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Exposed limestones of the Northern Province of the Great Barrier Reef

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[Plates 1–4]

The exposed reef limestones occur principally on the inner-shelf reefs and can be separated into two groups – organically cemented (reef-rock) and inorganically cemented (beach-rock, rampart-rock, boulder-rock and phosphate-rock). No examples were found of exposed subtidal reef framework; the reef-rock exposed is entirely of intertidal origin resulting from incipient encrustration by intertidal corals and coralline algae. Most of the beach-rock, rampart-rock and boulder-rock exposures are intertidal and many show vadose cement fabrics. The cements, chiefly aragonite needles in beach-rock and cryptocrystalline high Mg calcite in rampart and boulder-rocks, are thought to be derived from seawater, though the environments of precipitation on windward sides of reefs where rampart-rocks form are quite different from those on the leeward sides where beach-rocks form. Phosphate-rock develops supratidally on the surface of some sand cays. Solutions derived from guano precipitate thin layers of phosphatic cement which bring about the centripetal replacement of carbonate grains.

1. Introduction

The reefs examined in the Northern Province of the Great Barrier Reef lie on the Queensland continental shelf between Cairns and Cape Melville (about 300 km) to a distance from shore of about 40 km. The consolidated carbonate deposits that were found exposed above low water mark on these reefs were subdivided into the following types: beach-rock, rampart-rock, boulder-rock, phosphate-rock, and reef-rock.

The first three listed are essentially intertidal and are quantitatively the most important. Phosphate-rock was found on a number of sand cays. Reef-rock, although common on the reefs, is exceptional in that it is the only consolidated deposit with a predominantly organic cement. Table 1 lists the reefs' associated rock types and summarizes other relevant data concerning the reefs visited. The criteria used in subdividing these five limestone types include field occurrence, grain composition and matrix composition.

1.1. *Reef-top sediments*

It is necessary to consider briefly the sedimentary deposits above low water spring tide level on the reefs. The composition and form of the deposits relate very closely to the ecological distribution of the dominant carbonate producers and to the depositional processes operating.

1.1.1. *Windward side*

In the shallow-water zone of the reef front on the windward (southeast) side, branching and platy corals of *Acropora* are particularly abundant (figure 1)§. These are readily broken by

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§ Figures 1–8 appear on plate 1, figures 9–16 on plate 2, figures 18–25 on plate 3, and figures 26–31 on plate 4.

TABLE 1

				rampart-rock									
reef†	sand cay	beach-rock	ramparts	low bassett edge	high platform	low platform	boulder tract	boulder-rock	mangroves	freshwater vegetation	distance from shore/km	Maxwell's (1968) zone‡	Latitude S
Pipon	×	×	×	×	—	×	×	—	×	×	6	4	14° 07′
Waterwitch	×	×	—	—	—	—	—	—	—	—	35	5	14° 11′
Stapleton	×	×	—	—	—	—	—	—	—	×	26	5	14° 18′
Combe	×	×	—	—	—	—	—	—	—	×	24	5	14° 24′
Ingram–Beanley	×	×	×	×	—	×	×	—	×	×	22	5	14° 25′
Bewick	×	×	×	×	×	×	×	—	×	×	18	4	14° 27′
Watson	×	×	×	×	×	×	×	×	×	×	18	4	14° 28′
Howick	×	×	×	×	—	×	×	×	×	×	15	4	14° 30′
Newton	×	×	×	×	—	×	×	×	×	×	15	3	14° 31′
Sand	×	×	—	×	—	—	×	—	—	—	9	2	14° 31′
Houghton	×	×	×	×	×	×	×	—	×	×	15	4	14° 32′
Coquet	×	×	×	×	×	×	×	—	×	×	15	3	14° 33′
Leggatt	×	×	×	×	×	×	—	—	×	×	7	2	14° 33′
Sinclair–Morris	×	×	×	×	×	×	—	—	×	×	9	2	14° 33′
Hampton	×	—	×	×	—	—	—	—	×	×	7	2	14° 36′
Nymph	×	×	×	×	×	×	×	—	×	×	22	4	14° 39′
Eagle	×	×	—	—	—	—	—	—	—	×	28	4	14° 42′
Turtle V	×	×	×	×	—	×	×	—	×	×	17	4	14° 42′
Turtle VI	×	×	×	×	—	—	—	—	×	×	17	4	14° 42′
Turtle IV	×	×	×	×	—	—	—	—	×	×	17	4	14° 43′
Turtle III	×	×	×	×	—	×	×	—	×	×	15	4	14° 43′
Turtle II	×	—	×	×	×	×	—	—	×	×	15	4	14° 44′
Turtle I	×	×	×	×	×	×	×	—	×	×	15	4	14° 44′
E. Pethebridge	×	—	×	×	—	×	—	—	×	×	9	3	14° 44′
W. Pethebridge	×	×	×	×	—	×	—	—	×	×	7	3	14° 44′
Two Isles	×	×	×	×	—	×	×	—	×	×	17	4	15° 01′
Low Wooded	×	—	×	×	×	×	×	—	×	×	15	4	15° 06′
Three Isles	×	×	×	×	×	×	×	—	×	×	18	4	15° 07′
East Hope	×	×	×	×	—	—	—	—	×	×	13	3	15° 43′
West Hope	×	—	×	×	—	×	—	—	×	×	11	3	15° 44′
Pickersgill	×	—	—	—	—	—	—	—	—	—	20	4	15° 53′
Mackay	×	—	—	—	—	—	—	—	—	—	22	5	16° 03′
Undine	×	—	—	—	—	—	—	—	—	—	20	4	16° 08′
Low Isles	×	×	×	×	—	—	×	—	×	×	18	3	16° 23′
Michaelmas	×	×	—	—	—	—	—	—	—	×	39	5	16° 37′
Arlington	×	—	—	—	—	—	—	—	—	—	37	5	16° 40′
Upolu	×	×	—	—	—	—	—	—	—	×	28	4	16° 40′
Green	×	×	—	—	—	—	×	—	—	×	28	4	16° 46′

† All of these reefs were visually examined during the expedition. Many other reefs occur between latitudes 14° 07′ S and 16° 46′ S but other than the high (continental) islands, nearly all of those not included in this list have no surface exposure at low spring tide.

‡ Maxwell's (1968) zones are: 1, high terrigenous; 2, terrigenous; 3, transitional; 4, impure carbonate; 5, high carbonate.

strong wave action into platy and stick branches (figure 2) which, on near-mainland reefs, pile up to form ridges or ramparts (figure 3). These ramparts have a characteristic plan and profile form. In plan, their outer margins are convex and parallel to the reef edge. Their inner margins are cuspate and in places develop tongues (up to 100 m long) over the reef flat (figure 3). In profile these ramparts appear as large, asymmetric ripples with a steep foreset (60°) and a shallowly inclined (5°) stoss slope. The amplitude is normally 1–2 m and wavelength about 30 m. The existence of several discrete loose ramparts on one reef supports the theory that they are not being continually built, that is with new material added as they migrate to lee, but rather that each forms, in the main, during one depositional event and may later be moved, added to or eroded. Comparisons of rampart positions on reefs over several years suggest that the movement is not regular (Stoddart, McLean, Scoffin & Gibbs 1978, part B of this Discussion; Fairbridge & Teichert 1948). Coarse debris of coral plates, fungiid corals and *Tridacna* valves accumulate at the foot of the foreset slopes; the crests and stoss slopes consist predominantly of stick-like branches of corals. On lithification, these deposits become the *rampart-rocks* (figure 4). The overall distribution and plan morphology of the rampart-rocks are similar to that of the ramparts, though in detail, because of irregular cementation and also subsequent erosion or addition of deposits, the profiles are dissimilar. The highest shingle rampart had an elevation of 3.1 m above low water datum at Cairns (mean high water springs is 2.3 m) but loose ramparts rarely accumulate above high water mark. Their structures are normally sufficiently impervious to pond seawater into moats on the reef flat during low tide. Mangroves commonly colonize loose and cemented ramparts.

1.1.2. *Leeward side and flanks*

Waves are refracted over and around each reef such that at the confluence of the opposing sets, sediment accumulates as a leeward sand deposit which develops a cay with beaches and spits (figure 5). Fine sand is transported by wind from the beach and together with storm-wave swash sediment the cay can build higher than high water mark and support freshwater vegetation. Intertidal lithification of the beach material results in the formation of *beach-rock* (figure 6). Beaches and associated beach-rock are also occasionally found on the windward sides of reefs, usually in small embayments in the cliffs of rampart-rock (figure 7). Lithification of cay sediments above high water mark can result from phosphatic mineralization forming *phosphate-rock*.

In the shallow water on the flanking margins of the reef, massive corals, principally *Porites*, take over in abundance from the branching *Acropora* corals. These spherical or dome-shaped corals grow up to several metres in diameter. Movement of these corals, presumably by large waves during storms, produces either scattered isolated reef-blocks (figure 8) or a linear pile of contiguous boulders (figure 9) at the leeward flanks of the reef edge: the boulder tract. A large majority of the boulders (90 %) are single colonies of massive corals, suggesting that at the time of their erosion, these corals were not part of a solid reef framework of interconnected corals. The lithification of boulders results in the formation of *boulder-rock* (figure 10).

1.1.3. *Reef flats*

The reef flats that are exposed at low water are predominantly sandy with coral microatolls and *Tridacna* clams being the major macroorganisms that grow where sea water is ponded. In places of permanent water, such as well established ponds or even the outer edges of ramparts through which water is constantly seeping during low tide, corals (dominantly *Porites* and

Montipora) grow in sufficient abundance to build a thin organic framework. Encrustation by coralline algal growth on exposed shingle at the windward margin of the reef produces another form of organic cementation. These two are the major examples of organic cementation producing a consolidated *in situ* skeletal rock above low water mark – here termed *reef-rock*.

Although gradations do exist, in the main, each limestone type has its own characteristic location, gross morphology, constituent grain types and matrix. These characteristics will be discussed for each limestone type.

2. BEACH-ROCK

2.1. *Location*

Beach-rock was exposed on sand cays on the leeward side of most of the reefs in the Northern Province (table 1). Steers (1929, 1937) noted that beach-rock was found only on vegetated cays. Although this is the general rule we also found extensive outcrops bordering the unvegetated cay on Waterwitch reef. However, it was absent from other unvegetated cays, such as those on Pickersgill, Undine and Mackay reefs, that are just awash at high tide.

Beach-rock was rarely seen completely encompassing a sand cay, though obviously the present distribution of loose sand can obscure its true extent. Nevertheless, on some of the simpler cays like those on Eagle and Combe reefs, as well as those of 'low wooded islands' like Low, Two and Three Isles, the cays were bordered on two or three sides by bands of beach-rock. Normally the broadest expanse was found on the windward side of cays, suggesting a leeward migration of loose cay sands.

2.2. *Gross morphology*

Beach-rock takes on the form and disposition of the parent beach. In the field two types were recognized, here called inclined and horizontal beach-rock. The first and most common type occurs as linear or arcuate strips of thinly bedded units dipping seawards at 10–15°, and is similar to that described from beaches in many tropical areas. In places, discordant overlapping sequences occur which reflect local changes in beach position, for example on Newton cay five differently dipping sets of beach-rock are found superimposed. Inclined beach-rock was limited to the contemporary intertidal zone, commonly between heights of 0.8–2.3 m above datum, the latter being the level of mean high water spring tide. Frequently loose sand obscures the lower or upper portion of an outcrop. The friable nature of some beach-rocks suggest that they are forming at present. The second type, horizontal beach-rock, is characterized by an upper surface that is nearly horizontal. The outer edge is commonly eroded into a steep scarp, frequently notched or undercut at the base, which rises directly from the reef flat. The upper surface is typically at an altitude between 2.5 and 3.0 m above datum and is exposed for 3–5 m before passing inland beneath a veneer of cay sand. A bulk beach-rock sample from Houghton Island was dated at 2670 ± 70 a B.P. (ANU-1596).

A zonal arrangement of algae and animals was frequently observed across exposed beach-rock. Bioerosion was most active near to low water mark and locally beach-rock showed extensive encrustation by the oyster *Crassostrea* at the level of high water neaps. In some instances, surfaces were clean and showed signs of active wave abrasion. Elsewhere jagged irregular spray-pitted surfaces had developed around high water mark. However, on horizontal beach-rock this micro-morphology was replaced by smoother shallow pools and pits on the upper surface which frequently had a discontinuous cover of the succulent plant *Sesuvium*.

Table 2. Grain and cement composition of beach-rocks

sample no.	island	coral† (%)	mollusc (%)	coralline algae (%)	*Halimeda* (%)	echinoderm (%)	benthonic Foraminifera (%)	unknown (%)	mean grain size/mm	insoluble‡ residue (%)	cements§
30	Two	18	14	5	6	1	52	4	1.0	3.3	aragonite needles + calcite mud
43	Three	28	10	7	26	0	29	8	1.4	2.9	aragonite needles
19	Low	35	28	22	14	0	7	1	1.5	3.2	aragonite needles
3	Eagle	19	9	3	36	1	32	0	0.9	2.5	aragonite needles
10	Turtle I	48	23	10	7	0	13	0	1.1	2.7	aragonite needles
4	Ingram	28	16	23	21	1	9	3	1.3	0.8	aragonite needles
9	Turtle I	58	22	10	3	1	2	3	2.0	6.3	calcite mud + aragonite needles
7	Newton	14	16	4	34	1	26	4	1.0	2.5	aragonite needles
5	Bewick	24	13	8	19	0	32	3	1.5	3.1	aragonite needles
2	Stapleton	27	18	9	12	2	23	9	1.4	3.0	aragonite needles
35	Howick	17	10	22	32	2	10	5	0.7	3.6	aragonite needles
1	Waterwitch	20	40	7	24	0	3	6	1.5	2.9	aragonite needles
54	Nymph	23	13	15	9	0	29	11	0.8	4.4	calcite mud

† Percentage of total grains present in thin section: average number of grains of each thin section = 212.

‡ Insoluble residue as mass percentage of bulk sample after treatment in 10% HCl.

§ Cement mineralogy determined by staining with Feigl's solution.

