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CALM-WATER REEFS AND ROUGH-WATER REEFS OF THE CARIBBEAN PLEISTOCENE

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Examination of a number of late Pleistocene Caribbean shallow-water reefs revealed a pattern of wave-induced reef zonation analogous to that known from the Recent. Comparison of the zonal sequences of the Recent reefs with their fossil counterparts provides a key for the interpretation of paleo-hydrodynamic conditions, i.e. direction and degree of wave exposure during growth of the Pleistocene reefs. The spectrum of Pleistocene wave exposure recorded ranged from prevailing heavy surf generated by oceanic swell to no significant wave turbulence. The regional variation of reef types in the Caribbean area during late Pleistocene high sea level stands corresponds to the Recent pattern thus giving evidence for a basically similar distribution of wave energy (and consequently of wind force and directions) as can be observed today.

Key words: Caribbean Sea, coral reef, paleoecology, Pleistocene, reef zonation, wave exposure.

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INTRODUCTION

Marshall (1928) was the first to point out the striking influence of wave exposure on the morphology and ecology of Recent coral reefs. He defined two fundamentally different reef types from Australian waters which he called "rough water coral reefs" and "calm-water coral reefs". In a more detailed regional survey of Indian Ocean reefs Rosen (1975) recognized several coral associations adapted to intermediate wave turbulence. He described an entire spectrum of five distinct benthic associations that clearly reflect the degree of exposure to waves.

Similar studies conducted by the author in Recent shallow-water reefs of the Caribbean revealed six analogous benthic reef associations or "wave zones" which tend to parallel the topographical crest of each reef resulting in a distinct ecological zonation. Each of these wave zones is defined by certain predominant hermatypic organisms, listed below according to decreasing wave exposure: 1) Melobesieae ("algal ridge"), 2) *Palythoa* sp. and *Millepora* sp., 3) *Diploria strigosa* and *Acropora palmata,* 4) *Acropora cervicornis,* 5) *Porites porites,* 6) *Montastrea annularis* (see Geister 1975, 1977).

The distribution of wave zones within the reefs permits the establishment of six basic reef types which are adapted to the degree of wave exposure prevailing within clearly delimited reef areas. Each reef type is defined by the wave zone forming the reef crest community ("breaker zone") which is adapted to maximum wave exposure within each particular reef segment. Complete or incomplete sequences of further wave zones in front and to the rear of the crest reflect more protected conditions. Breaker zones and wave zones adapted to the same range of wave exposure characteristically exhibit the same reef associations. For practical purposes the reef types have been named according to their respective breaker zones (see fig. 1; Geister 1977).

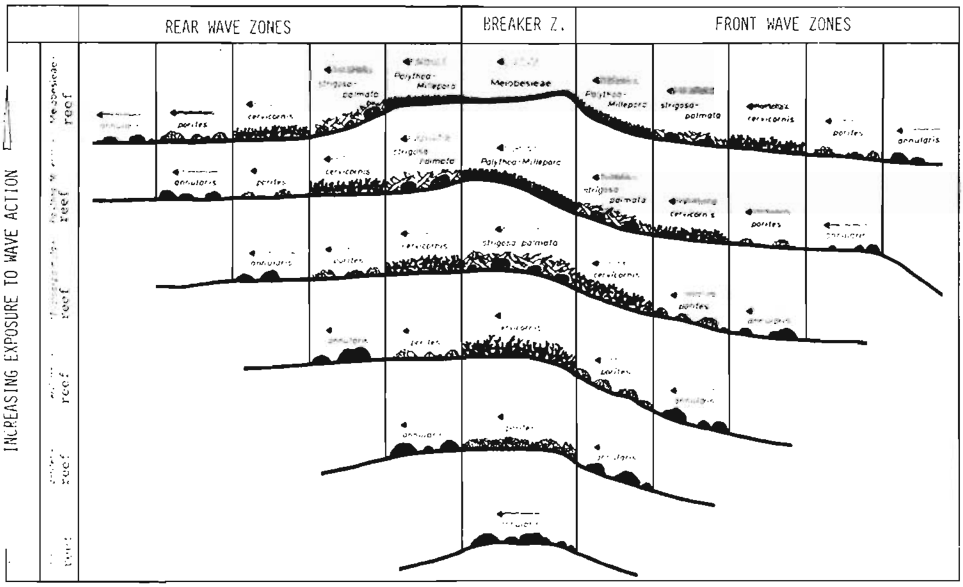

Fig. 1. Wave zonation pattern of the six basic reef types, recognized in Recent Caribbean reef complexes. The reef types are somewhat idealized. Generally zonal sequences are incomplete. The relative degree of wave exposure is indicated by arrows (from Geister 1975, modified).

With the results of these previous studies in mind, a number of emergent late Pleistocene West Indian reef complexes was examined in the field. The field reconnaissance and the survey of pertinent literature extended over the whole Caribbean area (fig. 2). As will be demonstrated by the following short descriptions of some selected reef sites, the Pleistocene pattern of reef zonation followed the same principles as the Recent one.

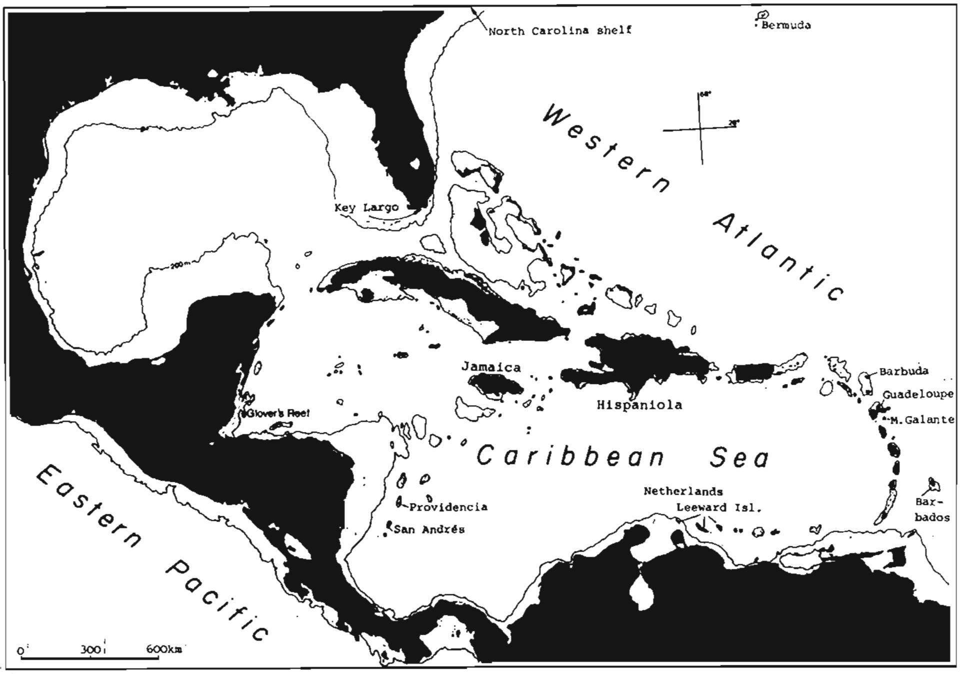

Fig. 2. Map of the West Indian region showing the location of the Pleistocene reefs mentioned in the text.

