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LIMESTONE CLIFF MORPHOLOGY AND ORGANISM DISTRIBUTION ON CURAÇAO (NETHERLANDS ANTILLES)

BY

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ABSTRACT

So long as the lithologic nature of the cliff and the physico-chemical nature of the sea water remain similar, variation of cliff morphology is largely a function of water turbulence (degree of exposure). Different cliff profiles (without, or with one or two notches; without or with surf platforms) are all part of a continuous range of variation.

INTRODUCTION

The islands of the Netherlands Leeward Antilles: Aruba, Bonaire and Curaçao, are situated in the southern Caribbean Sea, off the Venezuelan mainland (Fig. 1). Persistent strong easterly tradewinds prevail in the area, while at the windward side the coastal shelf is narrow (less than 200 m), without significant reefs or other barriers. These windward parts, i.e. the greater part of the northeast coast, and some parts of the southwest coast of Curaçao (Fig. 2), are therefore very exposed, while other coastal areas are relatively sheltered. The tides (de Haan & Zaneveld, 1959) exhibit a periodic change from diurnal to semidiurnal oscillations with a period of 13.7 days. Daily tidal range varies from 7 to 53 cm with an average of about 30 cm. There is also a seasonal variation of some 20 cm with lower tides around april, and higher tides around september. The islands consist roughly of a core of pre-Tertiary sedimentary and igneous rocks (Beets, 1972), surrounded by Neogene and Quaternary limestone fringes (de Buisonjé, 1974). The coastal region consists mainly of Pleistocene limestone terraces (de Buisonjé, 1974). The youngest and lowermost of these terraces generally has an elevation of 10 meters and forms the greater part of the shoreline of the islands (de Buisonjé & Zonneveld, 1960). The morphology of the cliffs which have been eroded into this limestone has been studied by Martin (1888), Wagenaar Hummelinck (1940), de Buisonjé & Zonneveld (1960), van den Hoek (1969) and Focke (1977a, 1978a).

DESCRIPTION OF THE PROFILES

Four main profile types are discussed: sheltered, leeward, lateral and windward; most of the cliff profiles found on Curaçao belong to one of these types. As will be discussed below, it is clear that these profiles are only examples from a continuous range of variation, depending largely upon degree of exposure. Still most of the cliffs fall within narrowly defined profile categories because the environmental parameters vary abruptly along the coast, and not gradually. The windward coast of Curaçao for example maintains the same orientation towards wind and surf over long distances, and then changes very abruptly into shorelines with almost perpendicular orientation. Consequently the cliff profile changes abruptly (from windward to lateral profile), without showing intermediate forms. Nevertheless, as will be shown, such intermediate forms can be found.

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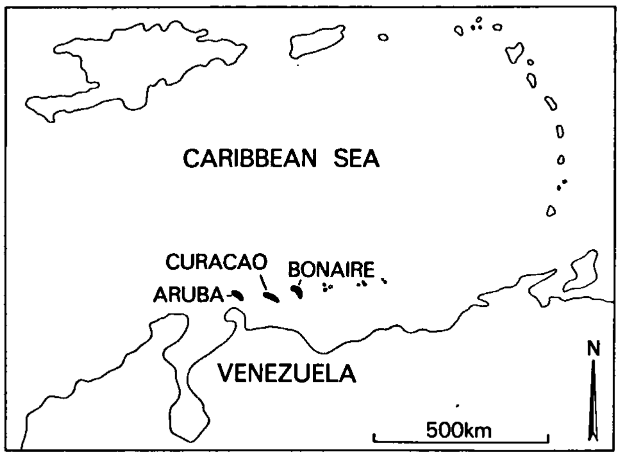

Fig. 1. Indexmap of the Netherlands Leeward Antilles.

The sheltered profile

The profile characteristic for very sheltered limestone cliffs (Fig. 3) is only rarely found on Curaçao; the ever blowing tradewinds produce significant turbulence even at the leeward side of the island. Locally, cliffs in the inner bays and lagoons show profiles of this type. Well-developed examples have been described from Bermuda by Neumann (1966). The cliff is undercut beneath mean sea level (Fig. 3), the roof of the undercut part may be emergent at low tides. If undercutting proceeds too far, the cliff collapses; blocks of limestone are common in front of the cliff. Neumann (1966) reports a maximum depth of undercutting of 4.6

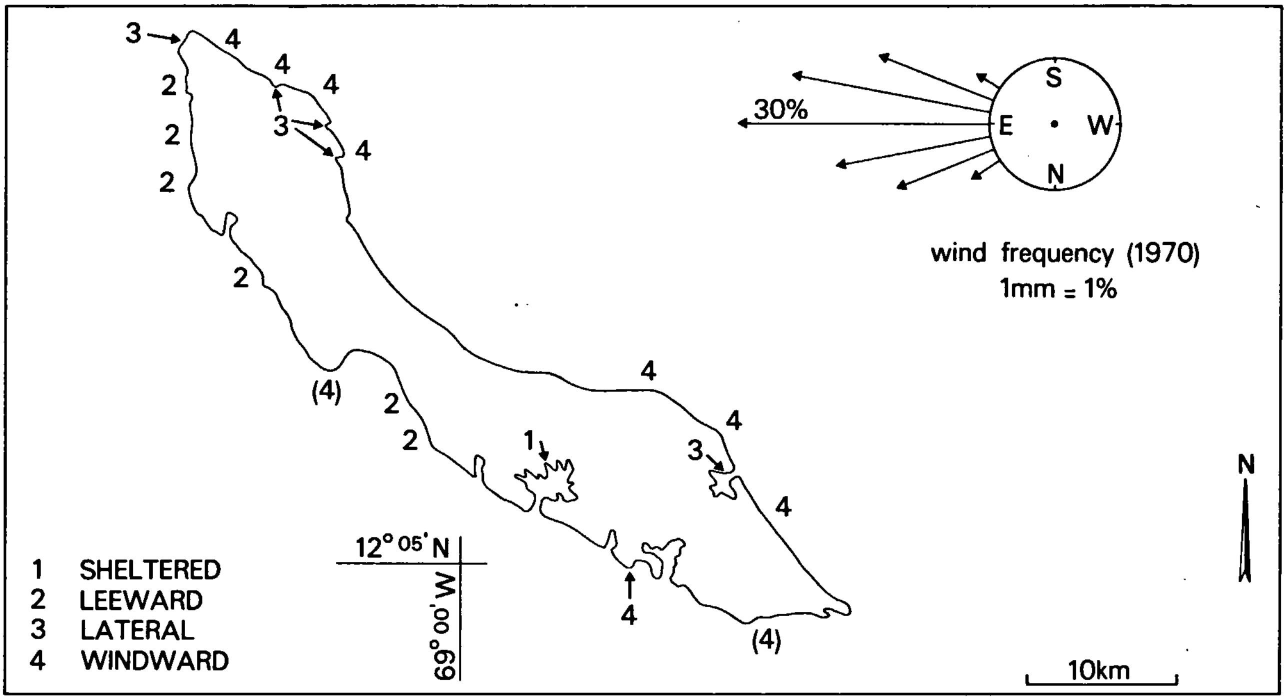

Fig. 2. Map of Curaçao, showing locations of well-developed cliff profiles; wind data supplied by the Dept. of Social and Economic Affairs of the Neth. Antilles.

