PART I: GEOLOGY

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The geology of these atolls has been described in several publications (Tracey, Ladd and Hoffmeister, 1948; Nugent, 1946; Emery, Tracey and Ladd, 1954; Fosberg and others, 1956, p. 74-132; and Fosberg, 1957 a). A summary of the geology follows.

Physiographically an atoll is the upper calcareous part of a broadly conical or irregularly pyramidal mountain mass rising from the floor to the surface of the ocean. Only the top of this is usually considered, geographically, and of this only the part which breaks the surface of the sea need be discussed here. Thus restricted, the northern Marshall Islands are a series of narrow platforms or reefs, usually irregularly ring-shaped or polygonal, commonly enclosing a shallow body of ocean water called a lagoon (pl. 1A). Of these platforms by far the largest areas lie at or just above or below tide level and are called the reef flat. The outer edge of this either falls off abruptly, as on leeward sides, or is elevated in the form of a low ridge, as on windward sides. The inner margins, where not occupied by islets, shelve off into the lagoon. The surface of the reef flat may be relatively smooth or locally quite rough or strewn with great boulders. Scattered along these platforms are areas that rise above high-tide level, called islets (perhaps a better term is the Polynesian word motu, but even this is not completely devoid of ambiguity) (pls. 1, 2). These islets, though forming only an infinitesimal part of the area and bulk of atolls, are in many respects the most interesting one, and that with which this report is principally concerned.

The entire structure of an atoll, except the deeply submerged part of the foundation, is made up of organic limestone sediments, either loose or variously consolidated. Deep borings on Bikini and Eniwetok have given much information on the nature of the sediments making up the part below sea level (Emery, Tracey, and Ladd, 1954; Ladd and others, 1953; Ladd and Schlanger, 1960.) These are mostly unconsolidated material, and extend downward to more than 4,000 feet below sea level. Some layers are consolidated or partly so. Most of the material resembles that deposited in the lagoon today. A few traces of carbonaceous material, with land plant pollen and fossil land and fresh-water shells, suggest that some of these sediments were once terrestrial and supported vegetation.

Origin of the reefs

Before considering the morphology and structure of the islets, themselves, it will be necessary to give brief attention to the origin and nature of the reefs and the materials of which they are composed. This is, in certain aspects, a highly controversial subject, and for more adequate treatment of it reference may be made to the publications cited above. The limestone is made up of the skeletons of lime-secreting animals and plants, mainly corals. Foraminifera,

and those algae which possess hard skeletons (see p. 56-74). These animals and plants add to the rocky structure on which they grow in two different ways. Some of them are firmly attached and cemented onto the rock, adding by the growth of their skeletons to the material of the rock itself, either in the form of crusts or as outgrowths. Storm waves may break these off. Others are either free or loosely attached, becoming free when they die. The loose material so formed, as well as that resulting from breakage, accumulates on the reefs, on the islets, in the lagoons, and on the submarine outer slopes of the atolls. That on the islets comprises the sediments that are the subject of this report.

The firmly attached organisms are of many different shapes and grow together very abundantly in the warm seas of the tropics. Attaching themselves to each other, as well as to the rocks, their skeletons form a rigid latticework of limestone, which may be filled in either by growth or by deposit of loose sediments in the interstices. Most of the corals (pl. 3) are branched; often they are miniature treelike structures that are rather fragile and easily shattered or torn loose by storm waves (pl. 3A, B). Some of those exposed to direct wave action have more compact growth forms and are more resistant. By themselves, however, most of the corals would not be able to make the stable structure known as coral reefs. The function of cementing and binding these corals together into a massive rock is performed by certain of the calcareous algae (plants) (pls. 4, 5) and by certain colonial hydrozoans (Millepora) (animals) related to corals, which grow with no fixed or definite forms but which make a shapeless hard crust over the surfaces of the other animals, smothering them, filling in the holes and spaces between them, thus presenting a smoother and more resistant surface to the force of the waves. These binding organisms, especially the plants, thrive best in the roughest, most thoroughly aerated water. For this reason the firmest structures of the atolls are on the windward sides where the swells break continuously. Growth of reef-building organisms, generally, is faster on the outer edges of the reefs where waves break, thus building up these portions more rapidly than the more protected parts (pl. 5A, C). Usually the most perfect and most intricately branched coral skeletons may be found in quiet places, such as lagoons (pl. 3), or in water below the active turbulence zone on the outer slopes, where they are not smashed by heavy waves. However, the greatest amount of limy material is added on the outer edges of the reefs. This area is also the source of much of the fragmentary material which forms the sediments that fill large parts of the reef structure. It has been shown by the studies at Bikini (Ladd and others, 1950) that loose material detached from the reefs, especially on the windward sides, is carried by currents, waves and winds and deposited in various other parts of the atoll structure to form the sediments of which the atoll is largely composed. Any hole in the latticework, any protected pool or cavity, as well as the lagoon itself, tends to be filled in by this loose material. This debris

may become cemented either by growth of such binding organisms as those mentioned above or by deposition of lime from the sea water, thus adding to the strength of the reef structure, or it may remain indefinitely as unconsolidated sediments protected from wave action by the surrounding rigid framework of the reefs.

It might well be supposed that these masses of limestone had grown up directly from their volcanic foundations until they reached the surface of the ocean. This cannot be true, however, because none of the important reef-building organisms can thrive in water too deep to permit a significant amount of light to reach them. The actual limits of growth of these organisms vary greatly, but there is certainly little material added below a depth of 300 feet, and the important addition is above 150 feet. These facts have been known for a long time and recent investigation has tended to confirm and amplify previous knowledge of these limitations. Therefore, it is clear that other principles must be involved in the presence of enormous masses of limestone below the limits of effective penetration of light into sea water. These principles have been the center of violent scientific controversy for more than a hundred years, and only the investigations of the last 20 years have brought matters to a point where a brief, reasonably convincing generalization can be made of the mode of origin of coral atolls.

There now seems little doubt that all reef growth took place in shallow water and that the volcanic foundations of the atolls have subsided with relation to sea level, the relative change in elevation being slow enough to allow upward growth to keep pace with the subsidence. In this way the zone of active growth would have remained within the levels where light was sufficient. Whether this relative change was due to actual subsidence of the volcanic islands or to worldwide changes in sea level is not certain, but it is probable that both took place. During the glacial periods, especially, there are known to have been considerable shifts of sea level and unquestionably these have had a profound effect on the present form of coral islands. It is believed, for example, that within the last few thousand years there has been a fall of approximately 6 feet (or 11 feet according to some authorities, especially Fairbridge , 1950, 1952) in sea level, leaving extensive areas of coral limestone reef rock above water. Remnants of these form much of the consolidated part of most of the islets on present-day atolls, the rest of it having eroded away since exposure took place.

The geology of the islets, themselves, may be treated in greater detail as these structures are largely made up of the sediments to be discussed in the present paper.

General features of islets

All the northern Marshall Atolls have some dry land in the form small islets (pls. 1, 2) scattered along the reef flats (pls. 6, 8). These range from tiny deposits of sand and gravel (pl.10) almost awash at high tide to flat expanses as much as several miles long and almost

half a mile wide. Not counted as islets are the rubble tracts (pl. 9) and storm-cast boulders lying on the reef flat (pl. 5D), though some of them may be exposed even at high water. The islets are essentially portions of the reef which lie above the general level of the reef flat. The materials are the same and there is no real difference except that they are exposed above sea level.

The surface of most islets lies between 4 and 10 feet above mean tide level but practically no accurate measurements of heights are available, nor have all the islets in the northern Marshall Islands been visited. Areas denuded by storms may lie close to high-tide level or even lower. Some islets have central depressions with bottoms at or slightly above high-tide level. Dunes, beach ridges, and boulder ridges may rise 6 to 12 feet or rarely even as much as 25 feet or more above mean tide level. A boulder-capped ridge on the south coast of Lae Islet has an altitude of about 18 feet. The highest altitude in the Marshall Islands is believed to be a beach or dune ridge on the lagoon side of Labinwor Islet, Likiep, on the leeward side of the atoll. Some parts of this ridge are more than 25 feet above mean sea level.

The islets may be regarded as ephemeral from a geological standpoint. This is shown by such evidences as ancient shorelines, indicated by beachrock, which do not coincide with the outlines of present islets, striking differences between outlines observed at present from those on maps of early surveys, and the relatively youthful character of the vegetation on some islets. That they are reasonably stable from a human standpoint however, is shown by the fact that a distinctive human population has occupied them for many generations; many islets show a well-developed vegetation, as well as populations of land animals, some of the latter unknown anywhere else.

Types of islets

Examination of a large number of islets shows that they are of three principal kinds: (a) those having a remnant of emerged reef rock, a mass of reef rock not yet eroded away, as a core; (b) those that are simply an accumulation of limestone detritus on the present reef flat; and (c) islets within lagoons. Type (a) islets are the result of a general lowering of sea level in relation to the reefs. This lowering of sea level is considered to have started several thousand years ago. Type (b) islets can be observed at present in all stages of formation in the northern Marshall Islands (pls. 9, 10). The three types and variants of them will be discussed separately, as they differ in some important respects. Types (a) and (b) are illustrated in figures 3 and 4.

Islets with a remnant of emerged reef rock as a core

By far the greater number of islets on atolls in the northern Marshall Islands are essentially platforms of reef breccia or conglomerate standing above the present reef-flat surface, with associated

accumulations of sand, gravel, and larger debris. Most windward islets are of this type, as well as those on south reefs. This type of islet (fig. 3) may be readily identified by the presence of a rock platform (pls. 11-13) above high-tide level, protruding from beneath the sandy or gravelly vegetation-covered part of the seaward side of the islet. The platform may extend beneath the loose material of the islet for as much as a third or even two-thirds the distance to the lagoon beach. More rarely it may extend all the way and protrude from under the sand at the top of the lagoon beach (pls. 11B, 12C). On the seaward sides of windward islets the platform may be of considerable extent (pl. 2A). It presents a rough pitted surface, blackened by the growth of microscopic algae. The rock of which it is composed is generally a highly consolidated reef conglomerate or breccia of unsorted, often very angular fragments, case-hardened by exposure to air. The highest rock surface observed, excepting the remnants of Bwokwla (Bokla) islet, Taongi (Pokak), was about 5 1/2 feet above mean low tide. Others were from 1 to 2 or more feet lower, having probably been eroded by slow solution by rain water. The pitting of these surfaces shows that this solution process is constantly taking place (pls. 14-16).

The suggestion has been made that some islets apparently of this type may really belong to the second type, the platform being simulated by subaerially consolidated sediments. This possibility is hard to eliminate unless reef material in growth position is found. It is by no means certain that such consolidation does actually take place under atoll conditions, but it is possible. Petrographic studies of the type of cementation and recrystallization involved might yield dependable criteria for distinguishing subaerial from intertidal and submarine consolidation, but we know of no such studies on atolls as yet. At present, degree of consolidation, indications of planation surfaces, and fossils of intertidal organisms in their characteristic growth habitats and positions are the best available criteria for concluding that the apparent platforms are of formerly submerged rock.

The edge of this platform may be more or less abrupt and ledgelike or it may slope. Commonly a ramplike slope of irregularly eroded rock, a few to many yards wide, extends from the edge or base of the ledge down to the reef flat just above low-tide level. There may be a transitional area of irregular or roughened rock slightly higher than the reef flat. The ramplike slope has been termed the erosion ramp (pls. 11A, 14A, B, D, 15, 16, 17B, D), as it is here that the active erosion of this elevated reef rock is taking place. Comparable erosion ramps may also be cut in beach rock (pl. 14A).

Several processes were observed which contribute to this erosion. Solution, by rain water and possibly by sea water also, is a factor, as is shown by the prevalence of the pitted surfaces characteristic of limestone erosion. The outlines of the animal skeletons of which the rock is composed are often left in relief. Solution basins (pls. 15, 17D, 20C) from about an inch to as much as a foot deep, with straight or slightly undercut sides, are commonly seen. An abundance of small mollusks (such as Nerita, Littorina) and other animals that feed on algae in the surface of the rock undoubtedly contribute to abrasion of the

surface in this zone. Abrasion by rolling back and forth, or swirling in pot-holes, of gravel, pebbles, and even larger rocks by waves leaves noticeable effects (pl. 19C, D). A conspicuous process is the spalling off of slabs of rock (pl. 16) from a foot to as much as 6 feet across, presumably due to sudden chilling of sun-heated rock by the rise of water with the tide. Spall planes cut through coral fragments and interstitial material alike, leaving smooth surfaces (pl. 16B). The constantly moving water of even small lagoon waves tends to cut away weaker beds and areas in the limestone, often undermining stronger rock, which then may collapse (pl. 14A, B), contributing large angular fragments to the loose rubble mass lying on the reef flat or erosion ramp. Just how important this process is and just how much of it occurs in normal weather and how much in storms are hard to estimate, but a combination of storm and normal erosion of this sort unquestionably accounts for the removal of a sizeable volume of material. Much of this material may be identified in the rubble deposits around the peripheries of the islets. What is probably the most important process of all is the weakening and crumbling of rock in the intertidal zone that result from the activities of boring organisms, especially one or more species of sipunculid worms. In many localities a narrow band of rock on the erosion ramp was seen to be riddled with the burrows of these worms, usually with the animals still inside. How the sipunculids accomplish the boring is not known, as they do not have boring mouthparts. They may, of course, dissolve away the limestone by acid body secretions. Other worms, mollusks, echinoids, sponges, and blue-green algae were also observed to contribute to the disintegration and erosion of limestone by boring in this intertidal belt.

The total effect of all these processes is the removal of an enormous amount of rock, resulting in planation down to low-tide level, and the production of large quantities of sediments. The extent of present-day reef flats (pls. 1, 2, 6, 8, 9), frequently half a mile to a mile wide, is a measure of the planation that is thought to have taken place since the fall of sea level which happened several thousand years ago.

Locally, the erosion ramp may be covered by beaches (pls. 17, 18) of sand, gravel, or cobbles, or the beaches may be restricted to an area above the edge of the protruding rock platform. The ramp itself is commonly found on the seaward side of the islets and frequently extends along the channels between islets, but has only rarely been observed on the lagoon side by us. Deposits of any sort of material such as sand, gravel, boulders, unsorted rubble, or even large slabs (pl. 20D) may be piled on and around the hard rock core of the islet. They may even cover it completely, in which case the islet may be mistaken for type (b). The lagoon side of type (a) islets is usually built of sand or small gravel (pls. 17A, 18). Often there are evidences of successive deposits of sand in the form of beaches or ridges which have been added lagoonward.

There is a tendency for islets of this type on windward reefs to be strongly convex on the seaward side and somewhat concave on the lagoon side, with prominent angles on the lagoon corners. The islets

may be widest in either direction but those elongated perpendicular to the trend of the reef have a tendency to broaden along the lagoon beach so that they are roughly T-shaped, with a narrow rock platform extending seaward from a bar of sand along the lagoon shore. Sand horns (fig. 3, pl. 2B) and sand lobes, spits extending from the inner corners, are common on islets on windward reefs. Sand aprons are broad deposits of material in shallow water just inside the reef, especially windward reefs.

Islets formed of accumulations of loose material on reef flats

Accumulation of sand, gravel, or unsorted material on the surface of the reef may result from any one of several causes or combinations of them: (1) Storms may deposit tracts of large boulders (pl. 9) on the reef, which are too heavy to be removed by ordinary wave action; later, smaller material may be piled around and among these; (2) The reef may be so wide that the force of normal waves is insufficient to carry loose material completely across and into the lagoon, and it may pile up on the reef; (3) The same thing may result from lagoon waves neutralizing sea waves, causing them to drop any loose materials they are carrying. Bars (pl. 10) formed in any of the above ways may become large enough to resist moderate storm waves which may then pile the material up above the high-tide level, or wind may also pile it up. These bars may become partially consolidated into beachrock (pls. 19, 20), which may survive even severe storms and serve to catch more loose material. Surfaces above high-tide level soon become colonized by plants (pl. 27B) the resulting vegetation further stabilizing the islets.

Regardless of how the loose material has become stabilized, these islets are essentially only piles of detritus on the flat surface of the reef. The core may or may not be of large boulders or consolidated material. Some islets which appear to be of this type may actually be of type (a), described above, but with the entire platform or remnants of it completely buried by loose material (fig. 4B).

Detrital islets may form on any part of the periphery of an atoll but are usually found on wider parts of the reef. Practically all islets on western reefs, many of those on southern reefs, and some on windward reefs may be so formed. They are of all sizes and shapes. Those on widened corners of atolls tend to be triangular or prolonged in the direction of the angle of the reef. Those on straight or gently curving reefs tend to be elongate in the direction of the length of the reef. Small bars tend to be crescent shaped, with the horns of the crescent downwind, or, rarely, concave toward the wind, but with the tips of the horns recurved in a downwind direction. Such small bars are frequently high around the periphery and depressed in the middle. Finer material is often removed from the surface by wind or waves, leaving a layer of loose gravel.

Islets of this sort, at least while small, are more vulnerable to the force of typhoons and lesser storms than those with a hard rock core. Storm waves, if severe enough, can move enormous quantities of loose

material, even chunks. They may, on the other hand, add material either from the outer margin of the reef or from nearby islets, or occasionally, perhaps, from sand aprons in the lagoon.

Islets within the lagoon

In addition to the two main types a few islets exist within the lagoons, especially just inside the passes. Most of these (perhaps all) are composed entirely of sand accumulated on patch reefs at or just below the level of the lagoon water. The sand is piled up in low hillocks or dunes and may be well vegetated. Such islets occur in the lagoons of Likiep, Kwajalein, Wotje, and Eniwetok, and perhaps one on Rongelap would be in this class. Eniwetak islet in Kwajalein Lagoon, was the only one of this sort examined closely, and that during a very short visit only. It consists of a relatively small flat area of sand 6 or 8 feet above lagoon level, with steep sides, and with one corner at a lower level forming a terrace. It is bordered, at least on one side, by a fringing reef.

The origin of these lagoon islets is obscure. They may be simply of sand deposited on the reefs by wind, but this does not explain their being usually located just inside passes. It has been suggested (K. O. Emery, oral communication) that the sand may have been deposited by currents prior to the fall of sea level; if so, these islets are a special case of type (a).

Shores

Shores (the strips of land between mean low tide and the high-water mark of ordinary storm waves), may be divided into those predominantly of loose or unconsolidated materials, called beaches (pls. 17, 18), and those of hard or consolidated materials or rock. These are not sharply separated, as loose materials may be scattered or spread in various manners over rock shores, rock may be variously exposed by erosion of beaches, and beaches may even become consolidated to form beachrock. Generally, the two types and obvious combinations of them may be easily distinguished.

Beaches

Beaches are, within certain limits, continuously and locally variable and may be classified only arbitrarily. Furthermore, the same beach may change completely even during the course of a single storm. Therefore, it is possible to speak only in generalities and in terms of what may be reasonably expected in certain situations. As to topographic position, beaches are readily divided into tidal and storm beaches (pls. 11B, 17A), the tidal beaches lying between low-tide level and extreme high-tide mark, storm beaches lying above high tide. In texture both of these may be sand, pebble, cobble, or boulder beaches, any combination of these, or intermediate between them. Beaches

commonly (but not universally) slope from the land toward the water, the nature and steepness of the slope being determined by the nature of the detrital material, the substratum on which it is lying, and a combination of all the forces of waves, currents, and winds which have acted upon it. The analysis of these forces is extremely difficult, formulation of it is not yet in a very advanced state and our data are not adequate for such detailed consideration.

Beaches exposed to the direct force of waves generated by the trade winds, or of frequent southerly storm waves and swells are generally much steeper than those on more sheltered coasts. Lagoon beaches generally are less steep than seaward beaches, except on leeward sides of large lagoons where strong waves may be generated. The slope is usually in the form of one or two shallow concave curves with a break at high-tide level. High sand or gravel beaches frequently have a sand terrace or berm (pl. 17A) at high-tide level between the storm and tidal parts of the beach.

Sand beaches (pl. 18A) may be found in any situation on either windward or leeward islets. However, they tend to be both more common and more extensive on lagoon shores than on seaward shores. On the lagoon shores of windward islets the sand is usually finer than on those of leeward islets, especially southern ones, where the beaches are frequently of gravel rather than sand. The sand particles of beaches on windward islets are generally much more angular than those of leeward ones, where they are worn and rounded. On islets with an exposed platform of rock there is frequently a storm beach above the rock platform. Where no rock platform is exposed, the beach commonly extends from the vegetation down to the reef flat, or erosion ramp, or on lagoon beaches down to the sand apron with which it merges. If there is a beachrock formation along the shore, there is more often than not a storm beach behind it, either continuous with the top of the beachrock or separated from it by a low escarpment or cuesta.

Pebble beaches (pls. 17A, 18B) are common along windward shores of windward islets. They also occur along the channel sides of all islets except those on the western reefs that consist mostly of sand; they are especially common on the lagoon shores of leeward islets on the south reefs. In texture pebble beaches vary from fine to coarse, where they merge with cobble or boulder beaches, and the particles may be well sorted or more rarely mixed in any proportion of sizes.

Sand and gravel beaches are commonly white to pinkish in color, particularly where the material is frequently disturbed and worked over by wind and waves. Where beaches are undisturbed for long periods of time, the color of storm beaches becomes progressively more grayish or even blackish, from the growth of microscopic algae on the upper surfaces of the particles.

Cobble or boulder beaches (pls. 13A, 17C, D) are commonly associated with storm deposits of coarse material (boulder or cobble ridges), hence are more frequently found on southern seaward shores; they may, however, be found in any position, though rarely on western leeward

islets. The size of the fragments of rock varies but may be a foot or more in diameter. Cobble size, from 3 to 10 inches, is more common. At times a combination of a storm beach of boulders or cobbles with a tidal beach of sand or pebbles, or the reverse, may be encountered; more frequently both tidal and storm beaches are of material of similar texture. Generally, the smaller sizes tend to be less angular than large boulders, presumably because small pieces are more frequently rolled around. This, however, is by no means always so. Beaches of such coarse material occur rather rarely on lagoon shores except adjacent to deep passes on south reefs. Even on Taongi (Pokak) where there is a short beach ridge of cobbles along the lagoon shore of Sibylla islet, the beach below it is of sand.

Rock shores

Rock shores are of two types, those of slanting beds of beachrock (pls. 19A, B, 20A, B) and those of reef rock (pls. 11A, 12) in which the bedding is obscure or horizontal.

Beachrock shores (pls. 19A, B, 20A, B) may slope at the angle of the bedding planes, ranging from 5° to more than 30°, or may be truncated by erosion to a much gentler slope than the dip of the beds. Frequently, where there is a wide series of beds, these may be represented by a series of sharp parallel ridges at or just above high-tide level. Where beachrock is between tides it may be smooth from abrasion by wave-rolled gravel, pitted with large potholes (pl. 20C) and solution basins, or it may be cracked into large slabs or blocks (pls. 14C, 20D). These, as on the lagoon shore of Yeldo (Enejelto) islet on the east side of Wotho Atoll, may be thrown up into an irregular windrow on the storm beach above (pl. 20D). Near and especially above high-tide level the surface may be extremely rough and pitted (pl. 14A, B), almost honeycombed, from weathering by rainwater. Here, also, the surface is likely to be very dark or almost black from algal growth. To the casual observer these jagged blackened surfaces may suggest volcanic rock, which is not exposed on atolls.

Reefrock shores (pls. 11A, 12) are of two principal types, those where a platform of elevated reef protrudes from beneath the vegetation well above high-tide level, ending either in a ledge or an erosion ramp; and those where the rock has been eroded down to high-tide level or below. The latter type is commonly rather rough and may end in a low cliff if on the lagoon side, or merge into an erosion ramp on other sides of an islet. Both these types may commonly be partly covered by beach deposits. On Bwokwla islet, Taongi (Pokak) Atoll, the lagoon shore is a platform about 1 foot above high-tide level and is conspicuously undercut. An approach toward this condition may be seen on other lagoon shores of south reefs. Where a similar emerged platform protrudes onto a reef flat there always seems to be some development of an erosion ramp (pls. 11A, 15, 16). This may be broad, as much as 100 feet wide, and gently sloping, or as narrow as 3 to 4 feet and steep. Steep clifflike shores may also be found lining inter-islet channels where

the islets are very close together, but still separated by water. Such a situation is to be seen between Anenlik (Enelik) and Jabwe islets, Ailuk Atoll.

Ledgelike shores frequently have their erosion ramps covered or partly covered by accumulations of coarse rubble. This is commonly in the nature of a mantle resting on the underlying rock, it is rarely banked up in the form of a beach. This may be seen most often near the seaward ends of passages between islets. The surface of the ramp is usually somewhat rough and pitted, sometimes extremely so. In other examples the roughness may be moderated by abrasion from wave-rolled gravel, as on some beachrock shores. The transition to the relatively smooth reef flat surface may be abrupt or gradual, in places marked by minor corrugations perpendicular to the waves. A good example of these corrugations is shown by Schlanger and Brookhart (1955, pl. 1). Elsewhere the edge of the ramp is irregular with many low spurs and reentrants.

Beachrock

A feature of atoll islets so common and conspicuous as to deserve special mention consists of narrow elongate beds of consolidated sand, gravel, or even larger material, dipping at the angle of inclination of a beach surface (pls. 19, 20). Such beds may consist of a single layer a few inches thick, or more commonly many such layers superimposed and dipping at the same angle. Owing to the small lateral extent of the single beds the actual vertical thickness or depth of such a series is very small. The total vertical dimension of the series is not more than the distance between mean high and low tides, except where such beds persist from an earlier higher sea level. In such cases, they may extend 1 or 2, or even 4 feet above mean high tide, and if recent beds have been added to the series, down to low-tide level. A continuous series of these beds may reach an extreme width of 20 yards or even more, but usually such a series is not more than 3 or 4 yards wide. The length is quite varied but may be as much as hundreds of yards.

Beachrock apparently forms beneath the surface of beaches and when first exposed by wind or wave action may be very weakly consolidated; the particles are cemented by a coating of aragonite needles. Exposure to air tends to harden the rock so that it may persist for a long period, as is shown by ancient beds now above high-tide level that must have been formed while sea level was higher than at present. This is undoubtedly a manifestation of the general phenomenon of "case-hardening" of exposed limestone, apparently due to recrystallization of calcite, which shows in some thin-sections of old, hardened beachrock.

Long strips of beachrock commonly occur around the peripheries of islets, usually sloping away from the islet, toward either lagoon or sea, in the manner of beaches of loose sand. However, locally the dip may be just the opposite of what would be expected, suggesting that the islet may not have always been in its present position. Such displacement of islets is also indicated by strips of beachrock found in the

interior of islets and in various positions on otherwise denuded reef flats, between islets, or away from them altogether. On some reefs, such as that extending westward from Utirik Islet, Utirik Atoll, there may be a number of parallel series of beachrock beds, the seaward ones dipping seaward, those along the lagoon dipping lagoonward. It is thought that a typhoon may have removed most of the loose material from the reef flat here, leaving beachrock marking former shorelines of the islet. In places, especially near reef angles and the corners of islets, extremely complicated arrangements of beachrock may be exposed, indicating many shifts in former shorelines. A conspicuous example may be seen on the eastern point of Likiep Islet, Likiep Atoll.