LATE PLEISTOCENE CARIBBEAN CORAL REEFS

MELOBESIEAE REEFS

1. North Carolina shelf and Bermuda

Algal reefs of latest Pleistocene to earliest Holocene age were reported from the outer margin of the North Carolina continental shelf (Menzies *et al.* 1966; MacIntyre and Milliman 1970), where they are submerged today to 80—100 m. Apparently they represent Melobesieae reefs consisting of true algal ridges, although no corresponding wave zones are known. They formed near sea level during deep stands 19,000 to 11,000 years ago (Milliman and Emery 1968).

Well-rounded pebbles and cobbles of algal reef rock have been described from the basal conglomerate of the Pleistocene Devonshire Formation at the south shore of Bermuda (Schroeder 1973). They indicate the former presence of Melobesieae reefs ("algal cup reefs") in the area, similar to those described from the Recent by Ginsburg and Schroeder (1973).

2. Barbuda Island, Lesser Antilles (fig. 3; pls. 50 and 51)

Barbuda is surrounded by a low island terrace on which Pleistocene coral rocks and accretionary sediments have been deposited ("Codrington Limestone"). The narrow (100—200 m wide) terrace along the eastern coast of the island represents a raised fringing reef corresponding to a Pleistocene high sea level some 6 m above the present one. This is indicated by a deep intertidal notch in the landward fossil limestone cliff (Russell and McIntire 1966; Wigley 1977).

On the seaward side of the fossil reef the high swell of the Atlantic breaks along a nearby Recent fringing reef almost entirely of the Melobesieae reef type. On the landward side, the Pleistocene reef ends at a high escarpment in the older "Highland Limestone" from where large blocks fell onto the inner reef flat towards the end of the Pleistocene transgression (pl. 50: *a*). Since the regression the reef surface has been lowered for about 1m by weathering, as indicated by the position of the original Pleistocene reef surface preserved below the protective cover of the blocks. This amount of limestone solution would agree with a late Pleistocene age of the reef terrace of about 120 000 years (see Stoddart 1969: 481) as estimated by Russell and McIntire (1966: 31).

The best outcrops of the Pleistocene fringing reef were found in a narrow band, some 10—50 m broad, along the present shoreline. In combination with scattered landward outcrops they permit the recognition of the following subparallel wave zones: front *strigosa-palmata* wave zone, Melobesieae breaker zone, rear *strigosa-palmata* wave zone, rear *annularis* wave zone. As indicated by the well developed algal ridge ("Melobesieae breaker zone") we are confronted with a typical Melobesieae reef, similar to the Recent one which fringes the west coast of the island today.

Due to irregular erosion at the reef surface and at the Recent coastal cliff, as well as along major vertical fissures, a good insight into the internal zonal structure of the reef could be obtained. It can be seen that the algal ridge formed on top of a coherent thicket of *Acropora palmata* (fig. 3; pl. 50: *b*) that extends from the seaward to the landward margin of the ridge. A similar internal structure has been found by coring Holocene Melobesieae reefs of the eastern Caribbean (Adey and Burke 1976).

a) *Melobesieae breaker zone ("algal ridge")*. — Much of the Pleistocene reef flat is covered by fossil algal ridge deposits (pl. 51: *a*, *b*) which, because of the uniform gray aspect of their weathered surface, can easily be overlooked or mistaken for lithified lagoonal deposits after only superficial examination. The deposits are best preserved in a 6.5 km stretch along the coast line between "Two Feet Bay" in the north (grid coordinates according to official topographic map 1:25 000: East 629.6,

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EXPLANATION OF THE FIGURES 3—7

3. Zonal sequence of a late Pleistocene "Melobesieae reef". East coast of Barbuda Island near "Castle Hill House". The landward "rear *annularis* zone" would be to the right beyond the Recent beach!; 4. Zonal sequence of a late Pleistocene "*strigosa-palmata* reef". South coast of Hispaniola, 8—9 km E of Boca Chica/Dominican Republic (combined profile); 5. Zonal sequence of a late Pleistocene "*cervicornis* reef". West coast of San Andrés Island near Horn Landing. Vertical exaggeration ca. 4x; 6. Zonal sequence of a late Pleistocene "*porites* reef". South coast of Providencia Island, near South Point; 7. Generalized profile through a late Pleistocene "*annularis* reef". Key Largo, Florida. (No scale).

fig.3

fig.4

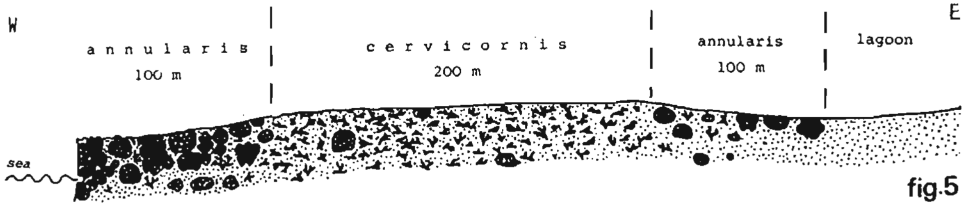
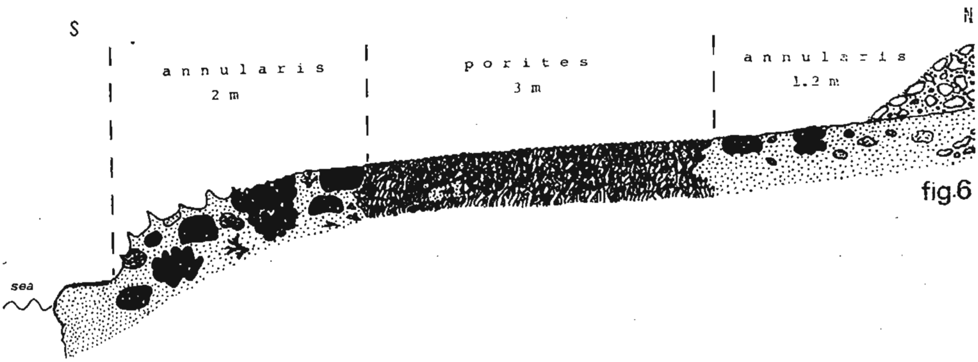