2.3. *Grain composition*

Irrespective of morphological type, the constituent grains of beach-rock are principally sand-sized and show a high degree of rounding and polishing. The grain composition of several beach-rocks was determined from grain-count analysis of thin sections and the results shown in table 2. The skeletal remains of corals, molluscs, benthonic Foraminifera and algae are the dominant grains. Two of the major benthonic foraminiferal components (together they constitute 17 % of the total grains) are *Baculogypsina* and *Calcarina* which live in abundance attached to short tufts of *Laurencia* algae on the windward lip of reefs. These foraminiferans are detached by wave action and then swept across and round the flanks of the reefs by long-shore drift to accumulate finally with other fine reef debris on the leeward sand cay.

Two types of reworked limestone material were found in beach-rocks: one was where pieces of earlier beach-rock had been recemented with no evidence of much movement of the cobble-sized fragments; the other was on those reefs where the windward and leeward intertidal deposits and rocks were adjacent (for example Turtle I). Here the beach-rock contained polished grains consisting of pieces of stick coral with a thin layer of brown micrite. As these stick corals and the brown micrite matrix are characteristic of the windward intertidal deposits (see later) it is assumed that these coated coral fragments have been eroded from rampart-rocks.

Little evidence of post-depositional solution was found in the beach-rock constituents and most grains appeared in a fresh state of preservation.

2.4. *Cements*

The most common cement fabric observed in the leeward cay beach-rocks was that of a thin fringe of acicular crystals around grains (figure 11). The individual crystals have a length: breadth ratio of about 15:1 (figure 12). These needles were identified as aragonite by staining (with Feigl's solution) and the needles grew in the interparticle pore spaces with the same fabric from substrates of all compositions – aragonite, calcite and non-carbonate rock fragments. Some beach-rock samples showed an even isopachous fringe of needles surrounding grains, but the majority had cement concentrated at grain contacts in the 'meniscus' position (Dunham 1971). As a result, the small interparticle pore spaces were commonly totally occluded by cement whereas the large pores were mostly vacant. Needles of a similar fabric to those in interparticle pores also occurred lining intraparticle pores, though it was noticed that the chambers of aragonite skeletons (*Halimeda*, gastropods, corals) commonly showed a better development of cement than the chambers of calcite skeletons (Foraminifera). It is quite common to see two or three generations of acicular cement in one rock. The fibrous layers are then normally separated by a very thin dark line.

Several examples of beach-rock have a micritic cement, and some such as the horizontal beach-rock at Houghton cay, contain both aragonitic and micritic cements. The latter takes various forms. It occurs normally at grain contacts and there may show flat-floored internal sediment characteristics indicating its sedimented origin, though it also occurs as an even layer around grains and in such cases it is commonly seen, under high power on the microscope, to be fibrous in detail. One example of micritic beach-rock cement revealed a vaguely pelleted botryoidal texture.

The beach-rocks with micritic cement were found only on those sand cays that were connected with the windward shingle deposits, and normally formed close to mangroves. More details of this micrite cement are given later for it is this same type of cement fabric which characterizes the rampart-rocks. Those beach-rocks with a micritic cement normally have a higher percentage of insoluble residue than the beach-rocks with acicular cements (table 2) and also they commonly show signs of a degree of post-depositional solution of grains, which was not apparent in the purer beach-rocks.

3. RAMPART-ROCK

3.1. *Location*

Coarse coral fragments accumulate as shingle ramparts or ridges only on those reefs close to the mainland and it is only these reefs that have rampart-rock (table 1). Steers (1929, 1937) and Spender (1930) called these exposed limestones coral or shingle conglomerates or conglomerate platforms, but the term 'rampart-rock' is favoured because, as Steers (1937) noted, they derive originally from ramparts or shingle ridges. Rampart-rocks occur on the windward side of the reefs usually about 50–100 m in from the perimeter at low water.

3.2 *Gross morphology*

Rampart-rock retains the main elements of the form of ramparts. In plan they commonly show a broad crescent shaped seaward margin and cuspate inner margin. In section the general shape and internal structure of a rampart is apparent but commonly the detail of the profile of an asymmetrical ripple is lost; for example, normally there is no obvious crest as in most ramparts.

Rampart-rock occurs either with a planar, essentially horizontal surface (figure 13), 'the upper and lower platforms, pavements or promenades' of Steers (1929, 1937) and Spender (1930), or with a jagged saw-tooth profile of inclined beds 20 cm thick projecting a fairly uniform distance above the reef flat and dipping steeply (20–70°) to lee (figure 14). The latter are the 'bassett edges'† of Steers (1929). Limestones with platform and bassett edge surface morphologies have essentially similar composition and both occur on the windward perimeter of reefs.

3.2.1. *Platforms*

Each continuous platform of rampart-rock has a fairly constant height. On several reefs (e.g. Three Isles, Nymph, Low Wooded Island) two platforms occur: an upper and a lower. The upper is normally found to the leeward of the lower and the two may be separated by a narrow shallow moat. The heights of the platform surfaces of several outcrops of rampart-rock on the reefs of the northern Great Barrier Reef were surveyed. Results revealed considerable variation in the altitudes of the upper and lower platforms from reef to reef, but where continuous traverses were run across both platforms on the same reef a difference in level of 1.0–1.2 m was found. In these instances the maximum elevation of the upper platform ranged from 3.10 to 3.53 m and lower platform 1.96–2.49 m above datum. (See McLean, Stoddart, Hopley & Polach 1978, this volume.)

3.2.2. *Bassett edges*

The inclined bedding of bassett edges represents cemented foresets of ramparts. The irregular projections result from differential cementation and weathering of the bedding with the layers more resistant to erosion, having more cement and also generally finer constituents than the less

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† Basset or bassett: 'The edge of a stratum showing at the surface of the ground; an outcrop' [O.E.D.].

resistant layers. The bedding occurs as steeply dipping foresets (40–70°) on the tongue shapes, like anticlines plunging to leeward (figure 4) but as shallowly dipping (20–40°) arcuate bands between. Presumably at least the inner buried portions of ramparts have to remain stationary for some time to allow lithification. It is perhaps for this reason that those parts of the shingle tongues more removed from wave action at the central parts of reef flats are the better cemented and preserved.

3.2.3. *Surfaces of rampart-rock platforms*

Although rampart-rock platforms appear at first sight to be remarkably level, height measurements indicate that they do fluctuate in elevation along their length, typically by about 0.4 m. The leeward margins of platforms are normally obscured by mangroves or superficial deposits and this masks their rampart profile. It should be pointed out that along their strike, loose ramparts too have a fairly constant elevation. The flat surface of platforms could be explained by either erosion down to a level or deposition and lithification up to a level.

If marine truncation, such as that at the reef flat rim, is invoked to account for the flat surface of platforms, one would expect a bevelling down of the upper parts of those coral boulders that project well above the general level of the platform in which they are seated, but this is not seen (figure 15). Also, it was noted that where a lower platform abuts an upper platform the two rocks are of different compositions, the contained coral debris are of different

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Description of plate 1

Figure 1. Windward coral assemblage of branching and platy forms of *Acropora*. 5 m depth. Lizard Group.

Figure 2. Windward beach of broken *Acropora* corals. Hammer 80 cm long. Turtle III Reef.

Figure 3. Loose shingle rampart on the windward side of Three Isles Reef. Rampart amplitude 1 m.

Figure 4. Arcuate outcrop of cemented foresets of ramparts giving bassett edge morphology. Beds 20 cm thick. Low Isles Reef.

Figure 5. Oblique aerial photograph of Sinclair–Morris Reef, showing leeward sand cay with spit. The sand cay has beach-rock around part of its rim and a cover of freshwater vegetation. Mangroves occur on the windward side of the reef. Altitude 200 m.

Figure 6. Intertidal beach-rock exposed on the leeward sand cay of Two Isles Reef.

Figure 7. Cemented beach in a small gap in the rampart-rock on the windward side of Nymph Reef.

Figure 8. Scattered coral boulders partly buried by sand on the leeward margin of Mid Reef.

Description of plate 2

Figure 9. Boulder tract exposed at low water on the leeward flank of Low Wooded Island. Boulders 30–100 cm in diameter.

Figure 10. Boulders cemented in a sandy matrix at the leeward margin of the sand cay on Howick Reef. Hammer 30 cm long.

Figure 11. Photomicrograph of rounded coral, algal and foraminiferal grains cemented by a fringe of aragonite needles. Plane polarized light. Beach-rock, Bewick Reef. Scale bar = 0.5 mm.

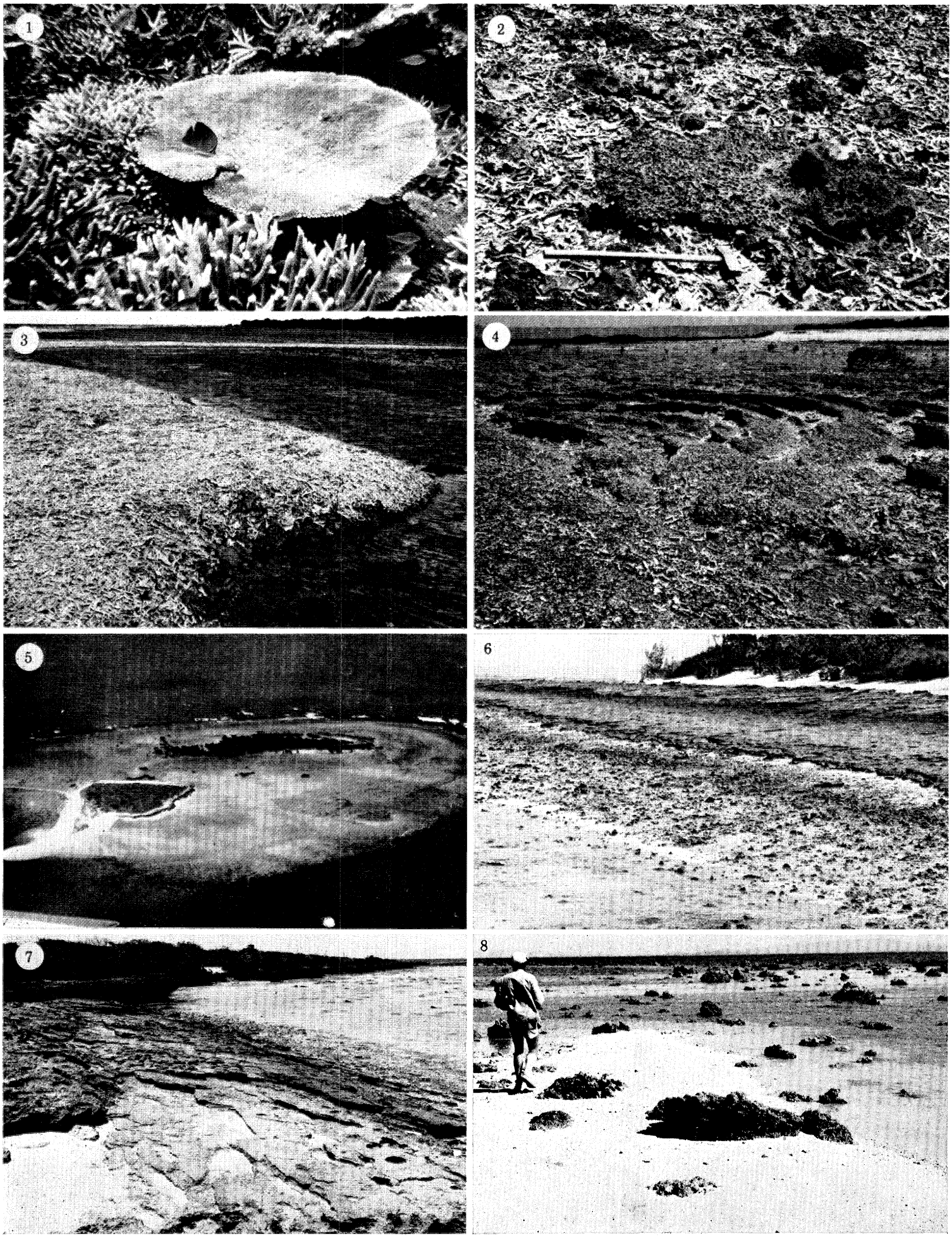
Figure 12. Scanning electron micrograph of a broken surface of beach-rock showing needles of aragonite cement on a sand grain. Bewick Reef. Scale bar = 20 μm.

Figure 13. Horizontal surface of rampart-rock, the lower platform, on the windward margin of Ingram–Beanley Reef.

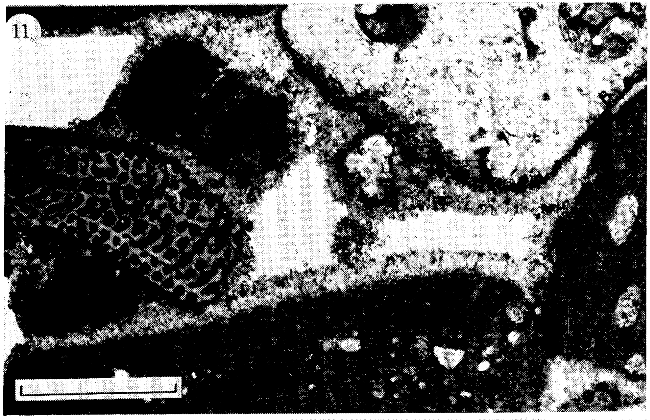
Figure 14. Bassett edge surface morphology of rampart-rock. Beds 20 cm thick. Watson Reef.

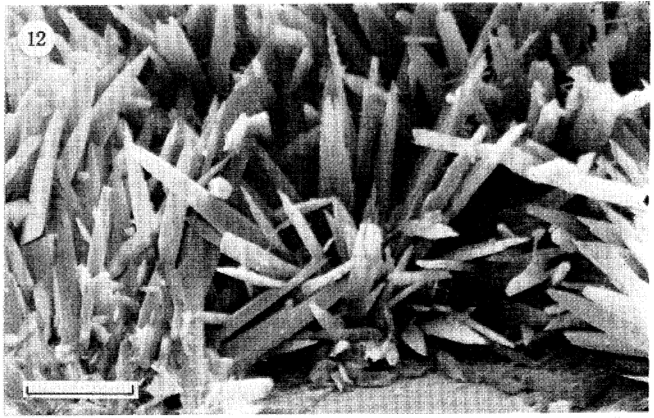
Figure 15. Coral boulder cemented in rampart-rock projecting above platform surface. Ingram–Beanley Reef.