Marginal ridges

Ridges (pls. 21, 22A, B) of unconsolidated limestone detritus are common just inside the margins of islets, especially along the seaward sides. The material varies in texture from fine sand, less than 0.5 mm in diameter, to cobbles and even boulders. The ridges may be interrupted or may extend continuously around an islet. Small islets are especially likely to have ridges all around them. The ridges are likely to be highest on the seaward side and the highest ones are on south shores.

These ridges may be normal beach ridges, piled up by waves, or by waves with the help of wind; they may be enormous masses of cobbles and boulders probably cast up by typhoons; or they may be dunes resulting from wind-blown sand caught by vegetation.

Beach ridges are the most common, existing at the tops of most beaches at least to some extent. They are commonly broad, low, and rounded in profile, seldom more than 2 to 4 feet above the general level of the islet surface. Where recent and not yet vegetated they may be narrow with sharp tops. Frequently they are double, the front crest sharp and narrow, the back one rounded and broad. In texture they generally correspond somewhat to the beaches that are in front of them, being sandy along most lagoon slopes except those on south reefs and frequently so along seaward slopes of windward islets. Along the lagoon side of islets on the south reef they tend to be of gravel, which often changes from coarse to fine from east to west along any particular islet, ending in sand at the west end. Gravel ridges as well as sand ridges may also be found along the seaward south shores of the islets where these are not occupied by storm deposits. The gravel is commonly rather rounded but may be angular in some situations. Many small sand and gravel bars are simple peripheral ridges surrounding bowl-shaped depressions.

The most conspicuous surface features of atoll islets are the enormous boulder ridges (pl. 22A, B), often termed "boulder ramparts", which occur on some islets of most atolls. These are beach ridges formed of large-size material. They are somewhat randomly distributed, being known from coasts facing in almost all directions, and from lagoon as well as seaward sides. They are, however, far more frequent along

the seaward coasts of islets on the south reefs, and least frequent on lagoon coasts and on islets on west reefs. The texture of the material ranges up through cobble to boulder sizes (pl. 22). Different segments and layers in the same ridge often may be of very different average size and have abrupt boundaries between them. The highest known boulder ridge in the northern Marshall Islands is on the south coast of Lae Islet, Lae Atoll. It is about 18 feet high, with the upper several feet composed of huge boulders, a foot or more in diameter. Generally the size range of the material is much smaller than this and the height is between 5 and 10 feet. The rocks are frequently very angular and sharp and the upper layers may have relatively little finer material in the interstices. The profile of the ridges varies from narrow, with the seaward side rather steep, to broad, as much as 100 yards wide, with very gradual slopes. Where the ridge is wide a secondary ridge may frequently develop at its seaward margin, this one much sharper and with a steep seaward slope.

There is no sharp distinction between the boulder ridges and ordinary beach ridges. Their occurrence in a more or less random distribution, with a predominance on south reefs, and the energy requirements for moving and piling up such large fragments suggest that boulder ridges may be thrown up by typhoons, whereas ordinary beach ridges are probably formed by milder storms or ordinary high waves in rough weather.

Both beach ridges and boulder ridges in some situations occur in series, with more recent ones partly superimposed on the older, arranged from older to younger in either a seaward or lagoonward direction, starting from the interior of the islet. This arrangement is thought to result from successive heavy storms, each depositing a great mass of material. The vegetation on such a series may be observed to be more mature on the inner ridges, and the rocks may be more blackened. Islets may be enlarged by such deposition, especially on the lagoon side, but only where shallow water, a reef flat, or a sand apron exists along the original shore. Often the lagoonward third or more of an islet seems to have been built in this way, usually of smaller size material than that found in seaward beach ridges or boulder ridges.

Dunes, likewise, may be found in almost any situation, but they are most common along lagoon shores, especially on islets on west reefs and the west ends of those on south reefs. They are also found on the rare islets inside the lagoons. The dunes in the northern Marshall Islands are all small and are mostly stabilized by vegetation. It is likely that the vegetation is principally responsible for their formation by stopping the wind-driven sand and causing it to pile up among bushes and trees. The presence of pebbles and even some cobbles and boulders in many of these dune ridges shows that storm waves have frequently had a part in their construction.

Interiors of islets

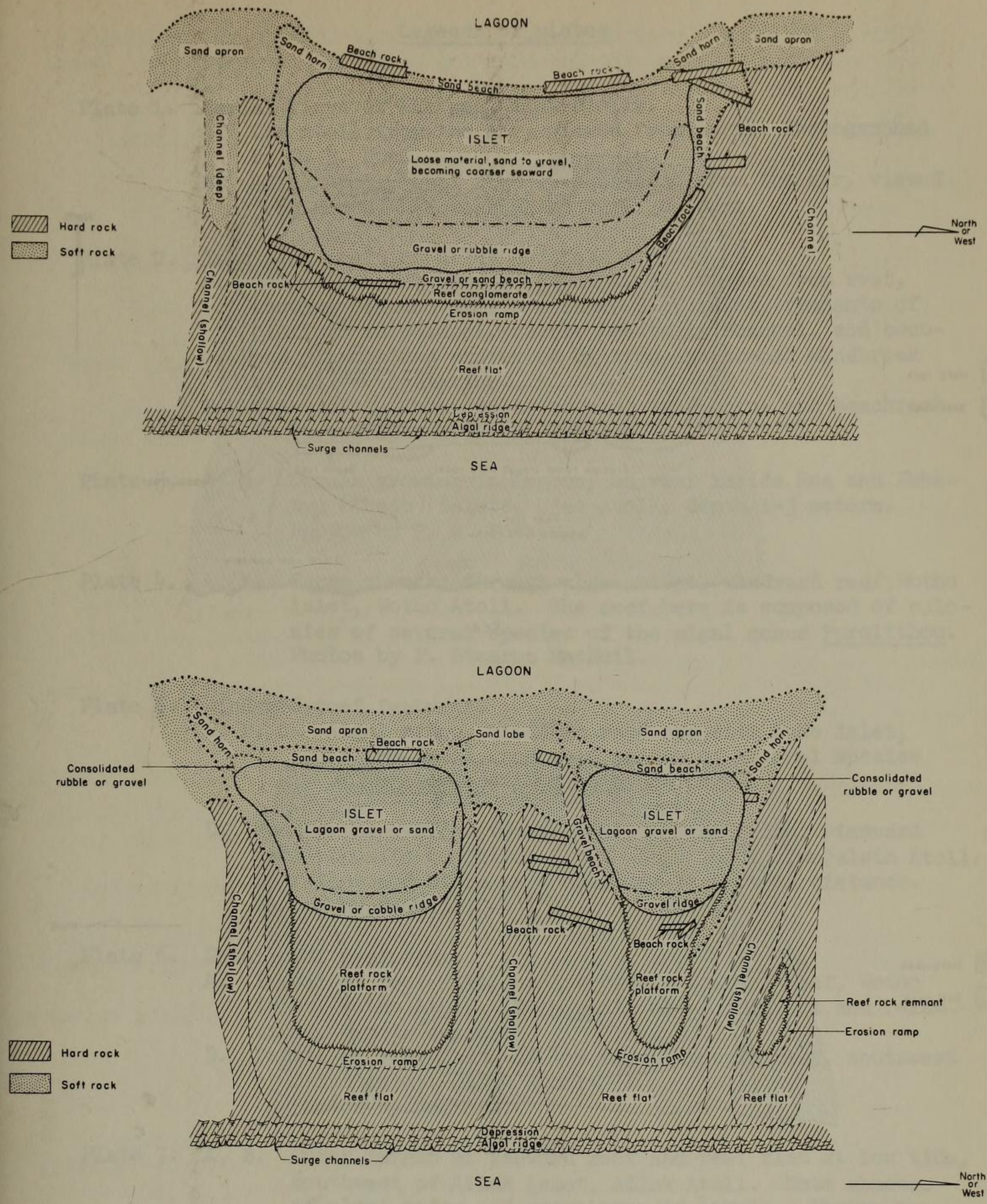
Inside the marginal ridge an islet may have little relief. It commonly shows an extremely slight slope upward from the lagoon side, with a surface of sand near the lagoon, becoming gradually coarser toward the sea. Boulders and blocks of reef rock, many of enormous size, are scattered over the surface of many islets inward from the seaward side to as much as 200 yards, or even more. These are more common where there is a well-developed boulder ridge along the seaward coast. The only apparent explanation is that they were carried inland by enormous typhoon waves. Their presence vividly illustrates the power of such waves, as the largest boulders must weigh tons. Occasionally there are areas, termed block fields, which are thickly covered with such boulders and large rubble, even to a depth of 1 to 4 feet. The narrow seaward parts of some windward islets may be composed entirely of coarse, loose rubble. The seaward sides of islets on south reefs may be covered by several feet of boulders and blocks, 6 inches to 3 feet in diameter, extending 200 feet or more back from the beach. This type of deposit usually but not always assumes the form of a broad low ridge, as described above under boulder ridges. Holes, loose blocks, and a tangle of vines may make footing here precarious.

Other topographic features may be found locally. Broad central depressions may occur. On Lado Islet, Likiep Atoll, there are at least two such broad depressions parallel with the long axis of the islet. On long islets there may be two different types of transverse depressions. One results from the filling in of the gap between two islets, uniting them into one, usually with some indication of the former separation in the form of an inward scallop of the seaward beach. The depression is commonly very gradual and slight. The other type apparently results from partial breaching of an islet by typhoon waves, which sweep the loose material into sea or lagoon. This type of depression is likely to be more abrupt, with sand, rock, or coarse rubble on the bottom. The appearance of a reasonably recent scour of this type may resemble that of a dry stream bed, though of course there are no streams on these islets. The inner ends of both these types of transverse depressions are often filled by a lagoon beach ridge of gravel or sand. Broad flat areas at lower levels than that of the rest of islets are usually either recently filled by wind or storm deposits, or are areas scoured by typhoon waves.

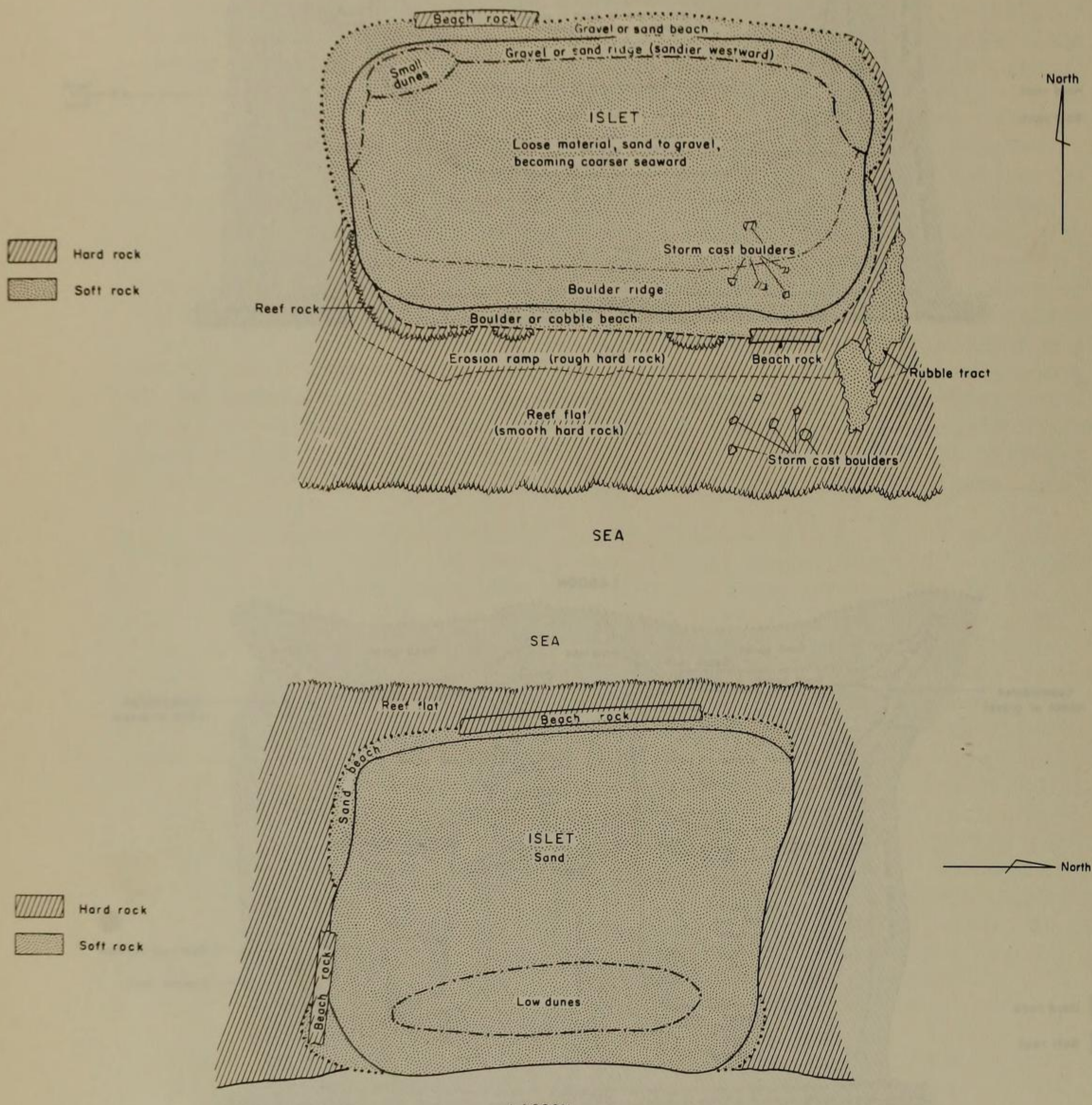
More abrupt, smaller, or irregularly winding depressions, from pond-like to trench-like, 3 to 6 feet deep, surrounded by piles of excavated sand and gravel, and usually with mucky soil in the bottom, are ancient taro pits dug by the inhabitants but abandoned many years ago. They are usually found near the centers of large islets or inward toward the lagoon. They are rarely found on atolls north of Ailuk. They are conspicuous on Wotho and Lae. Very rarely, small depressions are found containing tiny mangrove swamps. One such is found at the south end of Pigowak (Bekrak) Islet, Utirik Atoll, another on Jeltonet (Jeltoniej) Islet, Likiep Atoll.

Islets composed, entirely or in their lagoonward parts, of successive beach ridges have a topography of alternate ridges and furrows parallel with the lagoon margin. At places, as near the north end of Taka Islet, Taka Atoll, there is what appears to be a storm deposit of small sharp rubble rising slightly above a general surface of sand or gravel, well inward from the beach. This may be the result of growth of the islet subsequent to deposition of the rubble.

In the interior of a number of islets, such as Utirik Islet, and several of those on Wotho Atoll, are rounded mounds, a few yards in diameter, of small sharp coral fragments. These mounds may rise 2 to 4 feet above the general level of the interior of the islet. There is generally little or no fine material in the interstices, at least in the surface layers. The origin of these mounds is not clear but they may result from the pushing up of rubble by the roots of trees, possibly accentuated by the blowing down of trees by storms. Stages in this process were observed on the islets of Wotho Atoll. They differ, however, from the tree-fall mounds observed in continental forests in that they commonly have no hollow alongside, of the sort regarded as characteristic of such features. It may be that there is some other explanation, entirely, for them.



3. Diagrams of typical windward islets showing position of surface features. A, single islet on reef flat; B, two small adjacent islets on reef flat.



4. Diagrams of typical leeward islets showing position of surface features. A, islet on south reef; B, islet on west reef.

Legends of plates

Plate 1. Aerial views of Lae and Ailuk Atolls.
A. Lae Atoll from the air, viewed from north. Photographed by D. B. Doan.
B. Ailuk Atoll, east reef with islets, from the air, viewed from south. Photograph by F. R. Fosberg.

Plate 2. Islets on reefs of Ailuk and Taka Atolls.
A. Islets on east reef of Ailuk Atoll, viewed from west, showing denuded platform seaward of islet, remnants of platform in channel, rubble tracts in channel, and coconut plantations protected by crescent-shaped windbreak of native vegetation.
B. Eluk islet, Taka Atoll, showing sand horns and beachrock. Photographs by F. R. Fosberg.

Plate 3. A, B. Corals growing in lagoon, on reef inside Rua and Ebbetyu (Ebeju) islets, Ujae Atoll, depth 1-3 meters. Photos by F. R. Fosberg.

Plate 4. A, B. Surge channel through algal ridge, windward reef, Wotho islet, Wotho Atoll. The reef here is composed of colonies of several species of the algal genus Porolithon. Photos by F. Stearns MacNeil.

Plate 5. Windward reef features.
A, B, C. Algal ridge, windward reef opposite Lado islet, Likiep Atoll, composed mainly of several species of Porolithon. Photos by Fosberg.

D. Moat or back-ridge trough behind algal ridge, windward reef opposite Lojjairok (South Loj) islet, Kwajalein Atoll. Reef-flat and storm-cast boulders to left in distance. Photos by MacNeil.

Plate 6. Details of reef flats.
A. Detail of reef flat, at low tide, windward reef, Wotho islet, Wotho Atoll. Note small algal colonies and relatively smooth surface.
B. Detail of reef flat, at low tide, leeward reef, southwest of Ailuk islet, Ailuk Atoll.
Photos by MacNeil.

Plate 7. A, B. Outer margin of leeward reef and reef flat at low tide, southwest of Ailuk islet, Ailuk Atoll. Note absence of algal ridge and prevalence of corals. Photos by MacNeil.

Plate 8. Windward reef flat, Taka Atoll, near Lojrong (Lojiron) islet, at low tide, showing solution basins with raised rims. Photo by MacNeil.

Plate 9. Rubble tract on reef flat, windward reef, Ujelang Atoll. Photo by MacNeil.

Plate 10. A. Crescent-shaped gravel bar on leeward reef east of Lotj (Loj) islet, Lae Atoll.
B. Seaward end of gravel bar, windward reef, Ujelang Atoll.
Photos by MacNeil.

Plate 11. Post-Pleistocene eroded reef platforms.
A. Post-Pleistocene reef platform with erosion ramp, Taka islet, Taka Atoll.
B. Lagoon beach, Taka islet, Taka Atoll, showing tidal beach, eroded post-Pleistocene reef platform, and storm beach.
Photos by MacNeil.

Plate 12. Exposure of post-Pleistocene reef platforms.
A. Ennimenetto islet, Ujelang Atoll.
B. Jabwe islet, Ailuk Atoll.
C. Lae islet, Lae Atoll, lagoon beach.
D. Lojjairok (South Loj) islet, Kwajalein Atoll.
Photos A, C, D by MacNeil; B by Fosberg.

Plate 13. A, B. Boulder beach and exposed post-Pleistocene rock platform with stack and perched boulder.
Photos by Fosberg.

Plate 14. Surfaces of erosion ramps.
A. Erosion ramp on Ulka (Ulika) islet, Ailuk Atoll, showing rough pitted surface and undercutting; storm beach in background.
B. Same, closeup, showing collapse of undercut limestone (width of foreground about 5 feet).
C. Beachrock on Yeldo (Enejelto) islet, Wotho Atoll, being undercut and quarried by waves (width of foreground about 8 feet).
D. Closeup of edge of erosion ramp, showing solution features, Ebbetyu (Ebeju) islet, Ujae Atoll.
Photos A, B, C by Fosberg; D by MacNeil.

Plate 15. Solution basins on erosion ramps.
A. Solution basins with overhanging rims, erosion ramp, Emejiwan (Enijwa) islet, Likiep Atoll. Photo by MacNeil.
B. Solution basins on erosion ramp, north end of Taka islet, Taka Atoll, showing chalky deposit in bottom. Photo by Fosberg.

Plate 16. Spalling off of erosion ramp surfaces.
A. Surface of erosion ramp, Erlie (Alle) islet, Ujae Atoll, showing spalled slab and spall plane. Photo by MacNeil.
B. Surface of erosion ramp north end of Taka islet, Taka Atoll, showing spall planes of different ages as indicated by different degrees of pitting and discoloration by algal growth. Area 2-3 square feet. Photo by Fosberg.

Plate 17. Gravel and boulder beaches.
A. Gravel beach on lagoon side of Bik islet, Ujae Atoll, showing terrace or berm.
B. Erosion ramp with small storm beach on left, Daisu(Raij) islet, Ujelang Atoll.
C. Boulder beach, Bock islet, Ujae Atoll.
D. Boulder beach, Ujae islet, Ujae Atoll, showing abraded erosion ramp.
Photos by MacNeil.

Plate 18. Sand and gravel beaches on lagoon side of islets.
A. Sand beach, lagoon side, Utirik islet, Utirik Atoll. Photo by Fosberg.
B. Gravel beach, lagoon side, Nelle islet, Ujelang Atoll. Photo by MacNeil.

Plate 19. Details of abraded beachrock.
A. Beachrock series on northwest corner of Emejiwan(Rikararu) islet, Likiep Atoll.
B. Beachrock cuesta at southwest corner of Emejiwan(Rikararu) islet, Likiep Atoll.
C. Abraded beachrock, Jemo island, showing abrasive agent.
D. Closeup of abraded beachrock on Jemo island, showing composition.
Photos A, B by MacNeil; C, D by Fosberg.

Plate 20. Details of beachrock.
A. Beachrock series, Rua islet, Ujae Atoll.
B. Beachrock showing anticline-like arrangement, dipping seaward (to right) and lagoonward (to left), Rua islet, Ujae Atoll.
C. Potholes in beachrock on lagoon beach, north end of Bokanaetok islet, Wotho Atoll.
D. Slabs of beachrock quarried by lagoon waves and piled up at top of beach, Yeldo (Enejelto) islet, Wotho Atoll.
Photos by Fosberg.

Plate 21. Beach ridges of pebbles and cobbles.

A. Beach ridge of pebbles, Ailuk islet, Ailuk Atoll. Photo by MacNeil.

B. Beach ridge of cobbles, Utirik islet, Utirik Atoll. Photo by Fosberg.

Plate 22. Details of boulder and cobble ridges and other coarse deposits.

A. Boulder ridge, south side, Sibylla islet, Taongi (Pokak) Atoll.

B. Details of mixture of boulders and cobbles, boulder ridge, Utirik islet, Utirik Atoll. Large boulder in lower right about 16 inches across.

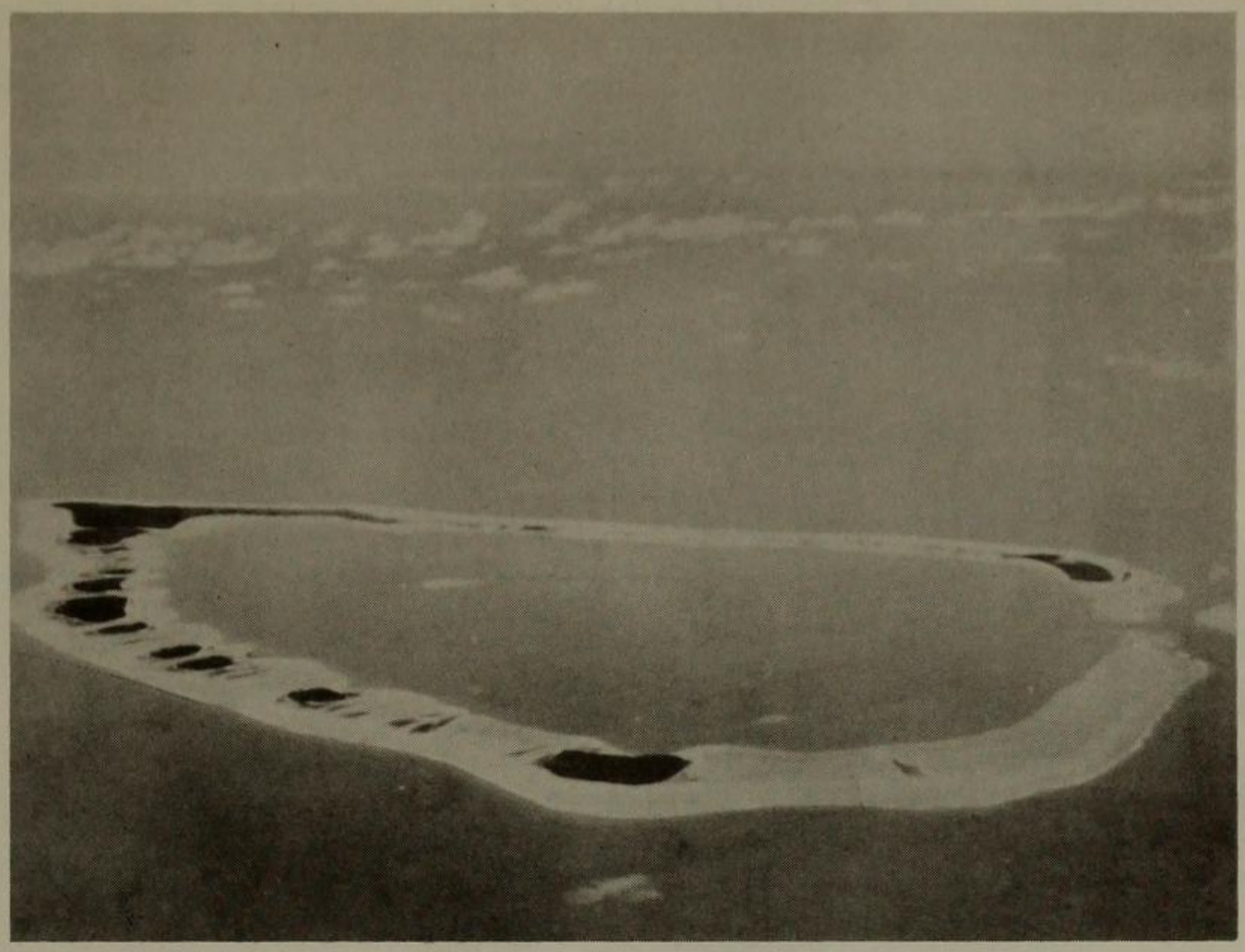
C. Details of coarse gravel, with tern (Procelsterna caerulea) nesting, beach ridge on small bar between Jabwelo (Jaliklik) and Almani islets, Bikar Atoll.

D. Details of small gravel on flat, with young noddy tern (Anous stolidus), Daisu (Raij) islet, Ujelang Atoll.

Photos A, B, C by Fosberg; D by MacNeil.