fig.5



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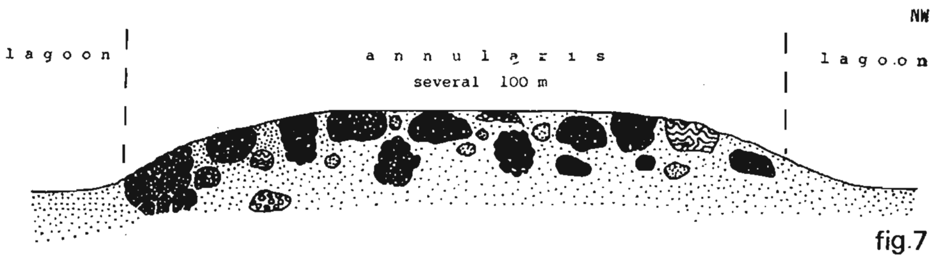

fig.7

North 1954.7) and the "Castle Hill House" area in the south (coordinates: East 633.5, North 1950.1). To the north of "Two Feet Bay" the fossil algal ridge becomes patchy and incoherent, although the underlying thickets of *Acropora palmata* are present. An isolated major segment of algal ridge has been localized in this area (coordinates: East 628.6, North 1956.2). It is believed that the algal ridge was rather complete along the west coast but lost much of its extent by the general erosional lowering of the Pleistocene reef surface since its emergence some 100.000 years ago.

The fossil algal ridge structure ranges from less than 1 m in thickness in the south to about 3 m near "Two Feet Bay" and attains a width of 15 m at the former locality, and at least 50 m at the latter locality. Hurricane wave broke off large blocks along horizontal and vertical fissures and deposited them together with storm beach rubble on the reef terrace (pl. 51: *b*). Here they mingle with blocks torn off from the Recent algal ridge, the latter material being easily distinguishable by its large unfilled voids.

Heavy encrustations by coralline algae (Melobesieae) form the bulk of the rock material with major additions by the coelobitic foraminifer *Homotrema rubrum* and vermetids. The same organisms are major constructors in the adjacent Recent algal ridge. Freshly broken surfaces of the algal rock appear whitish, exhibiting an internal laminated algal structure. The pinkish blotches present are due to enclosed skeletons of *Homotrema rubrum*.

In contrast to its Recent counterpart, no major open pores are visible in the Pleistocene algal rock. Instead, the interstitial space between the crusts has been almost completely filled with skeletons of coelobites, wave-driven sediments and cements forming a marble-hard, hammer-ringing rock. The void-filling and cementing mechanisms have not been studied in detail. However, they appear comparable to those described from the Recent Bermuda cup reefs (Ginsburg and Schroeder 1973).

b) *front and rear strigosa-palmata wave zones.* — These zones are indicated by the presence of more or less dense thickets of *Acropora palmata* (pl. 50: *b*) that may be associated with some *Diploria strigosa, D. clivosa* and locally a few large multilobular colonies of *Montastrea annularis*. They are well exposed in front and to the rear of the algal ridge, but in fact form a coherent layer under the cap of algal rock (fig. 3). All the corals are imbedded in a calcarenitic matrix. Due to the lack of deeper exposures nothing is known of the depth and composition of the foundation on which these *Acropora palmata* thickets have grown.

The *strigosa-palmata* wave zone is found along the entire eastern coast line of the island, surveyed from the "Castle Hill House" area to "Hog Point" in the north. It formed front and rear wave zones in areas with an algal ridge or a breaker zone where the algal deposits are missing.

Near the northern end of the Highland escarpment at "Gun Shop Cliff" the Pleistocene algal ridge extends to the old coastal escarpment in the "Highland Limestone". As a result no rear wave zones are developed here.

c) *rear annularis wave zone.* — Where the Pleistocene reef platform was broad enough the hydrodynamic conditions were favourable for the formation of a rear *annularis* wave zone at the landward terrace margin. This zone is represented by a loose association of larger multilobular and smaller hemispherical colonies of *Montastrea annularis* with local patches of *Porites porites* and some other species. The outcrop situation however is generally patchy, due to an extensive cover of Recent beach rubble and vegetation.

No indication for the presence of rear *cervicornis* or *porites* wave zones was found anywhere in the lee of the algal ridge.

PALYTHOA-MILLEPORA REEFS

It is interesting to note that until now no sufficiently dense and extensive framework of *Millepora* has been recorded from Pleistocene Caribbean reefs that would document the former presence of a *Palythoa-Millepora* wave zone in the area. Consequently a *Palythoa-Millepora* reef has not been recognized so far, not even in the western Caribbean where this reef type prevails today at the windward side of the islands.

STRIGOSA-PALMATA REEFS

1. Barbados W. I.

The sedimentary rocks of the Pleistocene coral cap of Barbados were studied in detail by Mesolella (1967), Mesolella *et al.* (1970) and others. Their results were summarized by James *et al.* (1977). According to these studies and my own field observations the Pleistocene rocks represent a series of uplifted barrier and fringing reef terraces deposited around the northern, western and southern margins of the island during glacioeustatic high stands of sea level. Several of these reefs, well described by the above authors, were visited in 1975 along a number of road cuts. From the seaward to the landward side they show the following general zonation pattern: front *annularis* wave zone, front *cervicornis* wave zone, *strigosa-palmata* breaker zone, rear wave zones.

a) *front annularis wave zone ("coral head zone" of Mesolella 1967).* — This zone is exposed in the deeper frontal part of many reefs and is composed mainly of hemispherical coral colonies, such as abundant *Montastrea annularis, Siderastrea* ssp. and *Diploria* ssp. as well as several subordinate forms.

b) *front cervicornis wave zone ("Acropora cervicornis zone" of Mesolella 1967).* — The rock of this zone is composed almost entirely of broken colonies of *Acropora cervicornis*. The zone attaints several dozens of meters in width, but may be missing locally.

c) *strigosa-palmata breaker zone ("Acropora palmata zone" of Mesolella 1967).* — The limestone of the reef crest is formed almost entirely by monospecific stands of *Acropora palmata* embedded in a calcarenitic matrix, although *A. cervicornis, Diploria strigosa, Siderastrea siderea* and several other species of minor importance may contribute to the rock material.

d) *rear wave zones ("rear zone" of Mesolella 1967).* — Behind the reef crest cccasionally a rear *cervicornis* wave zone and/or a rear *annularis* wave zone is developed. Generally both of these coral species mingle forming Mesolella's condensed polyspecific "rear zone", with major contributions also by *Porites porites*, *Diploria* sp. and a number of subordinate forms.