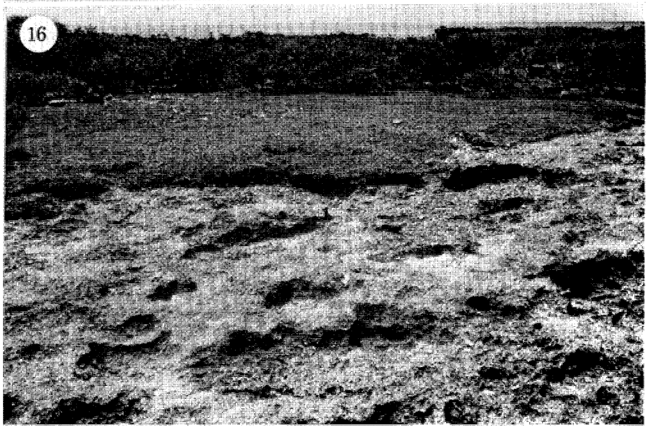
Figure 16. Rampart-rock coated on its leeward side by a thin friable veneer of shingle. Ingram–Beanley Reef.



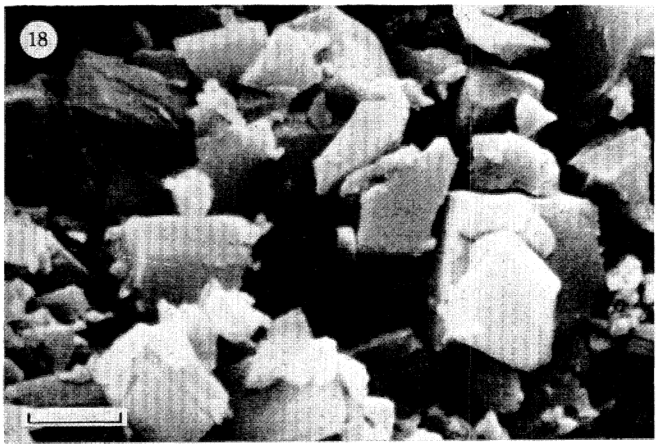
FIGURES 1–8. For description see opposite.

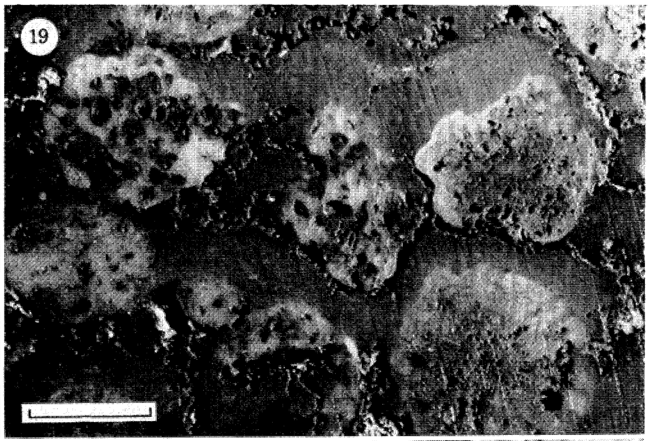


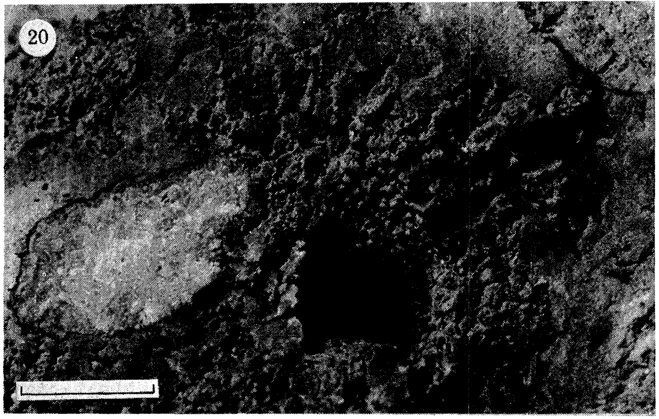


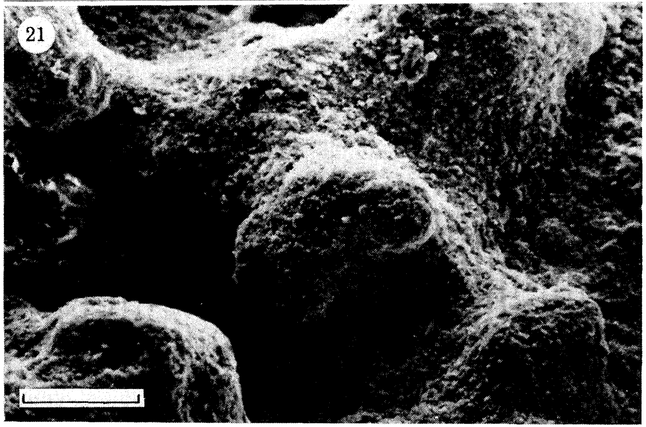


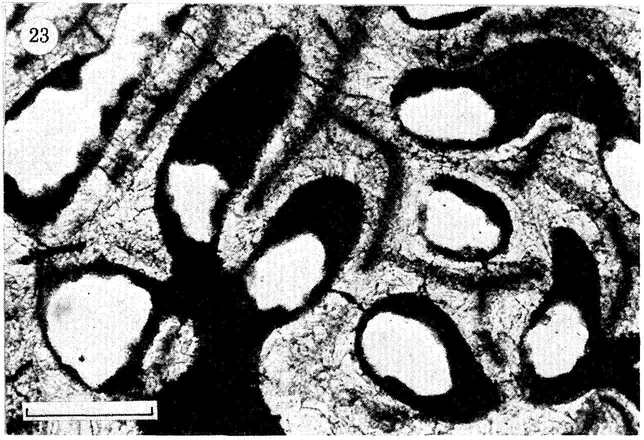
FIGURES 9–16. For description see page 126.

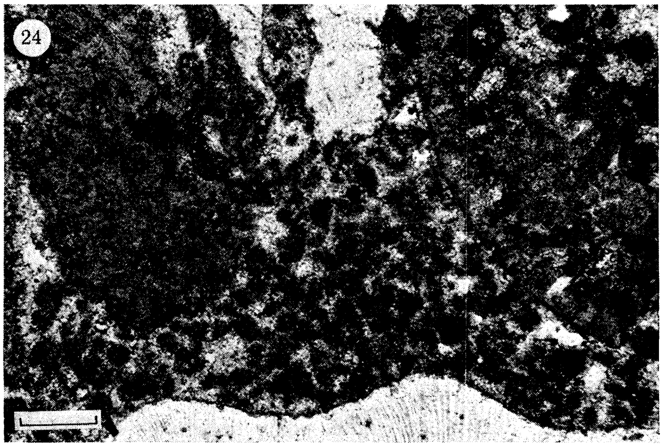


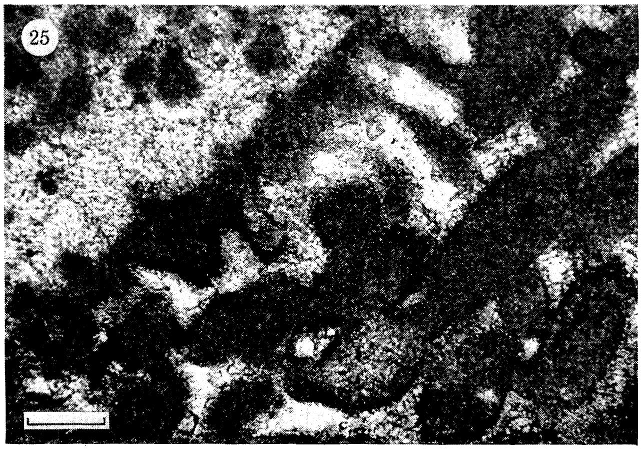












FIGURES 18–25. For description see page 127.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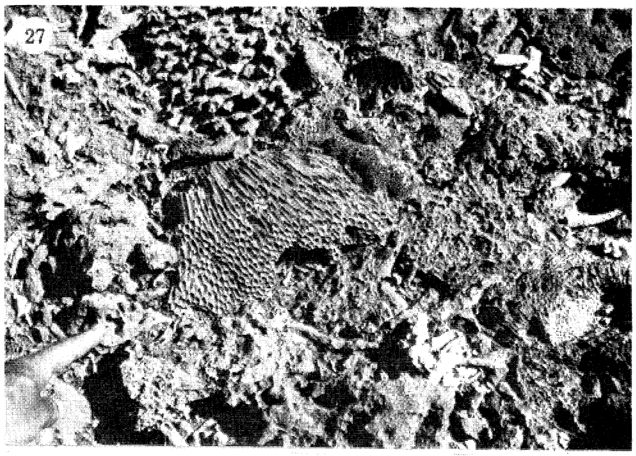
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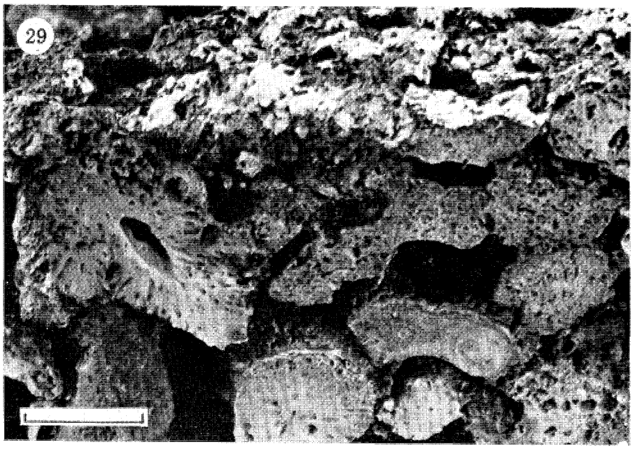
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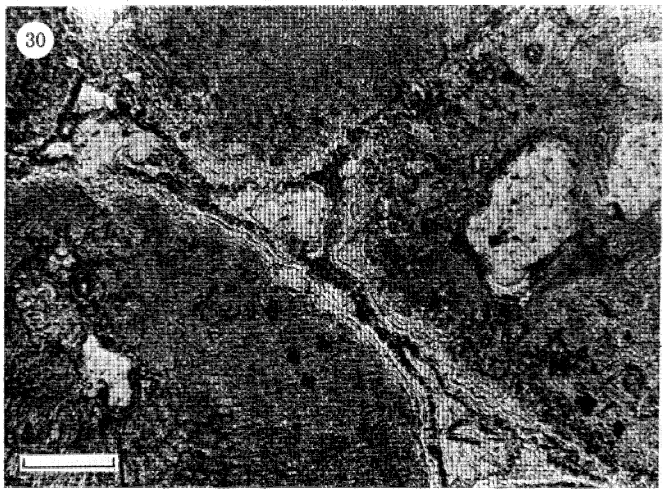
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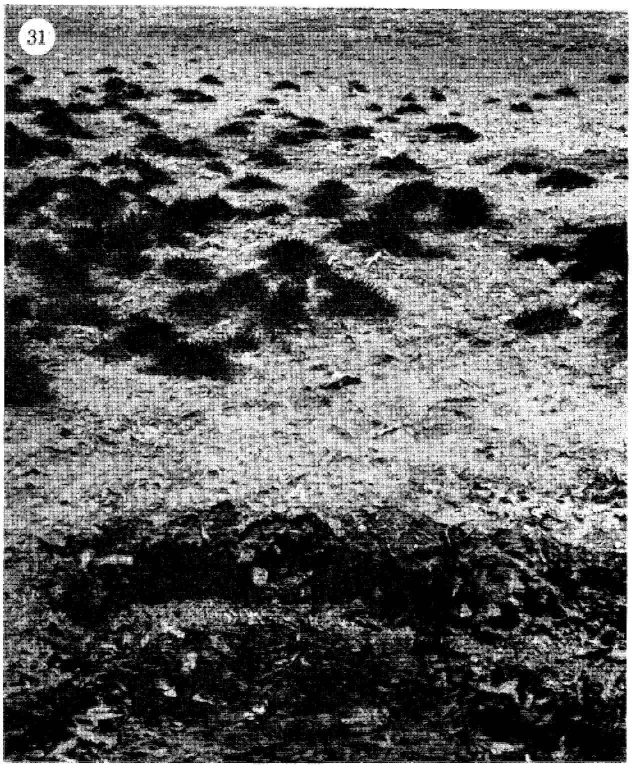
31

FIGURES 26–31. For description see opposite.

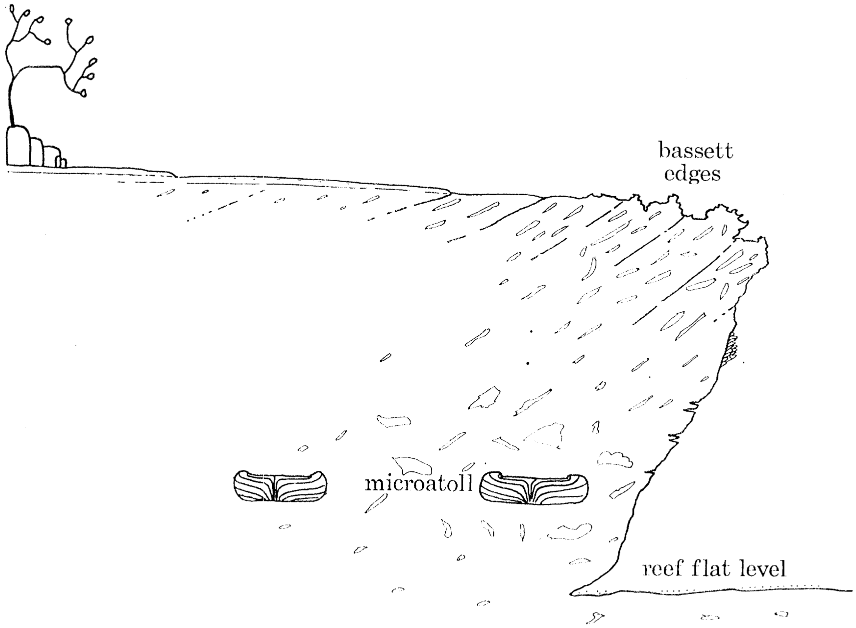

FIGURE 17. Sketch of a cross section of rampart-rock showing the lower facies with *in situ* microatolls and coarse coral debris and an upper facies of coral branches. The surface at the seaward edge, to the right, shows a bassett edge morphology with phytokarst, and to the leeward a veneer of shingle with mangroves.