Plate 1

A



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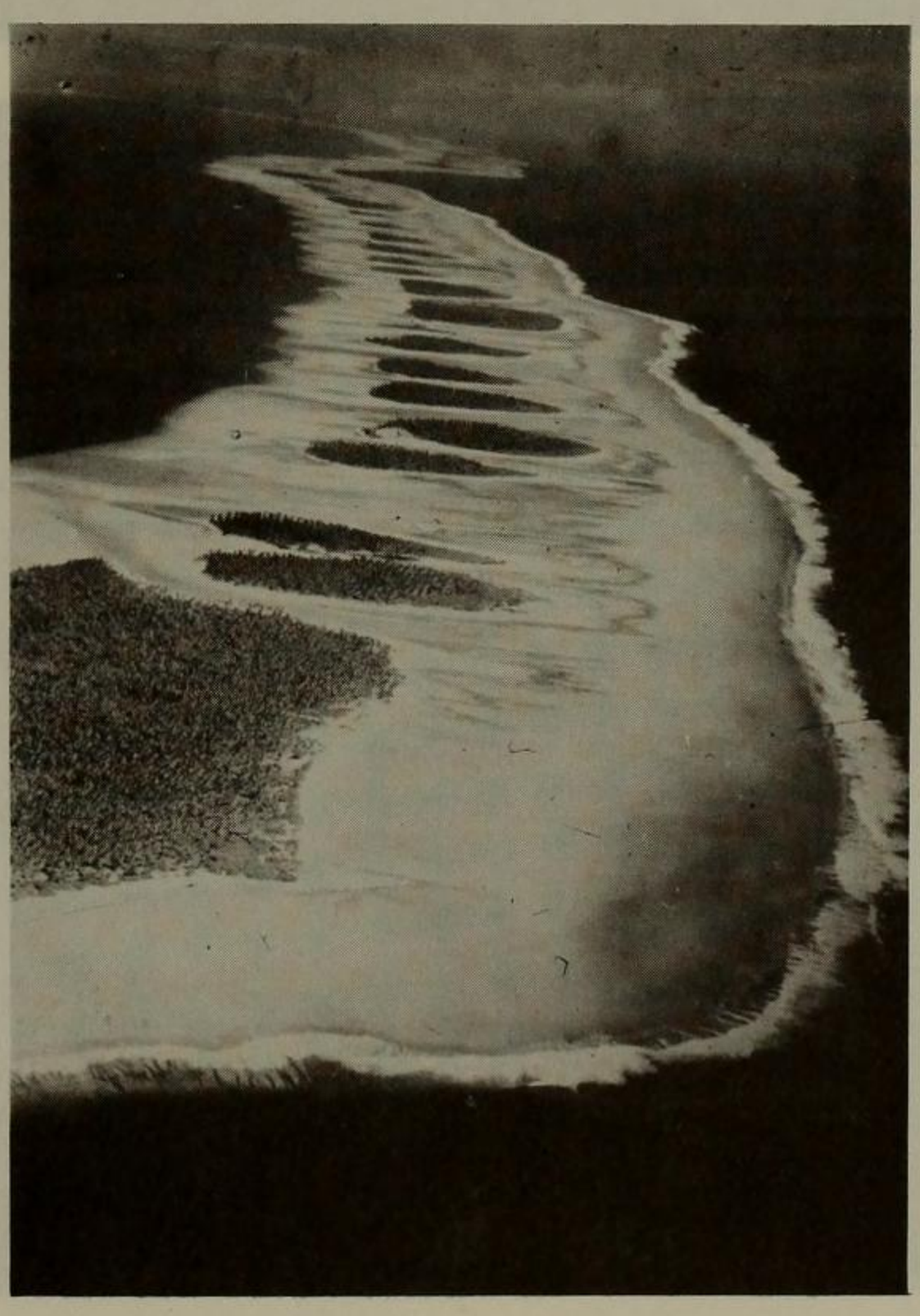

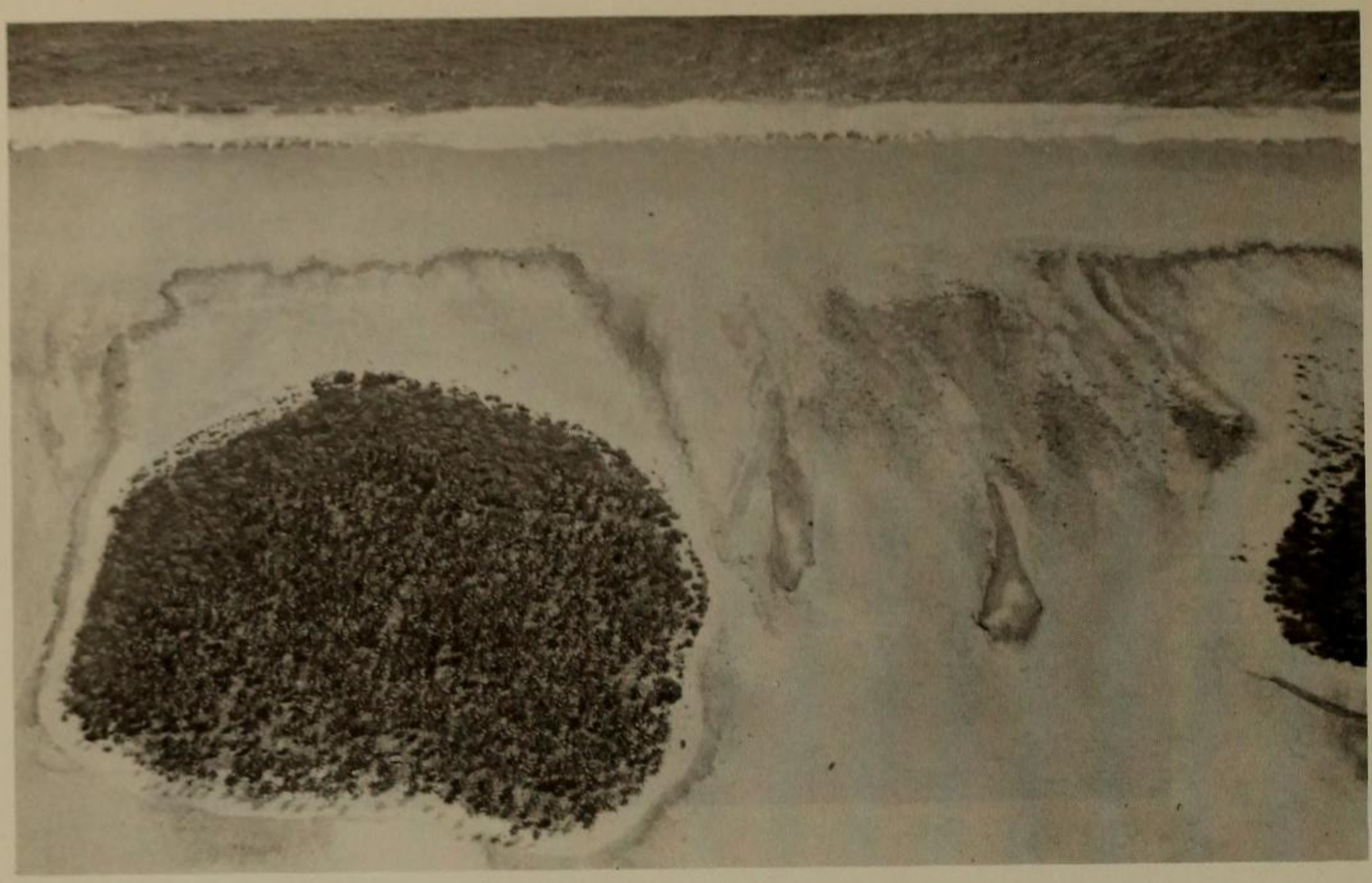

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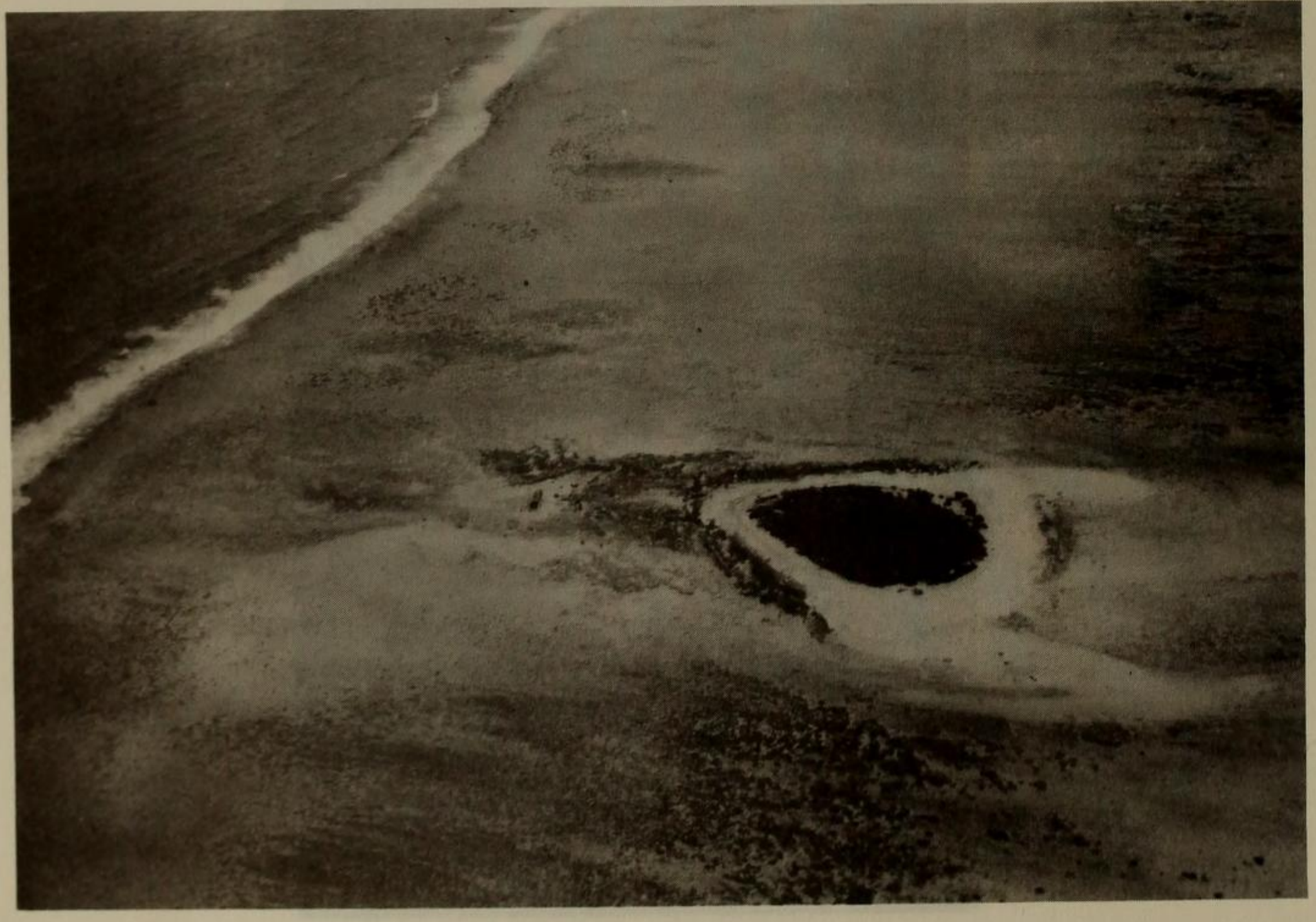

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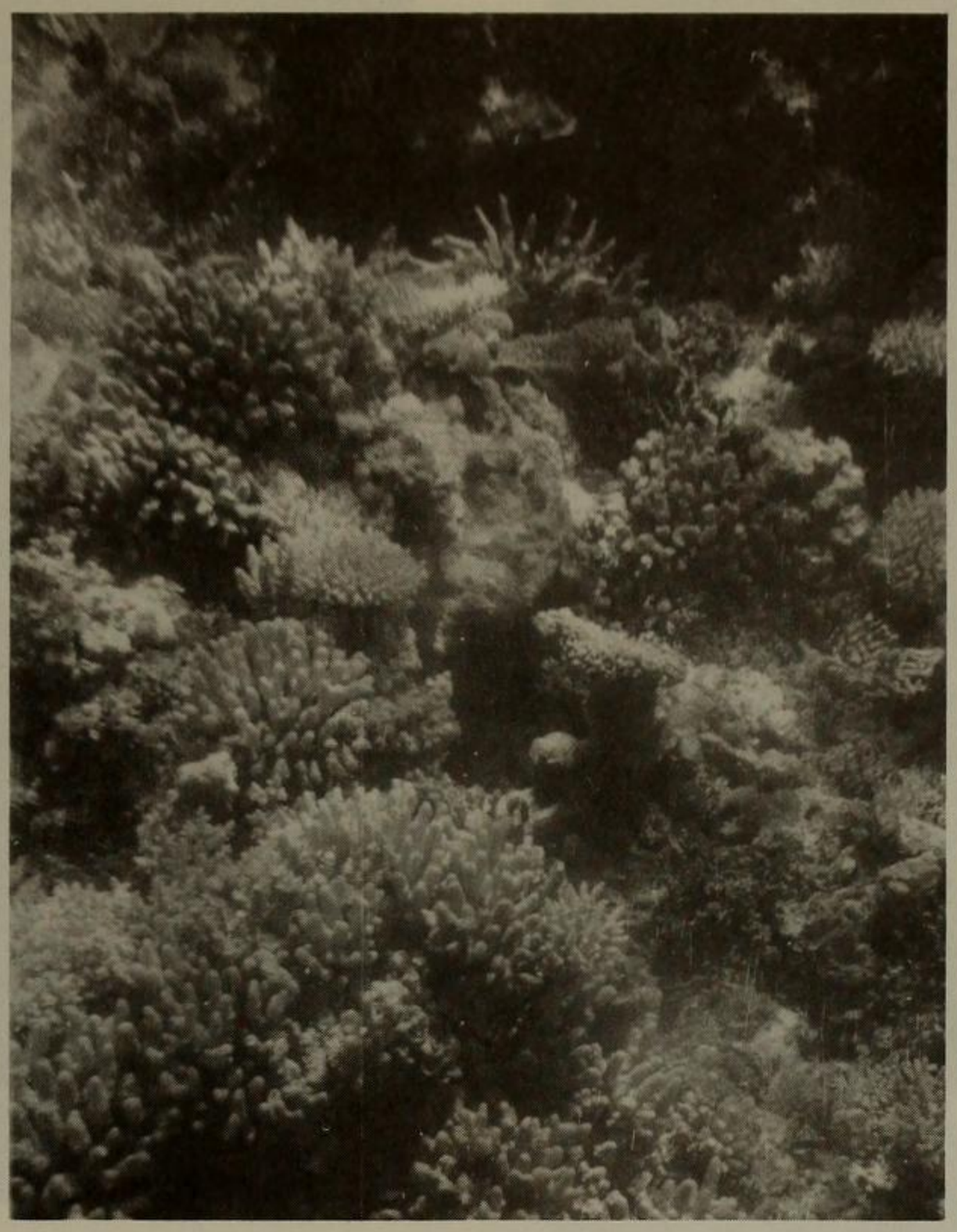

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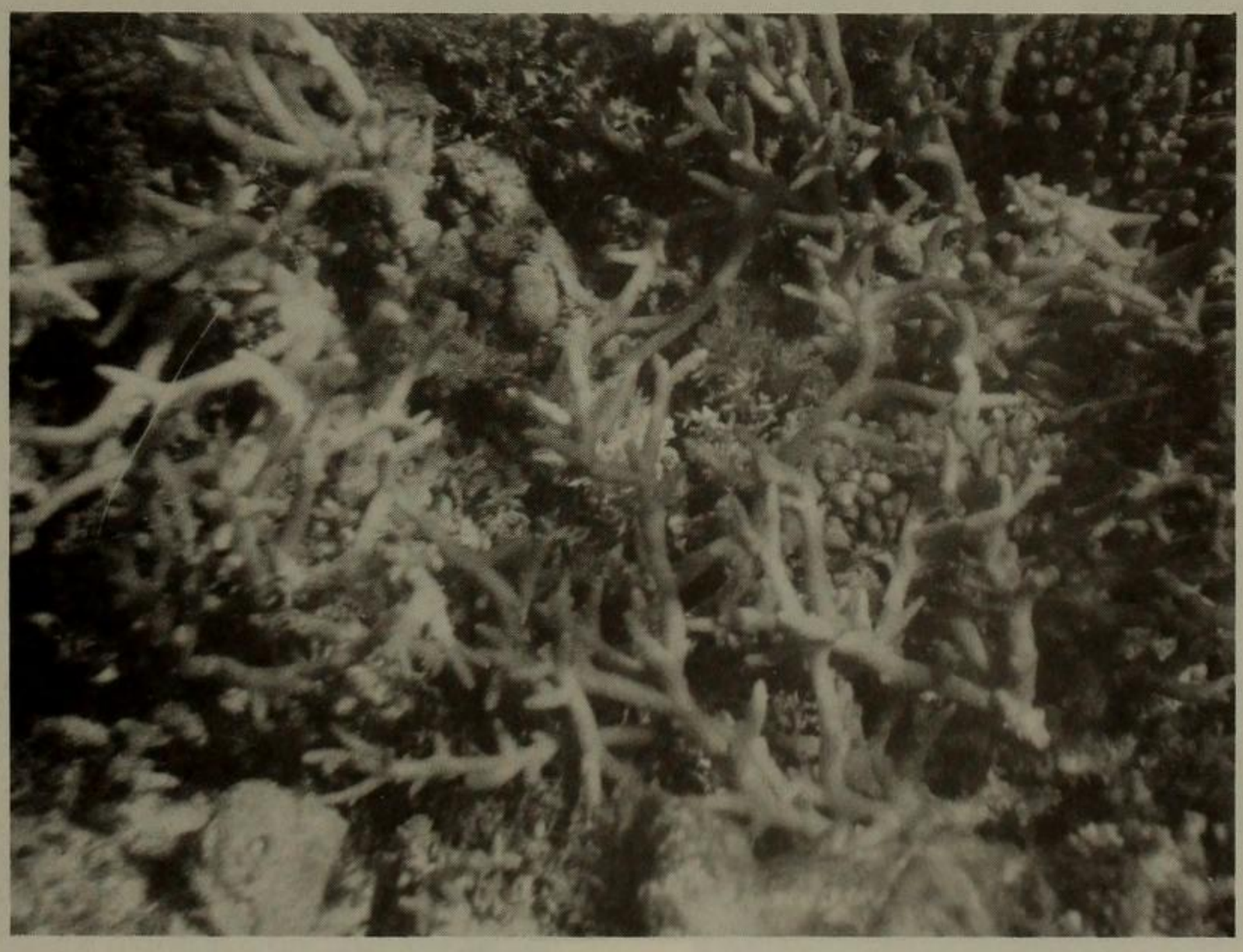

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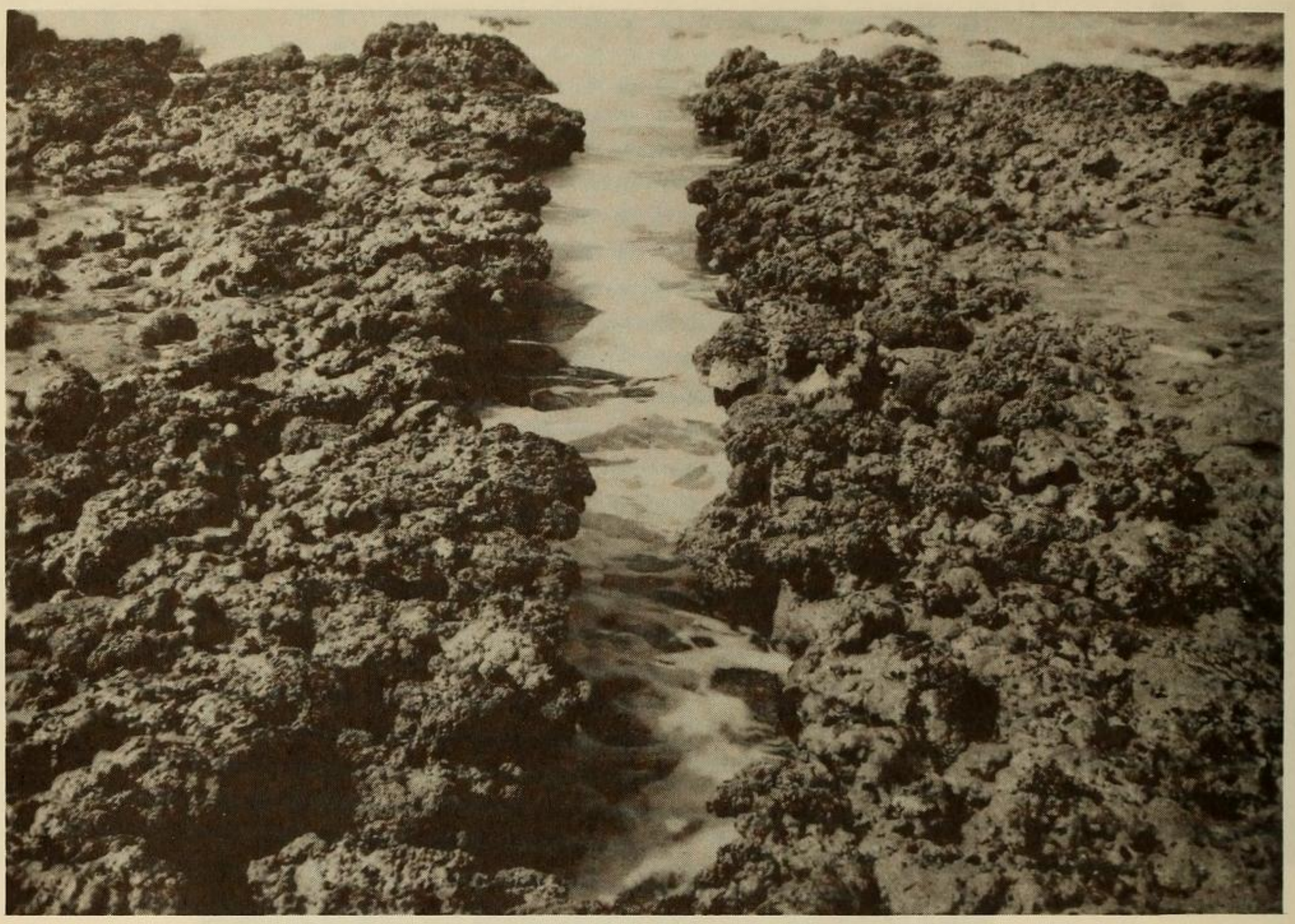

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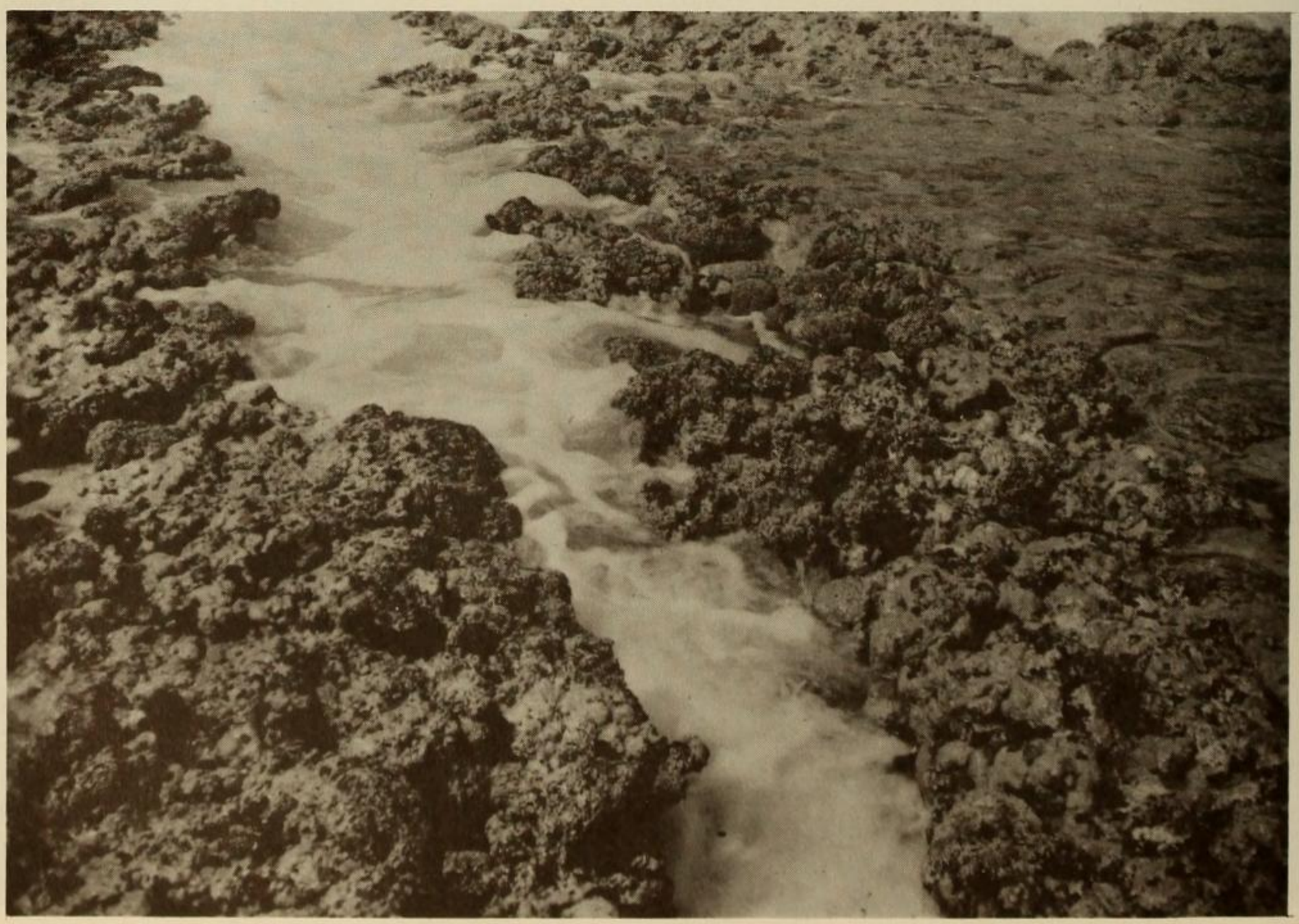

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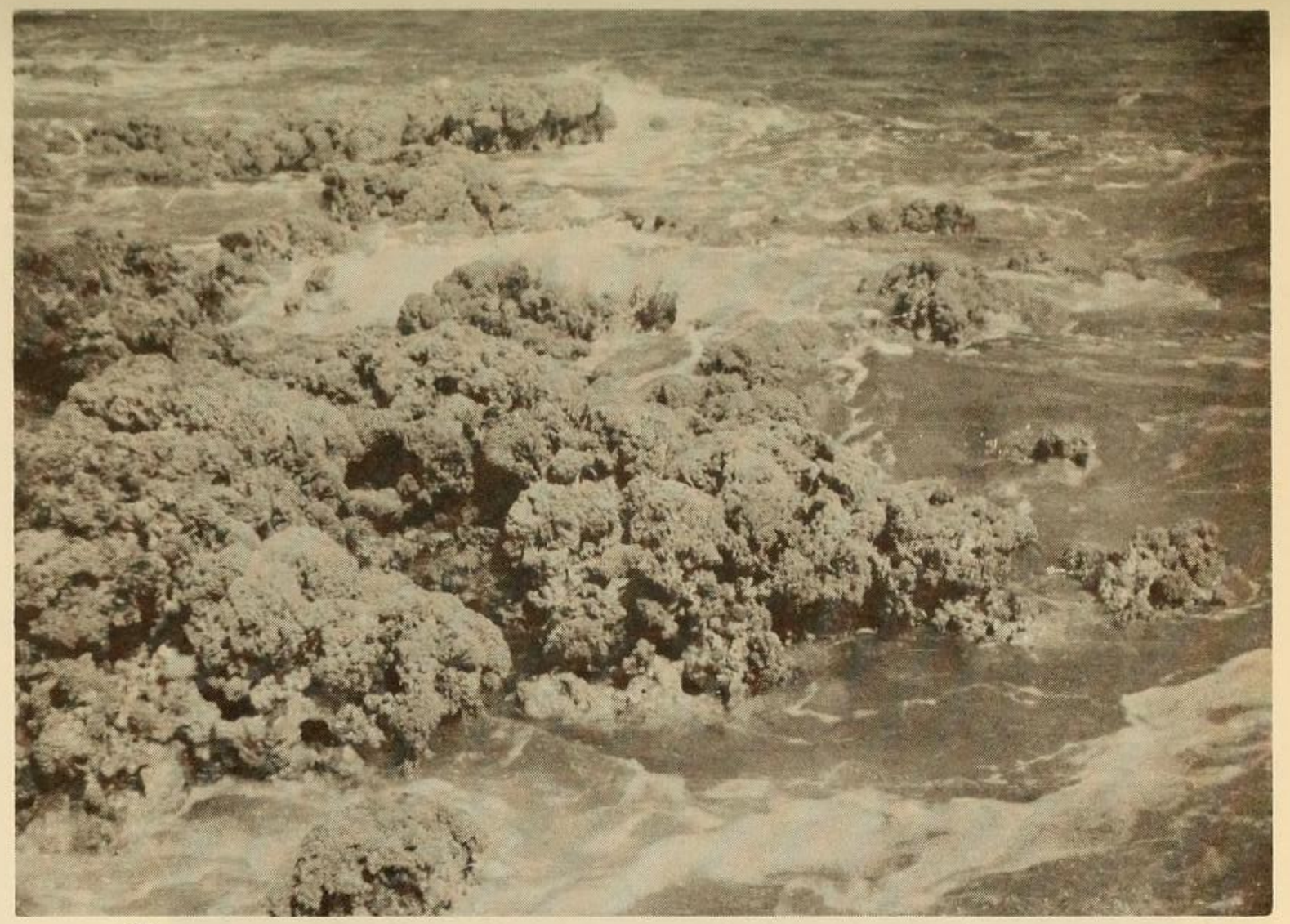