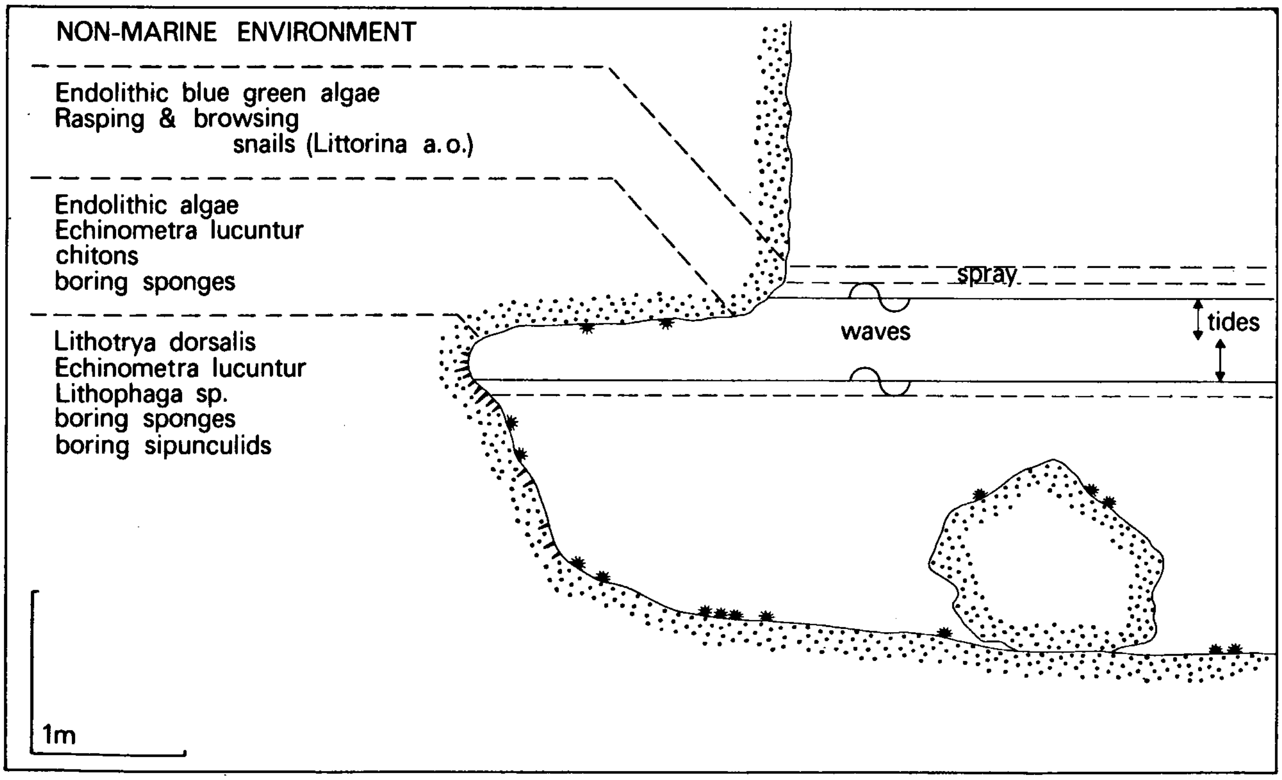

Fig. 3. The sheltered profile with spray zone, tidal levels and surf zone, and the distribution of major bio-eroders (cf. Neumann, 1966).

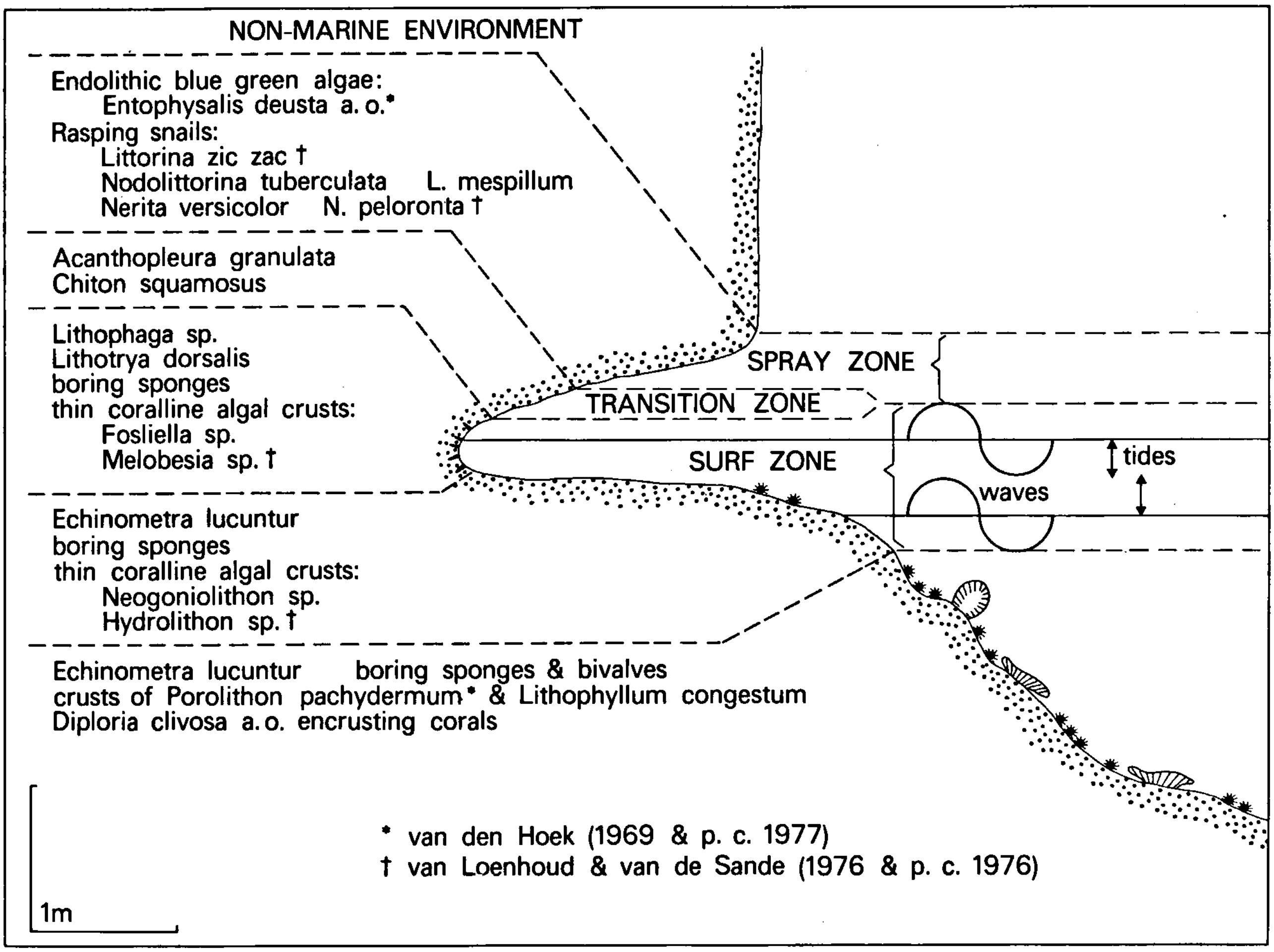

Fig. 4. The leeward profile; note that the notch is well defined as compared with the sheltered profile.

