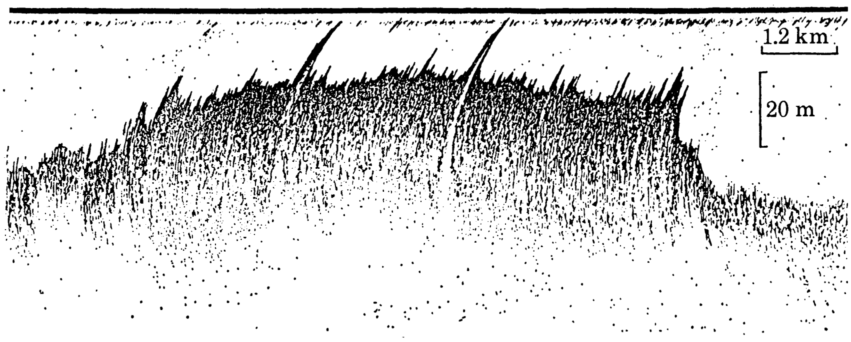

FIGURE 1. Echogram of a reef that does not reach sea level showing the steep coral covered projections; 16 km ENE of Three Isles.

DESCRIPTION OF PLATE 1

FIGURE 2. Underwater photograph of a coral prominence (or bommie) showing the steep side with projecting branching corals. Leeward margin of Green Island; 3 m depth.

FIGURE 3. Underwater photograph of fallen branches of *Turbinaria* regrowing in a new orientation from a valley floor. Turtle III 'Blue Hole'; 3 m depth.

FIGURE 4. Underwater photograph of the upper limit of open-water reef growth. Massive *Porites* corals develop microatoll form. Leeward flanks of Low Isles; 1 m depth.

FIGURE 5. Oblique aerial photograph of the leeward sand split on E Pethebridge Reef. Note the refraction of the waves. Altitude: 200 m.

FIGURE 6. Oblique aerial photograph of Sinclair–Morris Reef showing leeward sand cay with sand spit, partial surround of beach-rock and vegetation cover. The windward side has a smooth arcuate margin and thin mangrove cover. Altitude: 200 m.

FIGURE 7. Aerial photograph of the windward margin of Howick Reef showing the narrow extent of windward growth from the granite island. Altitude: 200 m.

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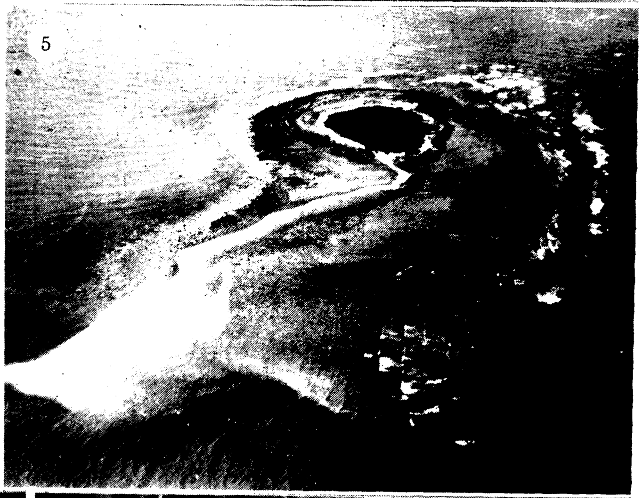

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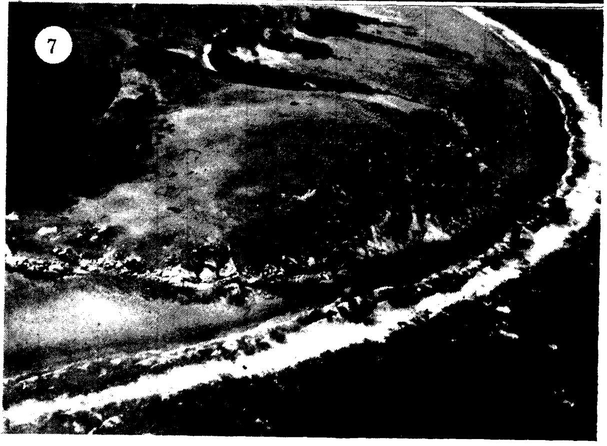


FIGURES 2–7. For description see opposite.

DESCRIPTION OF PLATE 2

FIGURE 11. Oblique aerial photograph of part of the Turtle Group of reefs showing their leeward development. Altitude: 300 m.

FIGURE 12. Oblique aerial photograph of the leeward margin of Michaelmas Reef showing numerous shallow bommies. The white area to the right is the east tip of the leeward sand cay. Altitude: 150 m.

FIGURE 13. Leeward flanks of Low Isles showing a large dead microatoll embedded in coral shingle. This microatoll probably represents a former open-water bommie.

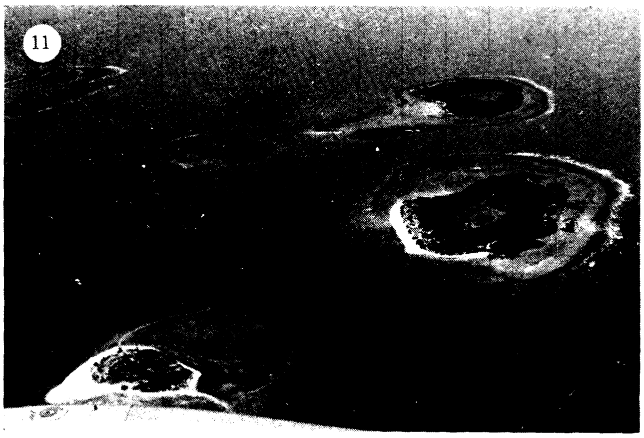
FIGURE 14. Loose shingle rampart on the windward side of Turtle III Reef. The rampart front advances over eroded cemented rampart foresets. Hammer 30 cm long.

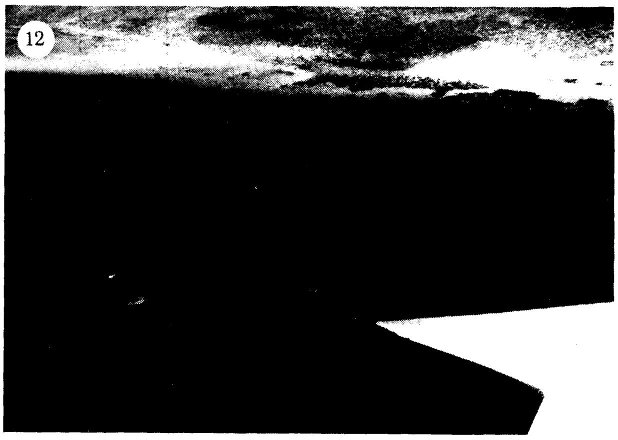
FIGURE 15. Vertical aerial photograph of Three Isles Reef taken in 1945 (by the Australian Royal Air Force). Maximum diameter of reef is 1 km.

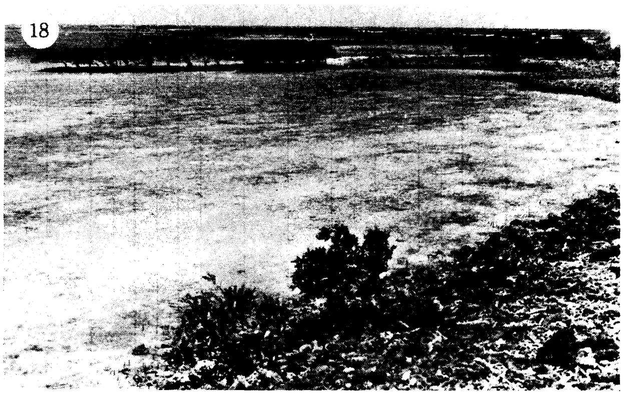
FIGURE 16. Oblique aerial photograph of the eastern flank of Three Isles Reef, taken in 1973, showing marked addition of rampart material since 1945.

FIGURE 17. Oblique aerial photograph of the western flank of Three Isles Reef taken in 1973 showing that the additional rampart material since 1945 is concentrated at former ramparts. Note that the long tongue of cemented shingle in the foreground is currently eroded at reef flat level (figure 25) to reveal former rampart foresets.

FIGURE 18. *Avicennia* mangroves colonizing ramparts. Pipon Reef.







FIGURES 11–18. For description see opposite.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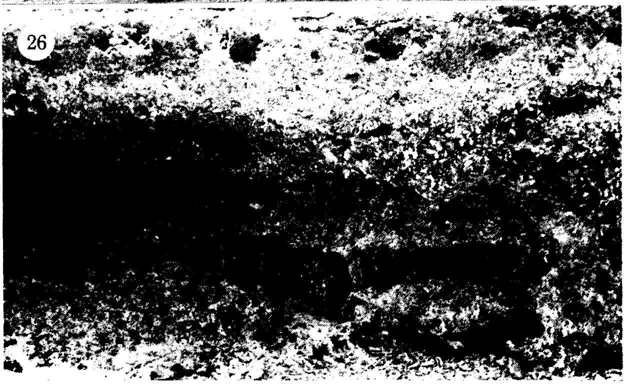
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Figures 19–26. For description see opposite.

2.2. *Reef development up to low water spring tide level*

Echogram profiles (figure 1) and visual observations during Scuba diving on shallow reefs show that present growth develops an irregular surface of knobs and depressions. These observations and the evidence from the bores in Low Isles reported by Marshall & Orr (1931) indicate that reefs do not grow from depth up to sea level as even broad solid structures but rather that growth is localized at scattered prominences. These projections are built of massive and branching corals (figure 2, plate 1) but it is the greater stability and resistance to erosion that permits the massive corals to remain in place while many of the platy and branching corals eventually break from the framework and fall into the valleys. Some of the toppled branches continue growth from valley floors though renewed growth may be at an angle to former growth (figure 3, plate 1) but most add to the accumulation of rubble and sand in the depressions. All factors favour the growth of prominences:

(*a*) shallow corals are known to grow more rapidly than deep corals;

(*b*) the higher surfaces escape excessive sedimentation;

(*c*) upward pointing growth is stable, whereas outward growth more readily breaks off. Consequently, once a few projections are established they could supply sediment to neighbouring valleys making growth there more difficult.

Eventually the framework structure reaches l.w.s.t. level and upward growth stops. Characteristic growth forms of massive and branching corals are developed at this level (Scoffin & Stoddart 1978, this volume) and the frame expands laterally only (figure 4, plate 1). The valleys become occluded and eventually grown over or filled up with sand. This flat surface of patchy framework and sand is then later veneered by intertidal deposits.