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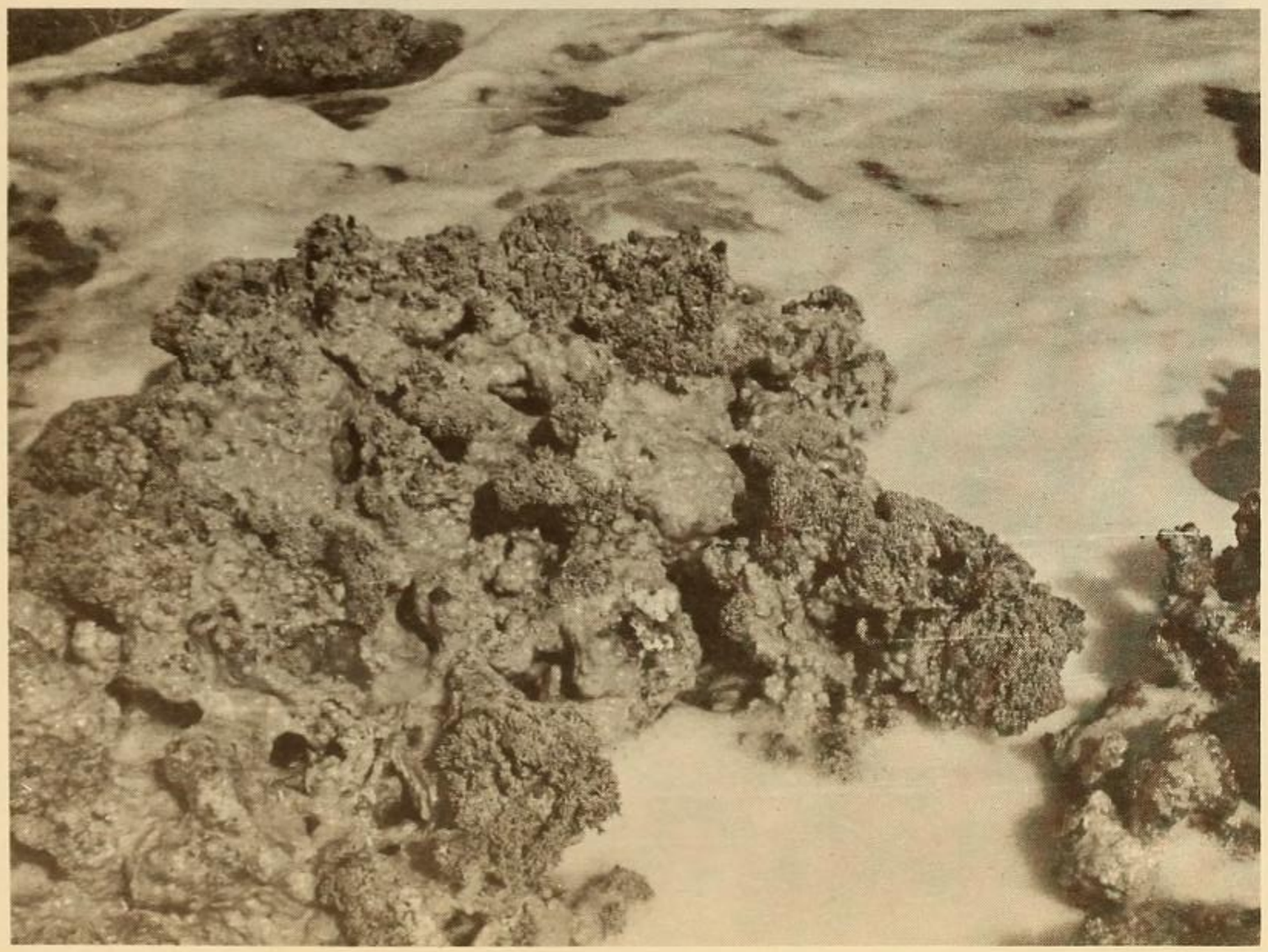

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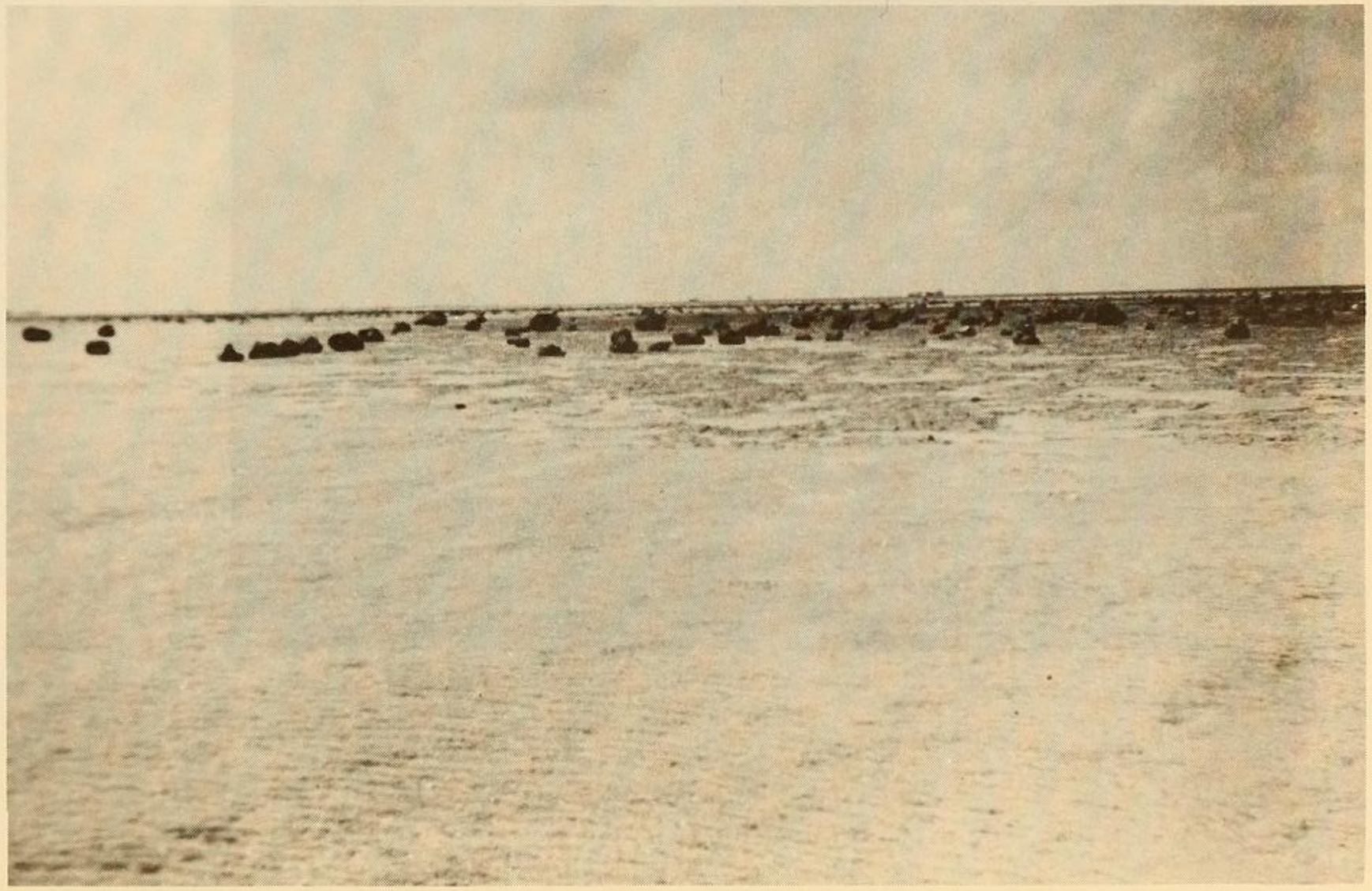

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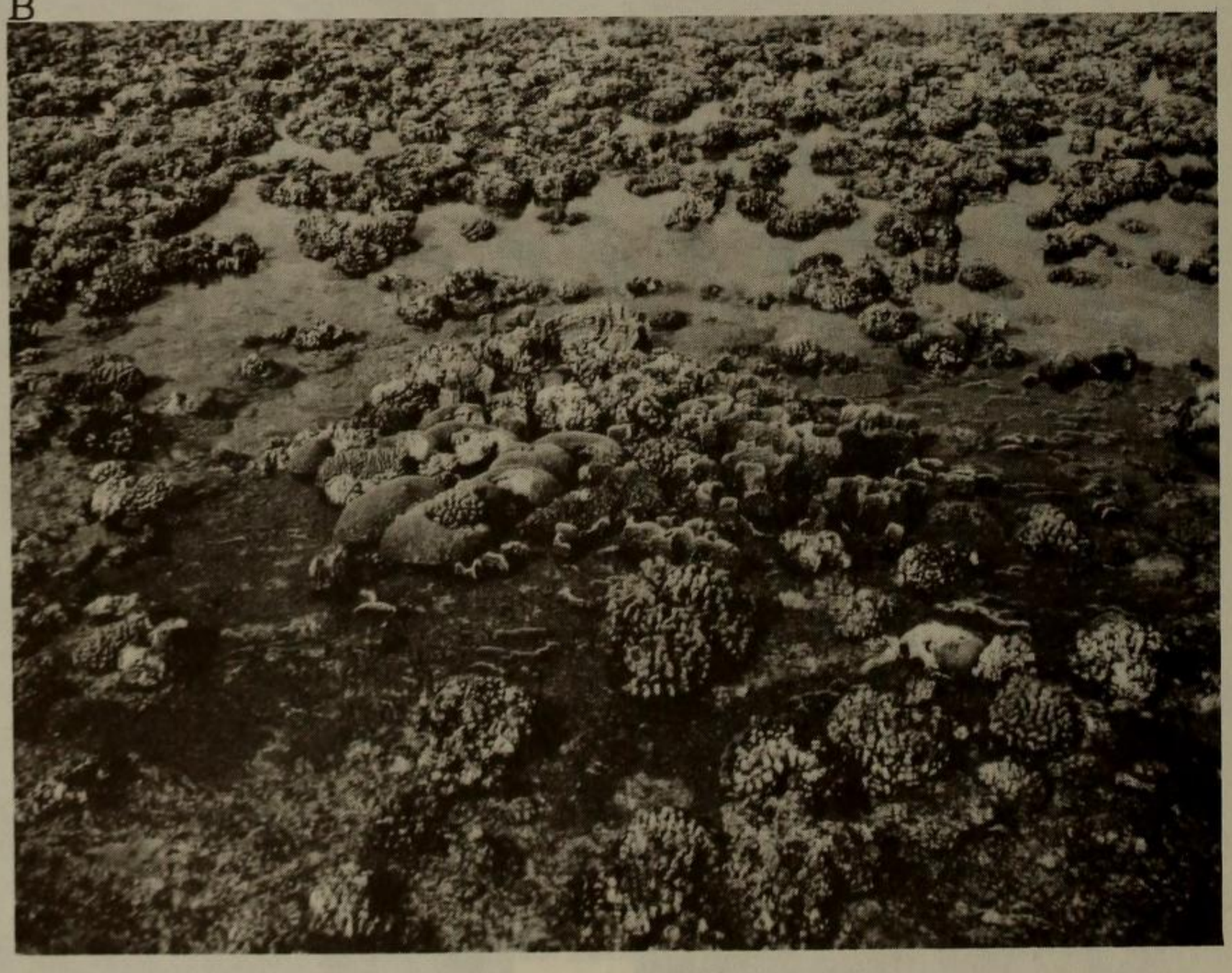

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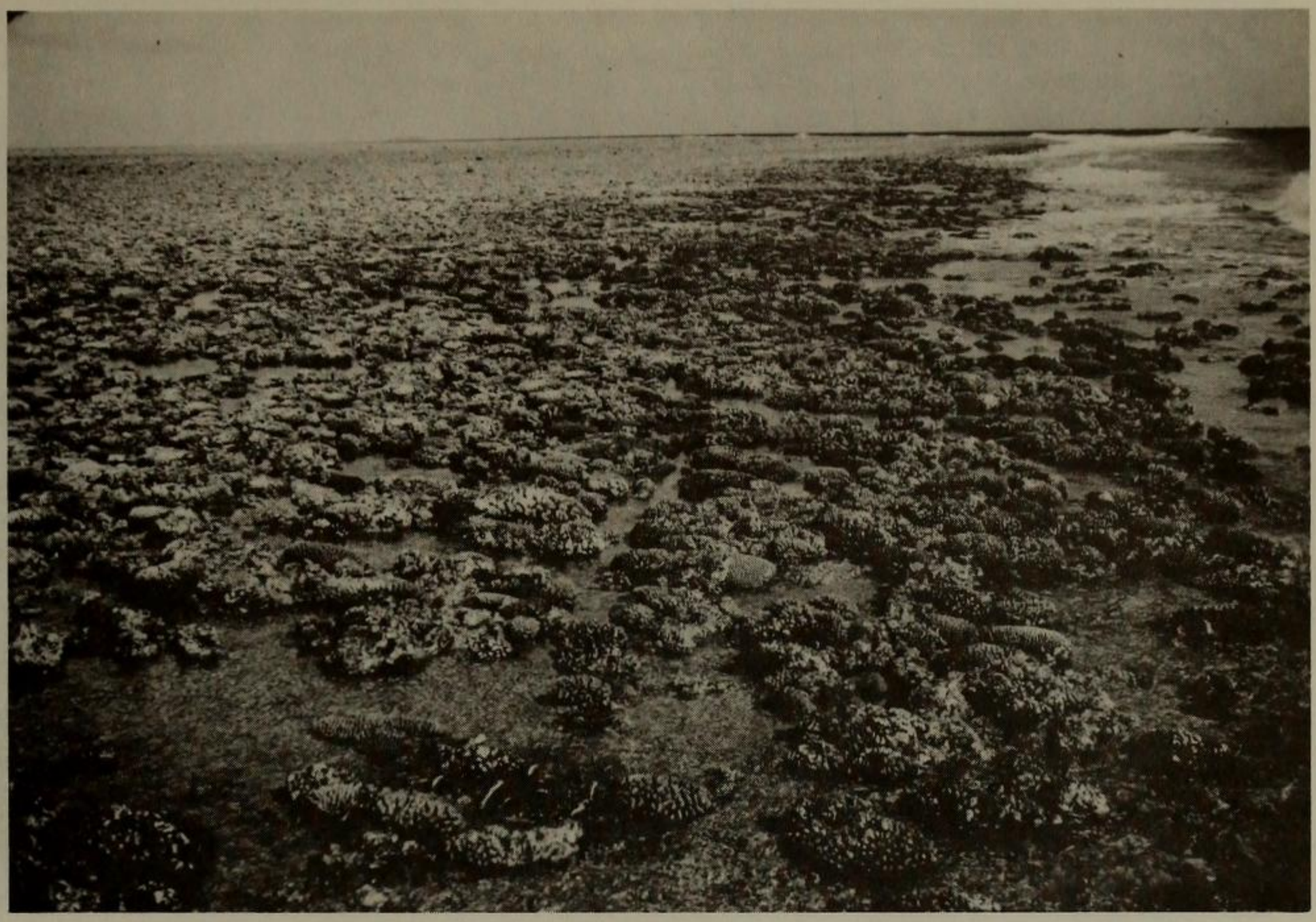

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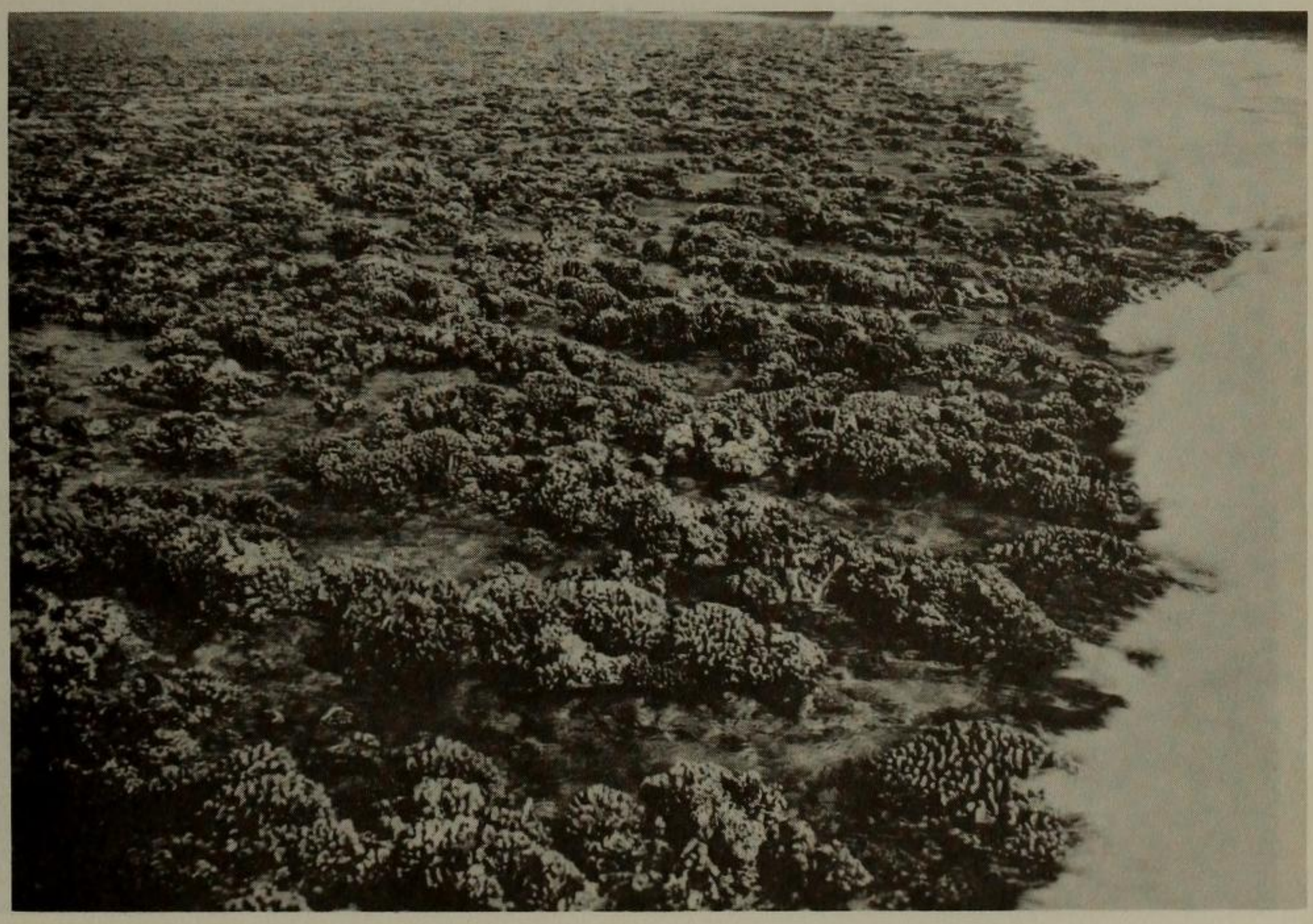

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Plate 8

Plate 9

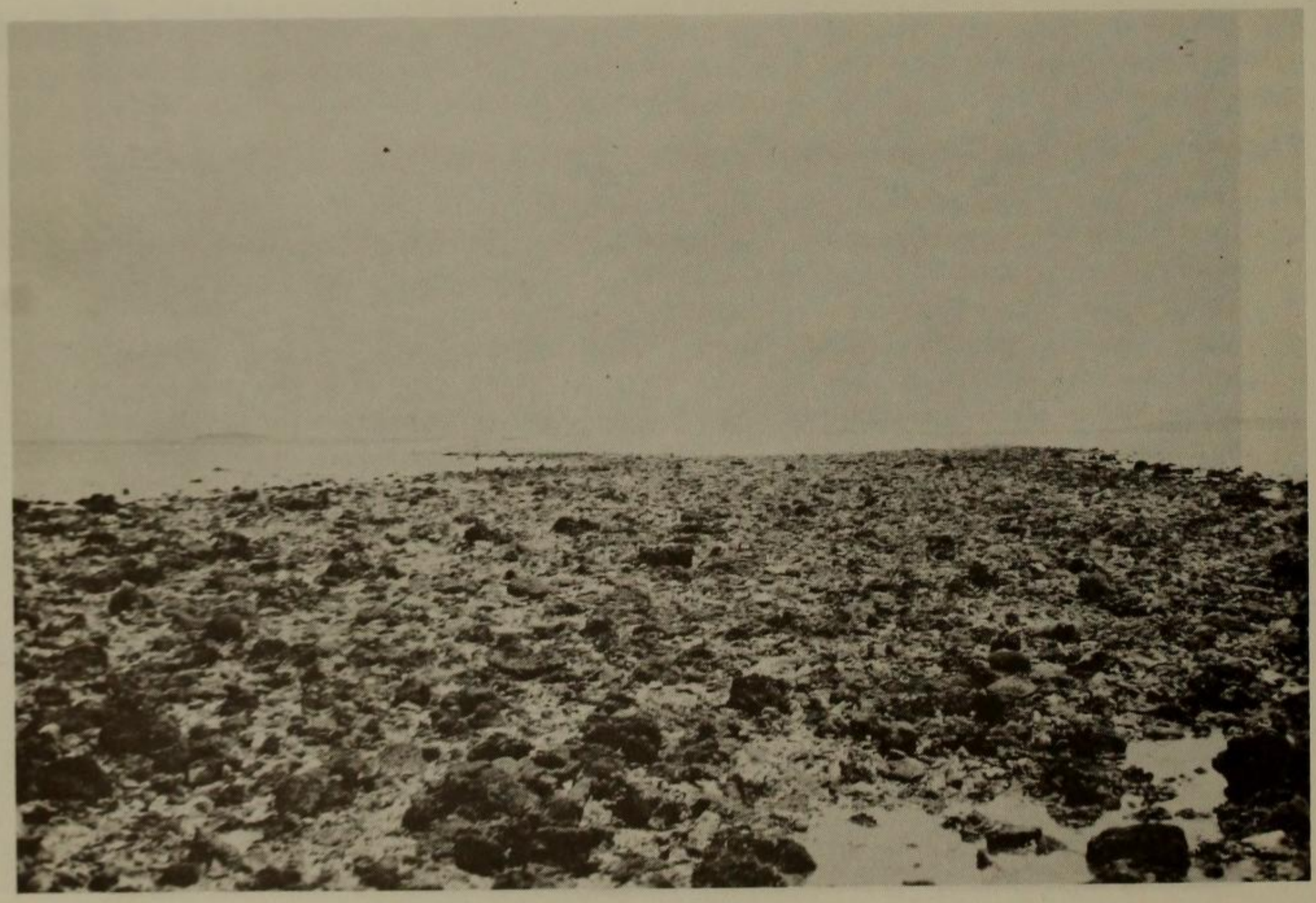

Plate 10

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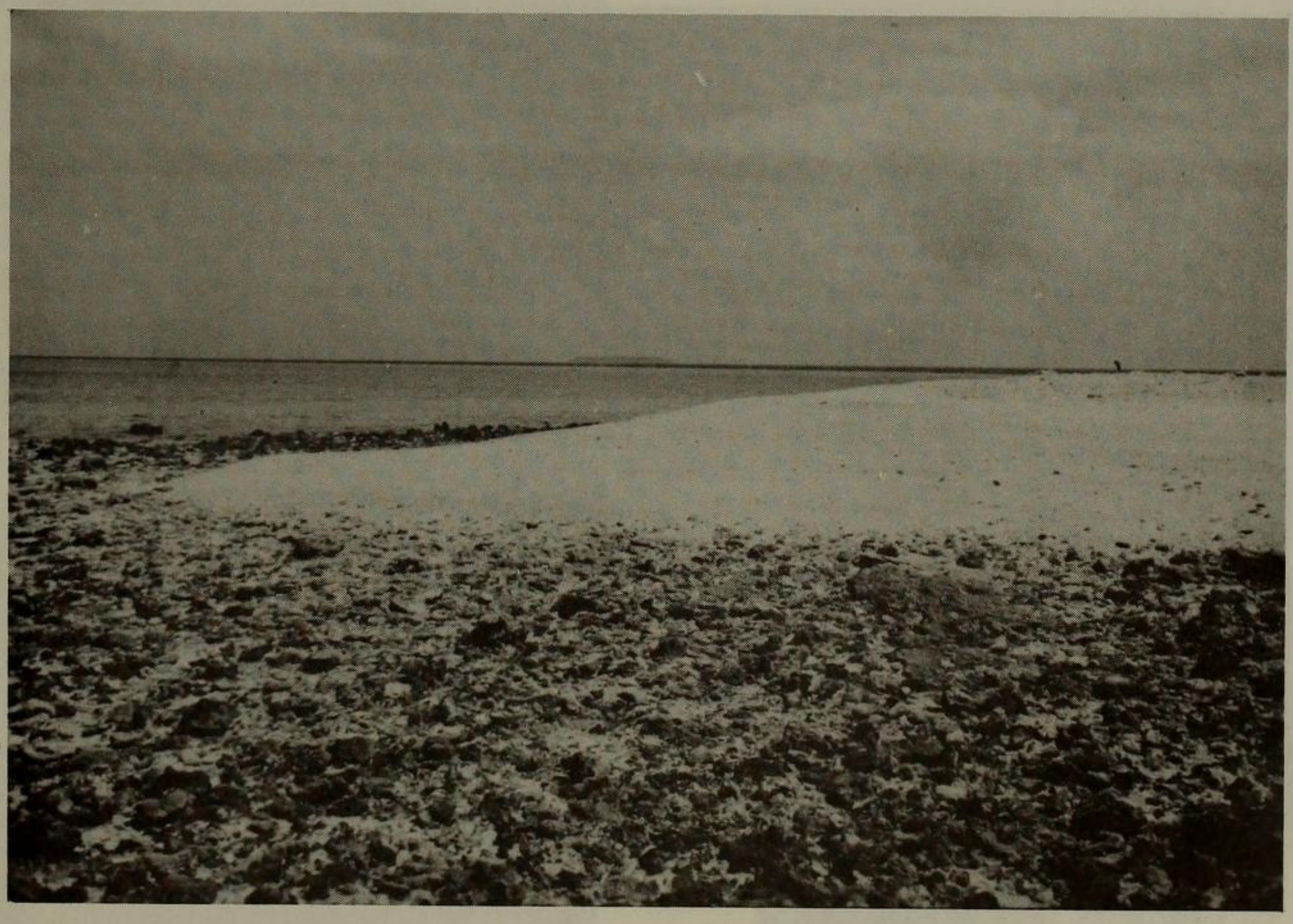