meter. He defined this type of subtidal undercutting as a notch, to distinguish it from nips which are defined as intertidal features. This distinction is not followed here. The position of the indentation relative to sea level is gradually raised with increasing degree of exposure (Focke, 1977b), and 'tidal nips' are never truly intertidal. Zoning of organisms, as far as bio-eroders are concerned, is not very well developed. The lower edge of the cliff, where the steep cliff face grades into the roof of the notch (Fig. 3), is characterized by endolithic bluegreen algae and rasping snails; the lower parts of the notch show a mixed occurrence of boring organisms (barnacles, bivalves, sponges, worms, echinoids, etc.). For details reference is made to Neumann (1966).

The leeward profile

The profile which is characteristic for the greater part of the leeward side of Curaçao consists basically of a vertical cliff wall with a well-developed notch ('nip') at mean sea level (Figs. 4, 5, 6). The depth of penetration varies from almost nothing to more than 2 meters, the height from a few decimeters to more than a meter. The cliff face is outside the marine environment. The roof of the notch is within the marine environment although it is situated above even the highest high-tide level (Fig. 4); it is kept wet by sea water spray produced by the waves, breaking inside the notch. Larger waves sometimes explode in the notch, when quantities of air are trapped and compressed in the back of the notch. The roof of the notch is infested with endolithic bluegreen algae, while large numbers of snails, notably *Littorina, Nodolittorina* and *Nerita,* are rasping and browsing on this limestone. In the back of the notch is a transition zone between the area dominated by spray water and the area dominated by surf water (Fig. 4). This transition zone is characterized by the abundance of chitons, notably *Chiton squamosus* and *Acanthopleura granulata.* Locally the gastropod *Purpura patula* may be abundant. Below the transition zone but still in the back of the notch (Fig. 4) is a zone with large numbers of the boring barnacle *Lithotrya dorsalis*: occurrences of up to 500 boreholes per square meter are common. The limestone between the boreholes, which may be 10 cm deep, is often coloured pink by several species of coralline algae (van den Hoek, 1969). The bottom of the notch, and the edge where the notch grades into the

Fig. 5. Notch of a 'leeward' profile, èxample from the Pleistocene of the windward side of Curaçao, and indicating that water turbulence was at that time significantly lower than at present, probably as a result of the presence of a barrier reef in front of the cliff.

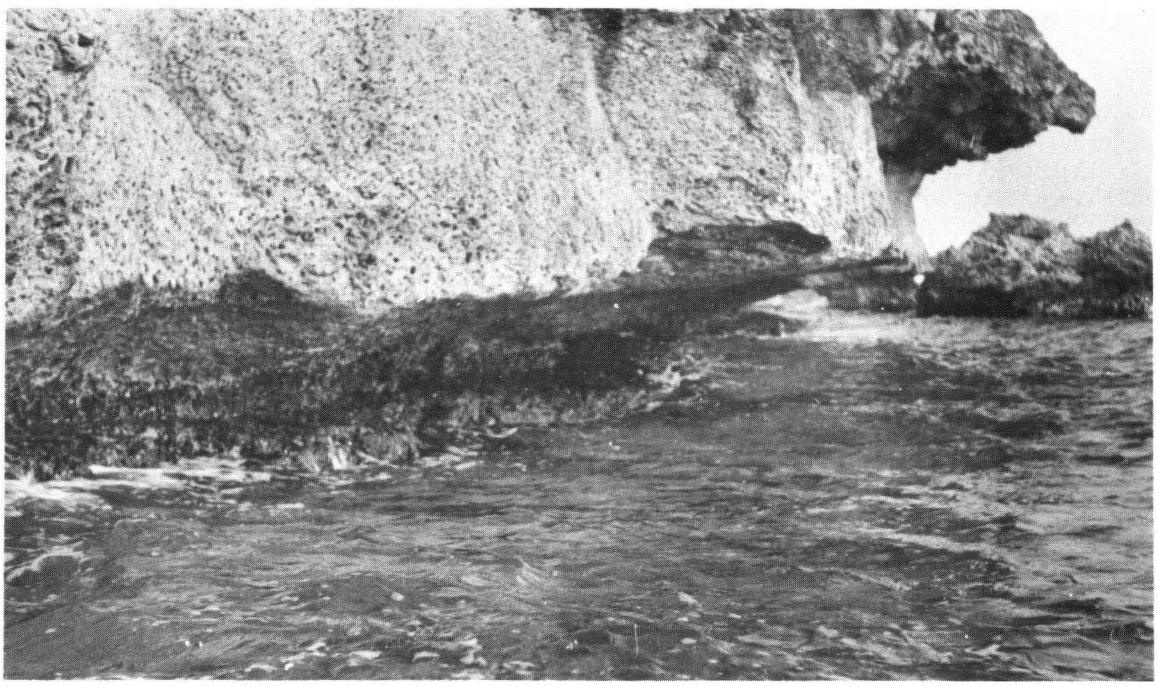

Fig. 6. Leeward notch, Piscadera, Curaçao.

Fig. 7. Collapsed cliffs near Playa Kalki, Curaçao.

lower part of the cliff and the sea bottom, are actively bored by clinoid sponges and the echinoid *Echinometra lucuntur*. Encrusters are common, particularly coralline algae on the bottom of the notch, and corals such as *Diploria clivosa* on the lower part of the cliff, below the notch.

The undermining of the cliff by the notch eventually results in collapse (Fig. 7). Initial stages of notch development can be observed in the newly formed cliff as well as around the blocks fallen into the sea. Large stretches of coastline however are free of collapsed blocks.