A well developed rear *porites* wave zone has only been seen in the 83 000 years old reef complex of northern Barbados (see also James *et al.* 1977: fig. 8). According to personal observations these reefs occur generally on the leeward coast of Barbados, exposed to waves of the Caribbean Sea rather than to the swells of the open Atlantic that would have approached from the east.

2. The Netherlands Leeward Islands

The raised reefs of late Pleistocene age on the Netherlands Leeward Islands exhibit a comparable zonation which has been described in much detail by de Buisonjé (1964). No front wave zones are preserved. A dense association of *A. palmata* and *D. strigosa* in growth position, at present under full attack by heavy waves along the exposed north-eastern cliff coasts of the islands, seems to represent the *strigosa-palmata* breaker zone of the former reef crest. A. *cervicornis* and *M. annularis* are abundant landward from this zone.

3. Jamaica

In his study of the late Pleistocene reef terraces of Jamaica, Cant (1973) observed that numerous depositional environments can be equated with environments of the modern Jamaica fringing reef. From the lowest (youngest) terrace he recorded a zonal sequence that corresponds well to that described by Goreau (1959) from the Recent fringing reef on the Jamaican north coast. The following wave zones were recorded proving the presence of a well developed *strigosa-palmata* reef: front *annularis* wave zone, front *cervicornis* wave zone, *strigosa-palmata* breaker zone and a polyspecific rear zone.

4. Islands of Guadeloupe and Marie Galante, French Antilles

The lowest Pleistocene terrace of Grande Terre (Guadeloupe) and Marie Galante show the following zonation in the easterly coastal sectors: The Recent cliff is generally formed by more or less well developed thickets of *Acropora palmata*. Landward this zone is followed by *A. cervicornis* and finally *Montastrea annularis*. Frequently only *M. annularis* is present.

Along the western coasts the occurrence of *A. palmata* is reduced to a few smaller coastal sectors. Fossil thickets of *A. cervicornis* with patches of *Pocillopora* sp. (Guadeloupe), or dense stands of *P. porites* or even *M. annularis* (Marie Galante) line the immediate shore. The landward zones are covered by vegetation. Although no front wave zones are preserved, it seems most probable that the eastern sectors mentioned belonged all to the *strigosa-palmata* reef type. It cannot be excluded, however, that a zone of higher wave exposure was present in front or on top of the *palmata* thickets which would have been eroded since emergence of the terrace.

5. Hispaniola (fig. 4; pl. 52)

The lowest Pleistocene terrace along the eastern shore of the Caucedo Peninsula (E of Sto. Domingo near "Aeropuerto de las Americas") exhibits a zonal sequence corresponding to the *strigosa-palmata* reef. In a 60 m band paralleling the shore the following coral zones were seen: front *annularis* wave zone, scattered front *cervicornis* wave zone, *strigosa-palmata* breaker zone (pl. 52: *a, b*). At the landward side storm beach rubble conceals the outcrops. Locally, the front wave zones have been removed by cliff erosion.

The south coast of Hispaniola between Sto. Domingo and La Romana was visited briefly in 1979. Where examined, the lowermost Pleistocene terrace showed a zonal sequence corresponding to the *strigosa-palmata* reef. A good, rather complete section of this has been obtained along the coastal stretch from 8 to 9 km east of Boca Chica (fig. 4). Here the terrace also shows well the former reef topography. The following coral zonation has been recognized:

a) up to 8 m front *annularis* wave zone near the coast line;

b) at least 3 m front *cervicornis* wave zone;

c) 60—80 m *strigosa-palmata* breaker zone;

d) ca. 30 m rear *annularis* wave zone;

e) several hundred meters lagoonal deposits.

Due to Holocene cliff erosion the front wave zones are not everywhere preserved.

6. San Andrés Island, western Caribbean

There is evidence for the presence of a late Pleistocene barrier reef of the *strigosa-palmata* type in front of the east coast of San Andrés. Besides the *Acropora palmata* framework no other wave zones have been recognized (Geister 1975: fig. 27). The fossil reef is submerged today and probably was also submerged several meters during the late Pleistocene transgression that formed the lowest terrace around the island (see below: San Andrés Island, western Caribbean).

CERVICORNIS REEFS

1. San Andrés Island, western Caribbean (fig. 5)

On San Andrés an extensive late Pleistocene reef complex was deposited at the low transgressive terrace that surrounds the central hill of the island (Geister 1975: 123—127). As part of this reef complex a fringing reef terrace, 250—1000 m wide and some 9 km long, formed along the western foot of the island's hill.

Today the seaward margin of this fossil reef is partly submerged or has been eroded near the present shoreline. Its landward margin is well marked by a steep to vertical, high cliff in the Miocene carbonates of the central hill, with a major intertidial notch at the +14 m level (Geister 1975: figs. 24, 25). Although the reef topography of the terrace is not very pronounced today, a distinct coral zonation can be recognized and has been mapped along its whole extent (Geister 1975: fig. 27).

The coral zonation corresponds essentially to the Recent *cervicornis* reefs as described from the lagoon of Glover's Reef, Belize (Stoddart 1962: 27—28) and as seen around the islands of Providencia and San Andrés. From the edge of the sea inland the following wave zones have been distinguished: front *annularis* wave zone, *cervicornis* breaker zone, rear *annularis* wave zone. The *porites* wave zones are lacking.

a) *front annularis wave zone.* — A dense growth mostly of large hemispherical and multilobular colonies of *Montastrea annularis* occurs along the outer lower margin of the reef platform. These mostly *in situ* colonies are frequently associated with a number of smaller species, the most important of which are the following:

Diploria ssp., mussids, *Eusmilia fastigiata, Madracis* sp., *Acropora cervicornis, Montastrea cavernosa, Porites porites.*

Locally, loose thickets of *Pocillopora* sp. are present in this zone too (Geister 1975: 155). In a landward direction, away from the outer margin of the reef platform, coral growth becomes scattered between the detritic sediments. This zone reaches locally more than 100 m in width, although much of its outer margin has been eroded as a consequence of the receding cliff since the end of the Holocene transgression.

b) *cervicornis breaker zone.* — The fauna of the central area of the reef terrace is characterized by numerous fragments of *A. cervicornis*, embedded in a calcarenitic matrix. Unfragmented *in situ* colonies of *A. cervicornis* are scarce. Isolated colonies of *M. annularis* and *Diploria* ssp. have been found associated with the predominant *A. cervicornis* of this zone. The transition to the seaward and landward wave zones is generally gradual.