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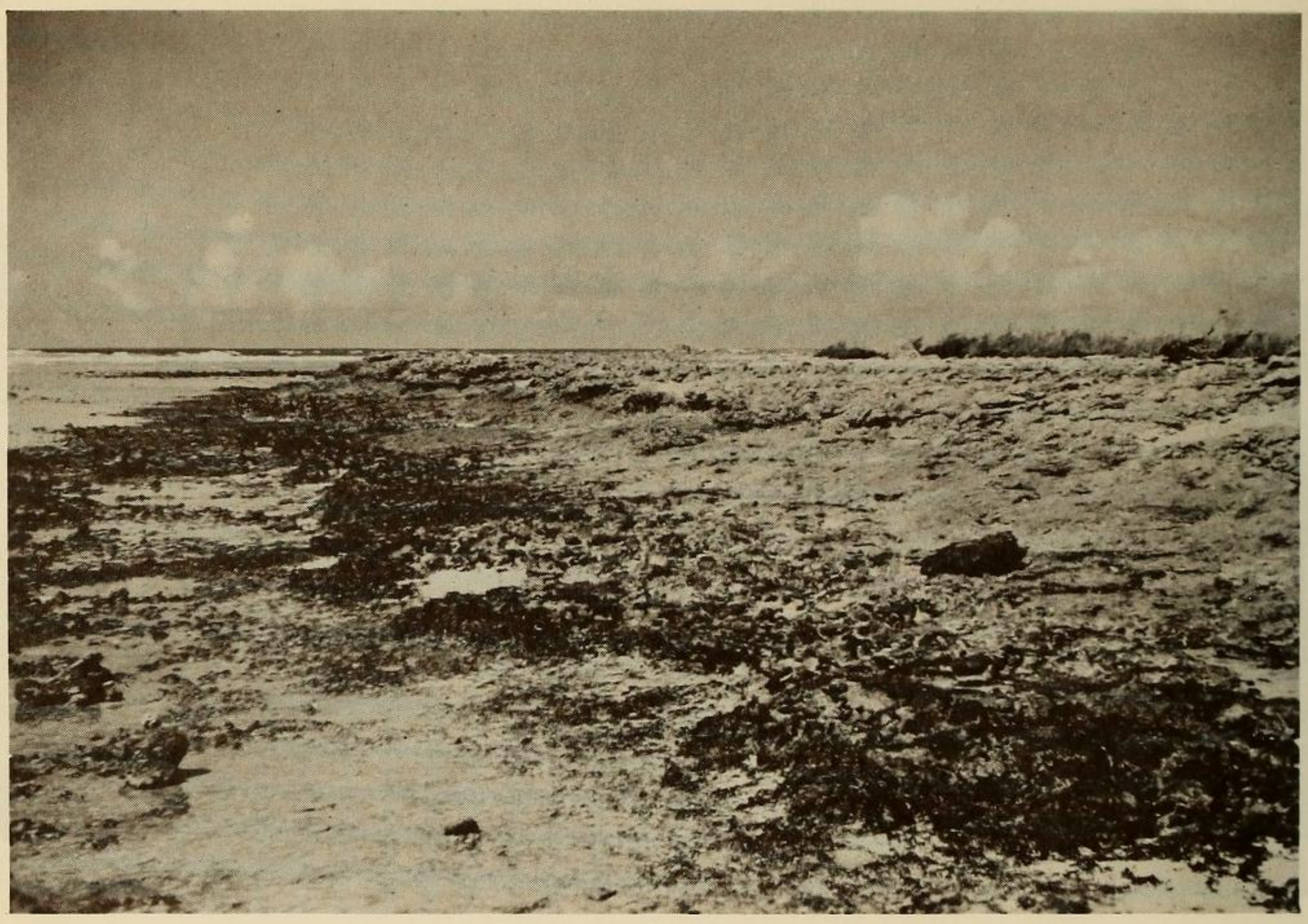

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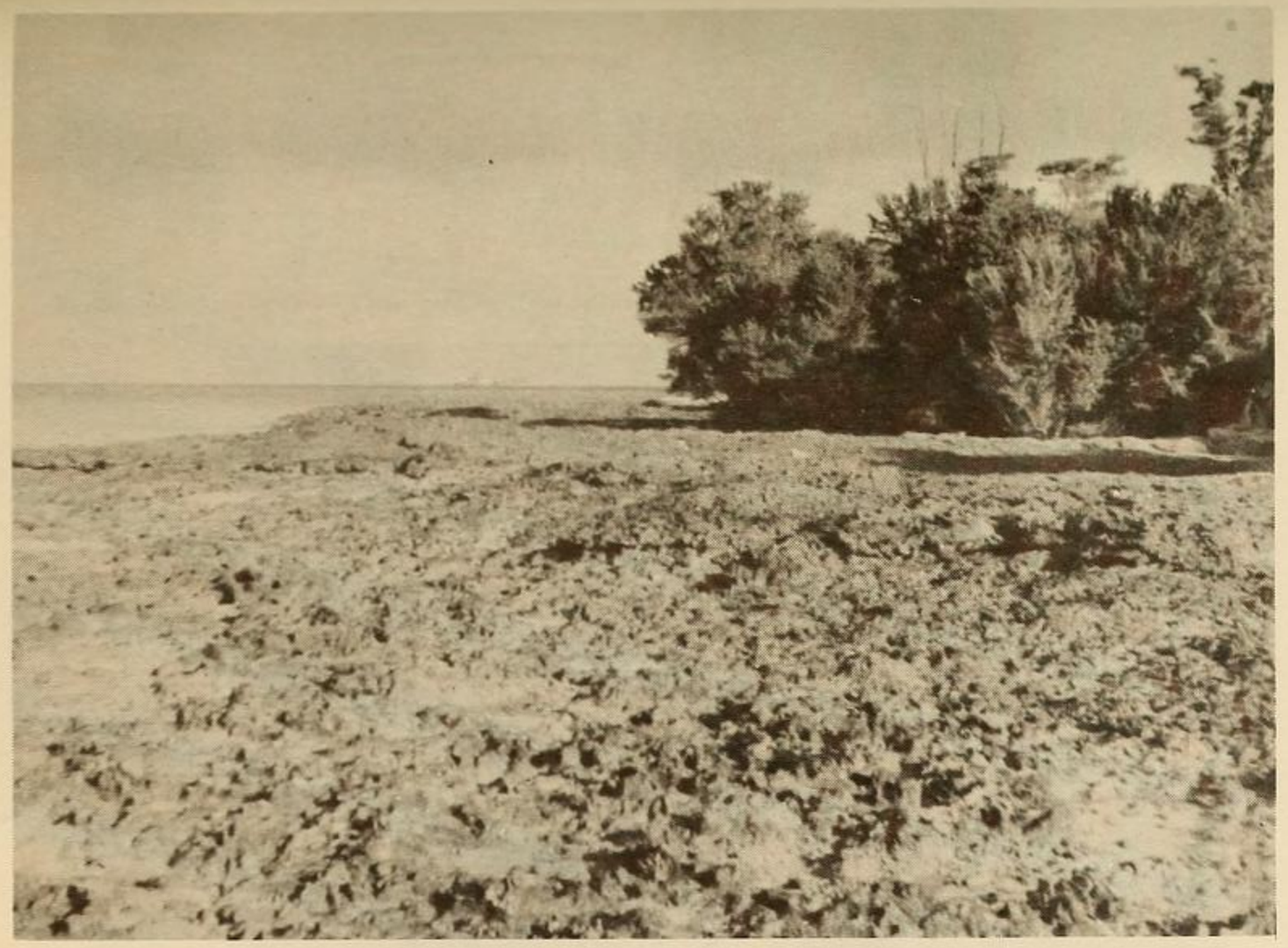

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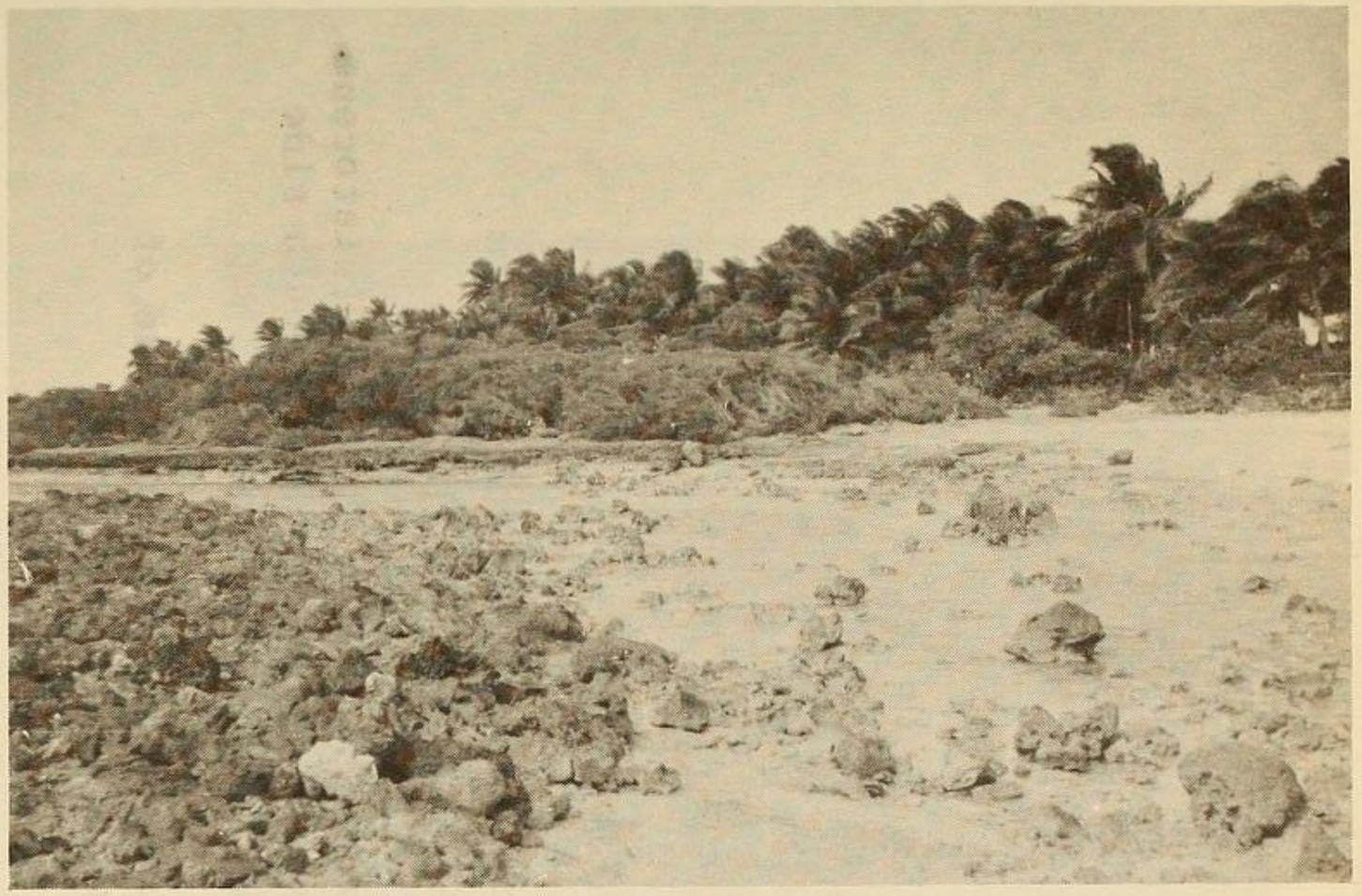

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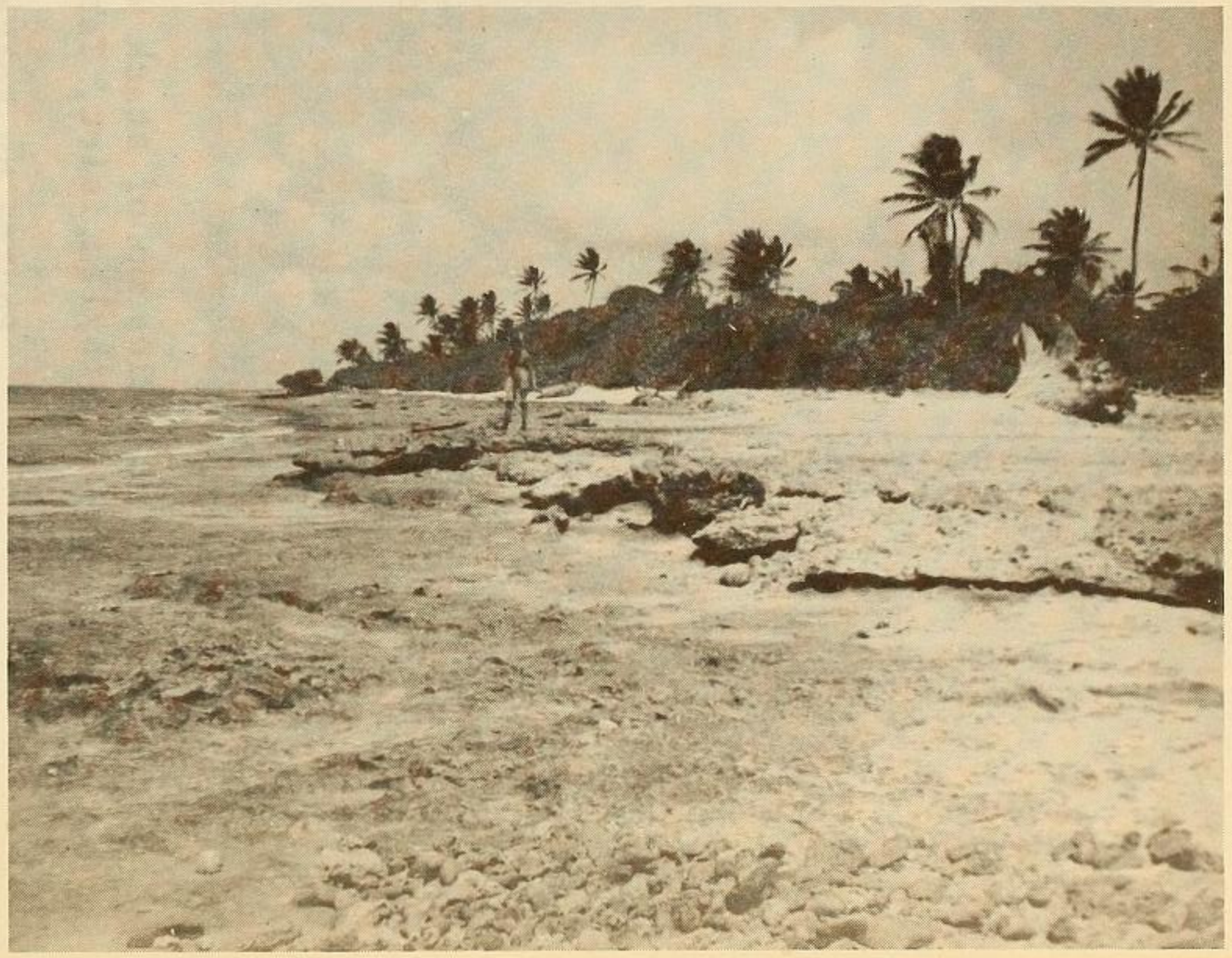
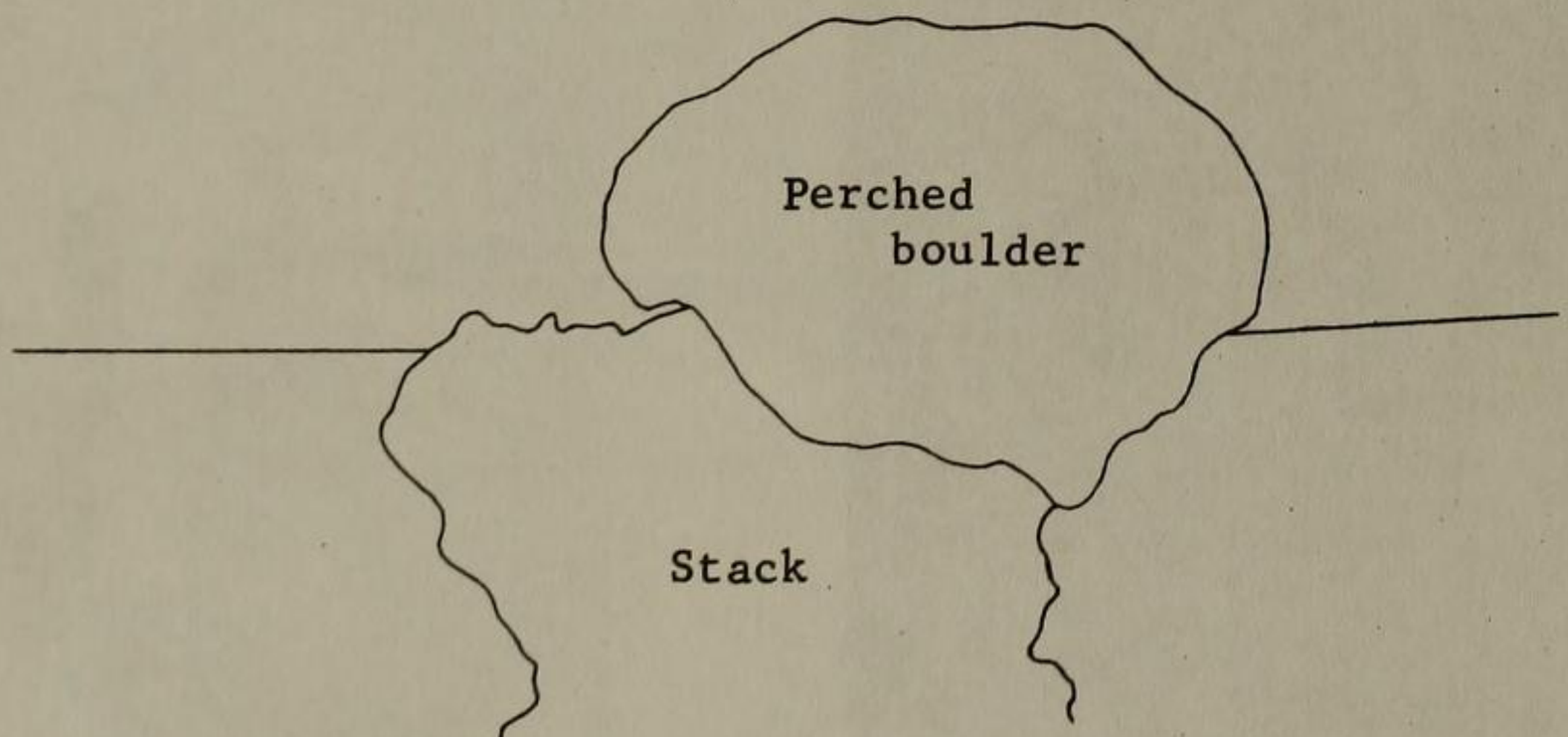


Plate 13. Boulder beach and exposed post-Pleistocene rock platform with stack and perched boulder.

A. Boulder beach with protruding exposures of post-Pleistocene rock platform, and stack with perched boulder. South side of Sibylla islet, Taongi (Pokak) Atoll.

B. Closeup of stack with perched boulder, south side of Sibylla islet, Taongi (Pokak) Atoll.

Photos by Fosberg.



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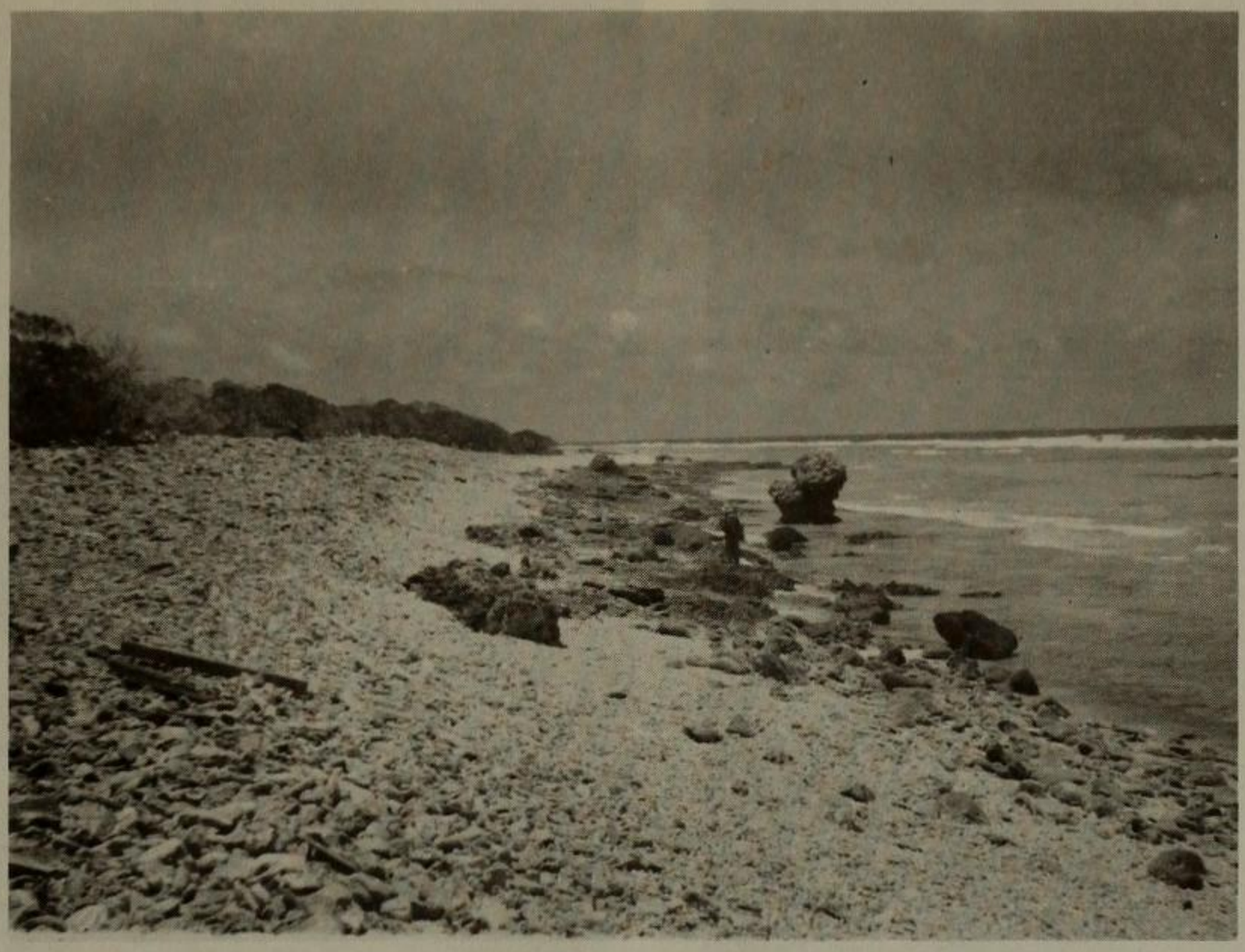

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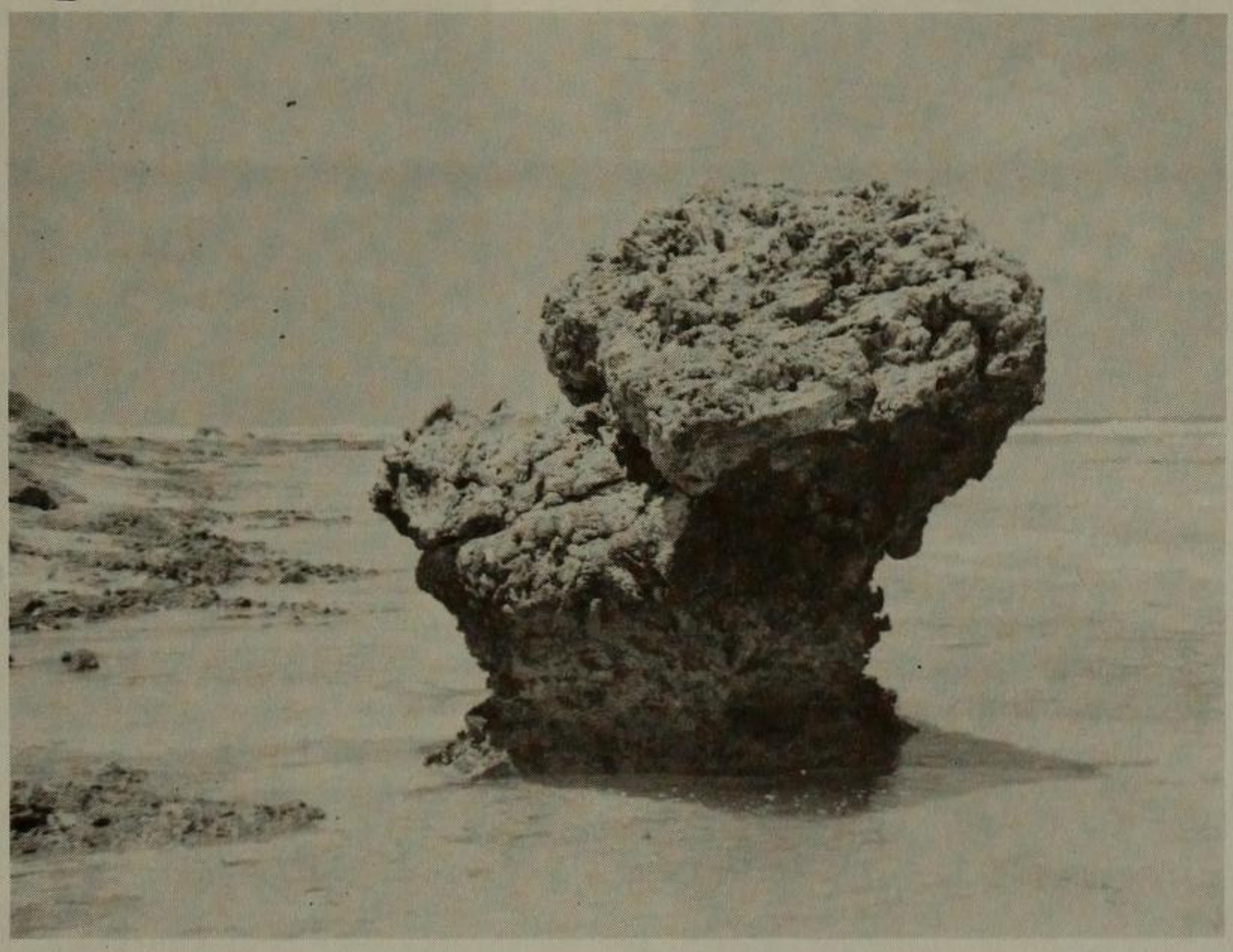