The degree of exposure varies with the orientation of the coastline. Cliffs which are somewhat more sheltered than the standard leeward cliff represented in Figure 4 show notches which are less well developed and significantly

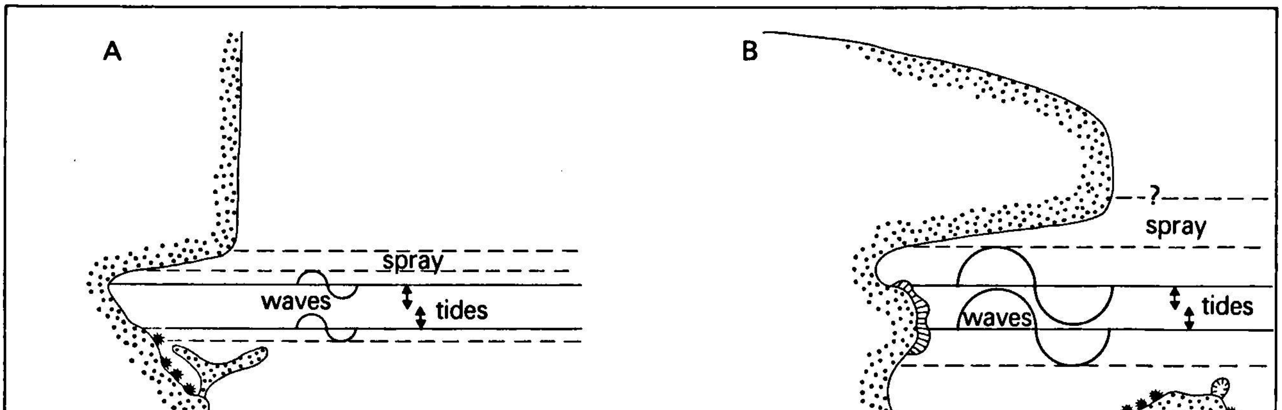

Fig. 8. A: Cliff profile, intermediate between the sheltered and the leeward profile (Westpuntbaai, Curaçao); B: cliff profile, intermediate between the leeward and the lateral profile (Malmok, Aruba).

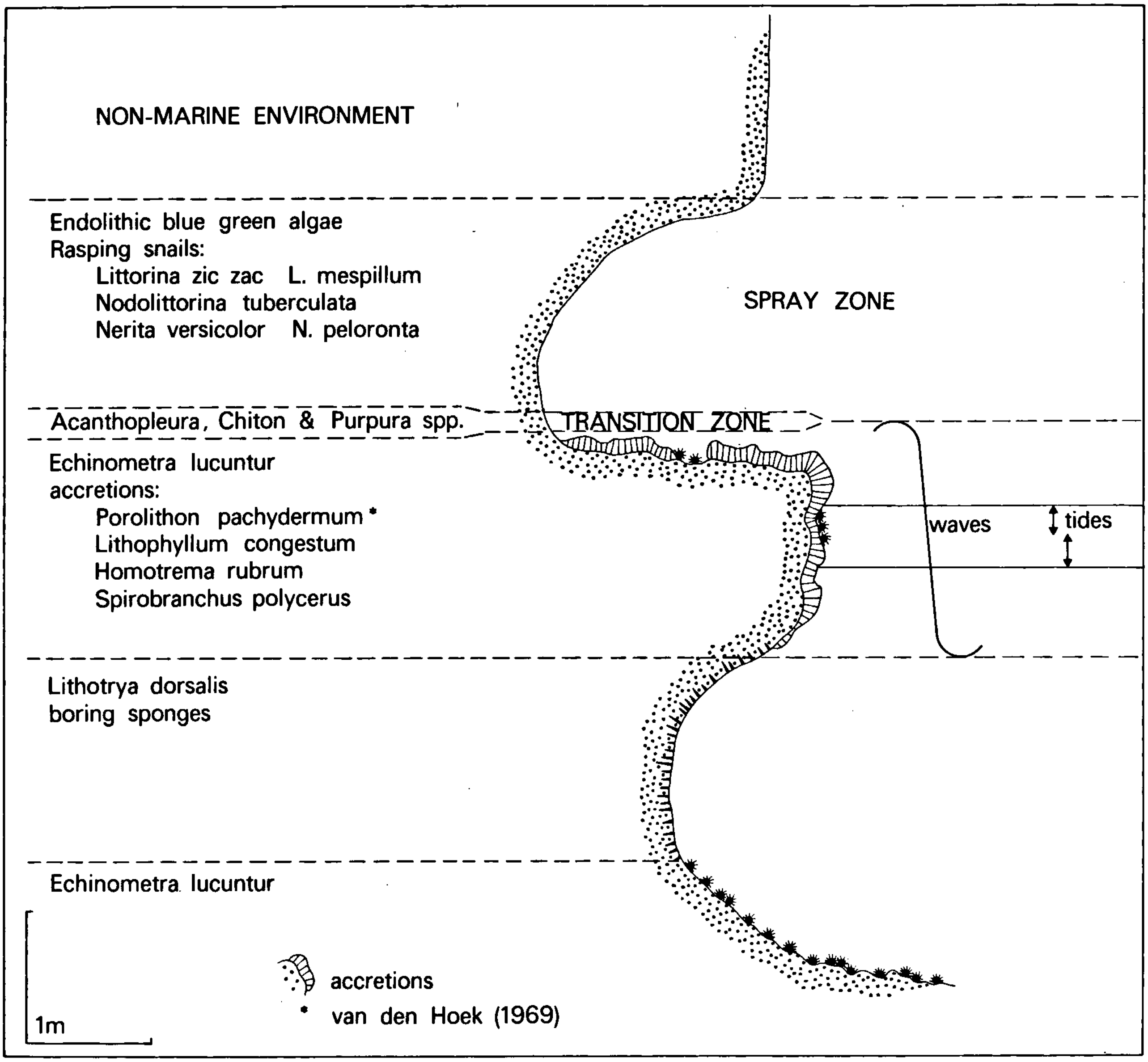

Fig. 9. The lateral profile; note the presence of two well-developed notches and the surf bench.

lower relative to sea level, and which more or less resemble the previously described sheltered profile (Fig. 3). Such profiles, clearly intermediate between the sheltered and the leeward profile, occur for example near the western tip of Curaçao (Fig. 8A). On the other hand, cliffs which are somewhat more exposed than the standard leeward cliff show a tendency to form a small bench within the notch (Fig. 8B). The bench is covered with organic accretions but is always underlain by Pleistocene country rock. The accretions are primarily built by the coralline alga *Lithophyllum congestum*, which forms a very porous framework up to 20 cm thick. Corals (*Porites astreoides*), foraminifera (*Homotrema rubrum*), vermetid gastropoda (*Spiroglyphus irregularis*), and serpulid worms (*Spirobranchus polycerus*) may all add significantly to the framework. The void space of the accretions is riddled with other sessile or free-living organisms such as branched coralline algae, bryozoa, worms, brittle stars and small crabs. The bench always occurs within the surf zone (Fig. 8B).

The lateral profile

Lateral profiles (Fig. 9) are characteristic for cliffs which are exposed to severe surf action, but where the spray which is generated by this surf is not reaching the upper part of the cliff. On Curaçao this situation occurs for example at the sides (hence the name) of the coastal inlets ('bocas') at the windward side of the island where the surf is extreme with wave heights of up to several meters, but where the orientation of the shoreline is more or less parallel to the direction of the wind. As a result the spray is blown sideways instead of onto the cliff. On cliffs perpendicular to the direction of the wind, where the spray is blown inland, the 'lateral' profile may occur if the cliff is too high and the wind too weak to bring the top of the cliff within reach of the spray.