DESCRIPTION OF PLATE 3

FIGURE 18. Scanning electron micrograph of the surface of an untreated sample of rampart-rock micrite matrix. Turtle VI Reef. Scale bar = 2 μm.

FIGURE 19. Cut cross section of rampart-rock showing micrite matrix draped over coral branches. Watson Reef. Scale bar = 1 cm.

FIGURE 20. Broken surface of rampart rock revealing in cross section the botryoidal texture of the micrite matrix in partly filled cavities between coral fragments. Nymph Reef. Scale bar = 1 cm.

FIGURE 21. Scanning electron micrograph of broken surface of micrite matrix in partly filled cavities in rampart-rock. Houghton Reef. Scale bar = 0.5 mm.

FIGURE 22. Thin section of fibrous cement coating the micrite matrix of rampart-rock. Howick Reef. Plane polarized light. Scale bar = 0.3 mm.

FIGURE 23. Thin section of micrite lining the walls of coral chambers in rampart-rock. Bewick Reef. Plane polarized light. Scale bar = 0.2 mm.

FIGURE 24. Thin section of pelleted matrix of rampart-rock. The pellets are in a calcite cement and fill an interstice between two altered *Halimeda* grains and, at the base, a mollusc fragment. Houghton Reef. Plane polarized light. Scale bar = 0.1 mm.

FIGURE 25. Thin section of partially dissolved *Halimeda* fragment which contains micrite-filled utricles. The top left corner of the photograph is pellet- and calcite cement-filled interstice. Houghton Reef. Plane polarized light. Scale bar = 0.1 mm.

DESCRIPTION OF PLATE 4

FIGURE 26. Sheet of cobble-sized equant fragments of corals on the flanks of Low Isles Reef.

FIGURE 27. Low coral conglomerate. Windward side of Low Isles Reef.

FIGURE 28. Framework of branching corals encrusted by coralline algae surrounding a giant clam (50 cm diam.) growing in ponded water on Turtle III Reef.

FIGURE 29. Cross section of coral shingle with a very thin veneer on the surface and around some grains of crustose coralline algae. Pipon Reef. Scale bar = 1 cm.

FIGURE 30. Thin section of thinly laminated phosphatic cement on algal and foraminiferal grains. Green Island. Plane polarized light. Scale bar = 0.1 mm.

FIGURE 31. Loosely consolidated shingle platform with scattered vegetation. Nymph Reef. Hammer 30 cm long.

ages and excavation shows that the deposits of the lower actually bank against a buried cliff of the upper platform deposits. Therefore, if marine planation did produce the flat surface of the lower platform, it is a remarkable coincidence that this cutting back ended exactly at the junction of the two rampart-rock deposits. These observations argue against a wave-cut terrace origin.

So an origin by deposition and/or lithification up to a level remains. An upper limit to marine lithification for one still-stand of the sea would be expected to give a fairly uniform upper level of rock formation but is unlikely to account for the smoothness or flatness of local surfaces; this feature is more probably the result of deposition up to a level.

Commonly there is a noticeable change in the character of the surface of platform rocks from their seaward edge to the lee. At their seaward edge the surface is hard and jagged with a bassett edge morphology but this is normally lost to the lee where the surface is smooth and consists of less tightly cemented shingle (figure 16). Cross sections of some platform rocks show an indistinct bedding with a steep leeward dip (the subsurface extension of bassett edges) near the seaward edge, whereas to the leeward commonly the upper few centimetres show horizontal bedding or else layers with a shallow seaward dip similar to that characteristic of beachrock (figure 17).

As it is not uncommon to find thin deposits of loose sand or shingle capping, sometimes being bound by vegetation to the surfaces of rampart-rocks, then it is reasonable to assume that where cementation conditions are favourable a cemented veneer on top of exposed limestones will result. At the southeast end of the rampart-rock at Watson Island, cemented coral shingle could be seen to be partly filling the potholed relief of an older rampart-rock. The distinction between veneer and earlier limestone is more obvious on some reefs than others. Where the veneer is similar in composition to the rock it blankets, and where no obvious bedding features are present in either deposit and no corrosion surfaces occur, then field evidence alone is inadequate to distinguish separate increments of sediment. It is concluded that generally a bassett edge relief characterizes the irregularly eroded surface of cemented ramparts and that this morphology may be masked by the subsequent lithification of thin blanketing deposits of sand or shingle to give the even surface of a platform (figure 16). The location, internal structure and surface detail of these flat topped deposits suggest that they accumulated on top of cemented ramparts by a ponding to the leeward. The stabilization of this veneer may have been greatly assisted by the vegetation common in this position such as mangroves, *Sesuvium*, grasses and filamentous algae.

3.3. *Petrography of rampart-rocks*

3.3.1. *Grain composition*

The constituent grains of most rampart-rocks are fundamentally the same as those of the present loose ramparts and unconsolidated shingle island deposits, that is over 90 % of the grains are broken clasts of branching corals, notably *Acropora*. Typically the clasts are about 10 cm long and 1–2 cm in diameter. Coral fragments of other growth forms, as well as molluscs such as tridacnids, are also present, but in subordinate numbers. In thin section some of the coral fragments show patchy encrustation by coralline algae, foraminiferans and bryozoans and many possess intragranular sediment or cement as void fill, the presence of which, based on analysis of unconsolidated shingle deposits from the same reefs, may pre-date intergranular lithification. (See McLean & Stoddart 1978, this volume.)

When examined closely in cliff section, rampart-rocks of the upper platform show two, and locally three, vertical facies. The lowest part contains *in situ* microatolls, coarse coral debris and sand sized particles with a whitish chalky cement that grades into an upper zone of smaller, predominantly stick coral fragments set in a splintery hard, brown micritic cement (figure 17). This succession represents one complete cycle of advance of a rampart across a reef flat, or moat, that contained microatoll corals. The sediment at the foot of the foresets of loose ramparts is normally coarser than that towards the crest producing the differentiation into lower and upper facies. This stratigraphy is also observed on shingle island beaches and has been described by McLean & Stoddart (1978, this volume). A thin, commonly friable, sandy or stick coral zone is often found at the surface of platforms to leeward of the exposed cliff. This represents a later addition to the rampart deposits. Exposed in some cliff sections are two distinct layers of the coral stick deposits and at low tide seaward-draining water seeps out of the cliff along the junction of the two layers. In such a case the lower layer has a less permeable matrix than the upper and commonly a brown film marks the boundary of a corrosion surface on the lower unit.

While the matrix between the stick corals is normally very fine grained, sand-sized particles are not uncommon. Locally cemented cross-bedded sands occur within sequences of rampart-rock, presumably as a result of beach-rock formation in gaps in the cliffs of rampart-rocks.

TABLE 3. ANALYSES OF THE MICRITE MATRIX OF RAMPART-ROCKS

	aragonite (%)	calcite (%)	MgCo$_3$ in calcite (mol %)	non-carbonate (%)
Brown hard micrite				
Low I.	16	80	13	4
Bewick I.	10	83	n.d.	7
Bewick I.	12	80	n.d.	8
Bewick I.	15	77	n.d.	8
Nymph I.	16	80	13	4
Houghton I.	10	82	14	8
Houghton I.	10	82	14	8
Low Wooded I.	10	86	13	4
White chalky micrite				
Three I.	29	68	8	3
Low I.	15	80	25	5

n.d., not determined.

3.3.2. *Cements*

Examination of over 50 thin sections and s.e.m. samples showed the cementing medium of all shingle rocks to be micrite which varied in colour from white to rusty brown. This micrite consists of roughly equant grains of 0.5–6 μm diameter (figure 18) and was found by X-ray diffraction to be 68–95% high magnesium calcite (14% $MgCO_3$) and 0–25% aragonite (table 3). Clay minerals constituted 5–8% of the matrix with kaolinite being the most abundant (65% of clay mineral fraction) and lesser amounts of illite (32%) and montmorillonite (3%) being present.

There is a consistent difference between the textures of the lower and upper facies of platform rocks. The lower parts, where water saturation is more persistent, have a relatively soft chalky micrite matrix which normally completely fills interparticle pores. The upper part which suffers greater exposure has a splintery hard brown matrix that only partially occludes interparticle pores. Both matrices have the same mineralogical composition. The splintery hard brown micrite has a most unusual texture for it does not always floor interparticle cavities producing a flat-floored geopetal fabric in a manner typical of normal internal sediments. In some cases it drapes over coral fragments and shows vague banding (figure 19), in others it accumulates in a pendant attitude rather like miniature stalactites (figure 20) of speleothem deposits. In most rocks both the 'drape' and 'drip' fabrics occur together commonly with the micrite at the inner margin of incompletely filled cavities having a botryoidal texture (figure 21).

This final pore lining is soft mud in some samples, brittle micrite in others. Although a flat-floored geopetal fabric is rarely seen, the presence of soft mud, the laminated texture in places, and the presence in the micrite of clay minerals and coccoliths (seen by using a scanning electron microscope) point to a sedimentary origin for at least part of the matrix.

Commonly, loose corals on the surface of rampart-rocks show an undersurface that is coated with a film of soft mud whose surface texture is similar to that of the splintery hard botryoidal micrite. Close inspection shows the pattern of the surface of the soft mud to be a replica of that of the skeletal architecture of the coral to which it sticks. Mud occurs in only the lower chambers of such corals; therefore the fine particles cannot have trickled through but must have adhered to the skeleton from beneath, perhaps during the evaporation of water draining from the skeleton. The dripstone texture of the brown micrite matrix of the upper facies of the rampart-rocks strongly suggests that lithification took place in a vadose zone of impermanent saturation by seawater.

The texture of the micrite matrices was commonly blotchy and when viewed with a high powered microscope some areas contained what appeared to be very small comminuted skeletal remains. The incompletely filled cavities normally showed a scalloped margin (without a flat floor) and in a few samples radiating clusters of fibrous cement could be seen coating parts of the surfaces of the cavities (figure 22). This fibrous cement was shown by staining to be calcite. Most coral fragments contained micrite in their outer chambers. In partly filled pores this micrite did not show sedimented characteristics such as a flat-floored geopetal fabric but instead was commonly seen lining the walls of the skeletal cavities (figure 23). At the centre of some corals, fibrous aragonite cement crystals formed a lining or a total filling of the pores.

Several samples of rampart-rock have matrices with a markedly pelleted texture (figure 24). The pelleted matrix commonly shows flat-floored geopetal fabrics and is found in rocks containing abundant *Halimeda* remains. Many of these *Halimeda* grains showed extensive solution and it is considered possible that the matrix pellets represent, at least in part, the deposition of the utricle contents (micrite) after solution of the *Halimeda* plates (figure 25). Schlanger (1964) noted marked solution of *Halimeda* particles in some fossil reef limestones in Guam. The mechanism of skeletal solution and chamber-fill stability was proposed for pelleted fabrics in internal sediments associated with bryozoans in Silurian reef limestones (Scoffin 1972).

3.3.3. *Alteration of grains*

Mineralogical analyses show coral and *Tridacna* skeletons from some of the oldest rampart-rocks to be still aragonitic. No evidence of recrystallization from aragonite to calcite in these skeletons was found.

However, there is marked evidence of skeletal and matrix solution in the rampart-rocks though the style of this solution varies from lower to upper facies. In the upper facies the skeletons (principally corals and *Halimeda*) and layers of the hard micrite matrix are seen to have been irregularly truncated before later matrix deposition though the remaining skeleton structure is well preserved. The brown colouring in the micrite is commonly most intense in a layer at the truncation surface and also coats those surfaces presently in contact with circulating water. Analyses of these brown surface films showed them to be relatively rich in iron and manganese. The suggestion is that those surfaces coated with such a film experienced prolonged contact with circulating seawater during which time iron and manganese salts precipitated. The corals of the lower facies with the chalky matrices showed a degree of peripheral truncation but also pervasive internal solution, giving all the internal surfaces a markedly etched appearance.

Though peripheral solution of grains was not uncommon, recrystallization was rare for all but coralline algal grains. The fine cellular texture of these algae is commonly partly or totally lost and many grains now appear as homogeneous micrite with just a vestige of cellular texture in places.

TABLE 4. RADIOCARBON AGES OF SOME RAMPART ROCKS

			mineralogy		
code no.	reef	age/a B.P.	aragonite (%)	calcite (%)	material
		upper platform			
ANU-1604	Low Wooded	3320 ± 70	97	3	*Tridacna* upper facies
ANU-1595	Houghton	3330 ± 80	99	0	coral basal facies
ANU-1413	Houghton	3550 ± 80	98	2	*Tridacna* surface
ANU-1592	Nymph	3420 ± 75	100	0	*Tridacna* surface
ANU-1383	Nymph	3540 ± 80	98	2	*Tridacna* middle facies
ANU-1380	Three	3750 ± 110	95	5	*in situ* coral basal facies
ANU-1382	Three	3050 ± 70	99	1	*Tridacna* surface
ANU-1478	Turtle I	4420 ± 90	90	10	*Tridacna* upper facies
		upper platform cements			
ANU-1602	Nymph	2350 ± 70	16	80	middle facies
ANU-1381	Three	2260 ± 80	29	68	basal facies
		lower platform			
ANU-1385	Bewick	640 ± 70	99	1	coral surface
ANU-1390	Watson	810 ± 70	98	2	coral surface
ANU-1477	Turtle I	1430 ± 70	100	0	*Tridacna* beneath surface
ANU-1475	Three	1460 ± 70	99	1	*Tridacna* beneath surface
ANU-1476	Nymph	520 ± 70	100	0	*Tridacna* beneath surface
		bassett edges			
ANU-1607A	Low	740 ± 70	n.d.	n.d.	coral
ANU-1601	Low	380 ± 80	15	80	cement

Ages determined by Radiocarbon Laboratory, Australian National University (see Polach *et al.* 1978, this volume).