The *cervicornis* breaker zone often forms a rather insignificant topographic high on the terrace rising in its central area a few meters above the landward and seaward zones. Its width varies between 100 m and almost 1000 m according to the locality.

The best outcrops can be visited in a 100 m broad fringe near the shoreline. Further inland the rock surface is generally covered with erosional debris and vegetation. However, sufficient scattered outcrops in caves etc. permit the recognition of the *cervicornis* breaker zone also in that area.

c) *rear annularis wave zone.* — This zone is represented by rather scattered growths of *M. annularis* heads, frequently merging to lagoonal environments near the inner margin of the terrace. The unsatisfactory outcrop situation, due to vegetational cover and debris from the Miocene rocks of the central hill, does not permit any detailed examination of this zone.

2. Barbados, W. I.

Several of the Barbados reef terraces do not show the full development of a *strigosa-palmata* breaker zone (Mesolella 1967: 638) as outlined above. After personal examination in the field it was found that in some of these cases the zonal sequence corresponds to the *cervicornis* reef type with front and rear *annularis* wave zones and a *cervicornis* breaker zone. Lowered wave exposure due to deeper water or a more protected position within the reef complex might have caused this zonation.

No further examples of *cervicornis* reefs from elsewhere in the Caribbean have come to the attention of the author.

PORITES REEF

1. Providencia Island, western Caribbean (fig. 6; pl. 53)

At "South Point" of Providencia a narrow emergent reef of late Pleistocene age rises from 1.2 to about 2 m above the adjacent sea level. The reef consists of two isolated segments, 90 and 250 m long and generally less than 5 m broad which fringe the steep island coast (Geister 1972: fig. 2; in print, pl. 7) formed mainly by Tertiary volcanic and sedimentary rocks. The inner margin of the fossil reef is covered by debris that has fallen down from the old cliff.

Radio carbon dates of a coral sample (*Siderastrea radians*) from the reef terrace gave minimum ages of about 30 000 years B. P. (Geister 1972). However, it is estimated that the reef is considerably older and rather dates from the last interglacial high sea level stand. No intertidal notch is preserved on the landward side that would indicate the position of the sea level at the time of the reef formation.

The foundation of the Pleistocene reef is probably a platform cut into Tertiary limestone during the Pleistocene transgression. This is indicated by blocks of Tertiary coral limestone, that apparently have been eroded from the base of the Recent cliff and thrown onto the Pleistocene terrace during heavy storms.

The fringing reef shows the following coral zonation: front *annularis* wave zone, *porites* breaker zone, rear *annularis* wave zone.

a) *front annularis wave zone.* — The generally loose coral association of this zone is patchy locally and has been partly eroded by the receding contemporary cliff. Where preserved, it may be more than 2 m wide and merges into lagoonal environments at its seaward side. Characteristic faunal elements are massive and multilobular heads of *M. annularis* but also of *Diploria strigosa* and *D. labyrinthiformis.* One multilobular colony of *Montastrea annularis* attains 4 m in diameter.

b) *porites breaker zone.* — The narrow (2—4 m) flat of the fringing reef is formed by dense, almost monospecific stands of *Porites porites,* almost all in position of growth (pl. 53: *a*) representing the breaker zone of the reef. Branching Melobesieae were frequently encountered between the *P. porites* colonies, as in Recent *porites* reefs. Minor additions to the scleractinian fauna are *P. astreoides* and *S. radians,* which generally occur near the inner margin of the reef flat. Locally restricted, smaller thickets of *A. palmata* developed at the outer margin of the reef flat, probably indicating a local increase in wave exposure. Similar *A. palmata* thickets in more exposed sectors of Recent *porites* reefs have been observed in the lagoon of San Andrés Island.

c) *rear annularis wave zone.* — This zone is only poorly represented by some patches of smaller *M. annularis* at the landward side of the reef flat (pl. 53: *b*).

P. astreoides and *S. radians* are equally frequent there. Lithified lagoonal sands and mud crop out at the surface of much of this area. Blocks of volcanic material and Tertiary limestone have fallen from the old cliff during the formation of the reef and became incorporated into the coral framework or mud. Slope debris also covers some 2 m of the inner margin of the fringing reef that, at least in part, might belong to this wave zone.

No other coral reefs of the *porites* type are known to the author from the Caribbean Pleistocene.

ANNULARIS REEFS

1. Key Largo, Florida (fig. 7)

According to Stanley (1966: 1937) and personal observations, rounded massive coral colonies, mainly of *M. annularis* but also of *Diploria* ssp. and others, are characteristic of the late Pleistocene Key Largo Limestone. Goreau's (1959) *annularis* zone (= "front *annularis* wave zone" of this study) corresponds fairly well to the reef framework in terms of main coral species and growth habits. In a detailed study Hoffmeister and Multer (1968) present evidence to interpret the Key Largo Limestone as a line of patch reefs in a back-reef area. The patch reefs would have been protected on its seaward edge by an outer reef which has since been lowered by erosion. Ecologically these reefs are regarded as typical *annularis* reefs which are recognized by the exclusive occurrence of an *annularis* breaker zone. Such reefs are indicative of very protected conditions or of a depth below normal wave base.

2. San Andrés Island, western Caribbean

Patch reefs of the *annularis* type, 10 or more meters across, were also found within lagoonal rocks of late Pleistocene age on San Andrés ("San Luis Formation"). They thrived in a position well protected from seas and swells by the Pleistocene barrier reef of the island (Geister 1975: fig. 27).

3. Hispaniola (Caucedo Peninsula near Sto. Domingo)

The lowermost Pleistocene terrace on the western side of the Caucedo Peninsula exhibits a framework consisting exclusively of corals of the *annularis* wave zone, as can be seen along the coastal outcrops. Provided non higher wave zones are covered under earth and vegetation further inland, the terrace might well represent a fringing reef of the *annularis* type.

REGIONAL DISTRIBUTION OF REEF TYPES DURING PLEISTOCENE AND ITS SIGNIFICANCE

Comparison of the late Pleistocene reefs with their Recent counterparts provides a standard for measuring the paleo-hydrodynamic conditions during their growth. The whole range of wave exposure recorded by the ecological zonation of the reefs ranged from heavy surf (Melobesieae reefs) over strong (*strigosa-palmata* reefs), moderate (*cervicornis* reefs), feeble (*porites* reefs) to no significant wave turbulence (*annularis* reefs). Not only rough-water and calm-water reefs *sensu* Marshall (1928) are recorded from the Caribbean Pleistocene but also reef types that indicate three intermediate conditions.