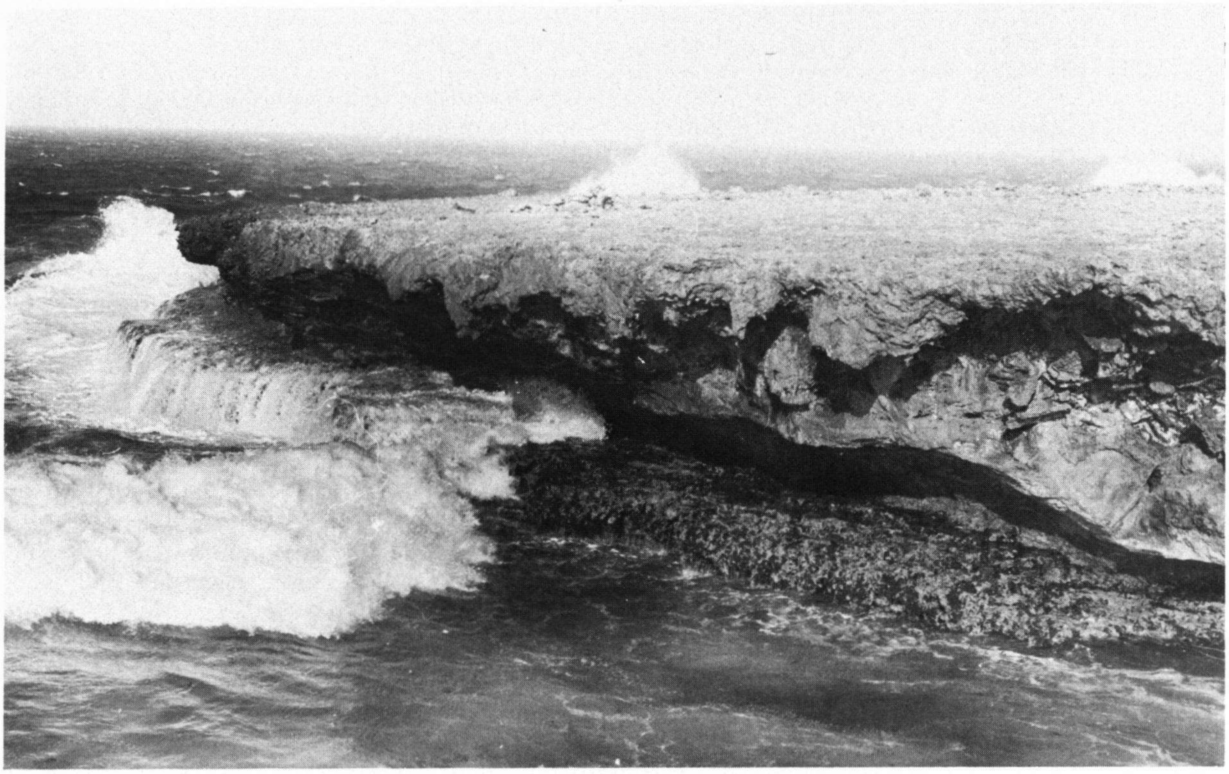

Fig. 10. The lateral cliff of Boca Sjon Meester (E of Boca Tabla), showing the upper notch and the surf bench; note the reach of the waves on the surf bench.

Fig. 11. The surf bench and the upper notch of the lateral cliff; note the wetting of the notch roof by splash water; also note the step-like lowering at the corner of the Boca (arrow).

The profile (Fig. 9) is characterized by the presence of two notches, separated by a bench. The upper part of the cliff is – as said – outside the marine environment. The roof of the upper notch is kept wet by spray water (Figs. 10, 11) just as the roof of the single notch of the leeward profile, and is eroded by the same organisms (endolithic algae and rasping snails). The back of the upper notch, kept wet either by spray or by surf water and designated as transition zone, again displays chitons in large numbers. It is important to note that the entire upper notch is above highest high-tide level, and consequently is not 'intertidal' in any way. The bottom of the upper notch is simultaneously the upper surface of the bench, and is always within reach of the surf (Fig. 10). The surface and the edge of the bench (the surf platform) are covered by organic accretions similar to those described for the relatively exposed leeward profile (Fig. 8B), except that the coralline alga *Porolithon pachydermum* is now, together with *Lithophyllum congestum,* the most important framebuilder. The bench has an irregular character with areas of virtually undamaged accretions, and areas which are heavily bored by *E. lucunter* and *L. dorsalis.* The accretions are lithified, an aspect which will be dealt with in detail in the next chapter. The thickness of the accretions does not exceed a few decimenters, and Pleistocene country rock is always found underneath them. The surf platform of the lateral cliff is continuous with the bench of the windward cliff (Fig. 12), but the lateral bench is considerably lower relative to sea level than its windward counterpart. Inside an inlet, going inshore, the lateral surf bench is gradually lowered with decreasing wave action. Superimposed upon this gradual lowering there is often an abrupt lowering (steplike) at the corner of the inlet (Fig. 11). This abrupt lowering coincides with a community change in the accretions, and indicates the locations where vermetid gastropods, dominant framebuilders on the windward surf bench, disappear.

The roof and the back of the lower notch (Fig. 9) are characterized by abundant boreholes of *L. dorsalis* and clionid sponges, the lower part and the adjacent sea bottom by the boreholes of *E. lucuntur.*

The windward profile

The cliffs along the greater part of the northwest and northeast coast, as well as a few cliffs on promontories along the ('leeward') southwest coast are subjected to the full force of the tradewinds and very strong surf action. The tradewinds blow straight inland, and as a result the spray water is blown directly onto the higher parts of the cliff (Fig. 13), and the vertical wall (the overhang), which on the other cliffs was outside the marine environment, is fully within the marine spray water zone on the windward cliff.

The following morphological units are distinguished (Fig. 13), mainly after de Buisonjé & Zonneveld (1960): a rampart or rubble ridge on top of the Pleistocene terrace

Fig. 12. The corner of the inlet Boca Cortalein, showing the continuity of the windward and the lateral surf platform, and the abrupt transition of windward spray zone (1) into lateral upper notch (2).