2.2.1. *Wind influence*

The trade winds from the SE drive waves, which are commonly 2–3 m in amplitude, across the shelf. The steady force of waves on shallow reefs causes the development of characteristic

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Description of plate 3

Figure 19. Oblique aerial photograph of the windward margin of Mid Reef showing concentric banding. Altitude: 200 m.

Figure 20. Platy coral shingle (each about 15 cm diam.) on the windward margin of the reef flat showing varying degrees of corrosion resulting from the boring activity of microscopic filamentous algae. Hampton Reef.

Figure 21. A freshly broken shell of a giant clam revealing large lined borings by *Lithophaga* bivalves (about 1.5 cm diam.) and numerous small borings by *Cliona* sponges. Meguera Reef.

Figure 22. A coral boulder (50 cm diam.) corroded by the borings of numerous *Tridacna crocea* shells. Low Isles.

Figure 23. A 1 m high cliff of rampart-rock that is notched at the mean low water neap tide level revealing in place microatolls of a former reef flat. Watson Reef.

Figure 24. A flat platform of cemented shingle that ponds water to leeward, to the left of the photograph, up to a level of 1.6 m above datum, at low tide. The loose shingle, to the right, ponds water to 0.8 m above datum at low tide. The open sea level at low water spring tide is 0.5 m above datum. Corals currently grow in each body of water up to the level at low tide.

Figure 25. Bassett-edge relief of a partly eroded tongue of cemented shingle (the long tongue shown in figure 17). The level of planation of this rock (reef flat level) is down to a former level of reef flat. Three Isles.

Figure 26. Cliff of cemented shingle showing present erosion is down below the foundation level of the *in situ* microatoll preserved in the rock. Hammer 30 cm long.

windward and leeward coral assemblages. On the windward margin branching corals of *Acropora* species are dominant; on the flanks and leeward margins, though branching corals are common, massive corals, especially *Porites*, abound. The different growth forms of the windward and leeward corals are reflected in the type of coarse sediment around the reef rim (Flood & Scoffin 1978, part A of this Discussion).

The waves play an important rôle in the transport of sediment on shallow reefs. The swell meets the windward front at 90° and is bifurcated. The two wave sets are refracted as they pass the flanks of the reef and they impinge at an acute angle to the reef margin. This results in longshore drift of sand around reef sides such that on the leeward margins spits develop, or where the two opposing wave sets meet a deposit of sand accumulates (figures 5 and 6, plate 1).

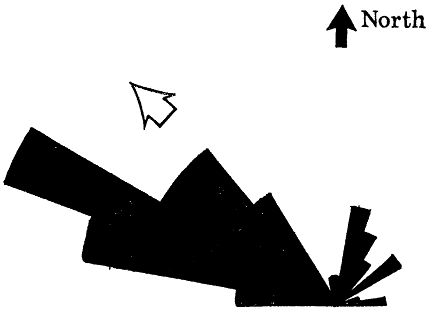

FIGURE 8. Rose diagram showing the direction of the long axes of 67 shallow inner-shelf reefs of the northern province. The orientation of Recent longitudinal dunes on the mainland at Cape Flattery is shown by the open arrow.

The wave refraction and consequent peripheral sand transport are thought to be the major factors responsible for the regular smooth arcuate form of the windward margins of so many inner-shelf reefs (figure 6). Most of those reefs without this regular arcuate windward margin are seen not yet to have grown close enough to sea level for the waves to have full effect. The dominant orientation of the longest dimension of the shallow inner-shelf reefs of this region is SE–NW (figures 5 and 8); thus it would appear that the trade winds play an important part in governing reef configuration. Winds may influence either the form of the reef foundation (for example in building longitudinal dunes as occur on the nearby mainland at Cape Flattery) or the lateral development of reefs during growth, or both. We have no data that allow us to propose the factors responsible for the foundation shape but we can see that there is a tendency for the present lateral development of reefs to be parallel to the wind.

Framework growth occurs all around the reef perimeter but even though the windward corals are more abundant and possibly grow faster than the leeward corals, the leeward sediment transport is at a much more rapid rate than windward framework expansion. The evidence for this is from aerial photographs, echogram profiles and sediment analyses.

Aerial photographs of the windward margins of the high (continental) islands (such as Howick, Noble and South Island, Lizard Group) show a very limited lateral development of reef structure to windward of the land compared with to leeward (figure 7, plate 1). This observation is further supported by evidence from echograms of the windward and leeward margins of the reefs. These are schematically shown in figure 9. The windward slopes are steep (averaging 50° between 4 and 30 m depth), commonly interrupted by terraces and in some cases surrounded by a narrow trough. The leeward slopes are more gradual (averaging 15° between 4 and 30 m) and lack terraces and a trough, though with scattered coral prominences (figure 10). The windward terraces occur principally at depths of 3–5 m, 10–13 m and rarely at 18 m. The trough, which is only a few metres wide, extends to one or two metres deeper than the surrounding soft seabed which is at about 30 m. The terraces are presumably the remnants of earlier erosion during periods of lower sea level. The origin of the windward troughs is unknown for they were not seen visually, only on echograms. They could result from scour related to currents from the SE, for they die away around reef flanks; if so, then they must be still active for such locations are normally the resting places of reef-front talus. The absence of terraces on the leeward slopes suggests that burial here is more rapid than on the windward slope.

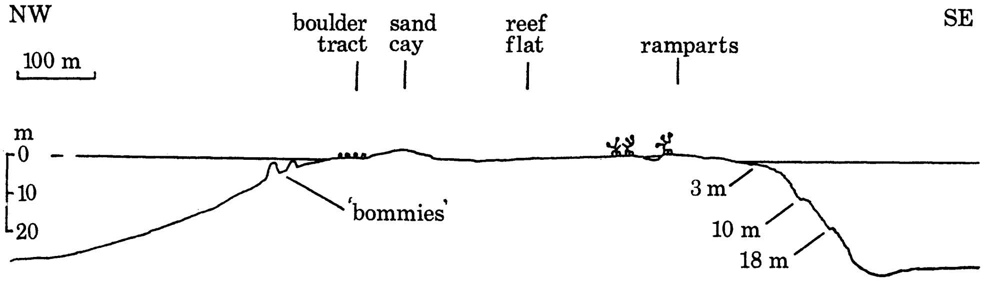

Figure 9. Schematic windward–leeward profile of an inner-shelf reef based on echograms from Low Isles, Three Isles and the Howick Group.

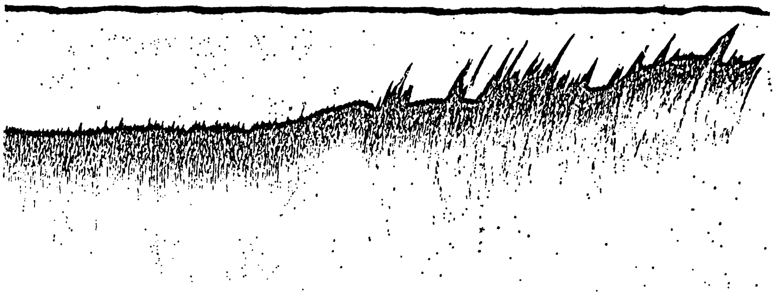

Figure 10. Echogram profile of the leeward margin of Michaelmas Reef (the reef flat is to the right) showing gradual sandy slope with steep coral covered projections or bommies. (Many bommies reach the surface (see figure 12) but were avoided during profiling.)

Dyed sand tracer experiments on Ingram–Beanley reef indicated a net leeward migration of sand across the reef flat (Flood & Scoffin 1978), supporting the conclusions of Marshall & Orr (1931) who conducted sediment trap experiments on Low Isles. Doubtless, wind-induced currents carry sand-sized and finer grains to leeward across reef flats during low water but also tidal currents drain to leeward across most of the central and leeward parts of the reef flat during ebb on account of the shallow slopes to leeward of reef flats. During flood tide the incapacity of the tidal current to carry sediment up-slope against still-draining water restricts the return of sediment. Both the physiographic features of reef marginal areas and the sediment composition (Flood, Orme & Scoffin 1978, part A of this Discussion) indicate the building of a leeward cone of sediment from a reef-top source. These submarine deposits plus the intertidal sediment tails and spits extending from innershelf reefs (figures 5, and 11, plate 2) cause the reef axes to parallel the wind direction and the main lateral development to be to leeward. The high coral patches (locally termed 'bommies') to leeward (figures 2, 10, and 12, plate 2) are progressively buried and incorporated into the reef (figure 13, plate 2).

It is difficult to assess the rate of this leeward extension of reefs. The observation of 30000-year-old reef sediment only 4 m below l.w.s.t. level on the leeward edge of the leeward sand cay on Bewick Reef (Polach *et al.* 1978) suggests that here little leeward extension beyond the elevated foundation has occurred over Holocene time, though the Stapleton reef core data (Polach *et al.* 1978) where 11 m below l.w.s.t. level a fossil coral dates at only 5260 years old, suggest more rapid leeward extension.

2.3. *Reef development above low water spring tide level*

Once the reef has reached sea level the physical gradients are markedly sharpened. Wave erosion of reef-front corals is intensified and the ability of waves to carry coarse sediment across the reef is rapidly reduced. The consequence of this is that coarse sediment eroded during heavy waves is piled up around the rims of reefs. Finer sediment spills over the rim to fill any remaining depressions on the reef top.

2.3.1. *Sediment bodies*

The tops of inner-shelf reefs that have grown to sea level are characterized by the following sediment bodies: shingle ramparts, boulder tracts and sand cays at the rims, and a reef flat sand blanket.

2.3.1.1. *Shingle ramparts.* The branching corals on the windward margin of reefs readily break to form rods or plates of shingle which pile up at the windward rim and flanks of reefs as large asymmetric ripples, known as ramparts, with amplitudes about 1 m (figure 14, plate 2). Commonly several sets of ramparts occur on one reef with the older ones lithified intertidally by cements precipitated from sea water (Scoffin & McLean 1978, part A of this Discussion). The ramparts may pile one on to another developing ridges or they may be separated by narrow shallow moats. Ramparts form and move significantly during heavy storms whose frequency is on the scale of years or tens of years (figures 15, 16 and 17, plate 2) (Stoddart, McLean, Scoffin & Gibbs 1978, this volume; Fairbridge & Teichert 1948; Scoffin & Stoddart 1978, this volume).

2.3.1.2. *Boulder tracts.* At the leeward margin of reefs, massive coral colonies abound and provide a source of sediment. Discrete coral boulders are piled up during storms at the leeward rims of reefs, into linear boulder tracts. It is thought that boulders do not move significantly once deposited on the reef top for the tracts are discrete features, successive boulder tracts being separated by a moat. Also boulders are commonly partly surrounded by matrix and cement. The pattern of boring, intertidal notching and encrustation on boulders is consistent with one position since deposition. If a boulder tract is immobile after formation and if it can be assumed that little lateral erosion of fossil boulder tracts has occurred, then the distance between two boulder tracts on one reef could represent the lateral expansion of a reef over the period between the two periods of deposition. The scant dating data available on boulders suggest that this expansion is of the order of 1.5 cm/a. This is not large considering that the sediment supplied to the leeward margin is derived from all around the reef and the reef top.