Regarding the distribution of the Pleistocene reef types the following observations can be made:

1) Pleistocene Melobesieae reefs are found along the coasts facing the open western Atlantic.

2) Pleistocene *strigosa-palmata* reefs are more characteristic for inner Caribbean open sea conditions.

3) Pleistocene reefs of *cervicornis, porites* and *annularis* are found in more or less restricted conditions along the west coasts of the islands or protected by barrier reefs.

It has been shown that the eastern coasts of the islands exhibit reefs of higher wave exposure than those of the western coasts. This indicates the former windward and leeward sides of the islands. Also the regional distribution of the late Pleistocene windward reefs coincides well with that recorded from the present (Geister 1977).

Not surprisingly, it appears from these observations that the trade winds blew from easterly directions as today and that the highest swell broke in the reefs open to the western Atlantic and with reduced energy in the windward reefs of the Caribbean. Minor differences between late Pleistocene reefs and their Recent counterparts from the same locality may be attributed to different water depths above the reef crest, diverging submarine topography around the reefs or to local erosion of the breaker zone of Pleistocene reefs.

Based on these observations it can be stated that the local and regional variation of reef types during late Pleistocene high sea level stands corresponded basically to the Recent pattern thus giving evidence for a basically similar distribution of waves (and consequently of wind force and direction) in the Caribbean area as that observed today.

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EXPLANATION OF THE PLATES 50—53

Plate 50

Late Pleistocene "Melobesieae reef" on the east coast of Barbuda Island, Lesser Antilles

a. Panorama of the east coast of Barbuda viewed to the SE from the top of the high cliff in the "Highland Limestone". The low-lying reef terrace in the centre of the picture was formed during a late Pleistocene transgression that ended at the cliff. Large blocks of the "Highland Limestone" have fallen on the terrace deposits which consist of coral rocks of the late Pleistocene "Codrington Limestone". The terrace deposits in this area are exclusively built by a fringing reef whose reef crest, (situated near the present shore line) is capped with a fossil algal ridge ("Melobesieae breaker zone").
   Further to the left white breaking waves in the sea indicate the position of the Recent fringing reef, also of the "Melobesieae reef" type.
b. View of the late Pleistocene reef near the shore line. The irregular eroded Pleistocene rocks in the foreground represent the *Acropora palmata* thicket on which the algal ridge has grown. The latter has partly been eroded in the foreground but still can be seen as the smoother rock and blocks (with bag and hammer) in the middleground and in the center left of the picture. Storm beach and Highland cliff seen in the background. View to the N. Coast near "Castle Hill House".

Plate 51

Late Pleistocene "Melobesieae reef" on the east coast of Barbuda Island, Lesser Antilles

a. Erosional surface of the late Pleistocene algal ridge ("Melobesieae breaker zone"). The algal rock reaches more than 1 m in thickness at this location, but already is partly eroded. The low-lying rock surface to the left corresponds to the approximate top of the *Acropora palmata* thickets that form the substratum on which the algal ridge was built. Coast of the "Castle Hill House" area, view towards SE.
b. The rock of the Pleistocene "Melobesieae breaker zone" is quarried by storm waves along the fissures, and blocks are washed onto the storm beach in the background, where they mingle with algal blocks torn off from the Recent algal ridge. Hammer (32 m) for scale in centre right. Coast of the "Castle Hill House" area, view towards S.

Plate 52

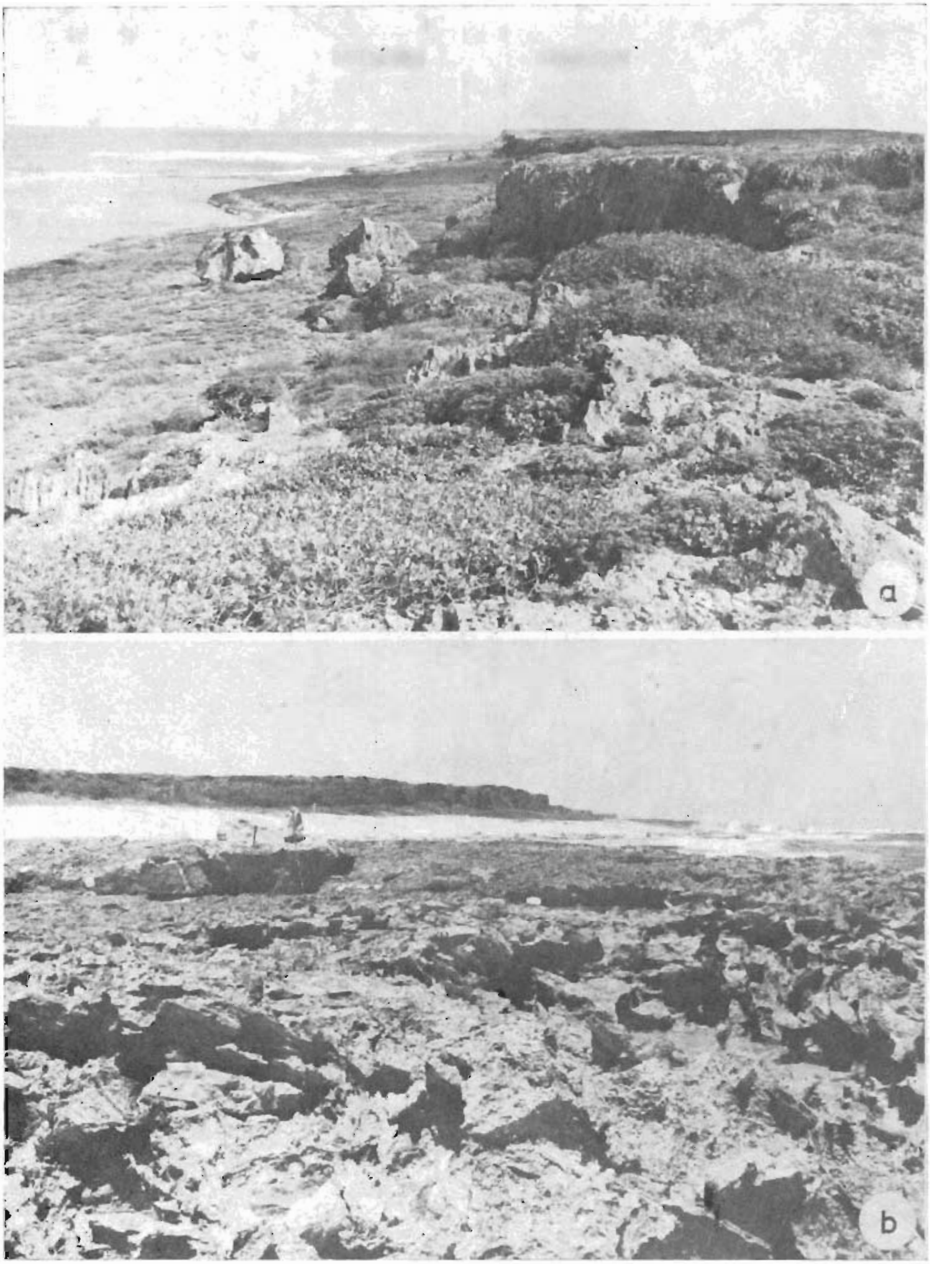
Lowermost Pleistocene reef terrace on east coast of Caucedo Peninsula, Dominican Republic