3.4. *Age of rampart-rocks*

Radiocarbon dates of corals and molluscs from the upper and lower platforms and bassett edges provide evidence for the age of the rampart-rocks (table 4). Eight determinations on constituents of the upper platform from locations where the surface equals or exceeds 3.0 m above datum give an average of 3547 a B.P. with a range from 3050 ± 70 to 4420 ± 90 a B.P. (Polach, McLean, Caldwell & Thom 1978, this volume). Ages of high magnesium calcite matrices are some 1200–1500 radiocarbon years younger than adjacent skeletal components. These dates strongly suggest that loose shingle ramparts accumulated before 3000 a B.P. and became cemented during the following thousand years to form rampart-rocks which are now in a sense fossil forms. Lower platforms and bassett edges that occur above the reef flat level contain corals and shells all dated at younger than 1500 a B.P., and the friable nature of parts of these deposits suggests that lithification is continuing.

4. BOULDER-ROCK

Many reefs contain near the margins of the reef flat a few scattered boulders; likewise in some, rampart-rocks and beach-rocks are cemented scattered isolated boulders (figure 15). However, the term boulder-rock is here intended to refer to those rocks where the grains of the rock are generally greater than 25 cm median diameter and are in mutual contact.

4.1. *Location*

The reefs with loose or cemented boulder tracts are shown in table 1. Stephenson, Stephenson, Tandy & Spender (1931) have described boulder tracts from Low and Three Isles reefs. Although most of the reefs near to the mainland have beach-rock and rampart-rock, only a few reefs presently have exposures of boulder-rock. One reef may have a boulder tract and an exposure of boulder-rock while its neighbour has neither. Those reefs showing good developments of loose and cemented boulder tracts occur in the Howick Group.

Boulder tracts normally have a curved trend at the perimeter of one flank of the reef and roughly link the windward intertidal deposits (ramparts) with the leeward sand cay. Boulder-rocks occupy the same general position but lie a short distance (30–100 m) in from the reef perimeter. In several examples the boulder-rocks parallel the loose boulder tract and are separated from it by a narrow moat.

4.2. *Gross morphology*

Boulder tracts, and the stretches of rocks they become once lithified, are about 100–200 m in length and 20–50 m in width. The indication from cliff sections is that they attain a maximum thickness of about 3 m. The density of boulders increases towards the centre of the deposit. Normally all except the very large boulders of loose and cemented boulder tracts are immersed at high spring tides. The surface of a cemented boulder tract may be irregular with protruding boulders or else essentially flat like a platform deposit; the configuration of the surface depends upon the extent of matrix infilling.

4.3. *Petrography*

Spherical, hemispherical or mushroom shaped colonies are the major forms of boulders (figure 9). The dominant corals are *Porites* (70 %) with *Goniastrea* and *Leptoria* making up the bulk of the remainder. A critical observation was that less than 5 % of the boulders were made of more than one coral colony. It thus suggests that these boulders were not plucked out of a structure of coral intergrowth but rather that they were seated individually on a surface from which they could easily be dislocated, perhaps even a sandy bottom. Kornicker & Squires (1962) have shown how buoyant many of the massive corals are when in water, so it may not have taken the great force that one initially envisages to carry them up on to the reef. Nevertheless the existence on several reefs of a discrete boulder tract isolated from an earlier boulder tract that is now cemented, suggests that each tract deposit resulted from one major catastrophic event, or at least from a period of boulder-producing conditions which was ephemeral and that little subsequent dispersal of boulders has occurred. Many of the coral boulders are riddled with animal boreholes and burrows, with boring barnacles, bivalves, worms, sponges and echinoids being presently active. The consistent positions of bioerosion structures in the very large boulders suggest that once settled the boulders do not move.

The matrix of boulder-rock commonly varies from the windward end, where it is dominantly coral shingle with a micritic calcite cement, to the leeward end, where it is dominantly sand grains with a fibrous aragonite cement. The matrix of boulder-rock is therefore similar to that of rampart-rock on the windward side and beach-rock on the leeward.

Locally, especially at the windward flanks of reefs, low-profile ridges or sheets occur consisting of cobble-sized equant fragments of corals (figure 26). Both in grain size and in gross morphology these deposits represent an intermediate between shingle ramparts and boulder tracts. Several examples of weakly cemented (by micrite) cobble-sized corals are seen forming patchy outcrops of conglomerate (figure 27), with a low relief normally on the windward margins of reefs.

5. Reef-rock

This *in situ* rock results from organic cementation. Currently, around all the reefs examined, encrusting calcareous organisms build a rigid structure up to sea level. This subtidal growing structure is built chiefly of large branching corals and where growth is sufficiently sturdy or else cemented by crustose coralline algae, a characteristic framework is produced which eventually develops a flat upper surface just below low water level of spring tides. No exposures of fossil subtidal reef framework were found on any of the reefs visited. This absence is one of the strongest lines of evidence against a significant drop in sea level over recent time. It is possible that *in situ* deposits of fossil subtidal reef framework lie just below the loose or cemented sand and shingle on the reef flat – though shallow excavations did not reveal any and none were reported from the boreholes on Low Isles by Marshall & Orr (1931). Alternatively, any former subtidal reef framework may have been eroded by wave-transported coral debris moving across the reef flat, though the preservation of fossil microatolls, boulders and rampart-rocks on the present reef flats argues against this.

The exposures of *in situ* skeletal framework above low water mark are all the result of growth that was above low water mark in areas of permanently ponded, draining or splashing water.

Massive (chiefly *Porites*) and branching (chiefly *Montipora*) corals grow and coalesce in reef flat moats and on the seaward slopes of those ramparts where tidal-flat water seeps through during low tide (figure 28). The anastomosing skeletons provide a degree of cohesion, though the deposit normally crumbles underfoot. Crustose coralline algae cement coral shingle into an algal rim at the windward margins of many, particularly outer-shelf reefs. The algal coat is normally quite thin (figure 29) and the rim surface, which is a few metres wide, is only a few centimetres above the level of the neighbouring leeward moat. The depression of the moat represents a zone where normal intertidal erosion (physical and biological) is relatively more effective than at the rim, where construction is dominant. The algal rim deposits are therefore dynamic features that are simultaneously built on their outer edge and destroyed on their inner edge as the reef expands laterally.

The intertidal exposures of *in situ* skeletal reef-rock are normally patchily distributed near the rim of all reefs but the limited degree of cohesion resulting from this incipient organic binding does not produce rocks of the solidarity and physical prominence of the beach-rocks, rampart-rocks and boulder-rocks.

6. PHOSPHATE-ROCK

Several sand cays on the reefs of the Northern Province have large colonies of migratory birds and some show consolidation of the cay sands by phosphate mineralization by guano. Such deposits are located on the highest parts of the sand cays. At Bewick and Three Isles the phosphatized sand occurs in a distinct horizon at depths between 20 and 60 cm with loose clean sand both above and below, while at Ingram the surface sands have been removed by deflation giving patchy exposures. On Stapleton cay the upper 10 cm of carbonate sand is bound by guano and organic debris, indicating the first stage in the development of phosphate rock. Green Island has a dense wooded vegetation and though at present it does not have an exceptionally large bird population, it is perhaps because it has a permanent one over a fixed location that results in the formation of phosphorites here. The consolidated grains form a veneer over loose sand and the field occurrence suggests a downward mineralization by phosphate solutions. The cemented sands contain 23 % P_2O_5 and the phosphates (X-ray diffraction indicates chiefly hydroxyapatite) occur as either a thinly laminated wavy layer (0.02 mm thick) around carbonate grains (figure 30) or as a brown structureless matrix. The phosphatic coating brings about a centripetal replacement of the grains to phosphate. This replacement affects *Halimeda* grains more readily than corals and the foraminiferal grains are the least altered.

It is significant that the only high supratidal cementation on sand cays was by phosphate. No occurrences were found of calcarenite cemented by sparry calcite on the reefs.

7. ORIGIN OF INTERTIDAL ROCKS WITH INORGANIC CEMENTS

7.1. *Beach-rock*

Numerous workers have suggested that the aragonite cement of beach-rock is derived directly from seawater (Stoddart & Cann 1965, Ginsburg 1953, see also Bricker 1971). Bathurst (1971) pointed out that in some areas of the world, calcium carbonate cements beaches made entirely of non-carbonate grains, endorsing the seawater origin. On the sand cays of the Northern Province of the Great Barrier Reef, the carbonate grains showed no post-depositional solution effects in the aragonite cemented beach-rocks so the grains themselves were not the source of the cement. The fact that the vertical span of modern beach-rock over the beach relates closely to the tidal range shows a direct control by daily soaking and evaporation. A further critical control indicated by this study is that those beaches without supratidal exposure do not normally develop beach-rock. This could simply be a connection with the stability of the sand cay, i.e. the beaches that are built above high water mark are more stable than those that are not (also these high cays normally develop vegetation which further stabilizes the cay), or alternatively it could be more complex, relating to either exposure to meteoric waters or the degree of exposure to evaporation.

7.2. *Rampart-rock*

Most rampart-rocks occur intertidally. The only exceptions are parts of the upper platforms which locally reach more than 1 m above present mean high water spring tide level. The cementation of the upper part of this deposit by high Mg calcite could be explained by one of three processes: (1) being on the windward side of reefs the upper surface receives a high quantity of spray, thus raising the effective level of lithification; (2) capillary forces within the muddy matrix draw evaporating seawater above h.w.s.t. level; (3) during its formation some

3000 years ago, the level of high spring tides was higher than it is today. Evidence from fossil microatolls (Scoffin & Stoddart 1978, this volume) contained in the upper platform does support the last theory. The highest fossil *in situ* corals contained in the upper platform are 0.7 m higher than the highest living corals found on the reefs at present. This strongly suggests some relative lowering in either mean sea level or tidal range since the upper platform formed. The exact amount of this fall is not possible to assess from lithification criteria alone for the surfaces of platforms need not necessarily represent the upper limits of lithification. The general elevations of platforms may even relate more closely to the size of the original ramparts, and it can be seen today that there is a considerable range in the scale of loose ramparts and in the elevations of the loosely consolidated lower platforms (figure 31). Nevertheless it still remains that some 3000 years ago, ramparts were built and lithified to heights of at least 3 m, and during the last 1500 years ramparts were built and lithified to heights of about 2 m.

The lower limit of rampart-rock formation is not precisely known though it is thought to be near low water mark. Excavation into the bassett edge structure of low rampart-rocks revealed the absence of cement at a shallow depth (30 cm).

Shingle ramparts occur on only those reefs on the inner portion of the shelf close to the mainland (whereas beach rocks occur across the shelf). The critical distance from shore appears to be about 20–22 km (table 1); beyond this distance ramparts do not currently build intertidally and rampart-rocks do not form. The majority of the reefs within the 20 km zone have intertidal ramparts.

To facilitate lithification, ramparts have to be stationary for some time and also they probably require a degree of interstitial fine sediment to aid in the retention of saturated waters at shingle grain contacts. Satisfactory stabilization may be brought about by a decline in the frequency and intensity of shore-face erosion and washover as the rampart migrates across the reef flat and its distance from the reef edge increases. Alternatively it can be achieved through the development of another rampart to windward, thus excluding wave action from the older deposit. Sequences of shingle ramparts and ridges, frequently separated by moats, are not an uncommon feature of inner-shelf reefs of the Northern Province. Mangrove colonization of rampart surrounds and surfaces may also assist in stabilization. In the sheltered area leeward of the ramparts, quiet water conditions allow the accumulation of fine sediment and the extension of mangrove swamps. Mud from these swamps later finds its way to rampart interstices. It is clear that the areal distribution of rampart-rocks relates very closely to that of mangroves, both at a regional scale (table 1) and local reef scale. Furthermore, most loose ramparts without associated mangroves have no muddy matrix, whereas most cemented ramparts have large quantities of interstitial micrite.

Rampart-rocks have an average mass percentage insoluble residue of 6.7, whereas sand cay beach-rocks have a much lower insoluble residue of 2.7 % (table 5). This variation is noted even on one reef. Analyses of sea floor sediments from just off the reefs show that similar quantities of clay minerals occur on the windward and leeward sides of reefs, so it appears that it is the special local reef top conditions governing deposition and preservation of fine sediment that control the amount of insolubles of these rocks.

An obvious contrast exists between the sand grains on the leeward sand cay beaches that are constantly being agitated by the lapping, small amplitude waves and the shingle grains of the ramparts that provide a semi-rigid network into which mud can percolate especially during low tide when reef-flat water drains seawards through the ramparts. It is something of a paradox that on the windward side of reefs in the zone of heavy surf are built rocks with a large quantity of fine interstitial sediment, whereas on the sheltered leeward sides of reefs the common rock type has clean, well washed grains free from mud.

The most striking contrast between the leeward and windward limestones is the composition of the cements. Characteristically, beach-rocks of leeward sand cays are lithified by fibrous aragonite crystals, whereas the rampart-rocks are cemented by cryptocrystalline high magnesium calcite. Regrettably, chemical analysis of interstitial waters was not feasible during the expedition. However, some important differences between the two environments of cement precipitation were recognized and we believe the cause of the contrast in the petrography of the two deposits to lie in these differences. Beaches on sand cays are kept free from fines and are bathed in open-shelf seawater throughout the tide cycle. Ramparts, on the other hand, are not cleaned of trapped fines and are immersed in a range of water types: normal open-shelf seawater at high tide, and at low tide ponded reef-flat water seeps through the rampart during its seaward drainage. This reef-flat water may have been (*a*) concentrated by prolonged evaporation, (*b*) diluted by freshwater after heavy rain, or (*c*) influenced by passage through mangrove swamps.