2.3.1.3. *Sand cays.* Sand cays develop on the leeward margins of reefs at the confluence of the two opposing sets of refracted waves. Sands from the beaches are built by storm waves and wind action into cays above high water spring tide level. The cays consist of well sorted, rounded sand grains derived from the reef top and margin and consist principally of coral fragments, benthonic Foraminifera, calcareous algae and molluscs. Locally pumice and soil horizons occur. Two main cay terraces have been observed on the sand cays at 3.5 and 5 m elevations (McLean & Stoddart 1978, part A of this Discussion) and the loose cay sands range in age from 2190 ± 70 a B.P. to 4380 ± 80 a B.P. of 18 samples ^{14}C dated (Polach *et al.* 1978). The sand cays are stabilized by freshwater vegetation and by intertidal lithification by fibrous aragonite cements into beach-rock (figure 6). Though cays do show slight seasonal variation in form (Flood 1974; Spender 1930; Steers 1937; Stoddart, McLean & Hopley 1978, this volume) it is thought that their positions have not altered significantly since their inception as relic beach-rock is not found far removed from present cays on reef flats.

2.3.1.4. *Reef-flat sand blanket.* All inner-shelf reefs have a large part of the intertidal reef top – normally the central and leeward areas – veneered by sand. Probing with a metal rod showed this loose sand to be less than a metre in thickness. The surface sand is mobile in all the exposed areas of the reef top but where the reef top has a dense cover of mangroves, sand and mud sediments are trapped and immobilized. The sandy substrates on reef tops support a varied in-fauna (Gibbs 1978, this volume).

2.3.2. *Reef-top biology*

The sand bodies that build on the reefs and their cemented equivalents, can locally influence the ecology of the intertidal reef surface. Ramparts and boulder tracts can pond water into moats which remain flooded throughout low tide. Marine organisms including corals live and grow in the moats. Characteristic of the moats is the microatoll form of coral which because of its limited upward growth develops a dead, flat top and living lateral margins. Moats are normally less than 50 cm deep depending upon the height and permeability of the damming ramparts, consequently moat microatolls are broad thin colonies with high breadth : thickness ratios (open-water microatolls have low breadth : thickness ratios; see Scoffin & Stoddart 1978, this volume). The maximum elevation to which microatolls can live is high water neap tides (i.e. 1.6 m above datum). Branching corals, dominantly *Montipora*, *Porites* and *Acropora*, are also common in ponded water on reef flats and are occasionally found growing on the seaward slopes of ramparts where moat water seeps through during low tide.

There is a strong correlation between rampart distribution and the occurrence of mangroves. On the local level mangroves are seen to preferentially colonize the less exposed parts of shingle ramparts (figure 18, plate 2). On a broader scale the limits of mangrove distribution across the shelf away from the mainland correspond closely with the limits of rampart distribution (Scoffin & McLean 1978, part A of this Discussion). The distribution of mangroves on reefs indicates that they require a stable substrate in the intertidal position for colonization. Pioneer growth is on loose ramparts (e.g. E Hope), later growth spreads to the now sheltered substrates of the windward side of the reef flat (Two Isles, Three Isles, Pipon, Low Isles, Watson, W Hope), and eventually the flat is overgrown across to the leeward sand cay (Bewick, Howick, Houghton, Coquet, Newton, Nymph, Turtles).

The other common marine vegetation present in the permanently flooded areas of the reef flat consists of marine phanerogams (notably *Thalassia*) and algae. *Thalassia* and some of the soft algae require loose sandy substrates of at least a few centimetres thickness, other algae (e.g. *Sargassum*, *Caulerpa*) prefer firm rocky substrates. This edaphic control is partly responsible for the concentric zonation of vegetation across the margins of the reef flats, since soft and hard substrates (probably related to former shingle deposits) occur in roughly concentric bands near the rim (figure 19, plate 3).

The reef-top carbonate-producing organisms can be subdivided into two groups: first, those that are either unattached or else readily disintegrate on death and secondly, those that are anchored to a firm substrate. The dominant members of the first group include benthonic Foraminifera (with *Calcarina*, *Baculogypsina* and *Marginopora* being the most abundant) and branching calcareous algae (chiefly *Halimeda*) and molluscs.

The organisms cemented to the substrate include corals, crustose coralline algae and some molluscs (notably oysters). Analyses of reef flat and sand cay sand samples (Flood & Scoffin 1978) reveal that coral fragments are the most abundant components indicating the effective breakdown of coral colonies on the reef margin and reef flat. The reef-produced sand grains are eventually carried off the reef top, principally to lee, but do not spread very far from their source (Flood *et al.* 1978, part A of this Discussion).

On the windward margin of reefs, wave action persistently pulverizes coral branches and on the reef flat numerous organisms either graze the surface of, or bore into, carbonate grains and, with time, cause disintegration to smaller particles. The dominant grazers are molluscs and echinoids and the major boring organisms are algae (figure 20, plate 3), sponges (figure 21, plate 3), worms and bivalves: *Lithophaga* (figure 21) and *Tridacna crocea* (figure 22, plate 3). The zone of most effective bioerosion is in the intertidal position between high water neaps and low water neaps. Any stable carbonate projections such as coral boulders, dead microatolls and large dead clams, are truncated down to the level of sand accumulation on the reef flat, that is about low water neap tides. Cliffs of cemented ramparts are undercut by bioerosion, producing a slight notch at the level of the present reef flat (figure 23, plate 3); this intertidal notch is an intermediate stage in the planation of the rampart rock.

Thus, in summary, the reef top is a surface of both aggradation and degradation, where the processes of growth and erosion compete. On shallow reefs, prevailing physical forces interact with the growing reef to produce intertidal bodies of sediment and in turn these bodies support characteristic faunal and floral assemblages. Ultimately a large portion of the reef top may become supratidal if the depositional processes dominate the erosional.

2.4. *Recent sea level and reef-top history*

There are presently exposed on the inner-shelf reef flats in-place intertidal microatolls that date at 6080 ± 90 a B.P., 4870 ± 70 a B.P., 3700 ± 90 a B.P., 2370 ± 70 a B.P., 800 ± 60 a B.P. and modern. From this it is deduced that the first time during the last marine advance that the sea reached its present level was about 6000 years ago but that since then the tidal range from l.w.s.t. to h.w.n.t. (i.e. the limits of intertidal microatoll growth) has always overlapped to some degree with the present tidal range from l.w.s.t. to h.w.n.t. (currently this is 1.1 m).

The highest in-place fossil microatolls are found in rampart rocks at 0.7 m above present high water neaps (Scoffin & Stoddart 1978, this volume) and they date about 3500 a B.P. (Polach *et al.* 1978). This indicates that 3500 years ago, high water neap tide level was at least 0.7 m higher than it is at present. However, this difference in level could result from a change in tidal range, or in mean sea level, or both. If there has been a change in mean sea level then other sea level indicators besides reef-flat microatolls should be preserved as fossils at high levels:

(*a*) Open-water reef framework (present maximum elevation l.w.s.t. 0.5 m). No exposures were found of fossil open-water reef framework, though this absence is not conclusive proof of no change in l.w.s.t. level, for a 0.7 m drop in sea level would place former open-water framework only at the level of the present reef flat. A few shallow excavations were made below the reef flat rocky and sandy substrates to maximum depths of 50 cm but they revealed only intertidal deposits. It is unlikely that high open-water reef framework did exist on the reef flats and has been subsequently eroded as so many other high features of this period have been preserved, including microatolls, ramparts and boulders. Presently large *Porites* colonies (locally termed 'bommies') grow on the flanks and leeward slopes of reefs (figures 10 and 12) up to levels of 0.5 m above datum. Exposures of large dead *Porites* colonies at reef rims (figure 13) with their surfaces at about 0.8 m above datum possibly represent fossil open-water 'bommies' though regrettably cores were not taken to confirm the low breadth/thickness proportions of these corals to indicate their open-water origin, neither were samples collected for ^{14}C dating.

(*b*) Limestones. Our observations suggest that beach-rock forms up to extreme high water spring tide level (2.9 m). Therefore a recent fall in sea level should expose beach-rock higher than 2.9 m on leeward sand cays whose loose sand dates at 3500 a B.P. or more. Though high beach-rocks are rare, there is evidence from Stapleton and Houghton of raised beach-rock about 0.4 m above present e.h.s.t.

Of special interest in this area of the Great Barrier Reef are the high platforms of cemented shingle (figure 24, plate 3). The deposits are basically lithified ramparts and the flat surface is one of deposition, not erosion (Scoffin & McLean 1978). Flat depositional surfaces form today at various intertidal levels and consequently it is not possible to interpret the high platform levels (maximum 3.5 m) by this criterion. If we use lithification levels and it is assumed that the maximum elevation of lithification of ramparts is the same as beach-rocks, i.e. e.h.s.t. (though a cautionary note should be added that rampart rocks all have a muddy matrix and it is not impossible that under the influence of capillary forces lithification could take place in the supratidal zone), then the surfaces of high platforms dated about 3500 a B.P. represent a former e.h.s.t. of 0.6 m higher than today.

(*c*) Erosional features. Present levels of reef flat erosion are about low water neap tides. Where high rampart rock is eroded flat surfaces of older shingle deposits are exhumed and their level corresponds to the dominant level of the present reef flat (figures 17 and 25, plate 3). No high erosional features are evident on the inner shelf reefs though the positions of the high microatolls in cliff sections (figure 26, plate 3) point to the seaward erosion after 3500 a B.P. of first those shingle deposits which formed the foundation on which these microatolls were seated, and secondly, the higher deposits which formed the barrier that ponded the water in which the microatolls grew.

It is the blending of these erosional features with masking depositional features that makes the interpretation of the recent history of the inner-shelf reef flats so complicated. Nevertheless, though complex, the features observed do present a consistent picture related to a recent change in mean sea level (McLean, Stoddart, Hopley & Polach 1978, part A of this Discussion). The available dating and levelling evidence point to the following conclusions:

About 6000 years ago, sea level reached its present level, and rose a minimum of 0.7 m (and a probable maximum of 1.1 m) about 3500 years ago. Subsequently, it fell to present levels perhaps by about 2000 a B.P.