a. Outcrop in "front *cervicornis* wave zone". Note almost exclusive occurrence of *Acropora cervicornis*.
   Hammer (32 cm) in center of picture for scale.
b. Outcrop in "*strigosa-palmata* breaker zone". Reef framework formed exclusively by *Acropora palmata*. Hammer (32 cm) in center of picture for scale.

Plate 53

Late Pleistocene "*porites* reef" on the south coast of Providencia Island, western Caribbean

a. View of the flat of the fossil reef exhibiting almost monospecific stands of *Porites porites* ("porites breaker zone").
   To the left, some smaller hemispherical colonies of *Siderastrea radians* may be recognized. Hammer (32 cm) for scale.
b. Group of *Montastrea annularis* colonies forming part of the incoherent "rear *annularis* wave zone" of the reef. A volcanic block from the old cliff is embedded in the Pleistocene matrix (right foreground). Hammer (32 cm) for scale.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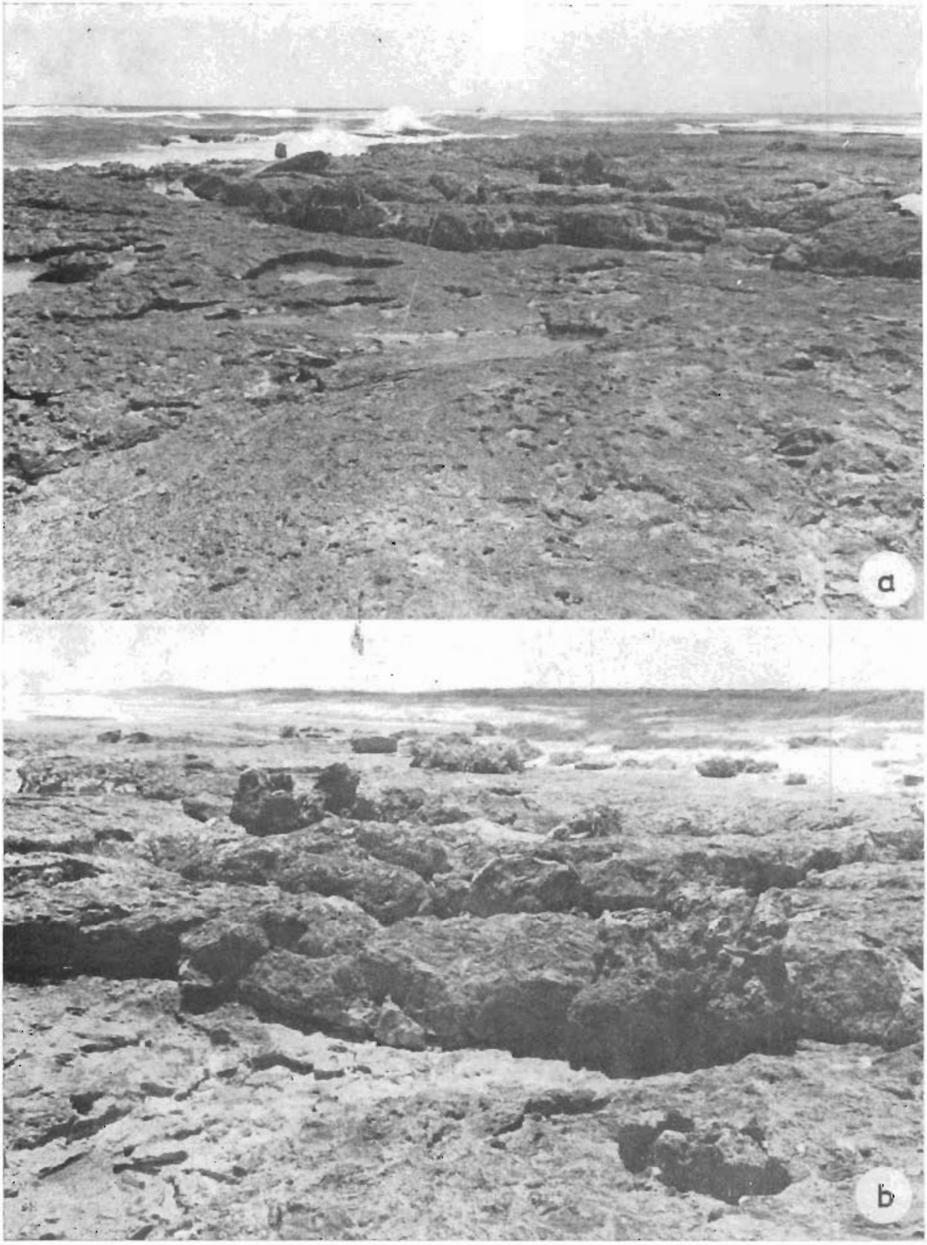
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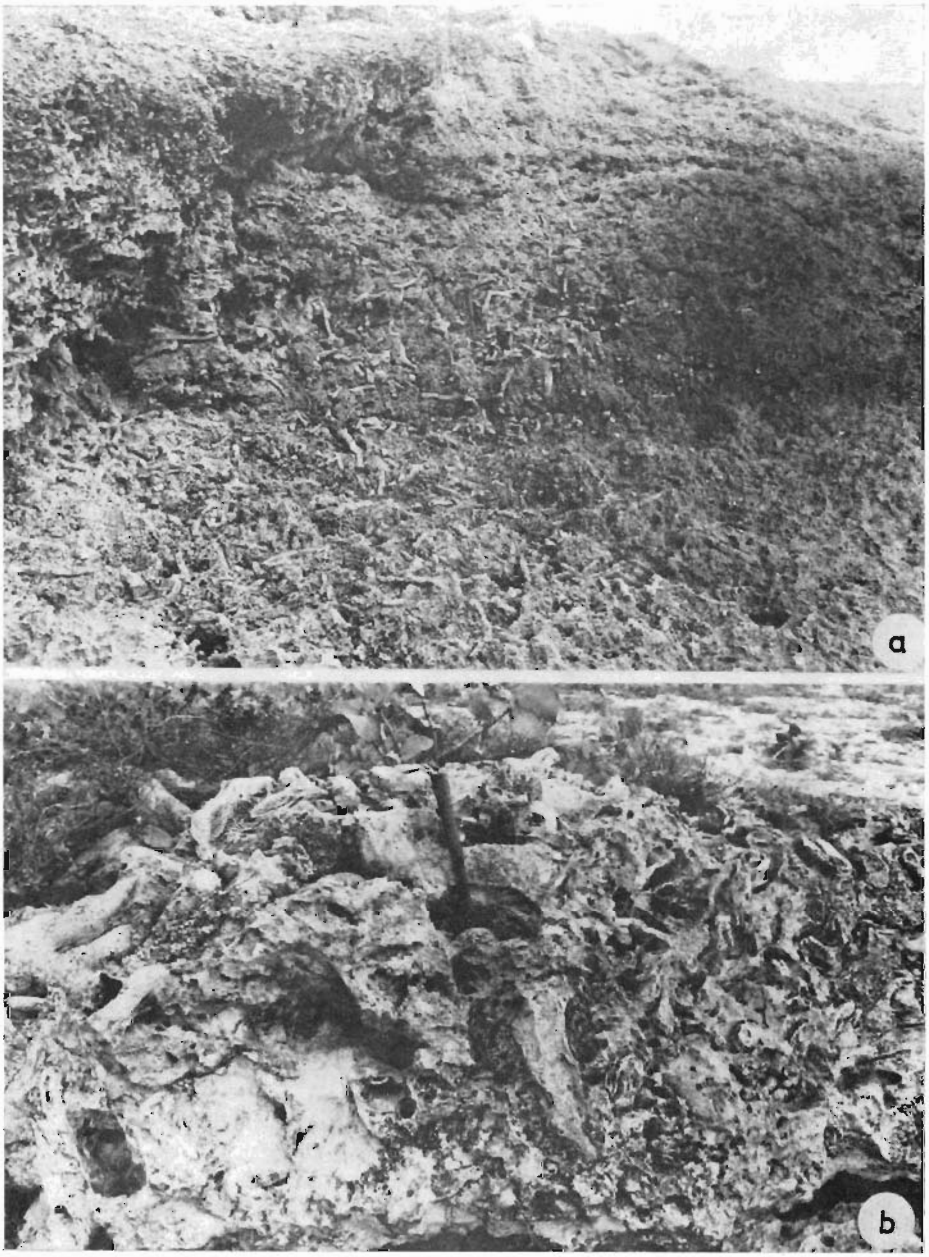
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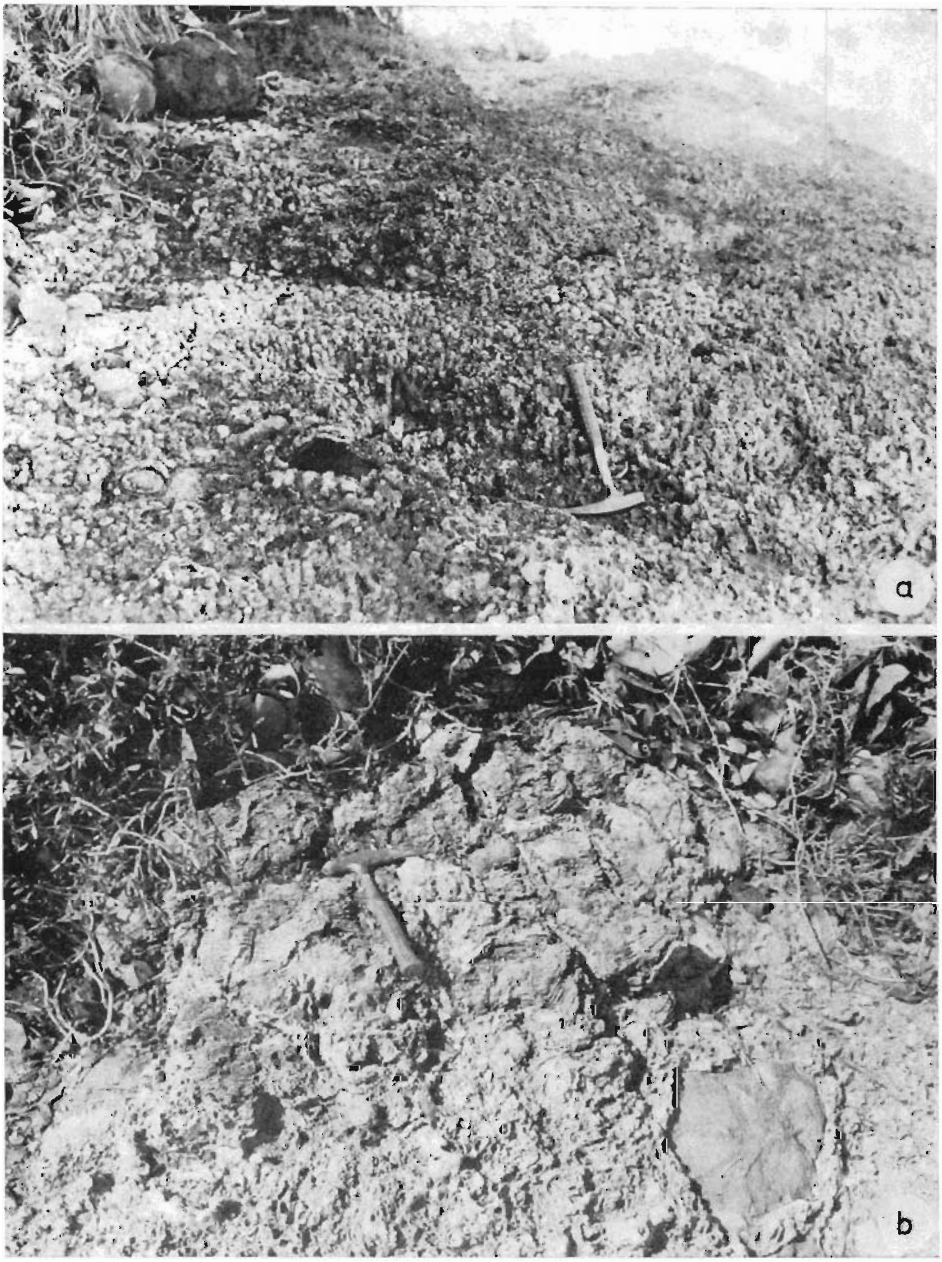
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