TABLE 5. MASS PERCENTAGE INSOLUBLE RESIDUES OF BULK SAMPLES OF EXPOSED LIMESTONES (IN 10% HCl)

rock type/island	insoluble residue (%)	average of similar types	location on reef
beach-rock			
Pipon	2.0	2.7	leeward – sand cay
Waterwitch	2.9		leeward – sand cay
Stapleton	3.0		leeward – sand cay
Ingram	0.8		leeward – sand cay
Howick	3.6		leeward – sand cay
Bewick	3.1		leeward – sand cay
Newton	2.5		leeward – sand cay
Eagle	2.5		leeward – sand cay
Turtle I.	2.7		leeward – sand cay
Two Isles	3.3		leeward – sand cay
Three Isles	2.9		leeward – sand cay
Low Isles	3.2		leeward – sand cay
beach-rock			
Houghton	2.9	3.7	leeward flanks – in platform
Nymph	4.4		windward – in gap in platform
rampart-rock			
Beanley	7.0	6.7	windward – lower platform
Houghton	8.1		windward flank – upper platform
W. Pethebridge	8.2		leeward spit
Three	3.0		windward – lower platform
West Hope	7.5		windward – lower platform
Low	7.0		windward – low bassett edge
Three	7.2		windward – upper platform (up. facies)
Three	5.3		windward – upper platform (low facies)
boulder-rock (matrix only)			
Howick	4.1	4.1	leeward flank
beach-rock (consisting of grains of reworked cemented rampart-rock)			
Turtle I.	6.3	6.3	leeward – sand cay

Apart from cement mineralogies the occurrence of solution fabrics in the rampart rocks and their absence in beach-rocks suggest conflicting compositions of the interstitial waters. The beach-rock interstitial water is seemingly permanently saturated or supersaturated while the rampart-rock water undergoes periods of undersaturation.

It was noted that where small beaches occur in gaps in rampart-rocks on the windward sides of reefs, the cement is similar to that of the neighbouring rampart-rocks, indicating the control this windward-mangrove environment has on the nature of the cement. Aragonite can precipitate on the windward side shown by its occurrence in the inner chambers of coral fragments in shingle rocks, but its presence here likely pre-dates rampart-rock formation. On the other hand, high magnesium calcite was only found in those beach-rocks that either contained grains reworked from rampart-rocks or were associated with mangroves and windward type environments. Recently, Morita (1976) has suggested that the microflora that is associated with coral debris that becomes anaerobic a few centimetres below the surface is responsible for the precipitation of a calcitic cement.

The main differences between the windward rampart-rocks and the leeward sand cay beach-rocks are summarized in table 6.

TABLE 6. COMPARISON OF WINDWARD AND LEEWARD INTERTIDAL ROCKS

	beach-rock	rampart-rock
location on shelf	across entire shelf	inner-shelf position less than 22 km from mainland
location on reef	leeward edge	windward edge
bed thickness	7 cm	20 cm
bed attitude	15° away from cay	60° to reef centre
grain composition	corals, molluscs, *Halimeda*, coralline algae, benthonic Foraminifera	*Acropora* coral branches
grain size	equant, 1 mm diameter	rods 100 mm long, 15 mm in cross section
mass percentage insoluble residue in 10% HCl	2.7	6.7
colour	white to fawn	white to rusty brown
cement mineralogy	aragonite	calcite (14% $MgCO_3$) (with local aragonite)
cement fabric	radiating fringes of needles most abundant in meniscus position at grain contacts (though isopachous fringes occur)	multiple generations of micrite commonly developing a dripstone fabric
post-depositional solution effects	absent	present

The suggestion is that the characteristics of rampart-rocks (the inner-shelf location, the occurrence of mangroves, the presence of fine sediment, the abundance of clay minerals and the high magnesium calcite cement) are interrelated. It is concluded that the hierarchy of dependency is as follows: the position on the shelf determines which reefs develop stable ramparts, and these ramparts govern the distribution of mangroves which trap fine sediment including abundant clay minerals. The ramparts pond water during low tide and this water drains through mangrove humus carrying fine sediment into the ramparts. This water, perhaps in conjunction with the special anaerobic surfaces of the shingle, permits calcite to precipitate here, whereas on the leeward sand cay aerated beaches, evaporation of open seawater causes aragonite to precipitate.

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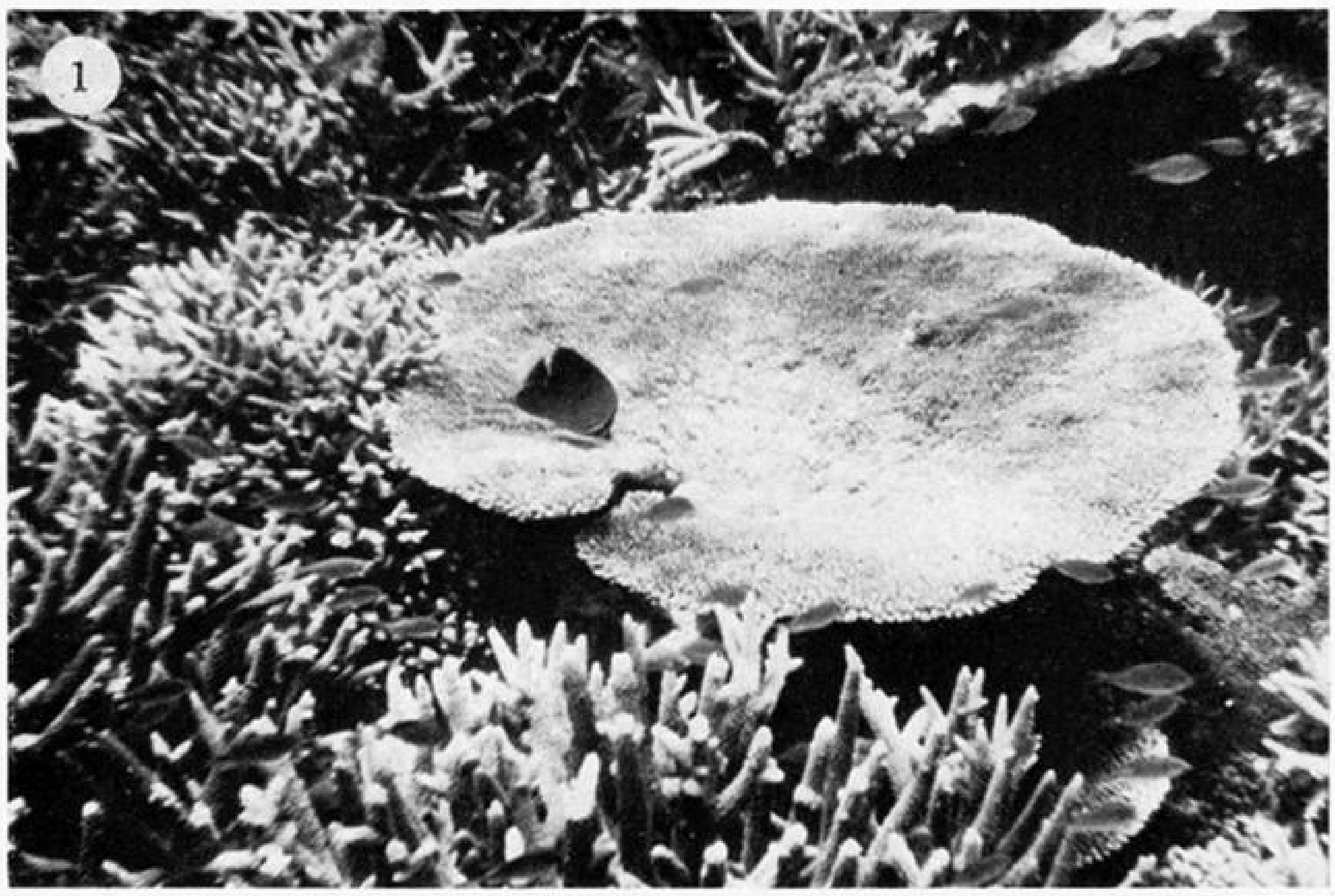
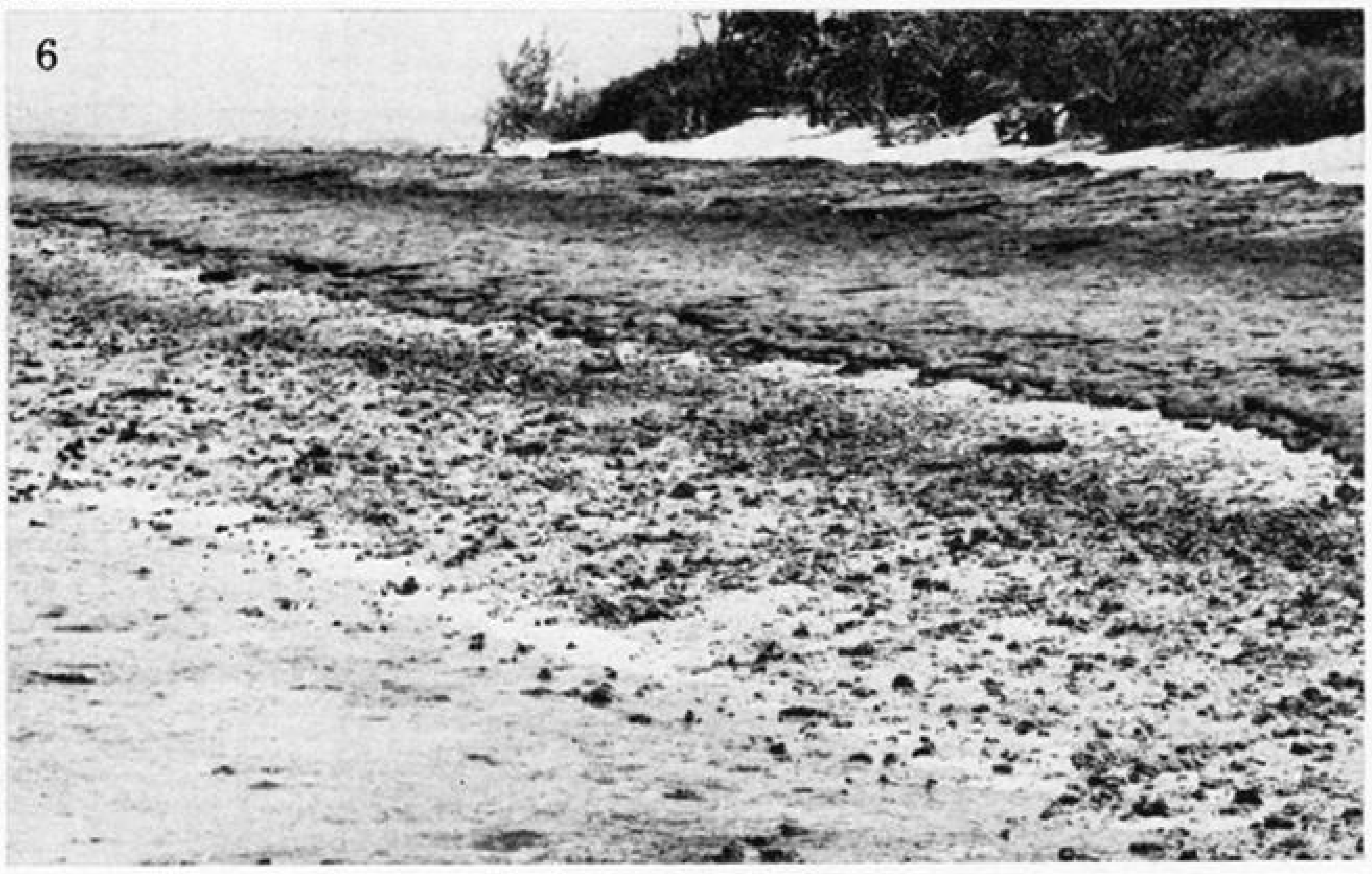
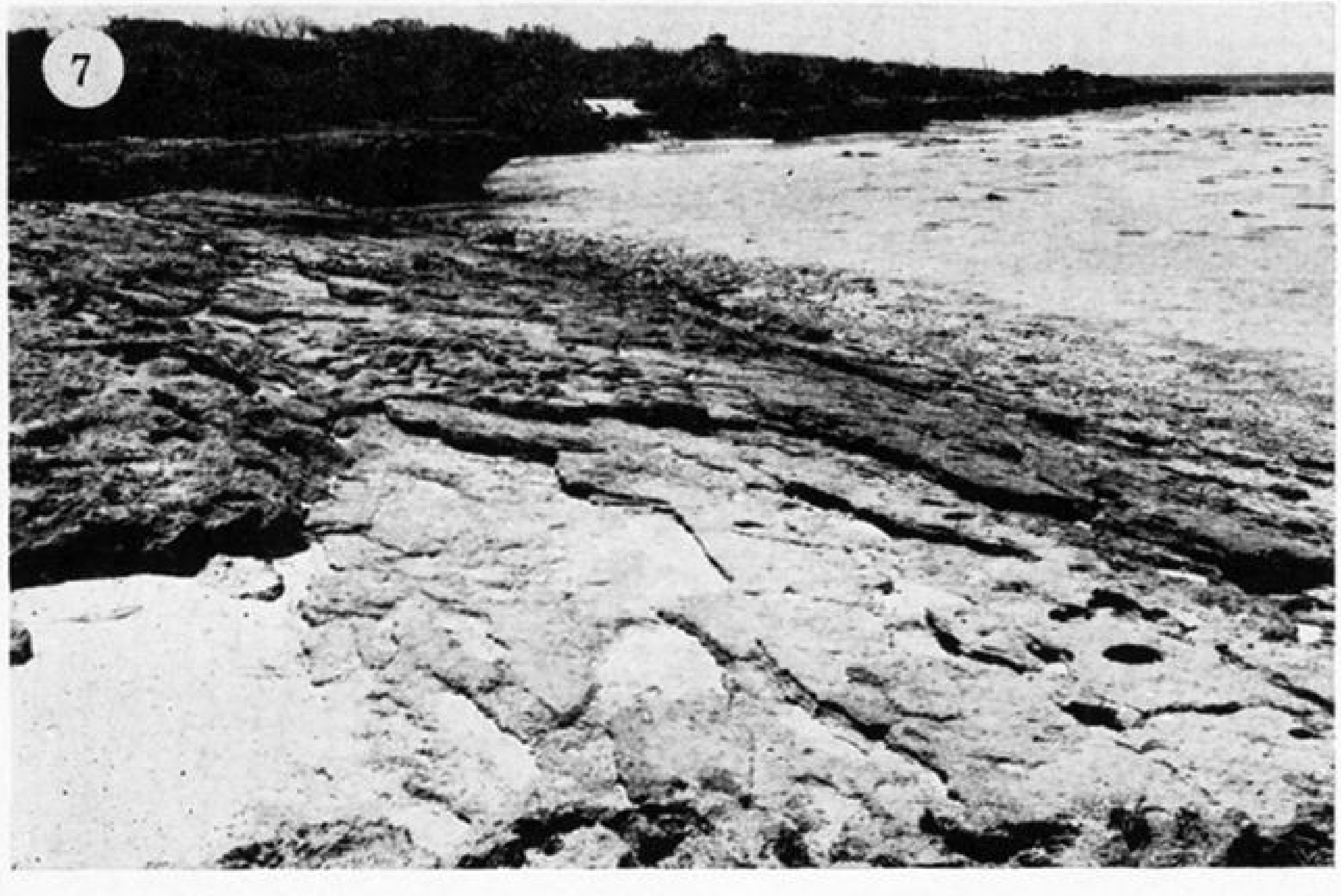
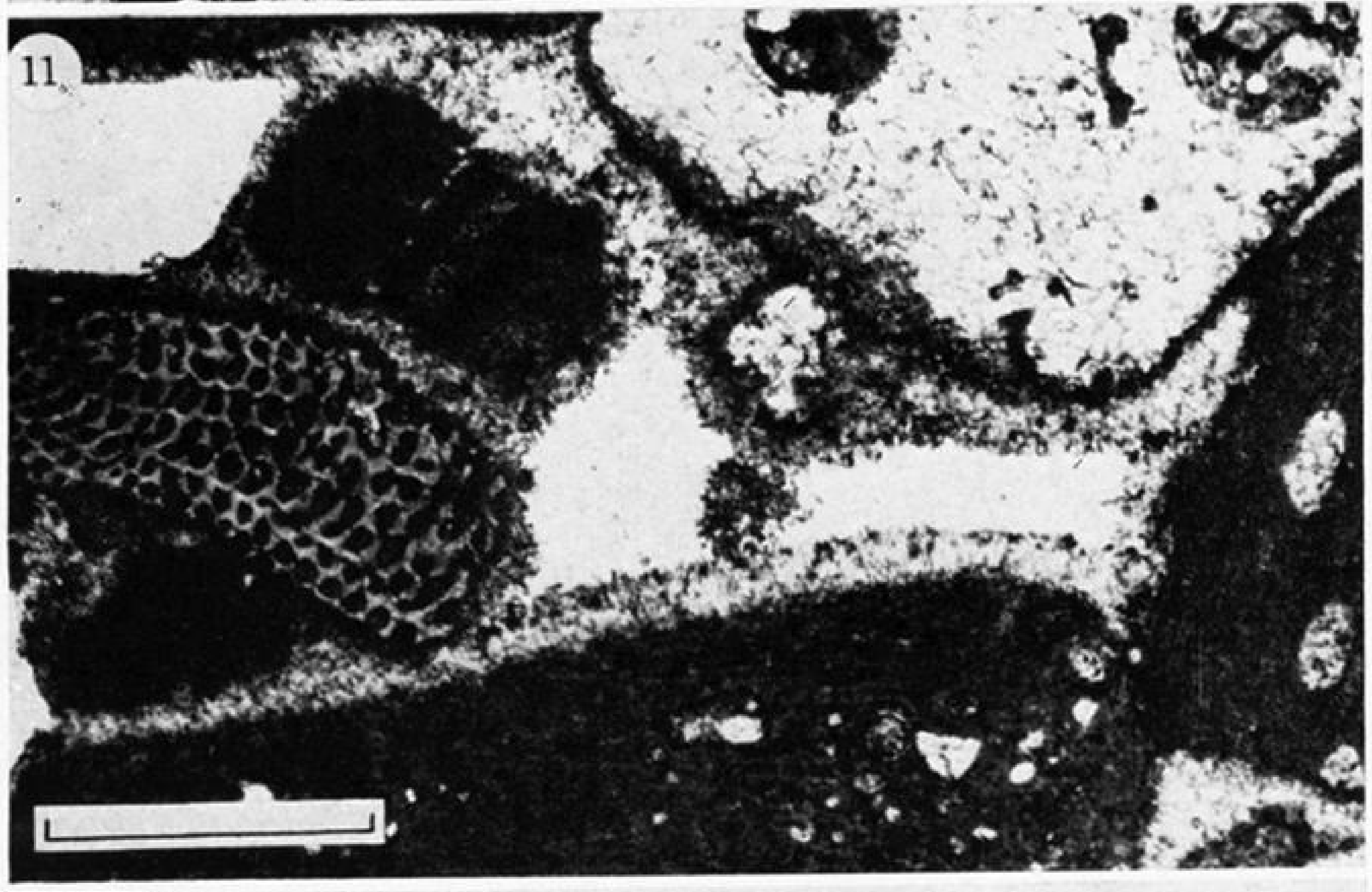
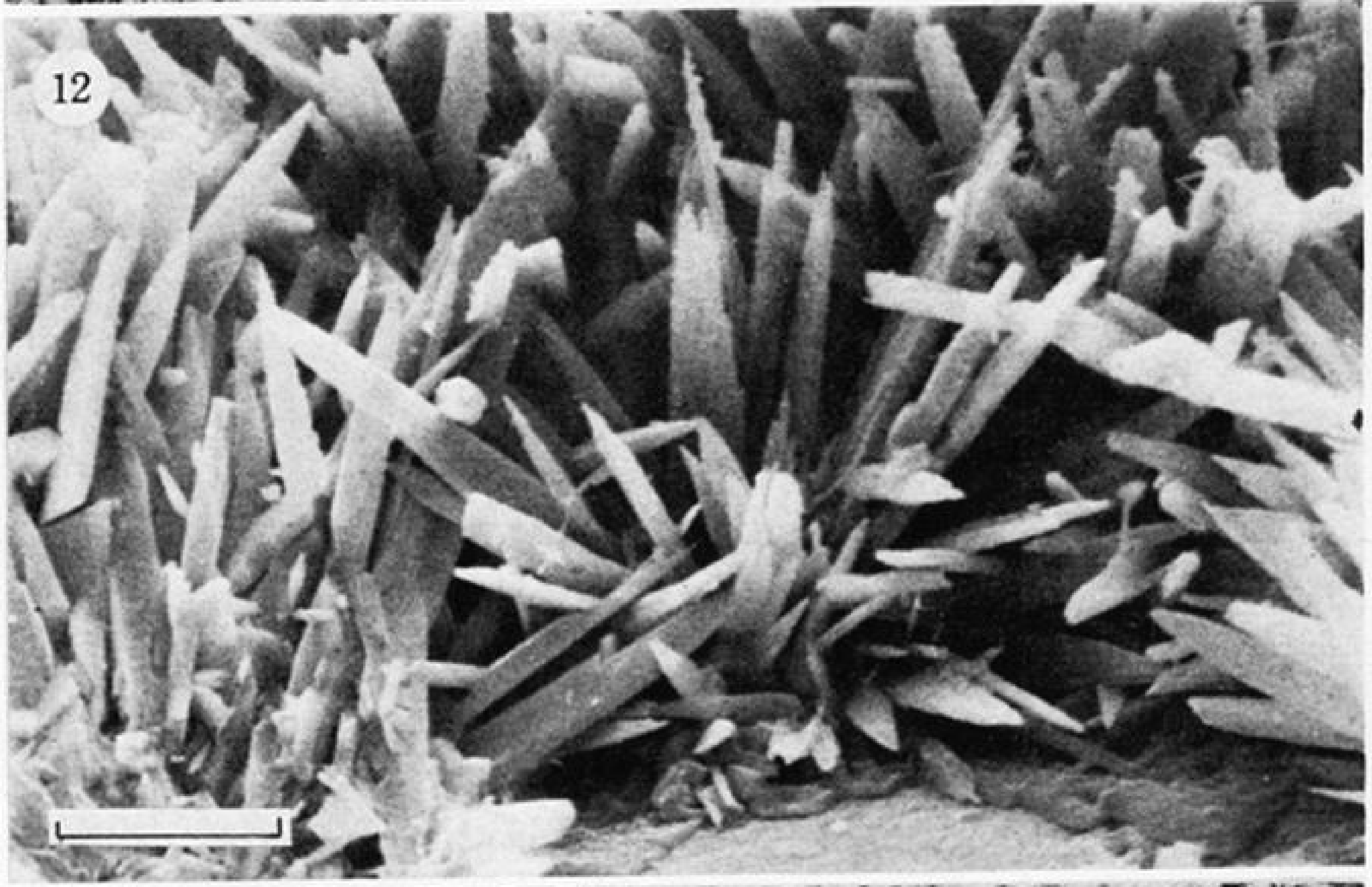