2.5. *A summary of the variation in surface features of exposed reefs across the shelf*

2.5.1. *Outer barrier*

The reefs of the outer barrier have relatively little surface relief though some have a shallow lagoon. Only one reef in this region has a sand cay. Large scattered boulders principally on the windward flanks are common but there are no leeward boulder tracts. The algal rim, though with little elevation, is well developed on the ocean side of the reefs. Living corals occur over a large portion of the reef top, and very low sheets of coral rubble are common.

2.5.2. *Outer shelf*

Less than 50 % of the exposed reefs on the outer shelf have a supratidal sand cay and most of these cays have only a pioneer cover of vegetation and some beach-rock. Many of the reefs are wide with very low relief, the bulk of the reef tops are sand covered, though some reefs have shallow lagoons with living corals. Exposed ramparts are absent though the reef margins show a concentric pattern. Scattered boulders at the edges of reefs are common.

2.5.3. *Inner shelf*

The majority of the exposed reefs on the inner shelf have a leeward sand cay and these cays commonly have quite mature vegetation. On most reef tops the entire surface is elevated above l.w.s.t. and has notable relief (up to 3 m). Loose and cemented ramparts are exposed on most of the reefs, and leeward boulder tracts are normally present. There is a general trend for the extent of mangrove cover of the reefs to increase towards the mainland. Corals abound in moats but otherwise the reef tops have few living colonies.

Reefs with shingle ramparts, mangroves, sand cays and vegetation were termed 'low-wooded islands' by Steers (1929) and 'island-reefs' by Spender (1930). The appearance of the low-wooded islands on the shelf is fairly abrupt though a reef such as East Hope with some of its surface still well below low tide level and without well established ramparts could be considered to be intermediate between outer-shelf type and inner-shelf type.

Spender (1930) proposed a sequential development of surface features for reefs in this region which he noted developed across the shelf from edge to mainland. The reef classes of Spender progressively develop first a leeward sand cay, then ramparts, and finally mangroves spreading from the ramparts. At least part of this sequence has been verified by recent surveys of mangrove cover (Stoddart *et al.* 1978, this volume). Spender (1930) suggested that the elevation of the reef flat was crucial in determining which surface features were developed. Though the reefs near the shelf edge have generally lower reef flats than those towards the mainland, the difference is small (normally less than 50 cm). It seems more probable that it is the ease with which sediment can be removed from the reef top (this property relates to both reef-flat elevation, including presence of a lagoon, and prevailing physical conditions) which is vital in the building of reefs above low water level. Once the whole reef top is at the intertidal level, ramparts can build and, providing mangroves and cements are available, they can be stabilized. The effect of an initial stabilized body of reef top sediment is cumulative, for when the level of the reef rim is slightly raised it reduces the power of waves to spread new sediment, so that additional deposits can bank up on reef margins. Eventually the force required to remove the compounded sediments is beyond the scope of the environment. It is probably this exponential effect that causes the relatively sudden appearance of low-wooded islands on the shelf.

The main deposits that build reefs high above l.w.s.t. consist of coarse coral shingle and these are principally deposited at reef rims during storms, but it is left to the normal prevailing waves to disperse these sediments after storms. Consequently, shelf edge reefs are more easily freed of storm deposits than inner shelf reefs. The landward increase in elevation of reef surface features across the shelf can thus be explained entirely by the decrease in the prevailing wave energy from the barrier edge to the mainland. Leeward sand cays on the other hand are building and not eroding during normal prevailing conditions. They are therefore found on many reefs across the shelf that have at least some of their surface at sea level.