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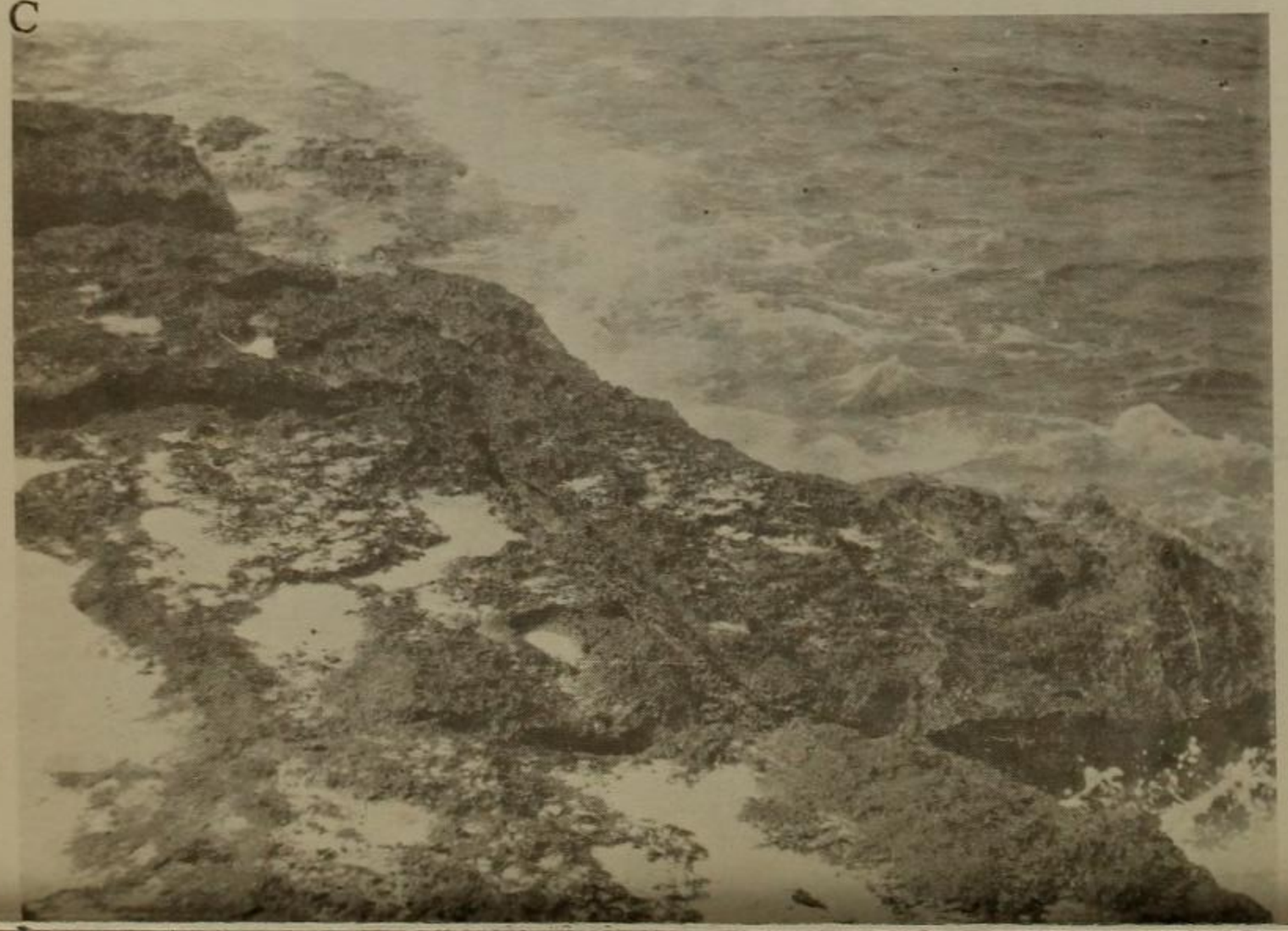

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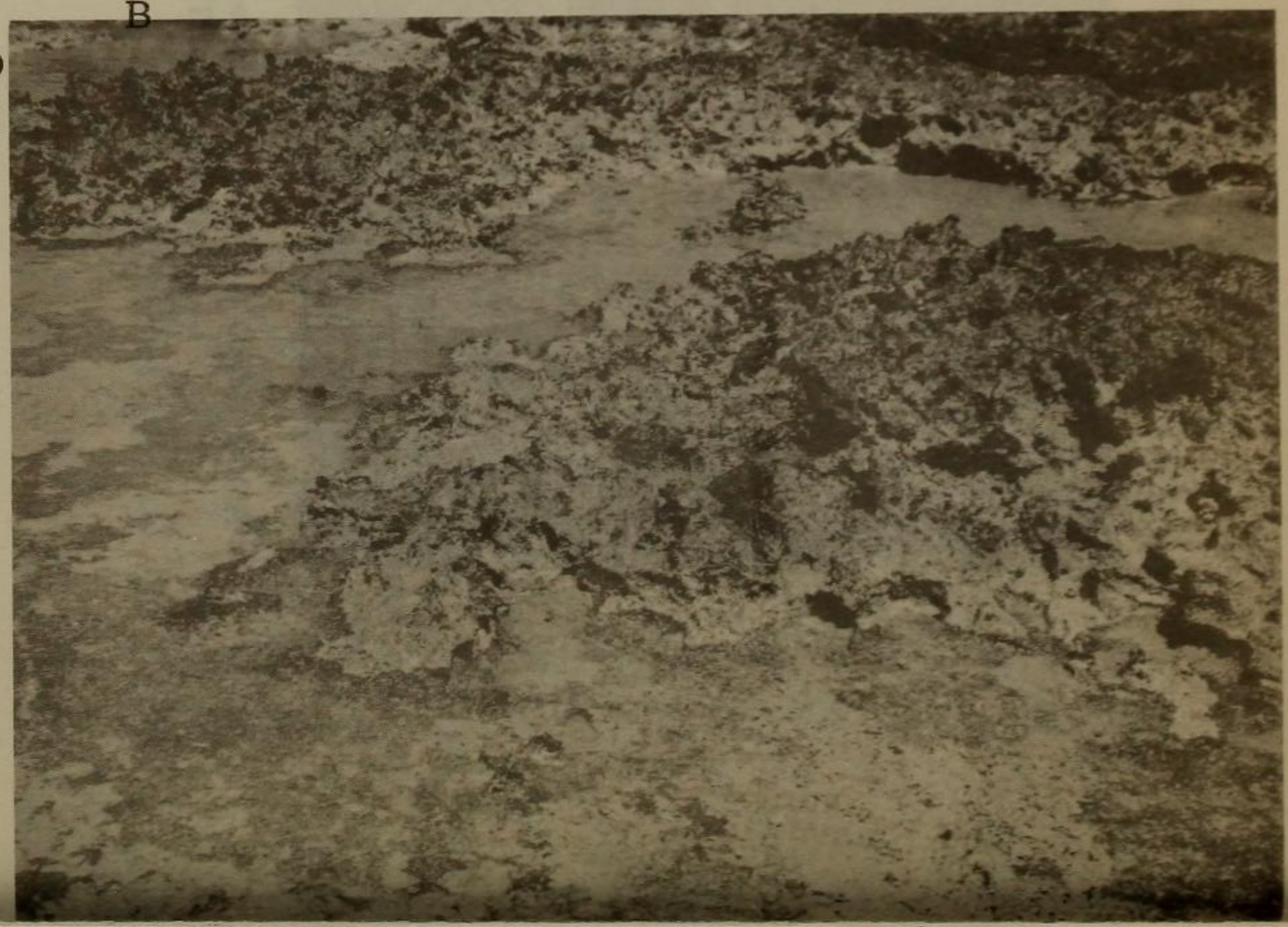

Plate 15

A

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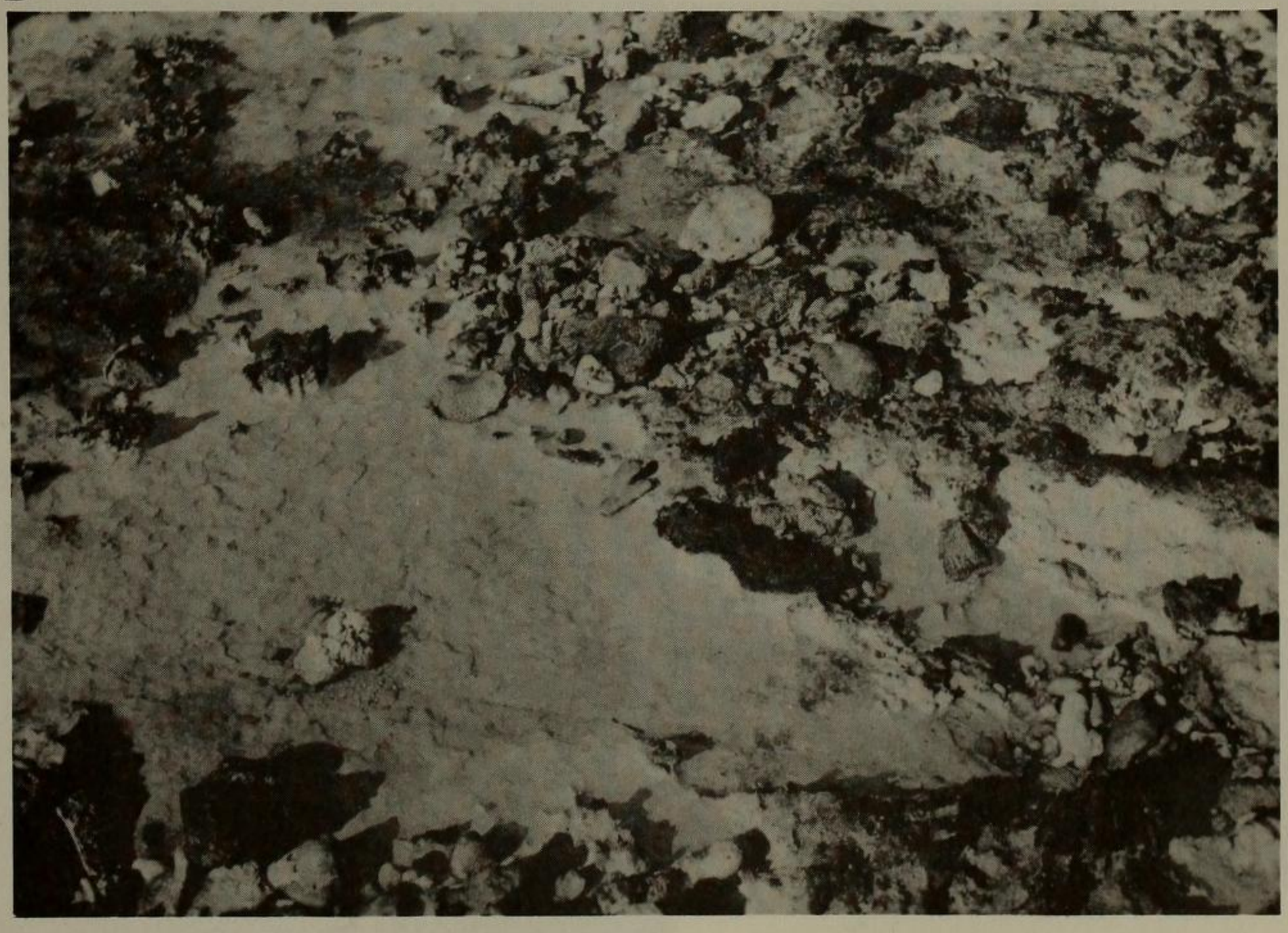

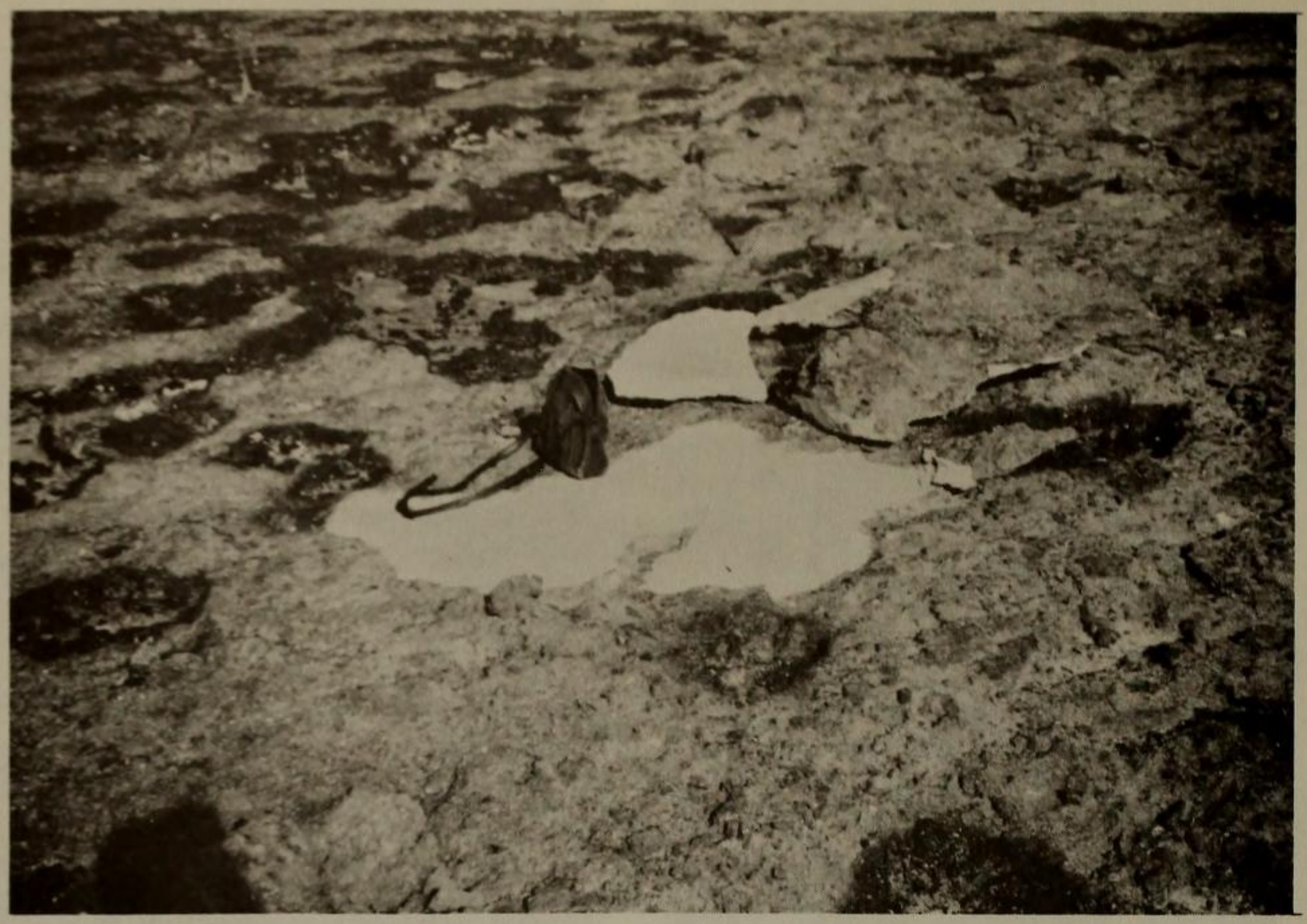

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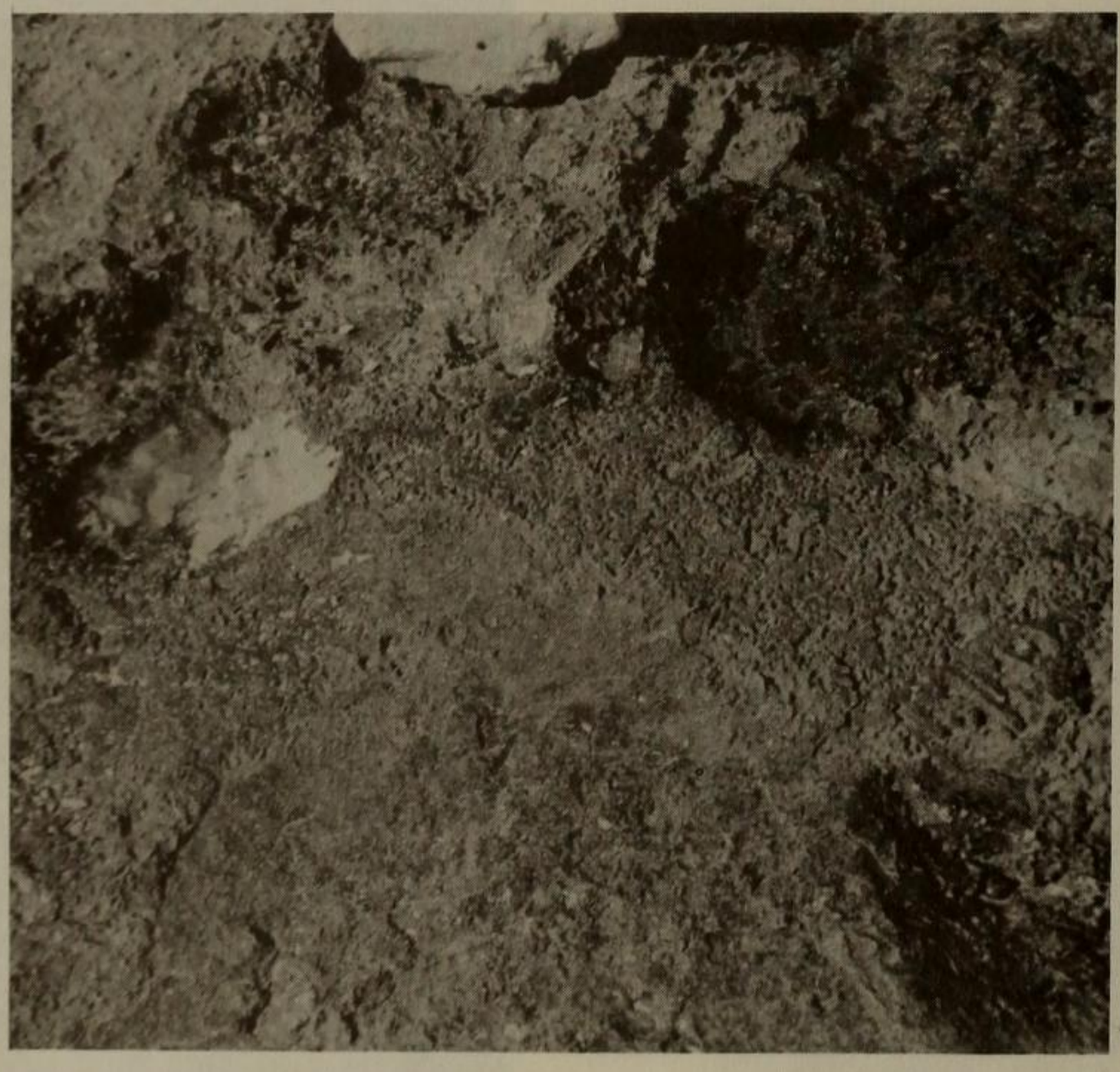

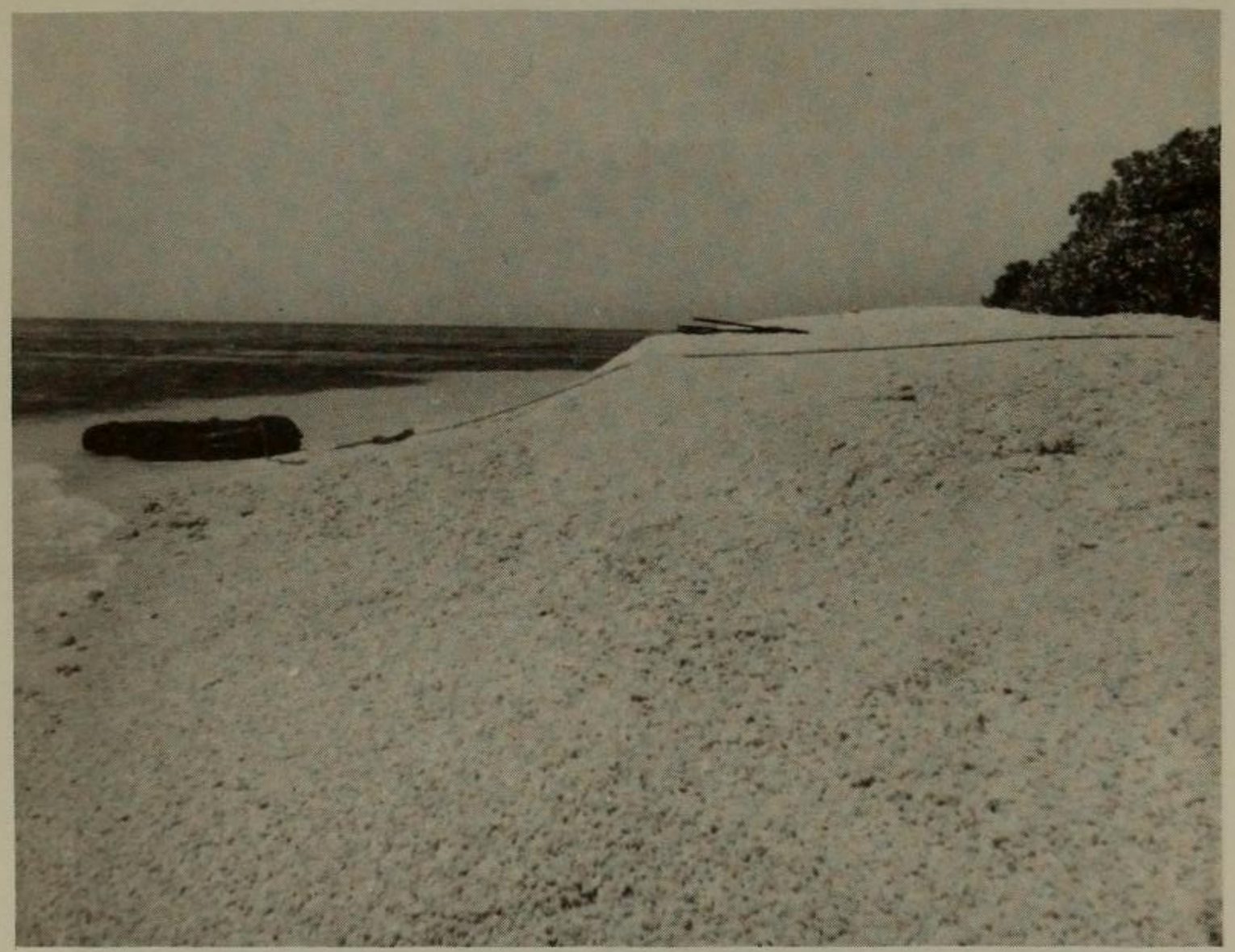

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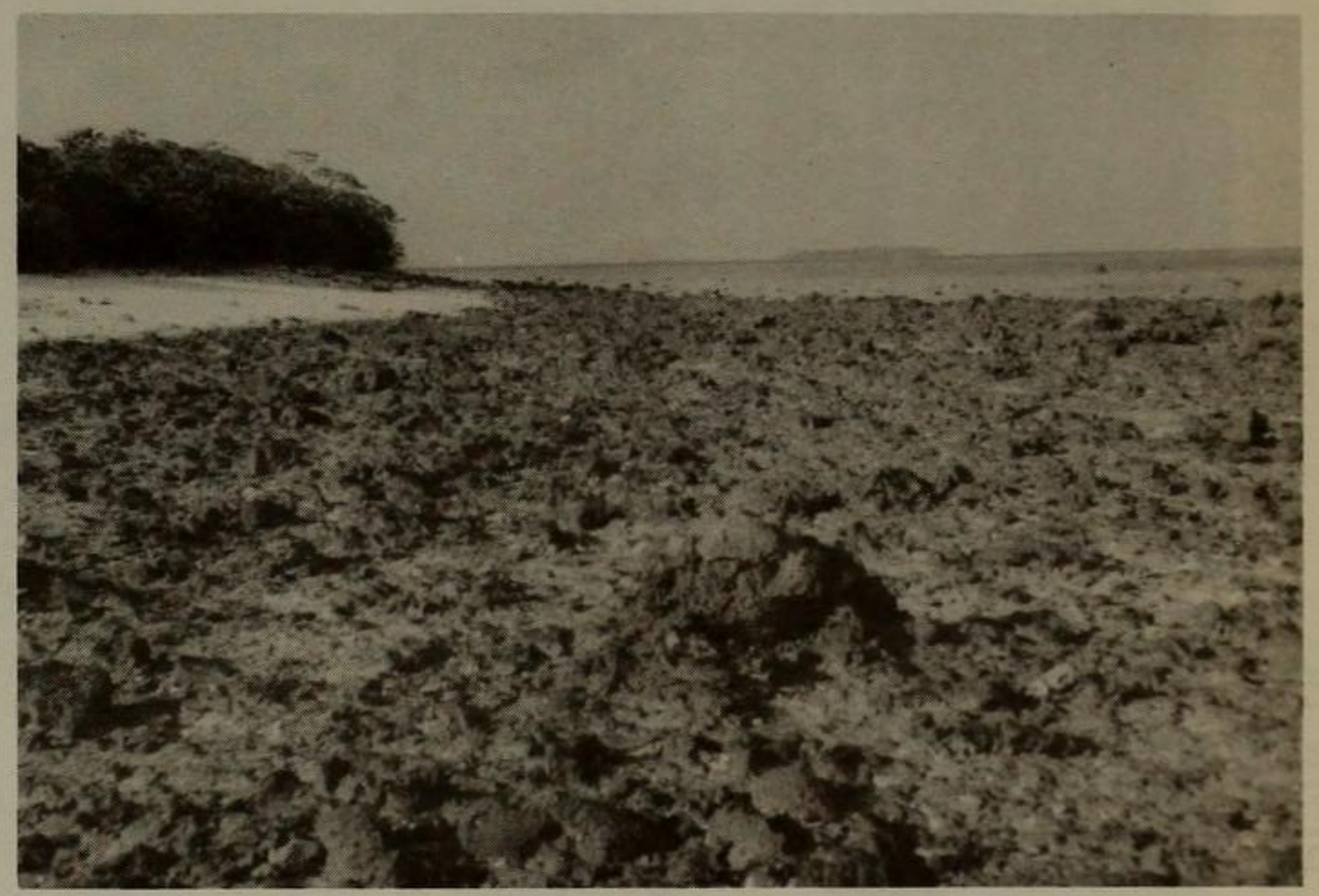