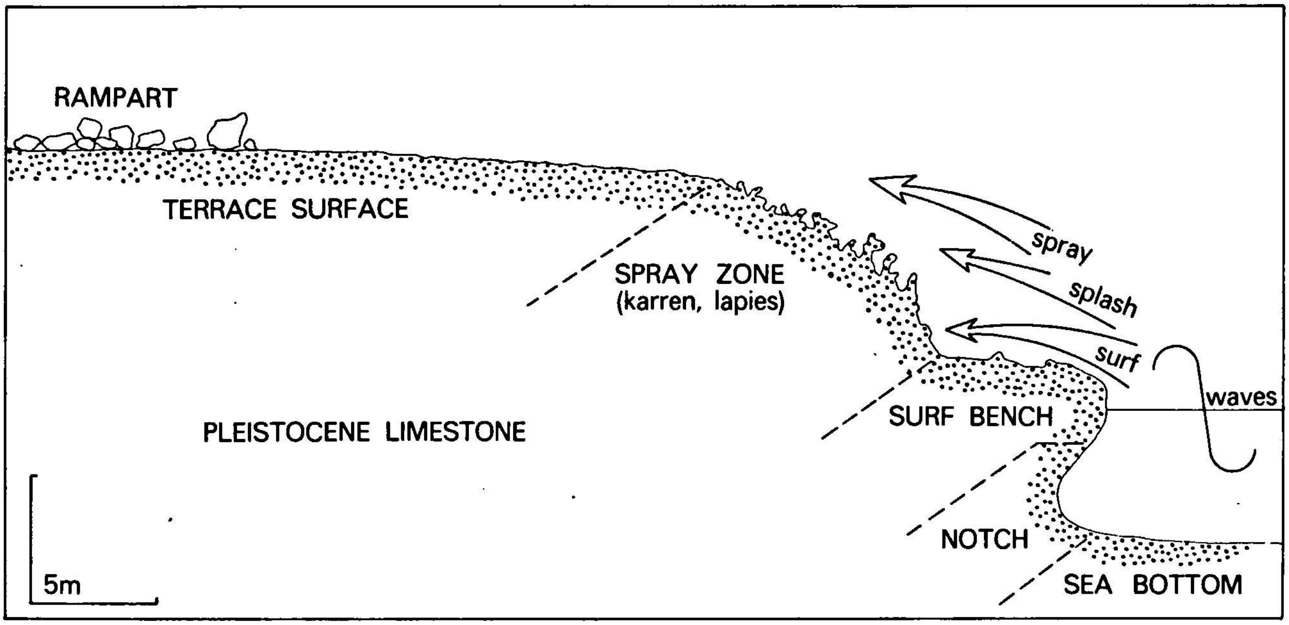

Fig. 13. The morphological units of the windward cliff; see Fig. 16.

several tens of meters from the shore; a spray zone, also called karren zone or zone of lapies; a surf bench or surf platform, locally known as sawa zone; a notch underneath this bench; and eventually the sea bottom in front of the cliff. The rampart is a linear pile of coral rubble and large boulders, separated from the cliff proper by a barren zone, 20 to 60 m wide (Fig. 14). The majority of the material consists of fragments of the coral *Acropora palmata*. There is no living *A. palmata* reef present in front of the cliff (except near the eastern tip of the island; Bak, 1975), and the only available source area for the boulders seems to be the present cliff, which is being eroded into a fossil barrier

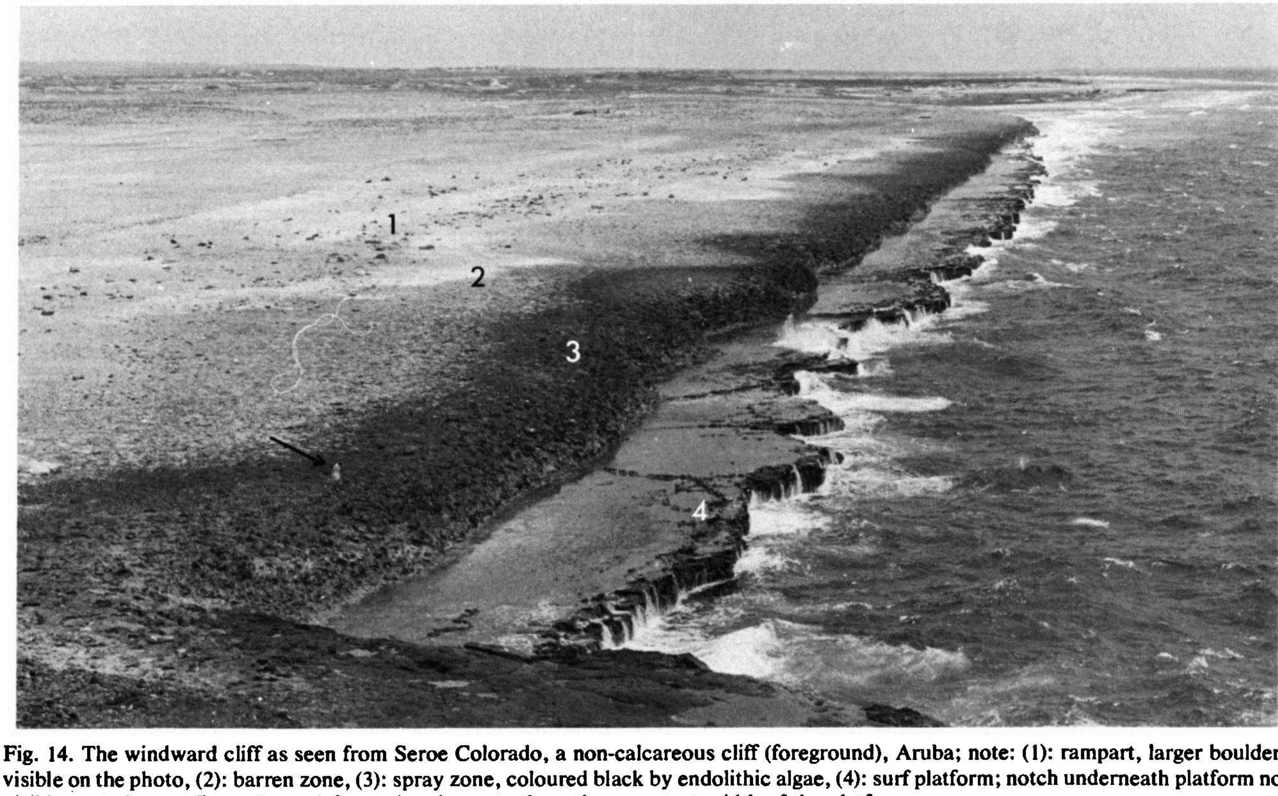

Fig. 14. The windward cliff as seen from Seroe Colorado, a non-calcareous cliff (foreground), Aruba; note: (1): rampart, larger boulders visible on the photo, (2): barren zone, (3): spray zone, coloured black by endolithic algae, (4): surf platform; notch underneath platform not visible; note human figure (arrow) for scale; also note the rather constant width of the platform.