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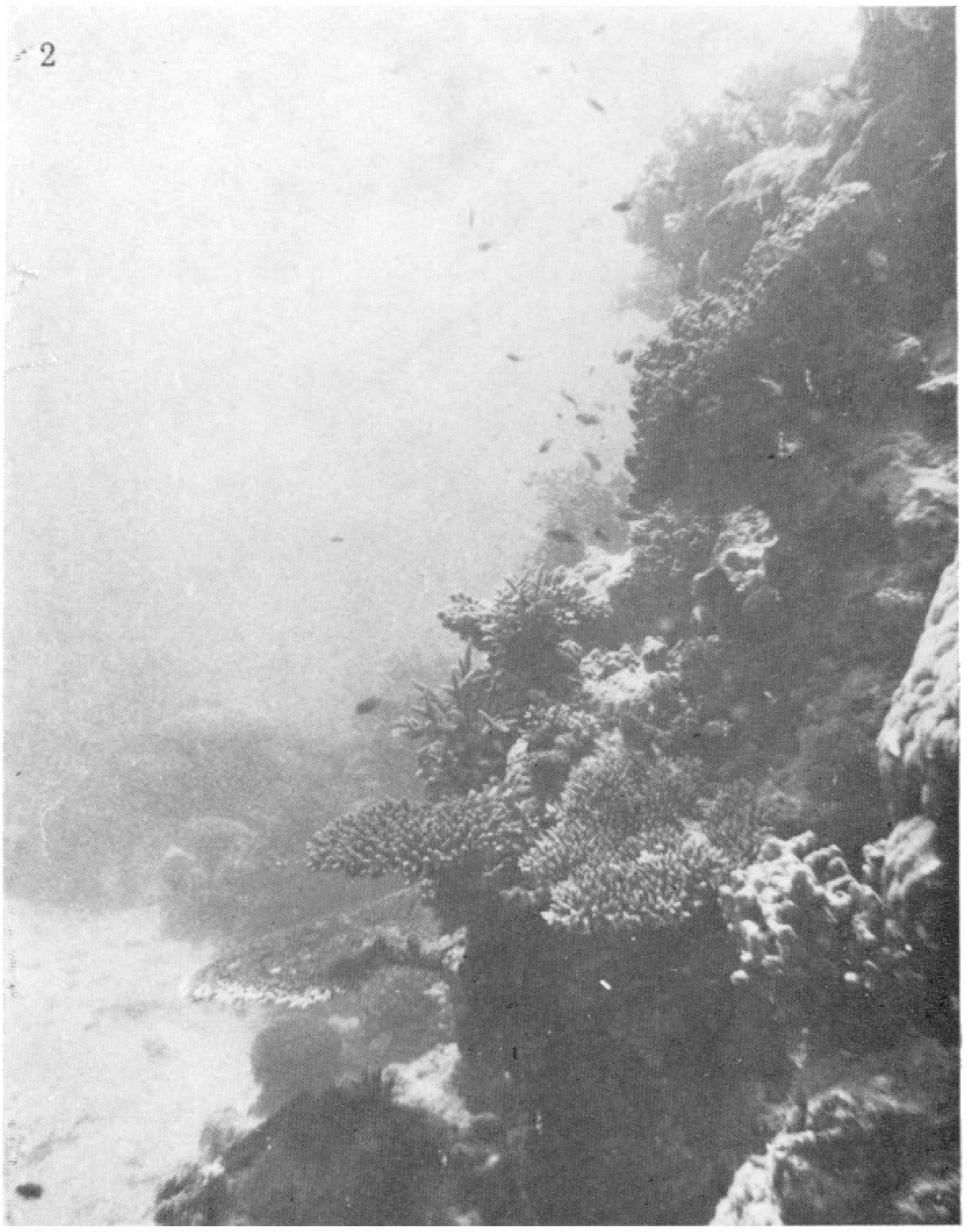
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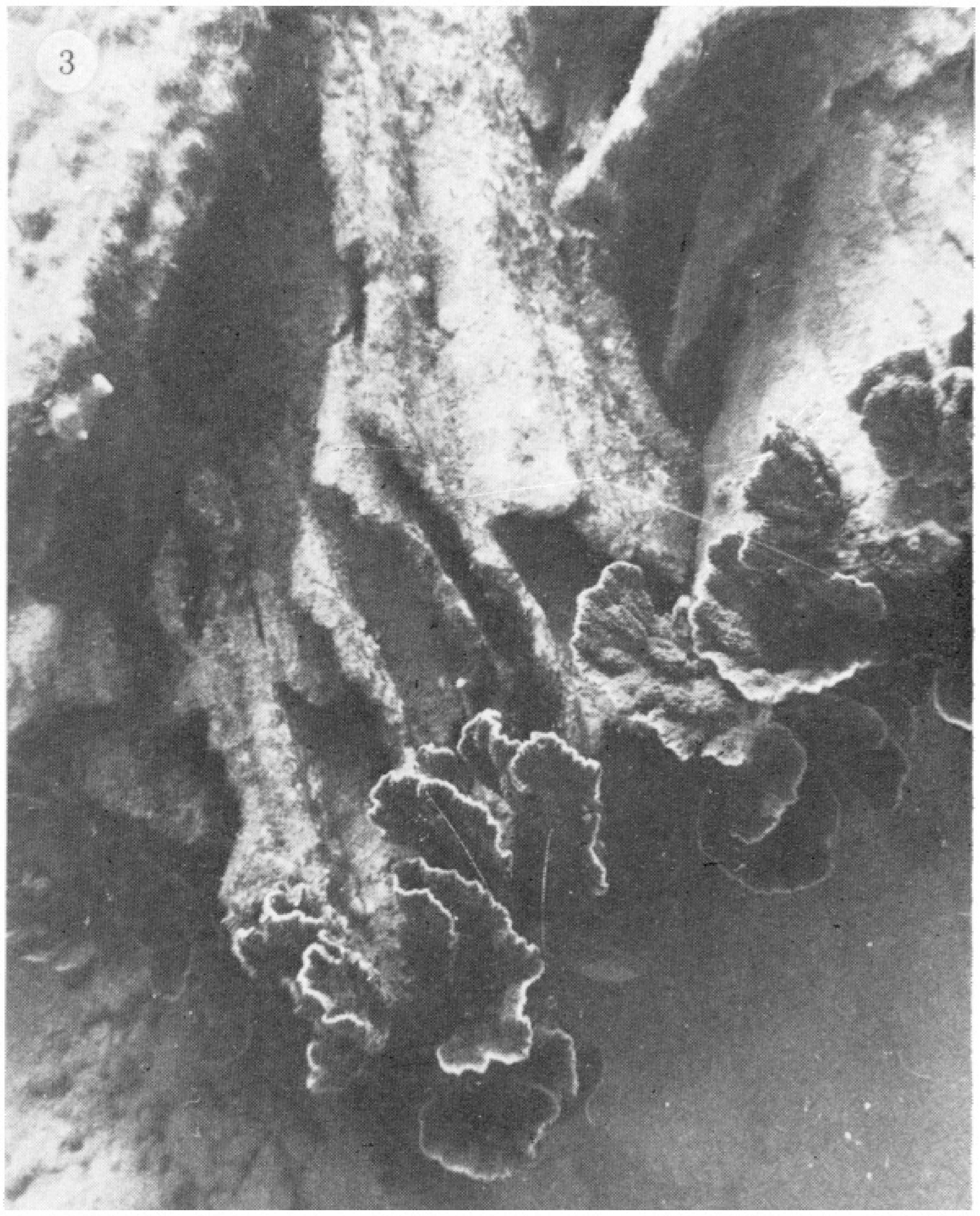
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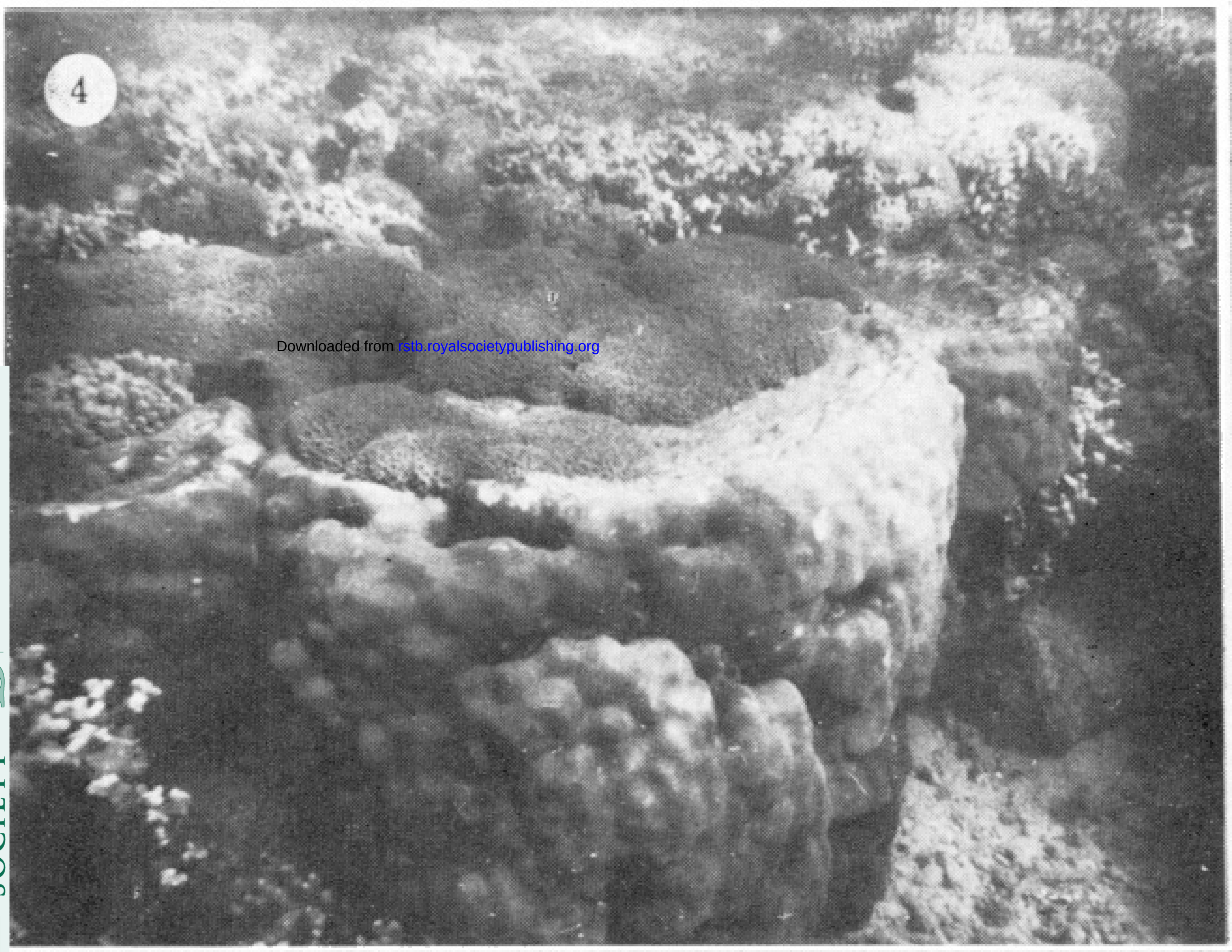
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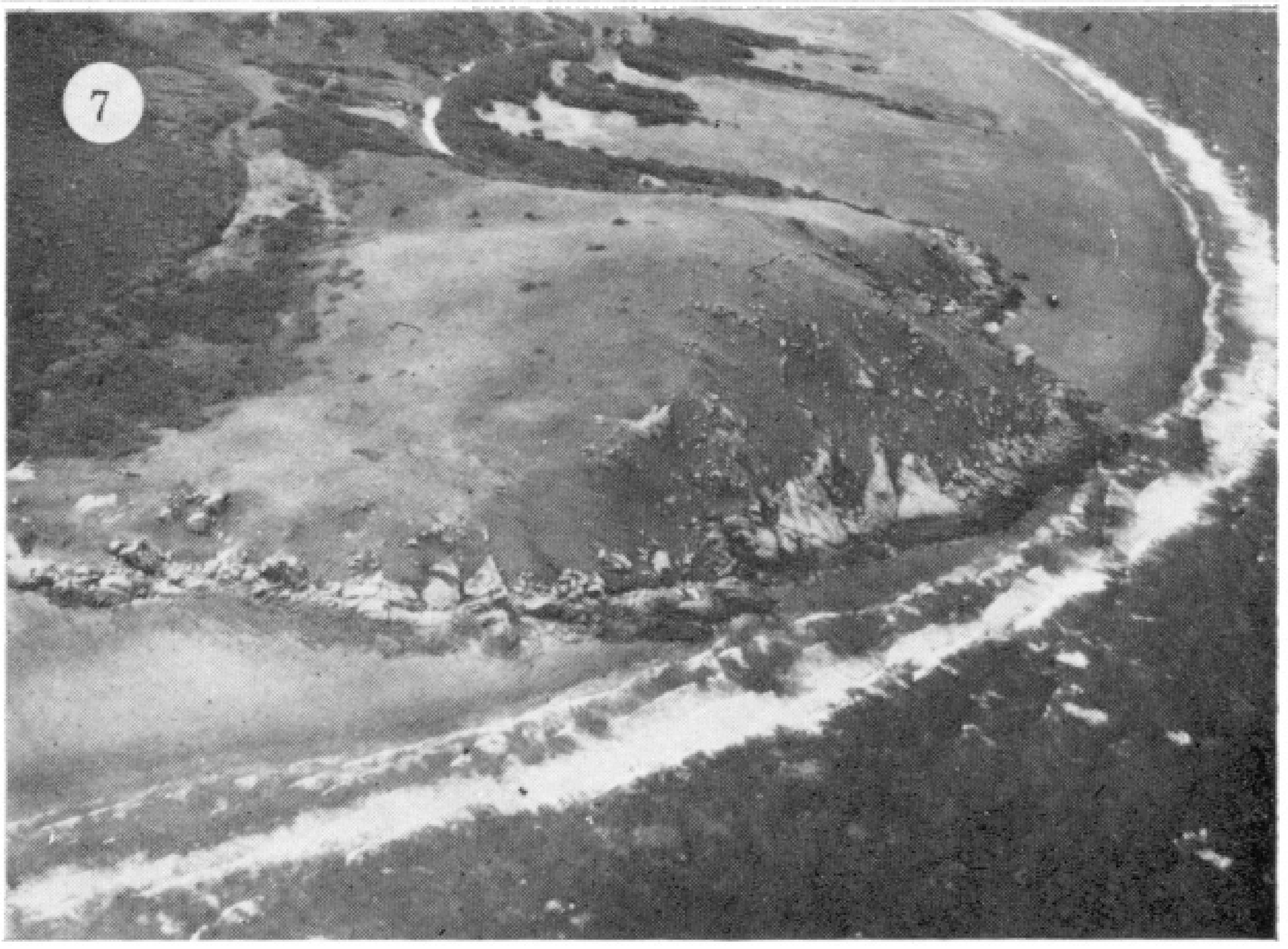
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FIGURES 2–7. For description see opposite.