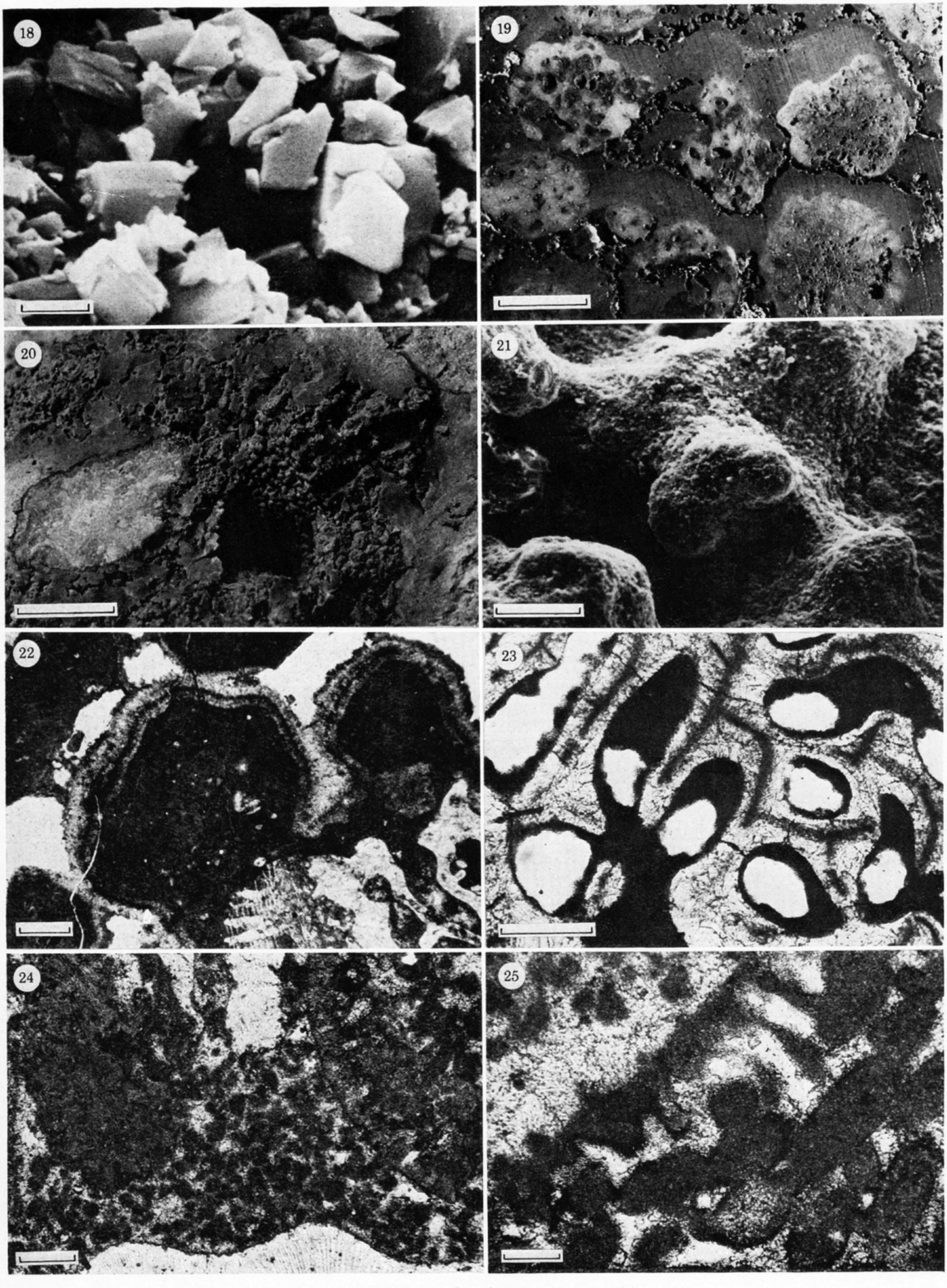


FIGURES 1–8. For description see opposite.





FIGURES 9–16. For description see page 126.



Figures 18–25. For description see page 127.