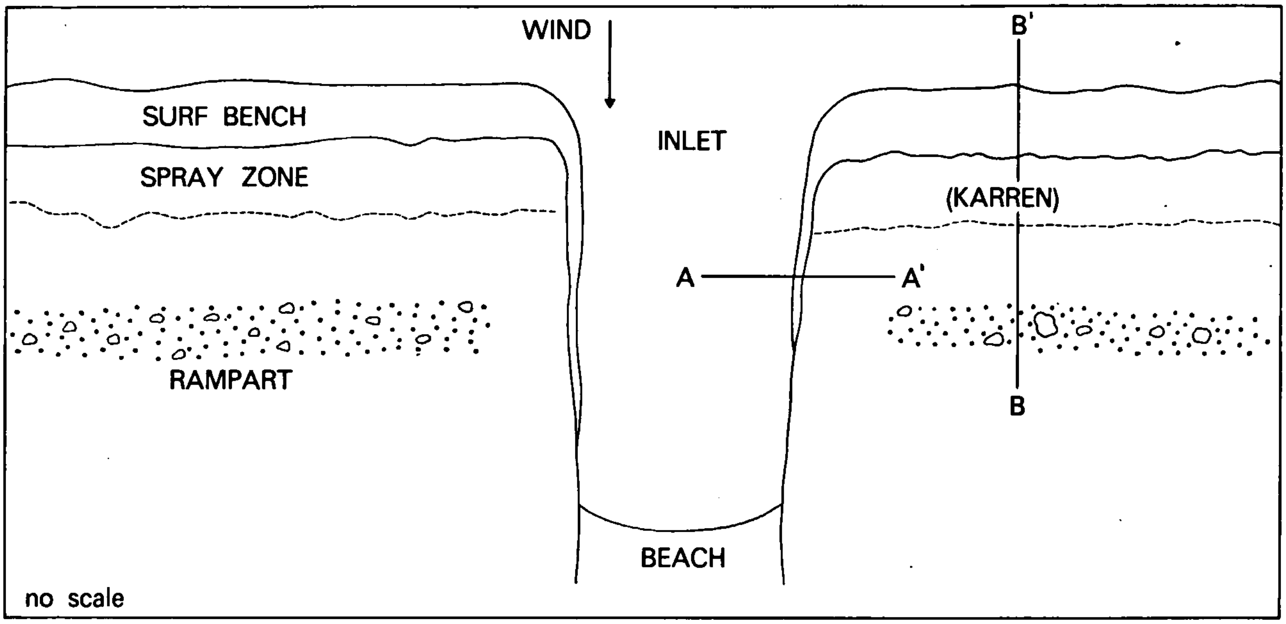

Fig. 15. The geographical relation of the windward and the lateral cliffs; AA'=lateral profile, BB'=windward profile; note that the rampart ends before reaching the inlet.

reef, made up predominantly of *A. palmata* colonies (de Buisonjé, 1974). This seems to be in support of the theory (de Buisonjé & Zonneveld, 1960) that the boulders have been thrown upon the cliff during storms or hurricanes. The distribution of the rubble also indicates such an origin. Contrary to a drawing by de Buisonjé & Zonneveld (1960, fig. 2), the rampart is not continuous up to the inlet, but ends a considerable distance from the inlet (Fig. 15), suggesting

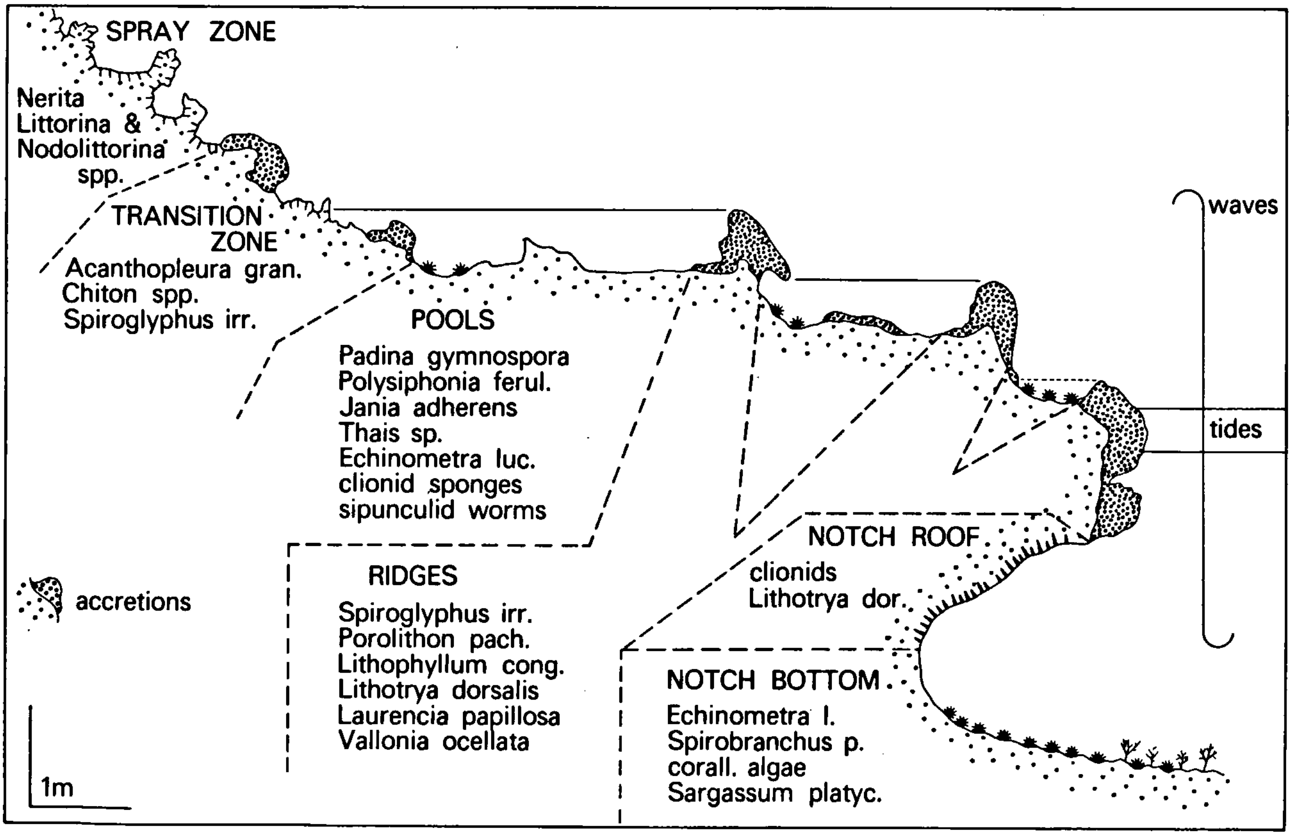

Fig. 16. The windward profile.

the effect of energy dispersion by the inlet. Finally, the rubble consists of low-magnesian calcite, also suggesting a fossil, rather than a recent source.

The spray zone (Figs. 12, 14) is dark coloured, 15 to 20 m wide, and has a very rugged topography with pits and sharp ridges. The peripheral 200 to 500 microns of the limestone are penetrated by bluegreen algae, many of which are active borers. The distribution of the algae is influenced by the orientation towards sunlight (van den Hoek, 1969; Bonvie, 1974). The abundance of the algae is far greater than in the spray zones of the other cliffs. The activity of these algae has been studied in detail by Golubic (1969, 1972), Golubic et al. (1975) and Schneider (1976). The gastropods *Littorina, Nodolittorina* and *Nerita* are grazing on the algae as in the spray zones of the other cliffs, again in greater abundance. Occurrences of several hundreds of snails per square meter are common. Within the spray zone the relation of increasing abundance with increasing spray water quantities is evident. The spray-zone morphology resembles that of the black phytokarst described from fresh water environments by Folk et al. (1973).