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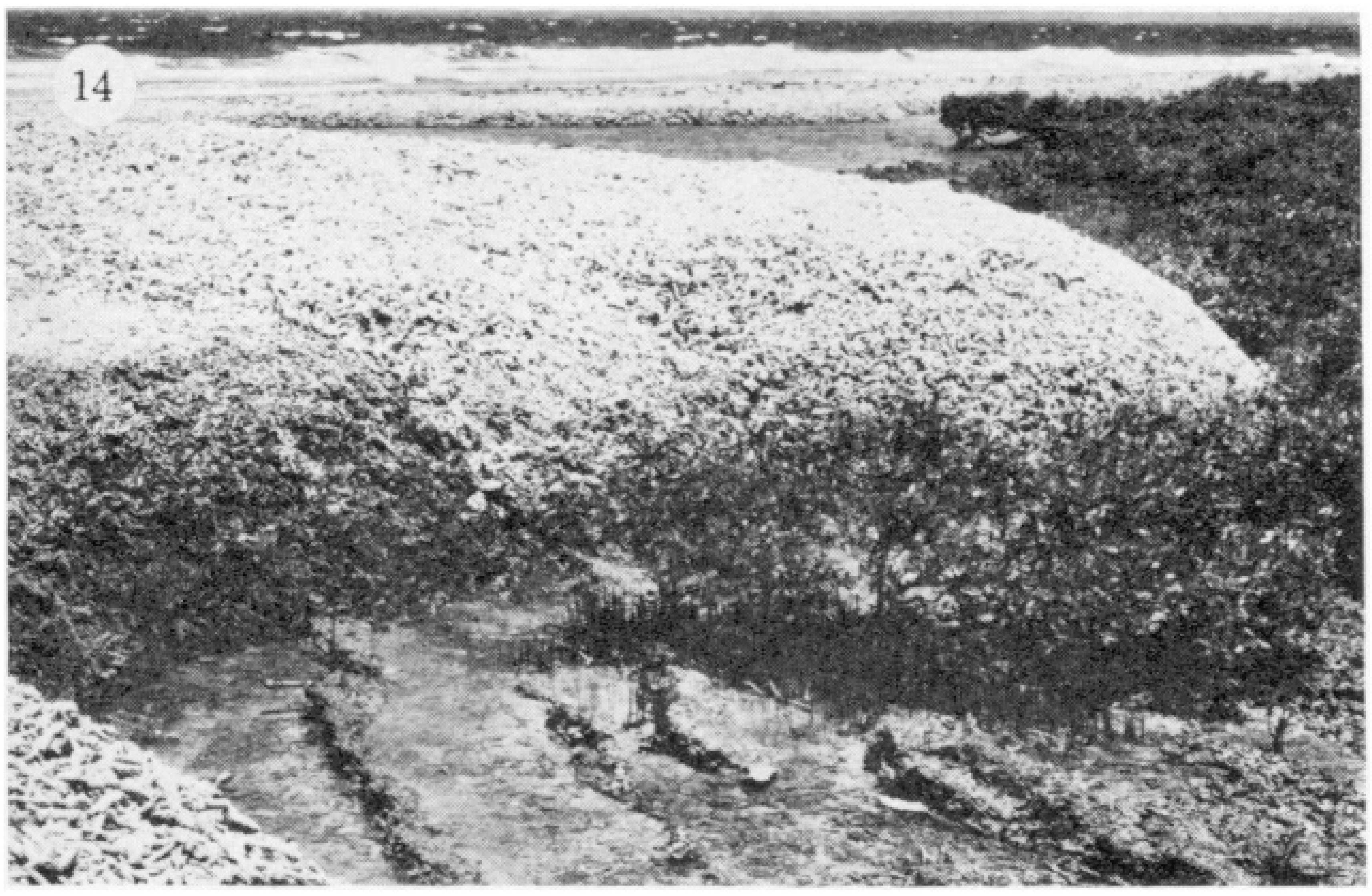
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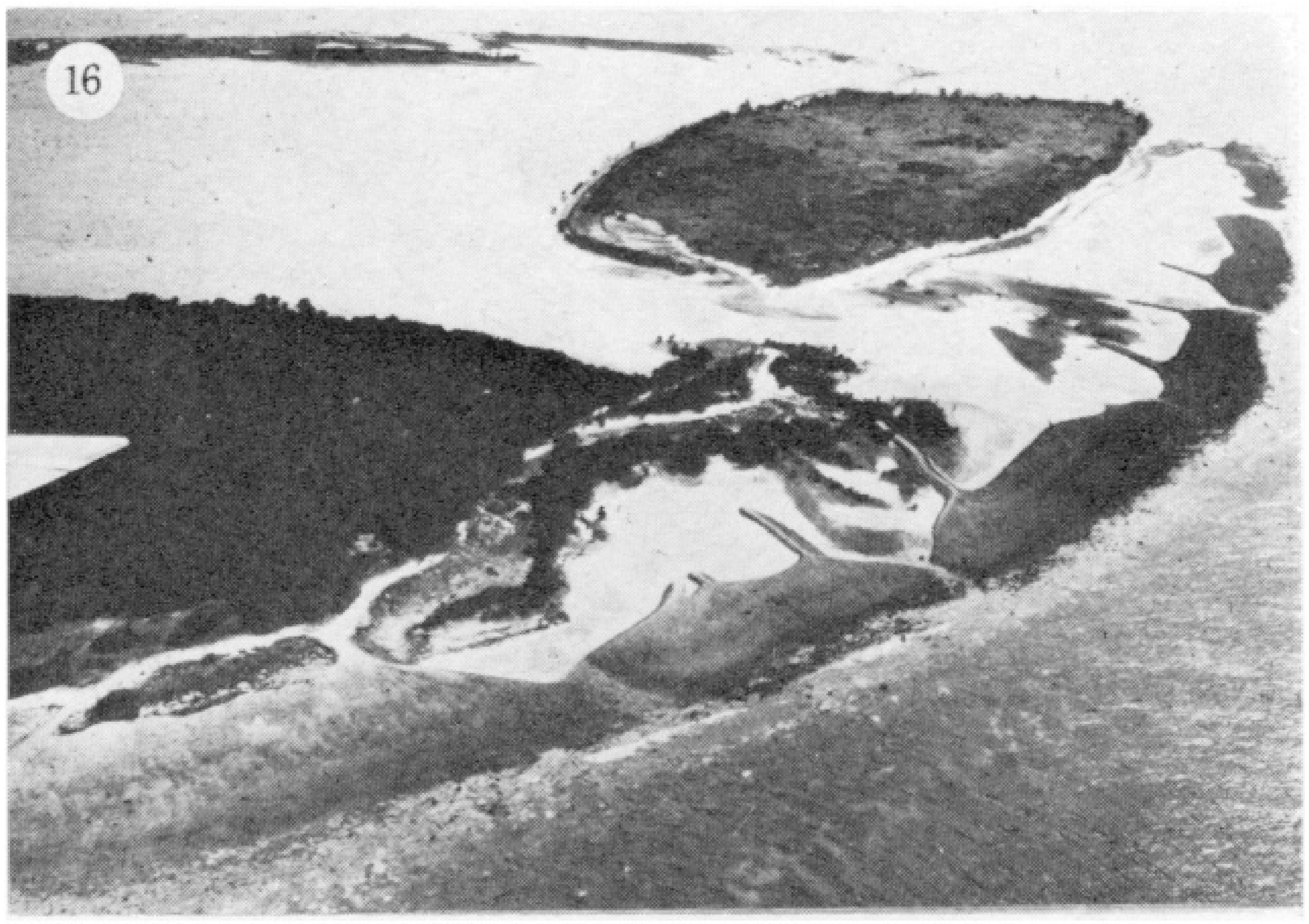
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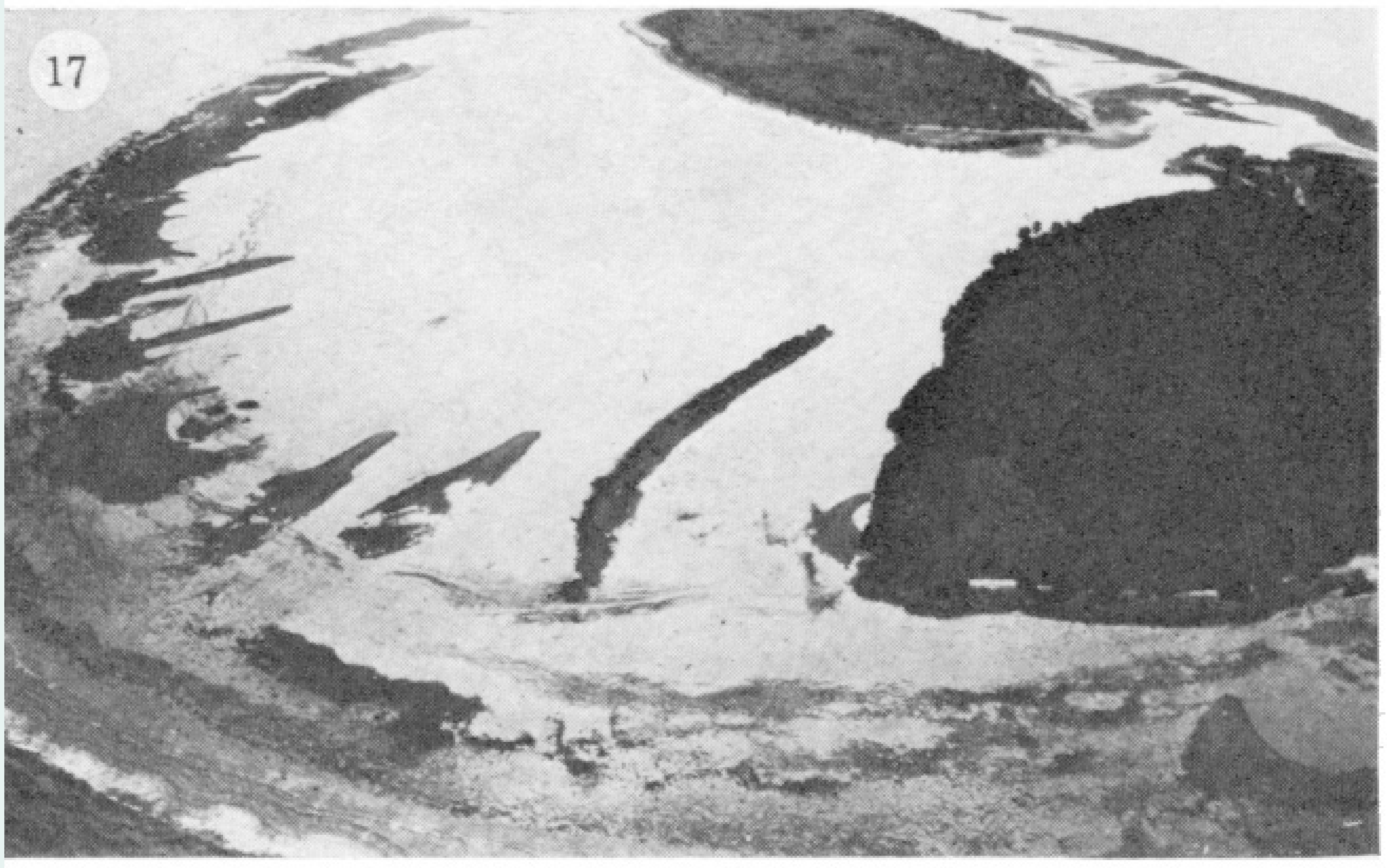
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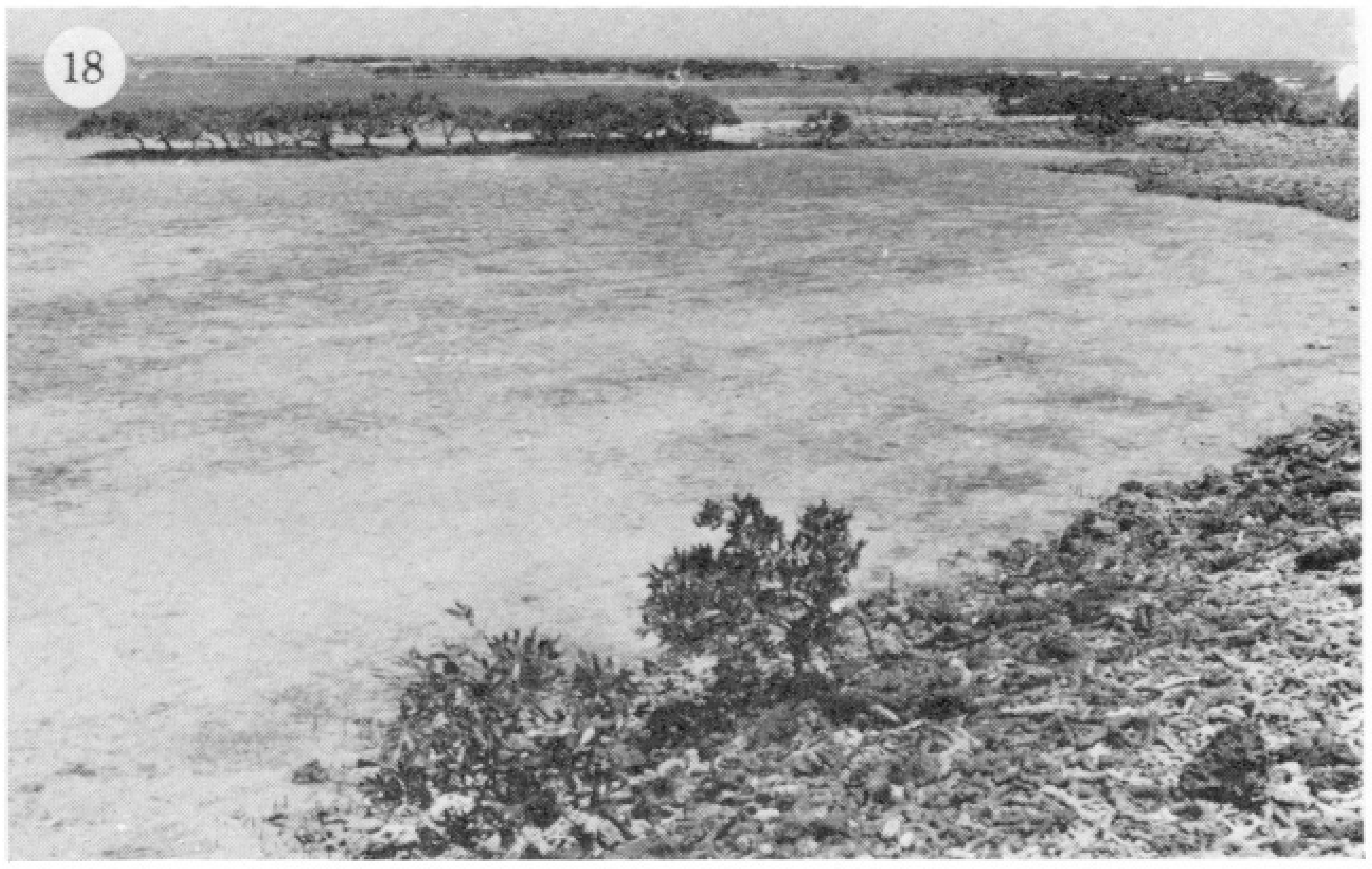
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FIGURES 11–18. For description see opposite.