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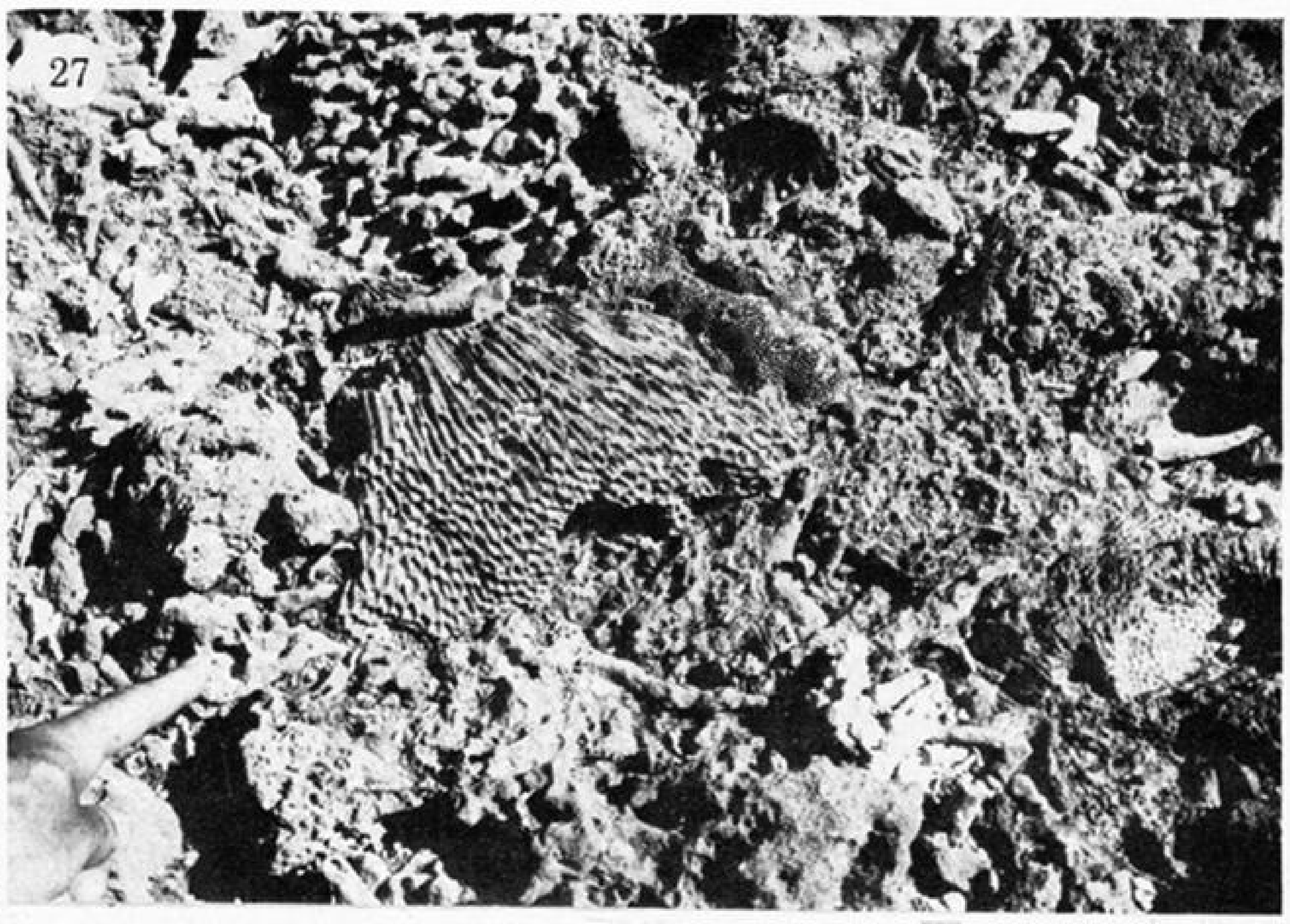

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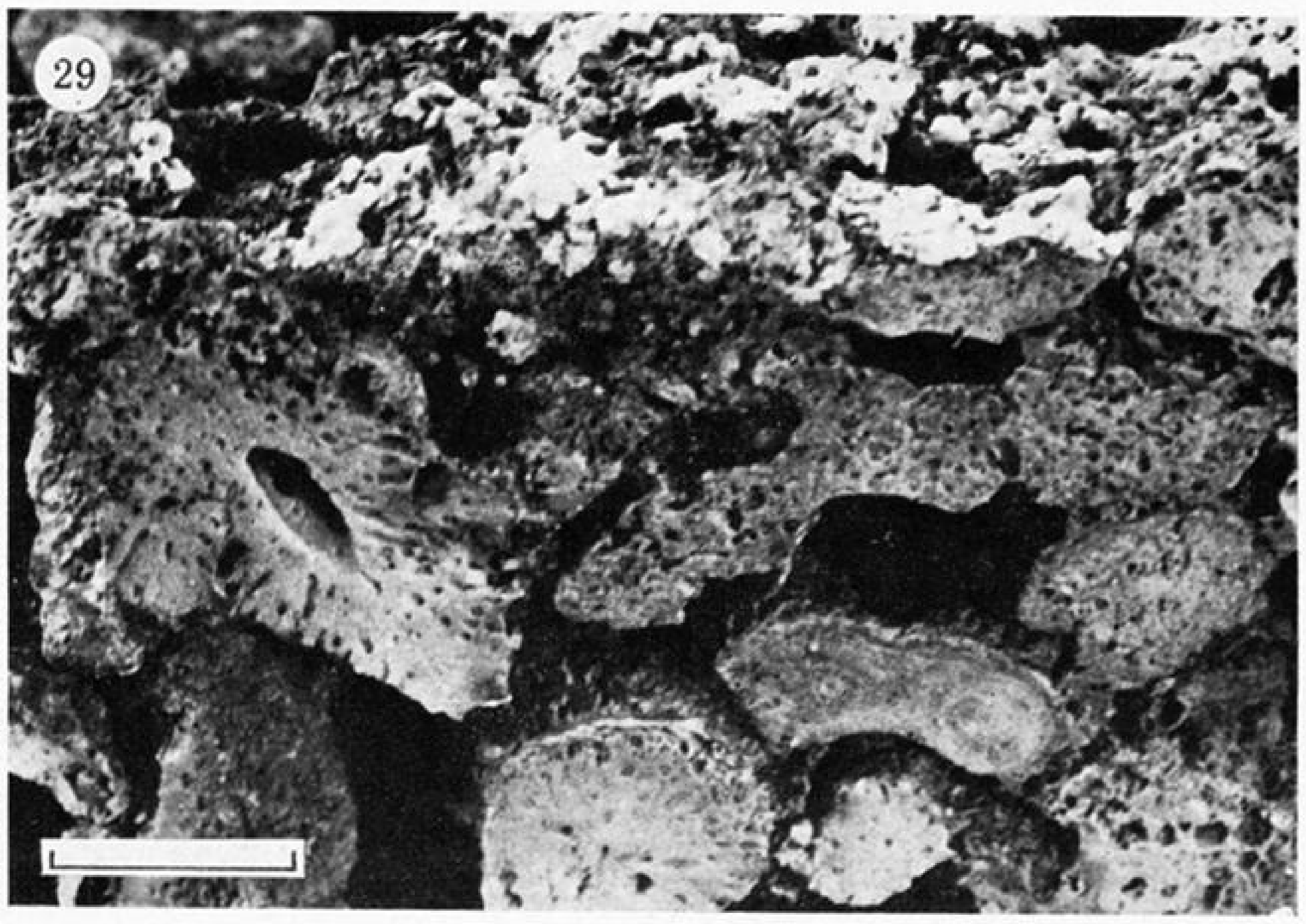

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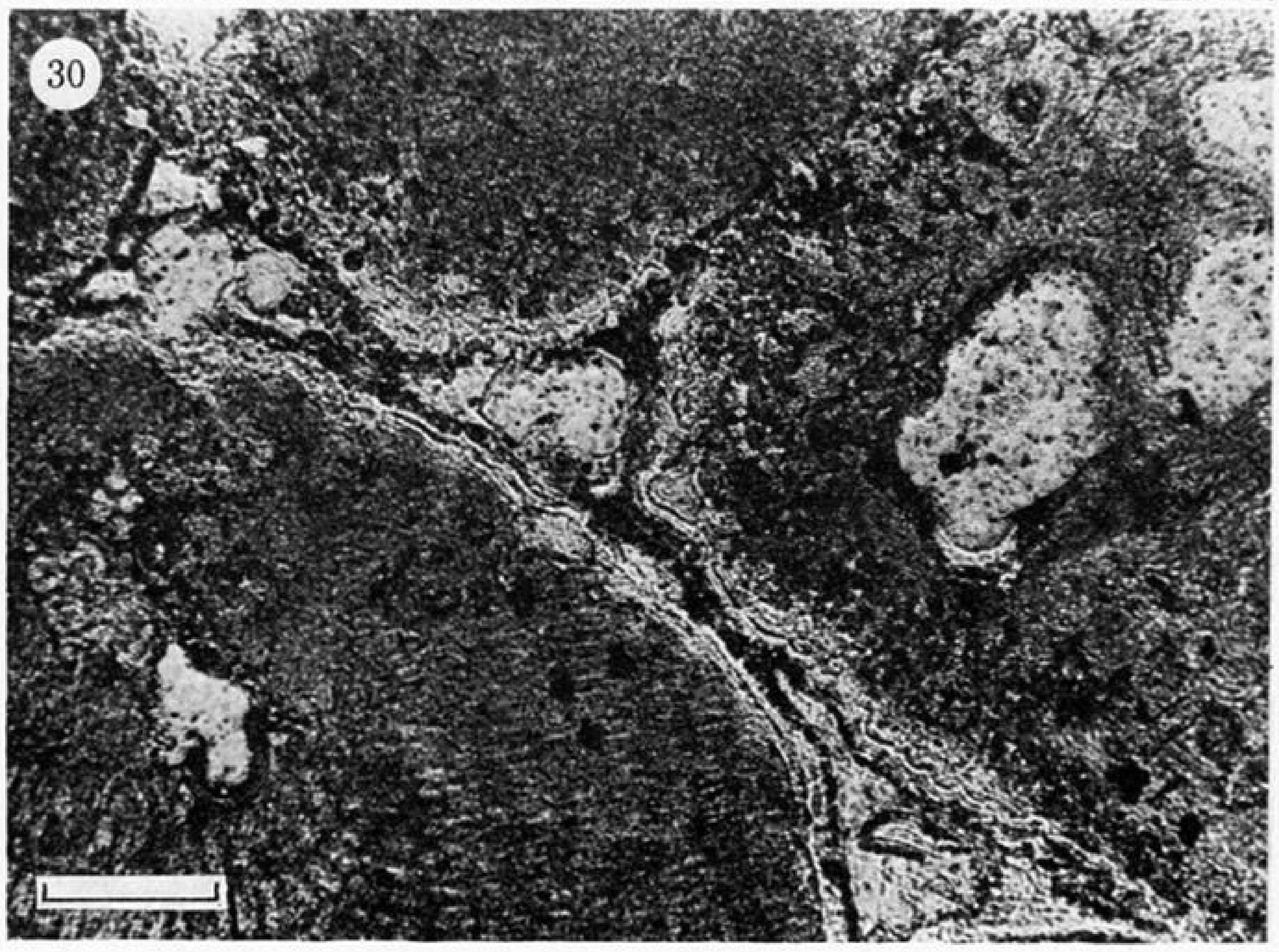

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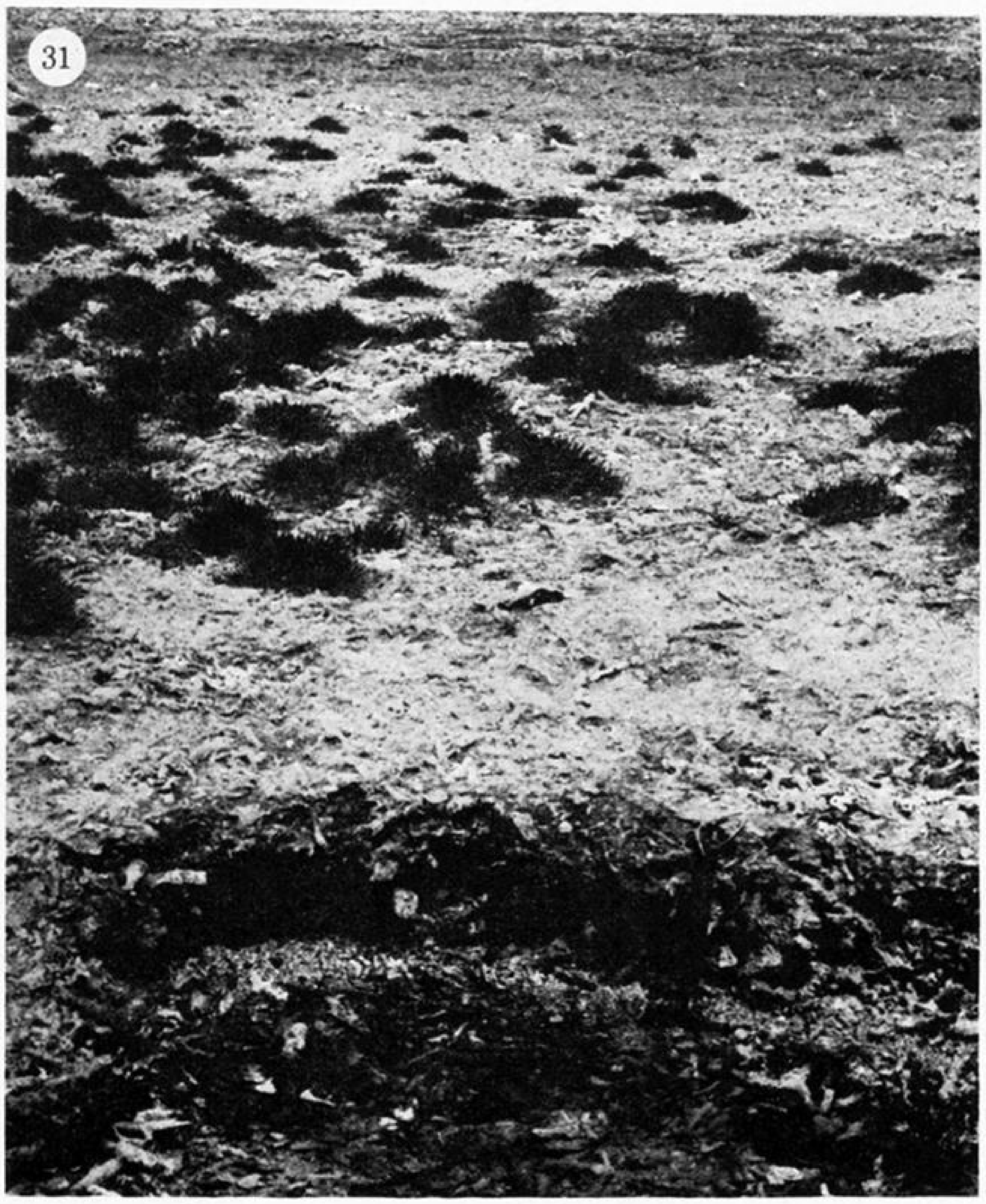

FIGURES 26–31. For description see opposite.