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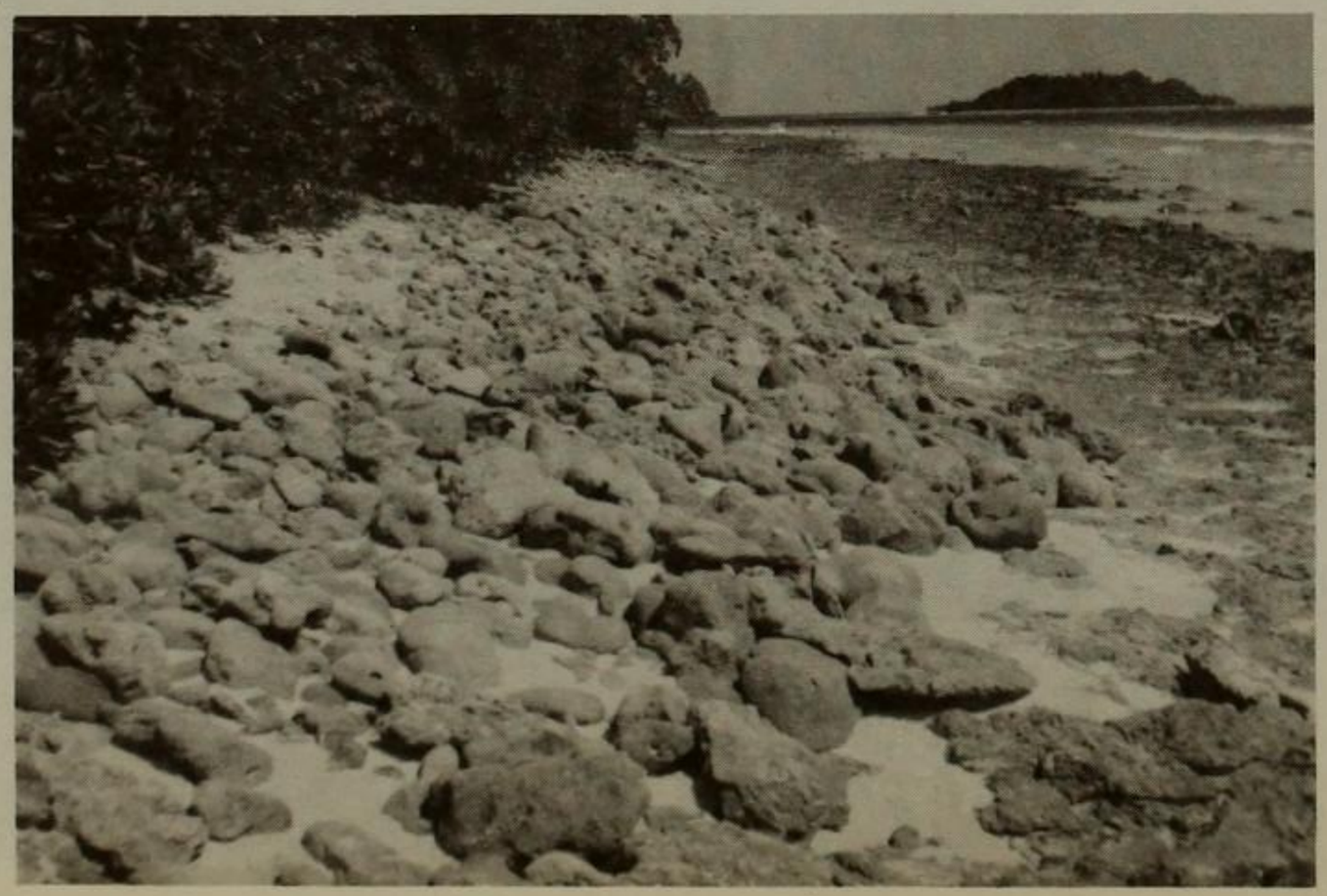

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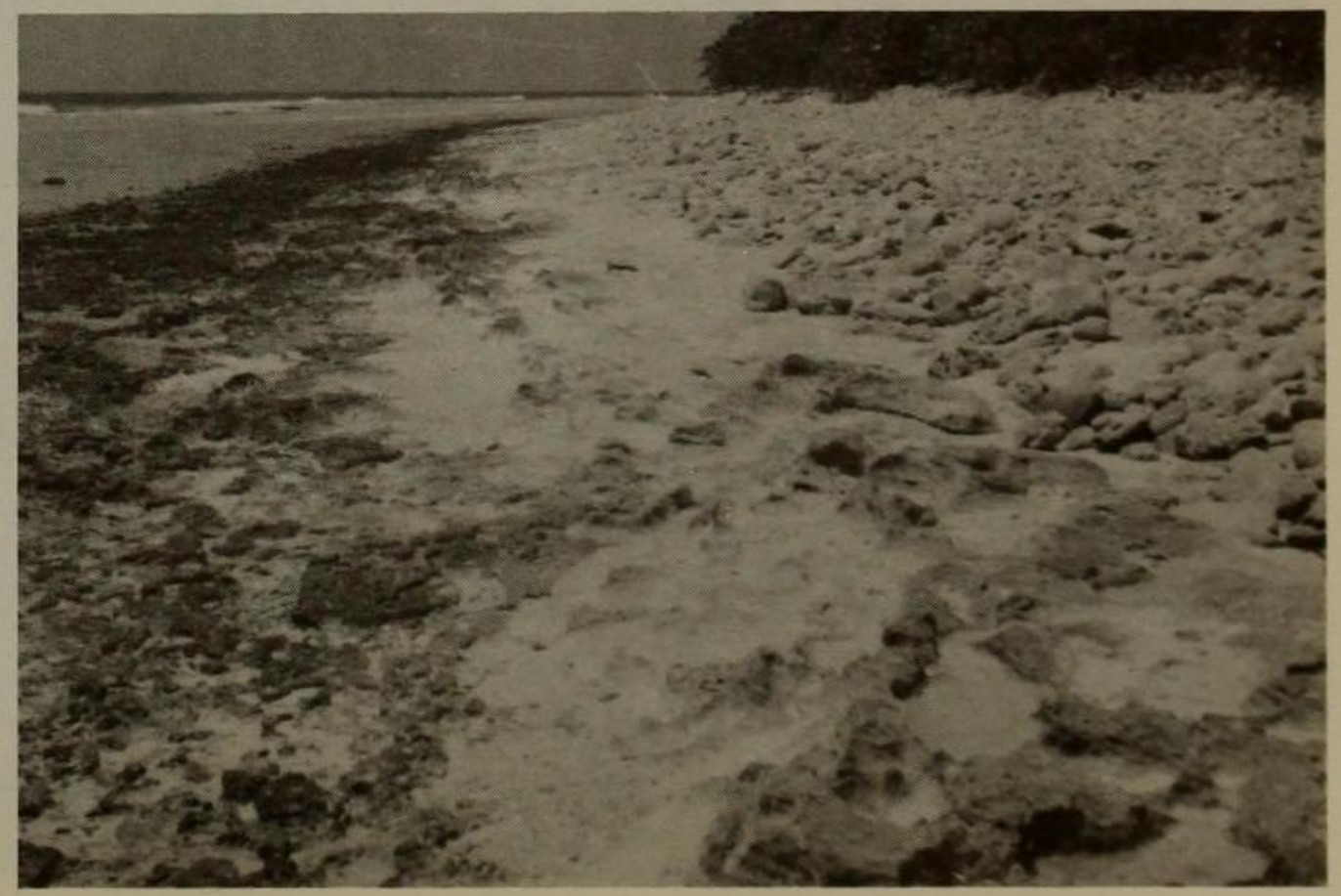
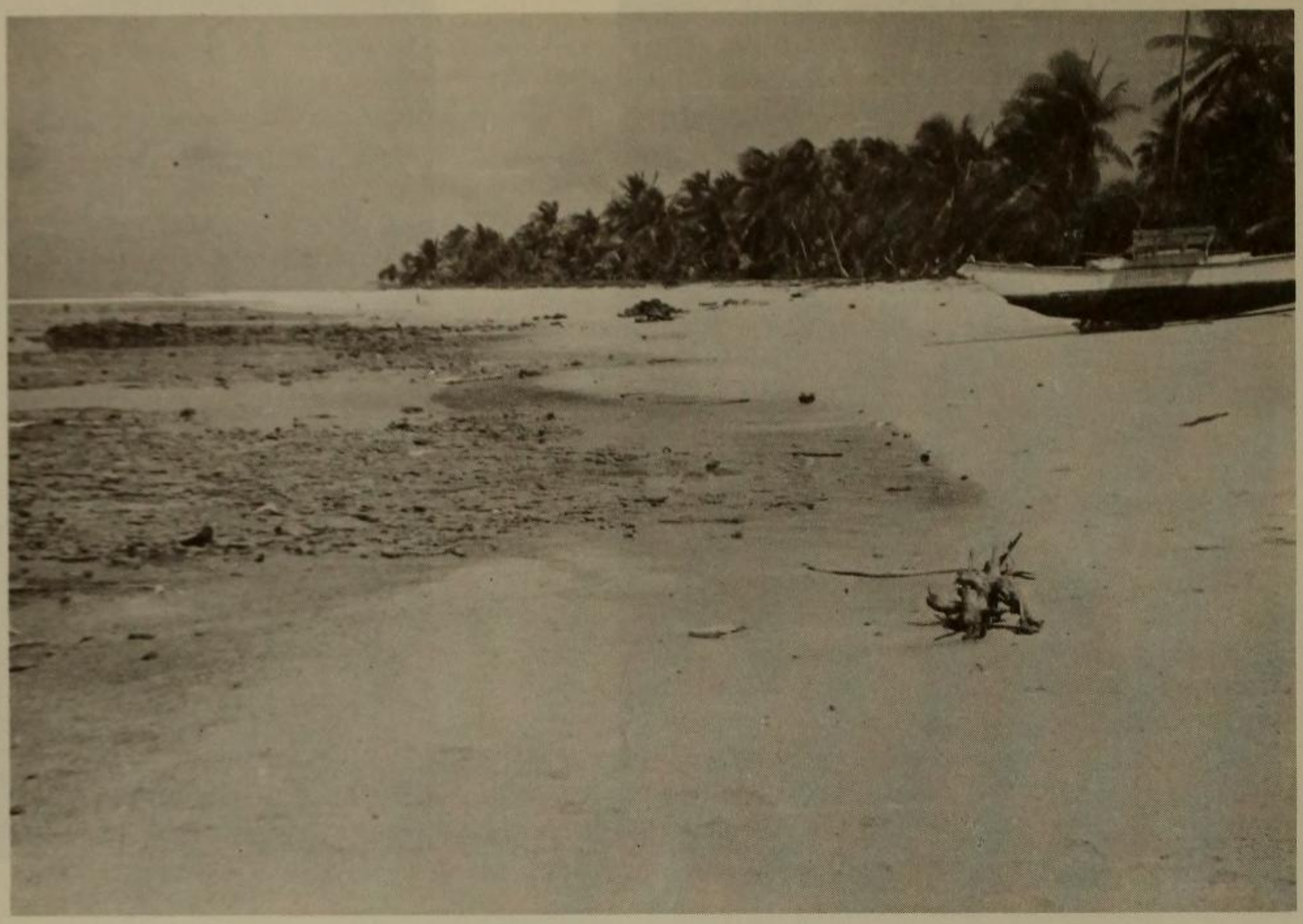


Plate 18



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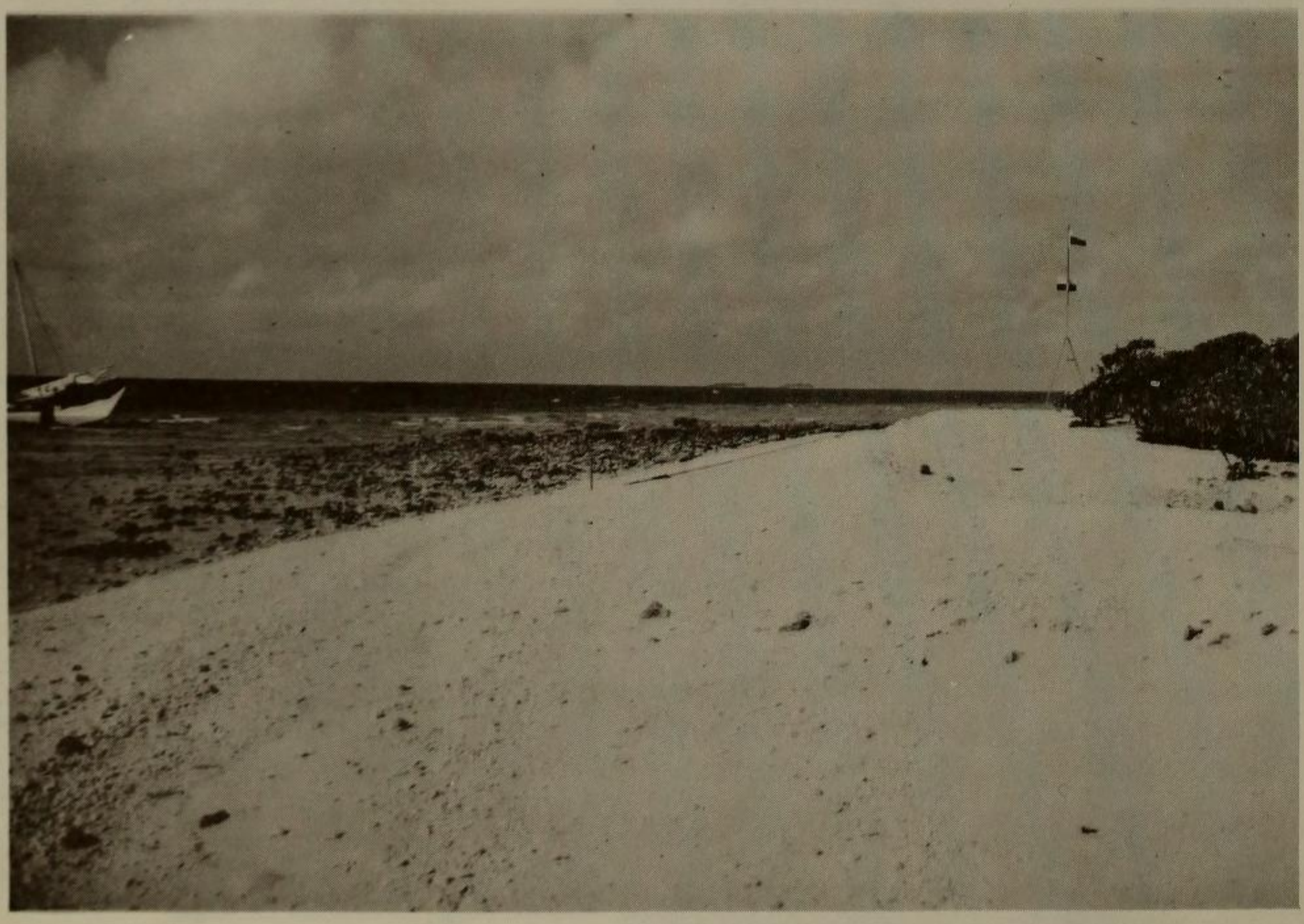

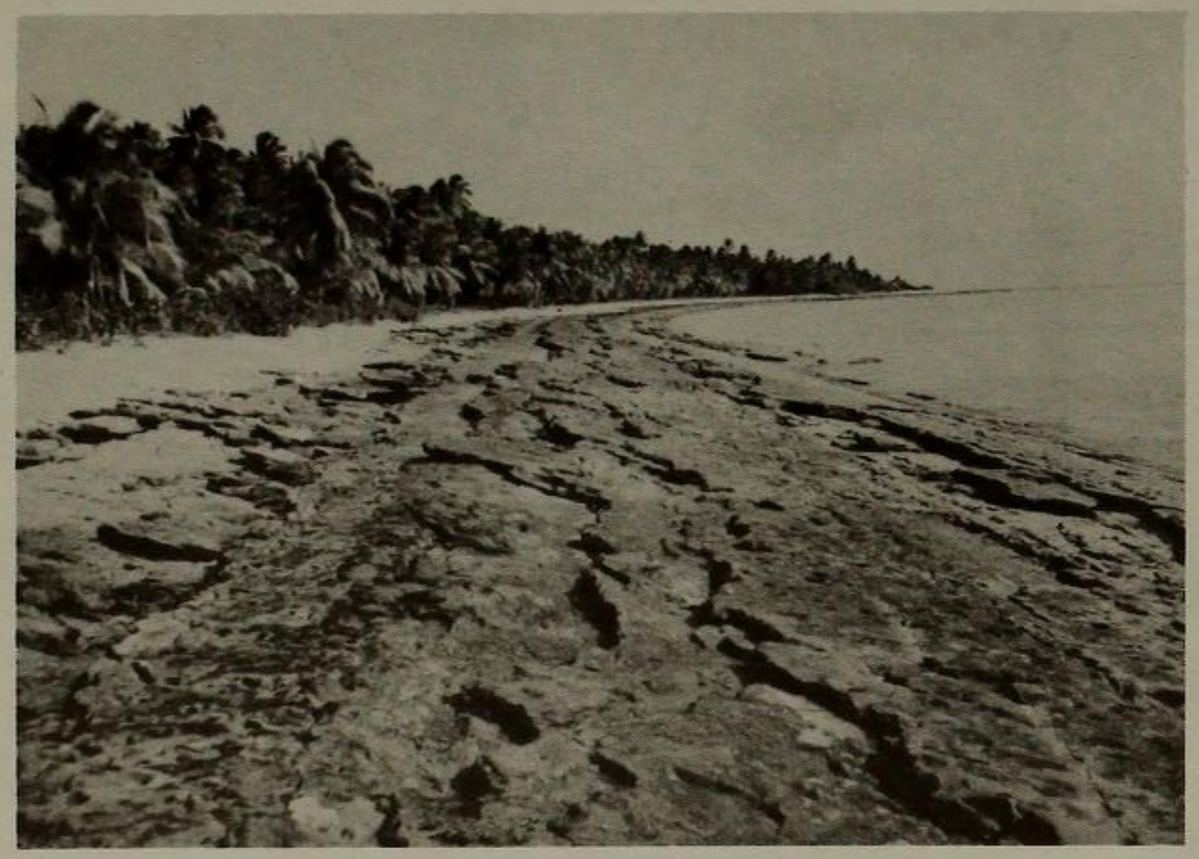

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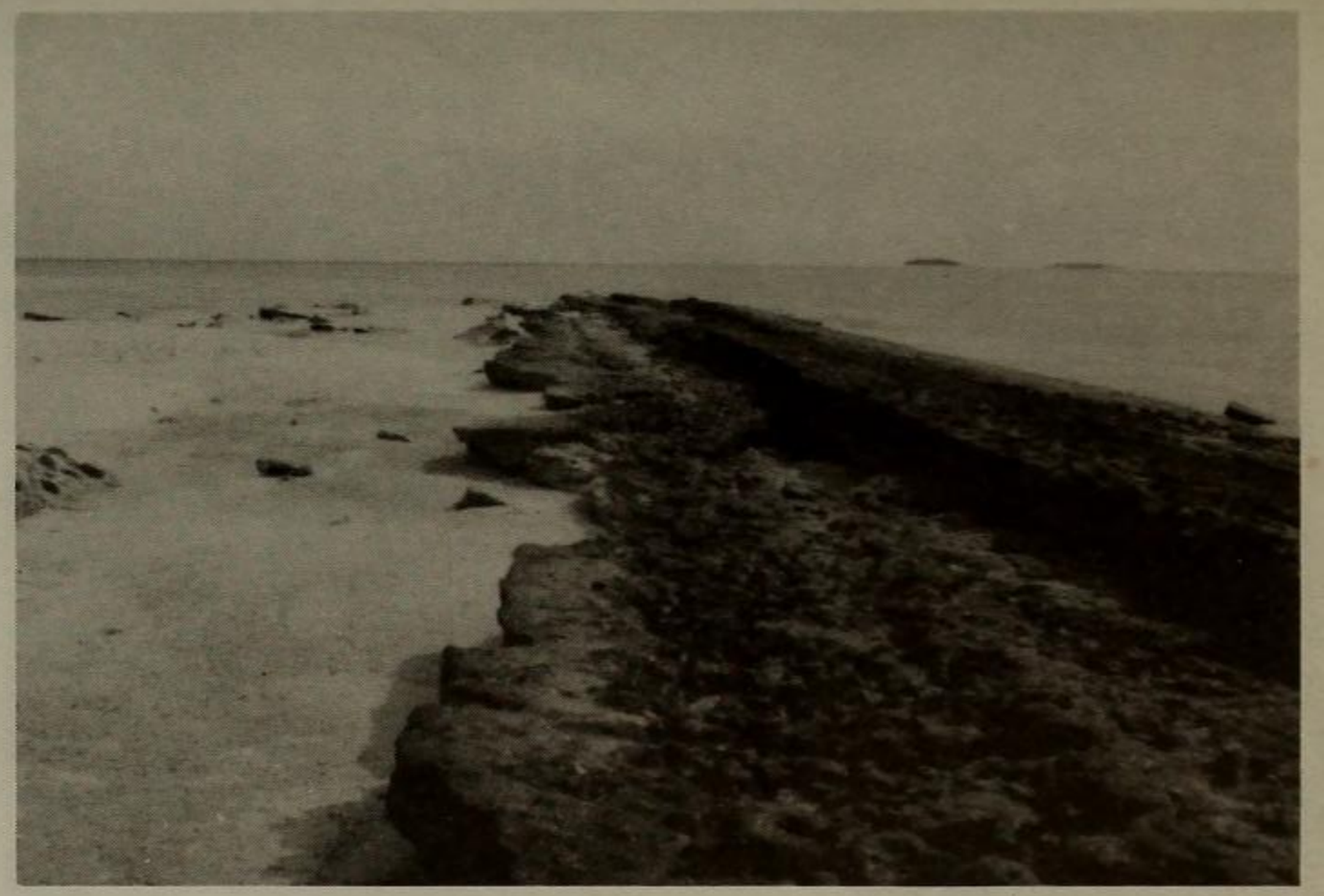

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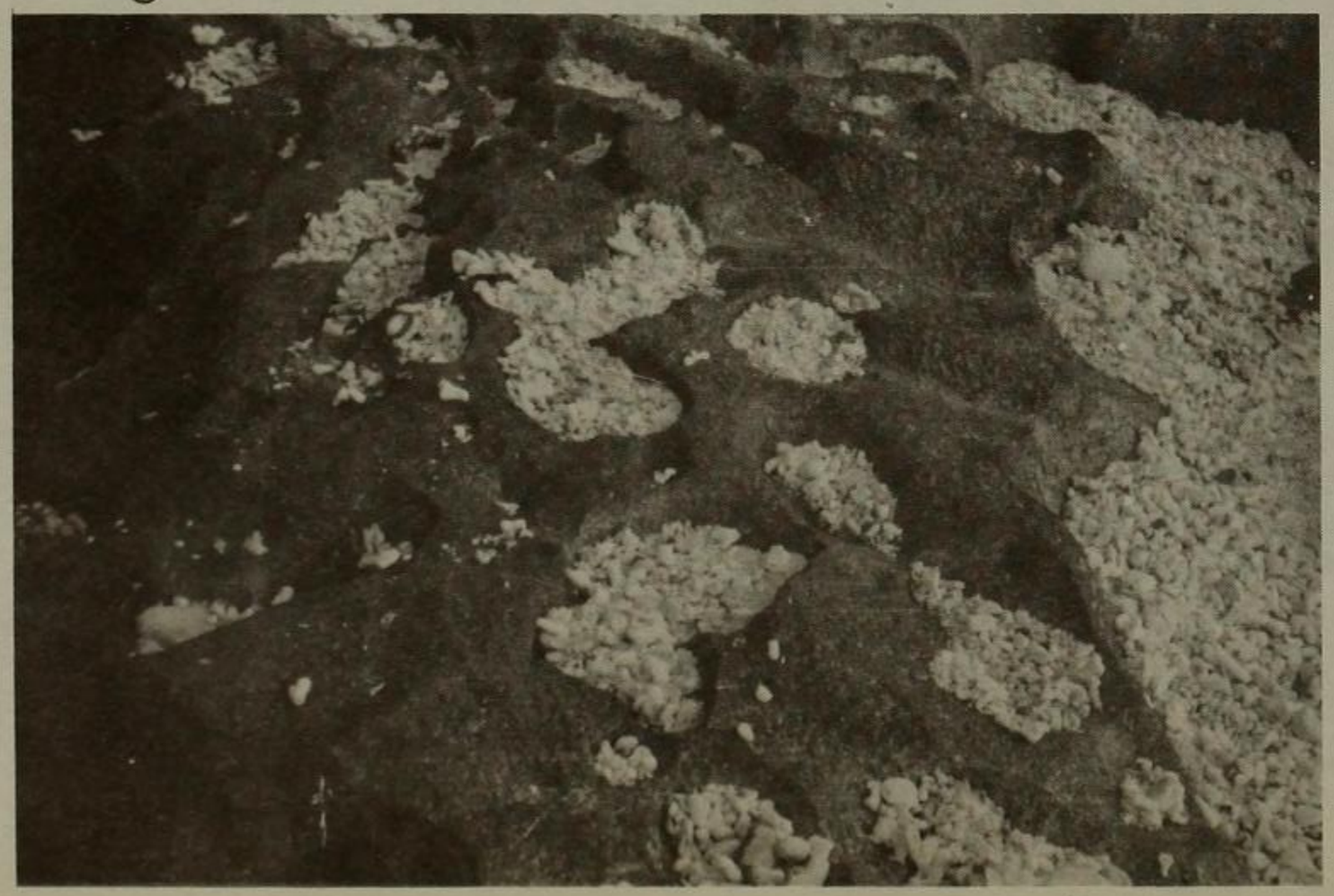

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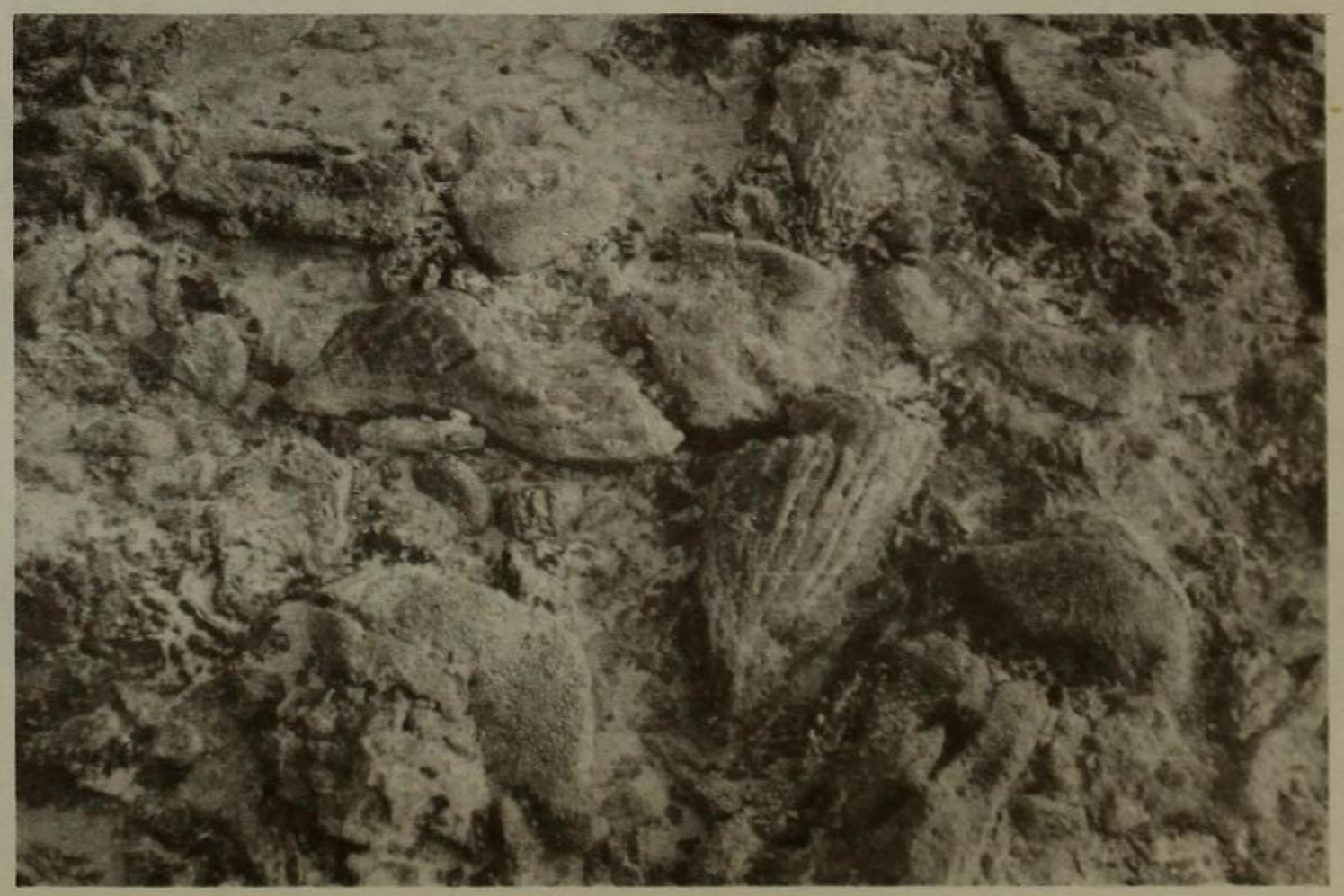