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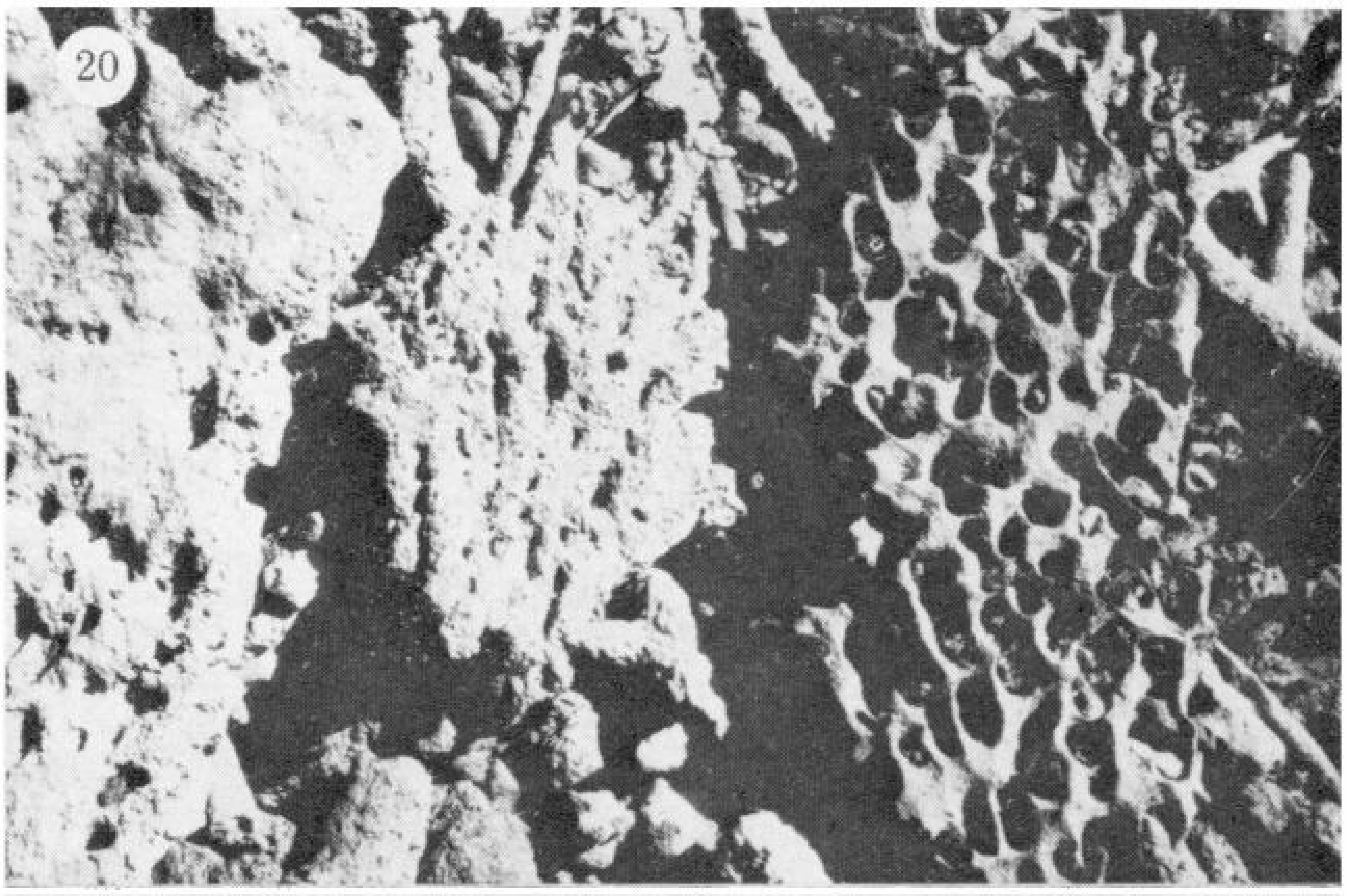
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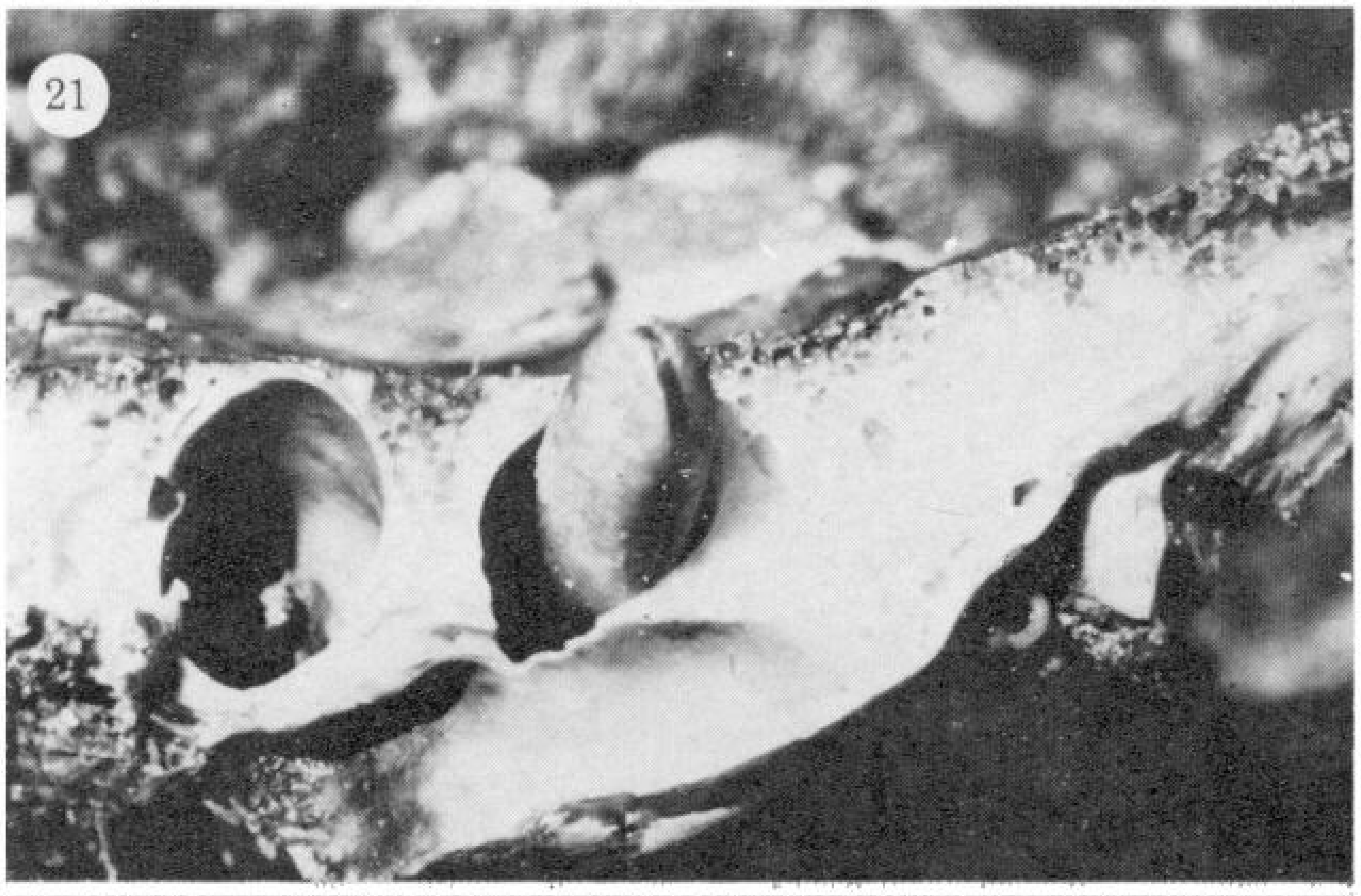
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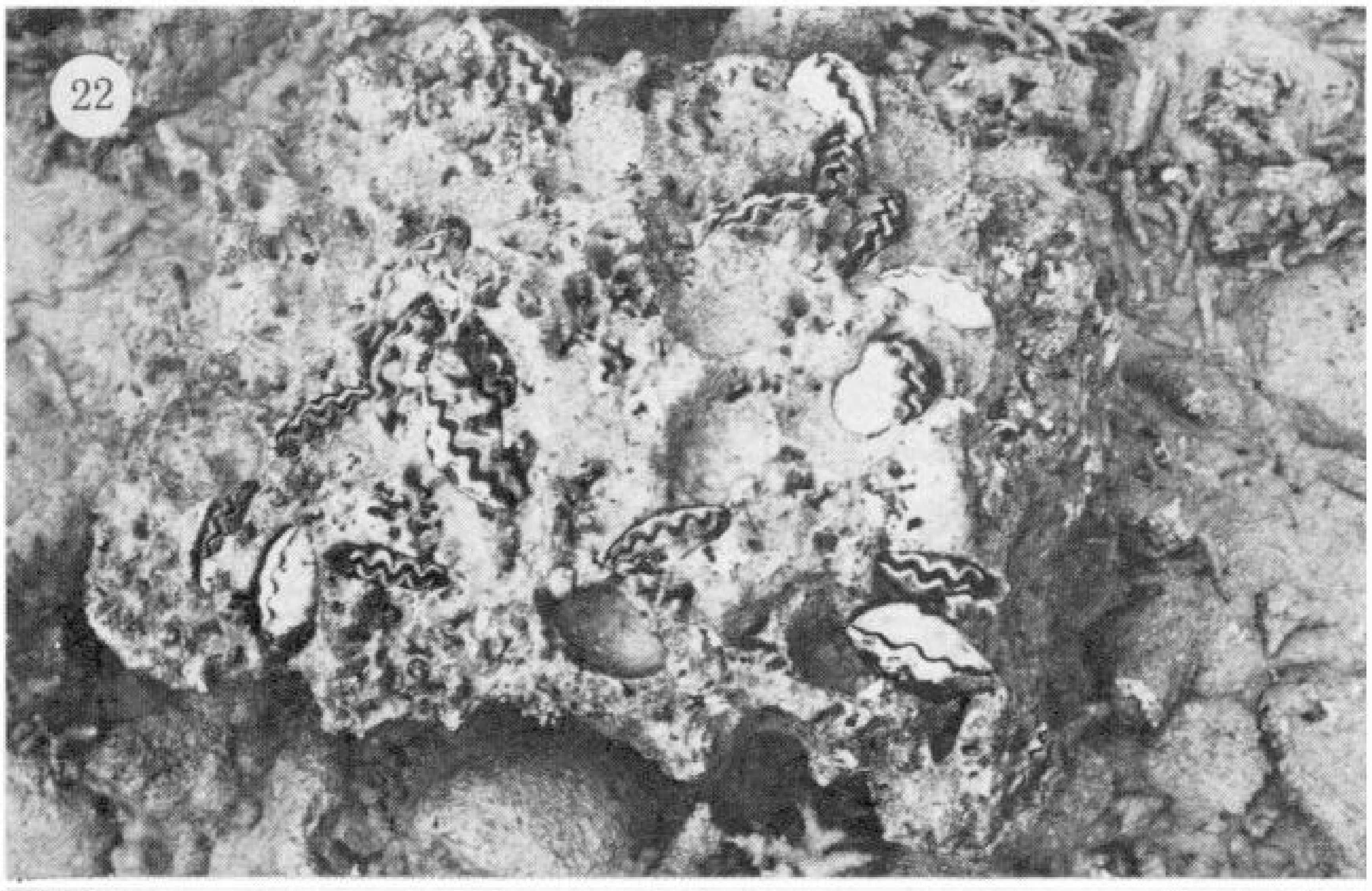