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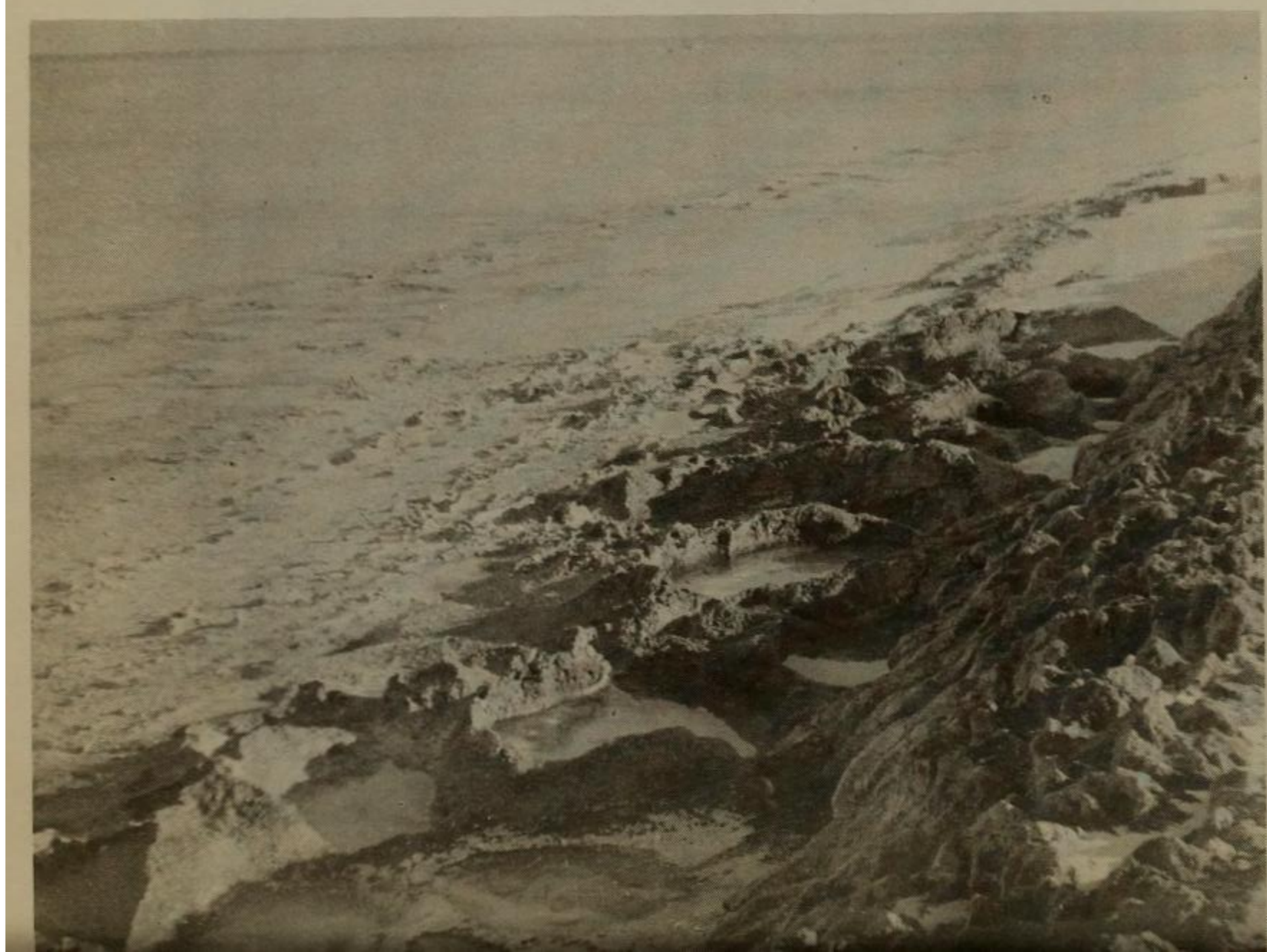

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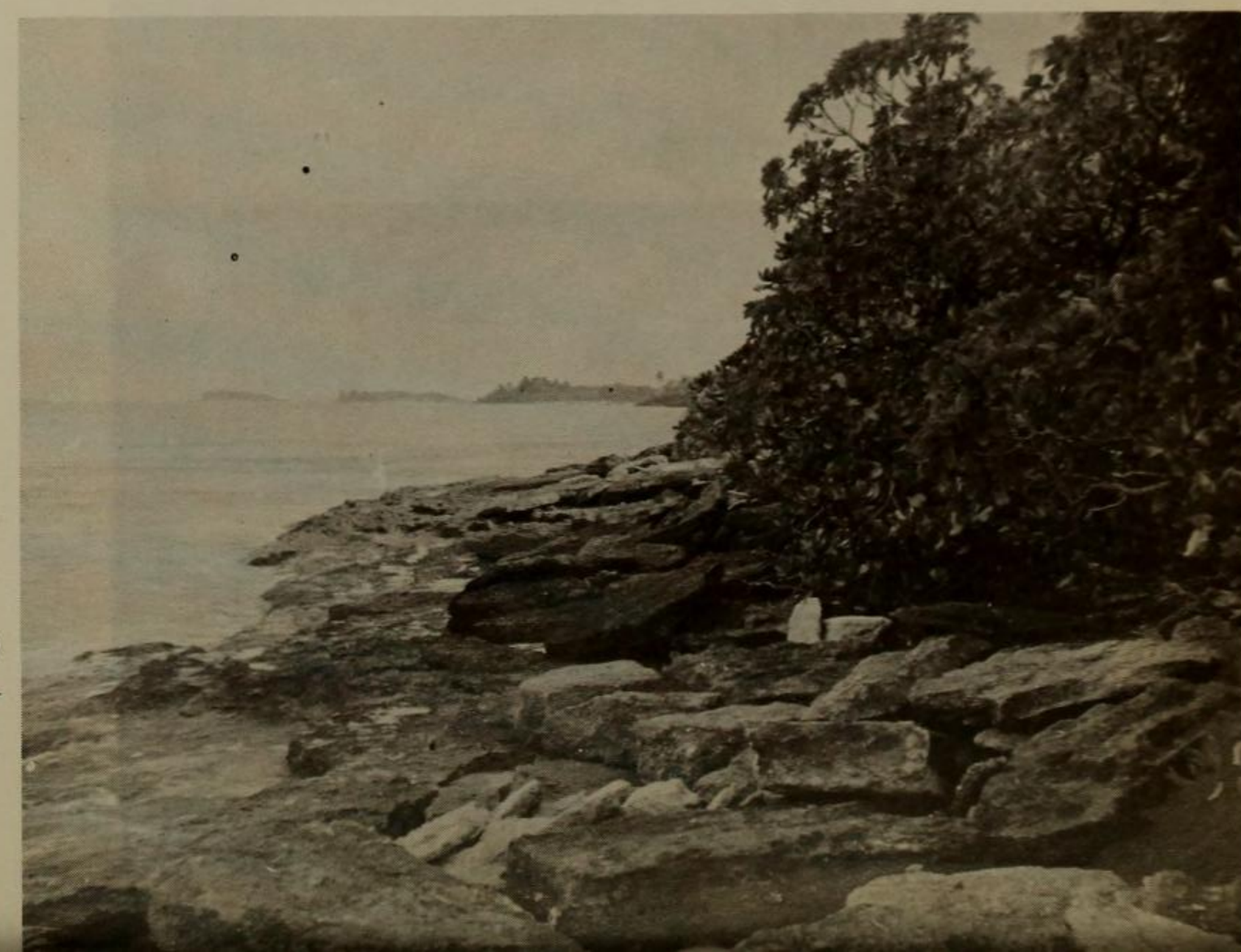

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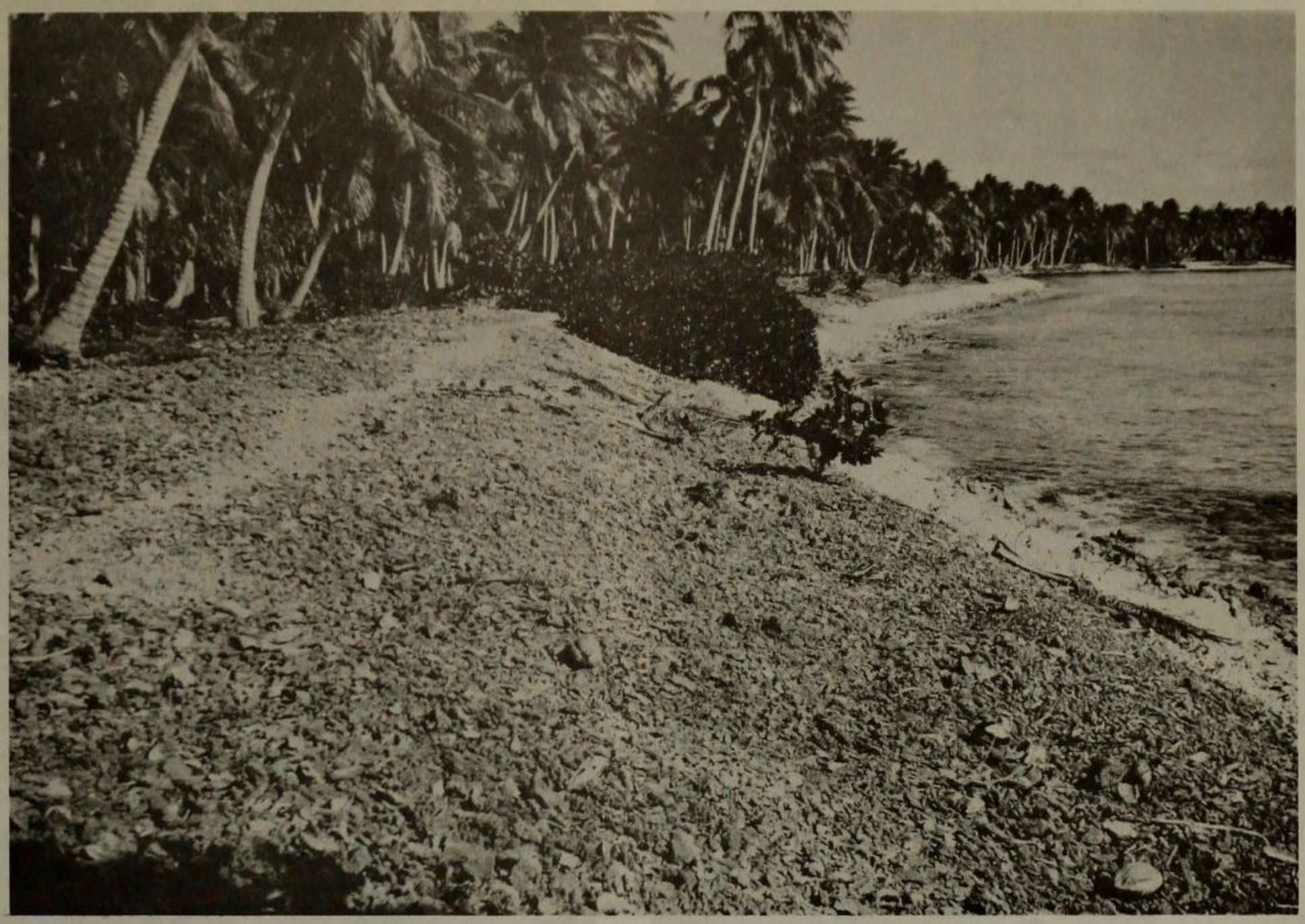
Plate 21



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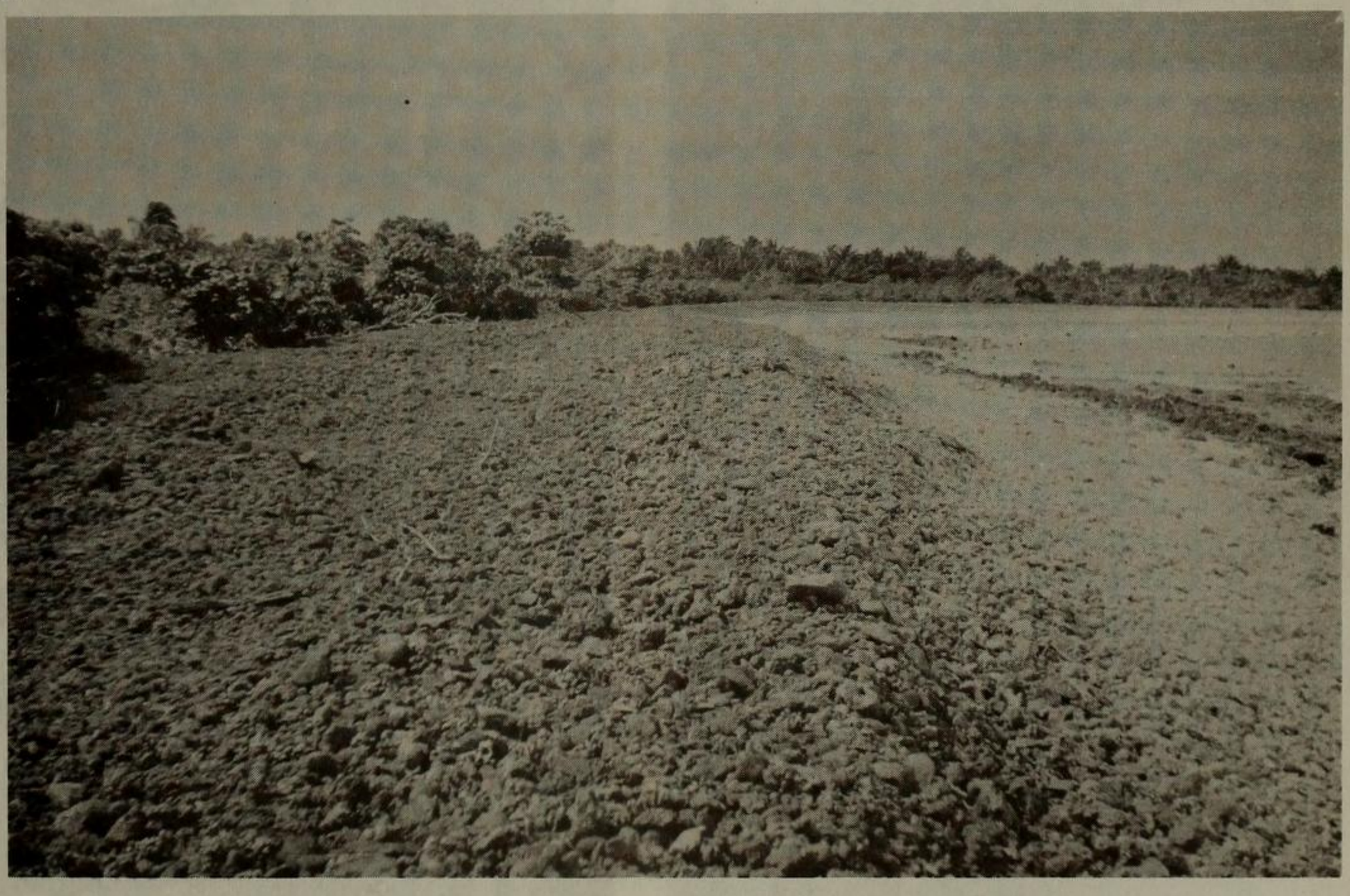

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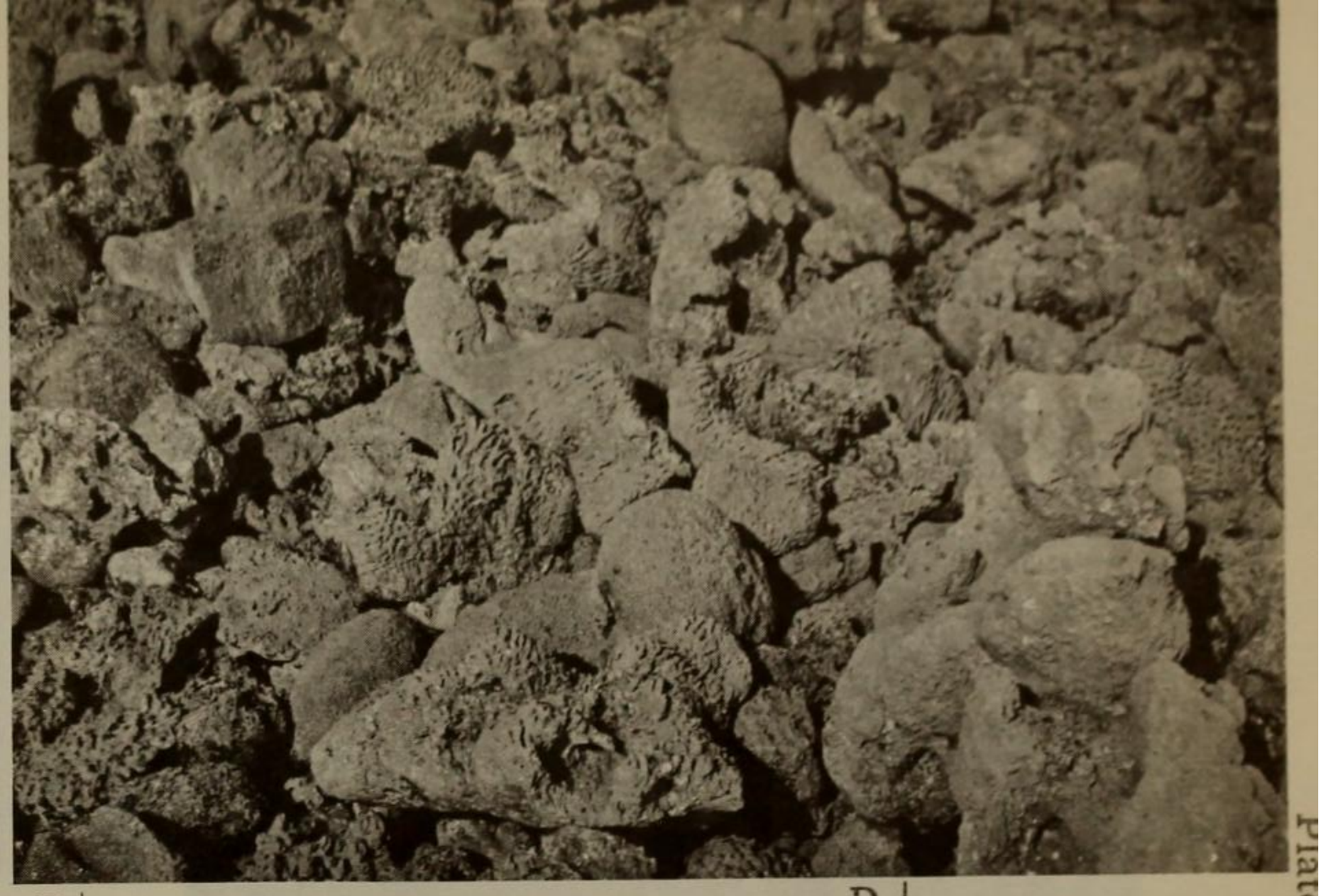
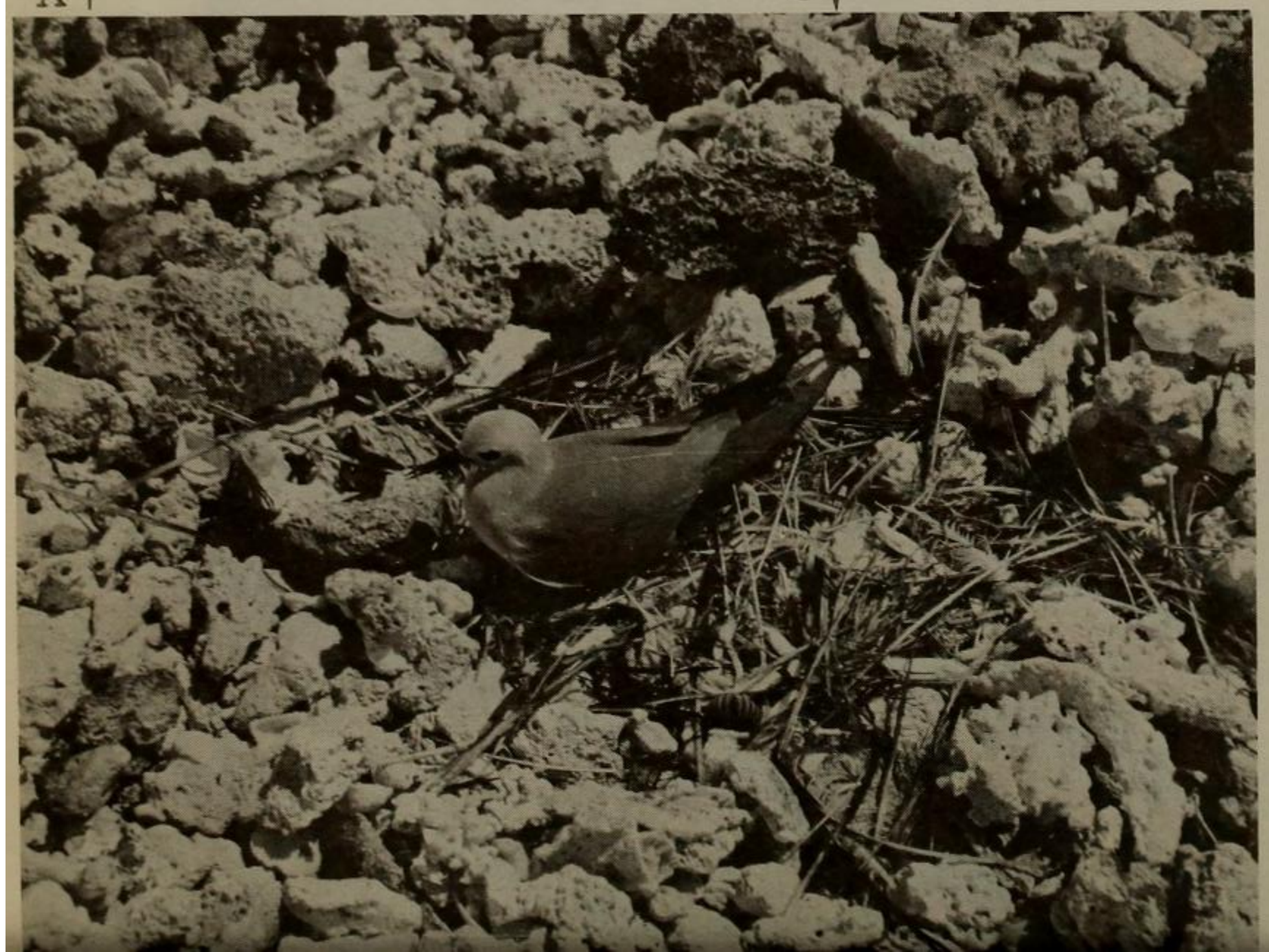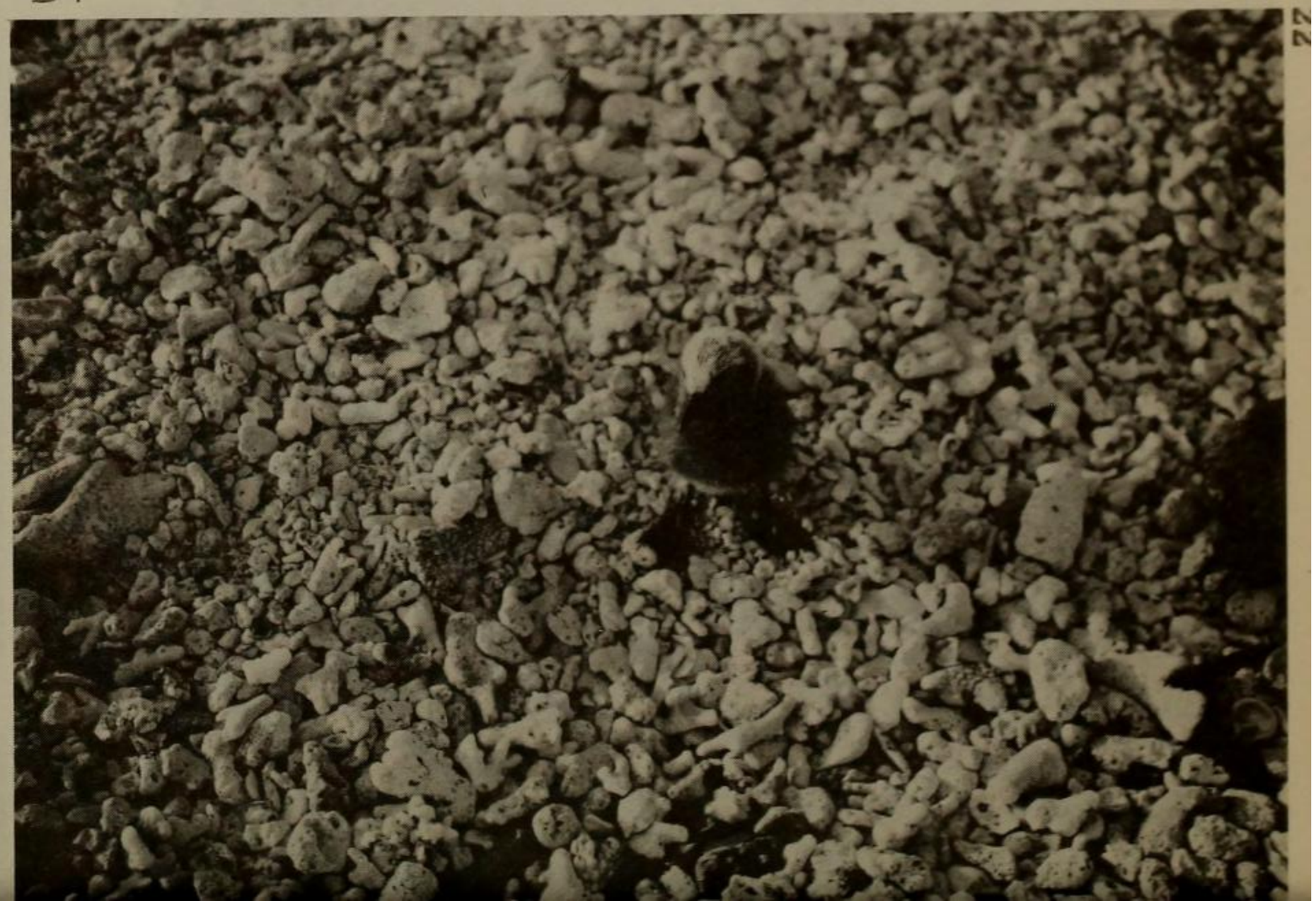
D ↓