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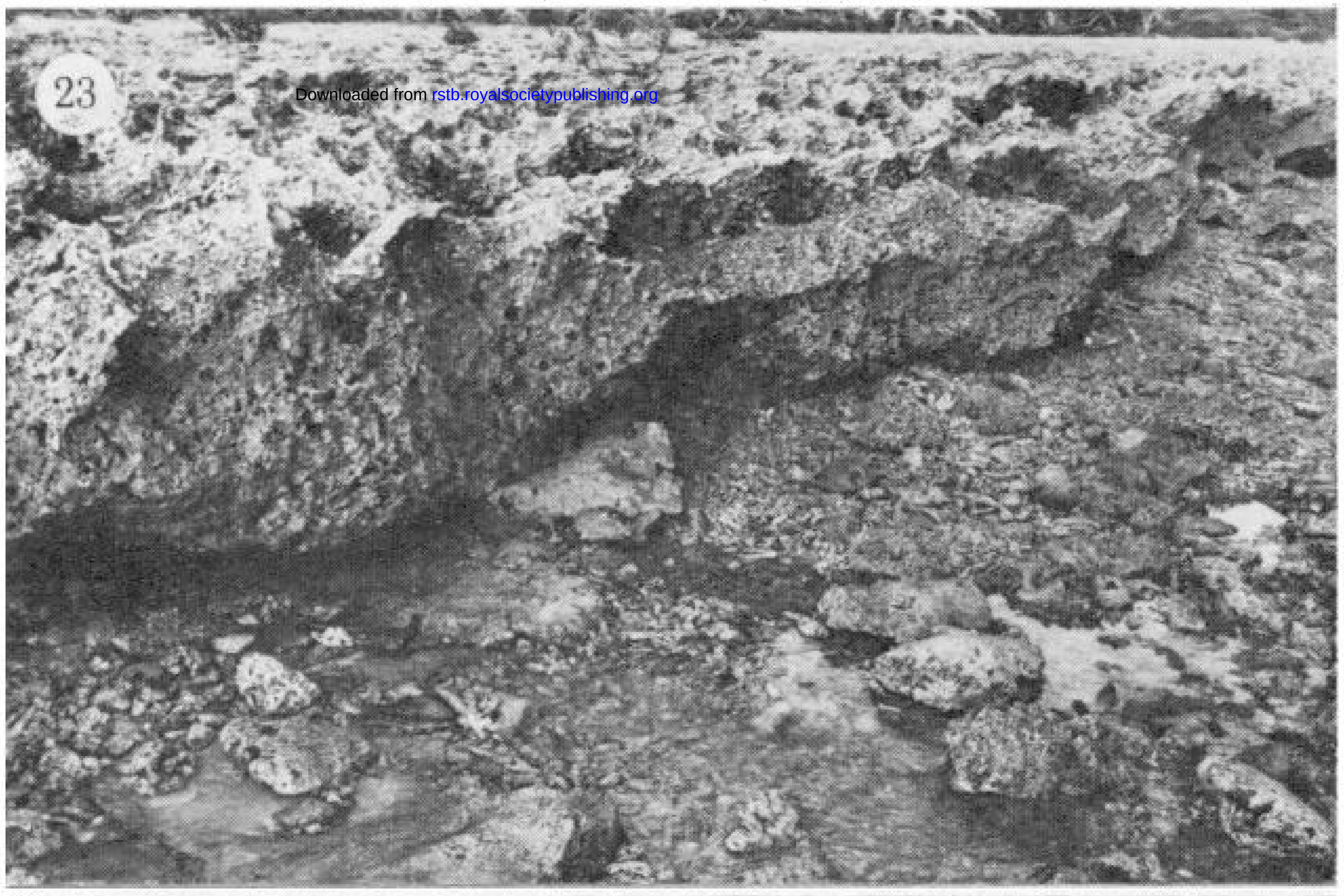
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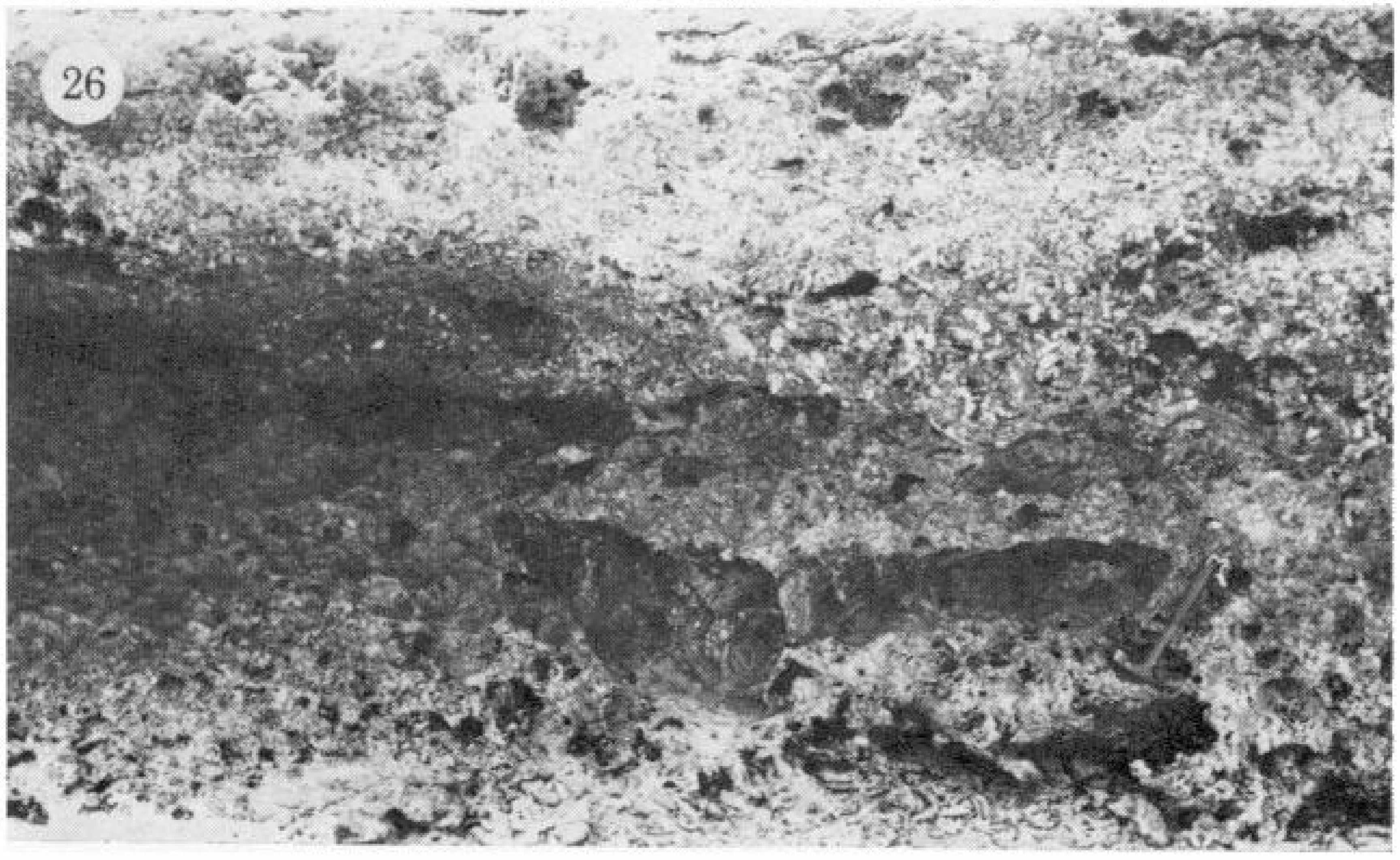
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FIGURES 19–26. For description see opposite.