With exceptions, the surf bench (Figs. 14, 16, 17) occurs along the entire windward coast of Curaçao as well as at a few relatively exposed locations of the leeward coast (Fig. 2). The dimensions of the bench are related to the degree of exposure; at the extremely exposed coast between Boca Grandi and Playa Grandi the bench is approximately 10 m wide and more than 1½ m above mean sea level; at less-exposed places these figures are lower. The general nature of the platform is remarkably horizontal (Fig. 14), notwithstanding the fact that the surface of the bench is terraced (Fig. 17). These terraces consist of shallow pools, surrounded by narrow ridges. The difference in elevation between adjacent terraces varies from a few centimeters to approximately 0.5 m; the depth of the pools varies from 10 to 30 cm. The upper level of an individual ridge forms an almost perfect horizontal plane (Fig. 19) which consequently forms the water level of the pool. The terraces form steplike sequences of successively lower pools (Fig. 17). At regular short time intervals the entire platform is violently flooded by the surf (Fig. 18), while in between these immersions the water flows back to sea from pool to pool, over the ridges. Many of the ridges originate at the lower end of the spray zone (Fig. 17). The ridges are constructional, and are situated upon a pre-existing topography of Pleistocene limestone (Fig. 16). They are built by a community, dominated by the vermetid gastropod *Spiroglyphus irregularis* and, on the lower parts of the platform, the coralline algae *Porolithon pachydermum* and *Lithophyllum congestum*. The ridges are covered with fleshy algae such as *Laurencia papillosa* and *Vallonia ocellata*, and are bored by *Lithotrya dorsalis*. Since they form barriers against the water flow on the platform, the ridges are the environment of the highest turbulence. The pools, although equally turbulent during the inundation of the platform are somewhat more quiet during periods of draining. On the other hand, during very rare periods of quiet weather the pools remain filled with sea water (unless the ridge is damaged), while the ridges dry out quickly. A two-week period of such dryness, however, observed in october 1976, was survived by most of the carbonate secreting organisms, while the communities of fleshy algae suffered only temporary damage. The pools are characterized by abundant *Echinometra* boreholes, thin coralline and vermetid crusts, and the fleshy algae *Padina gymnospora* and *Polysiphonia ferulacae* (for more details see van Loenhoud & van de Sande, 1977). Sometimes remnants of the karren zone lie as small isolated mountains of Pleistocene rock in the pools. For some reason they have not been used as a base for the establishment of accretions (ridges), and they are now heavily infested with boring sponges, worms, etc. The Pleistocene limestone underneath the thin crusts on the bottom of the pools is equally infested with borers. The seaward edge of the surf platform is – as its surface – covered by organic accretions. Here *Porolithon* is generally the most important framebuilder. Very large numbers of *Echinometra* and *Lithotrya* occur, actively boring through the accretions into the underlying Pleistocene rock. In some places the accretions are flourishing and undamaged, while in other places the effects of bio-erosion seem to predominate. In such places the edge is very irregular, and the country rock is often exposed. Many pool/ridge systems on the surface of the platform near the platform edge are also damaged. Weakened by boreholes the ridge collapses, the pool will be emptied, and the pattern of water flow is altered, further hampering the growth and maintenance of the remaining parts of the ridge. The entire pool system is then quickly

Fig. 17. Surf platform near Boca Wandomi shortly after immersion by the surf; the water is flowing back to sea; note the step-like arrangement of the pools, and the ridges originating at the lower end of the spray zone (upper right).

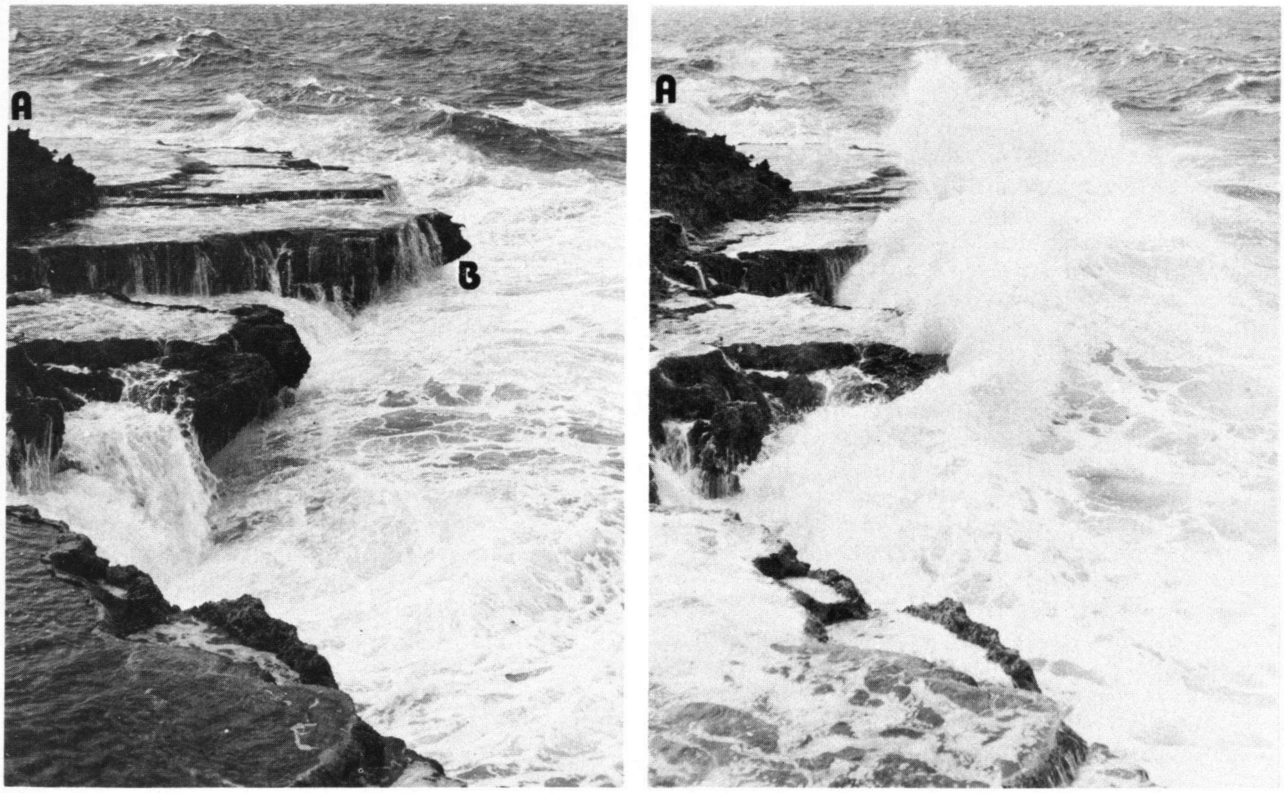

Fig. 18. Surf platform near Boca Wandomi between immersions (left) and (right) during immersion by the surf; A indicates spray zone (karren), B indicates notch (not visible); note the immense force of the waves (platform is ca. 7 m wide, and $1^1/_2$ m above mean sea level).

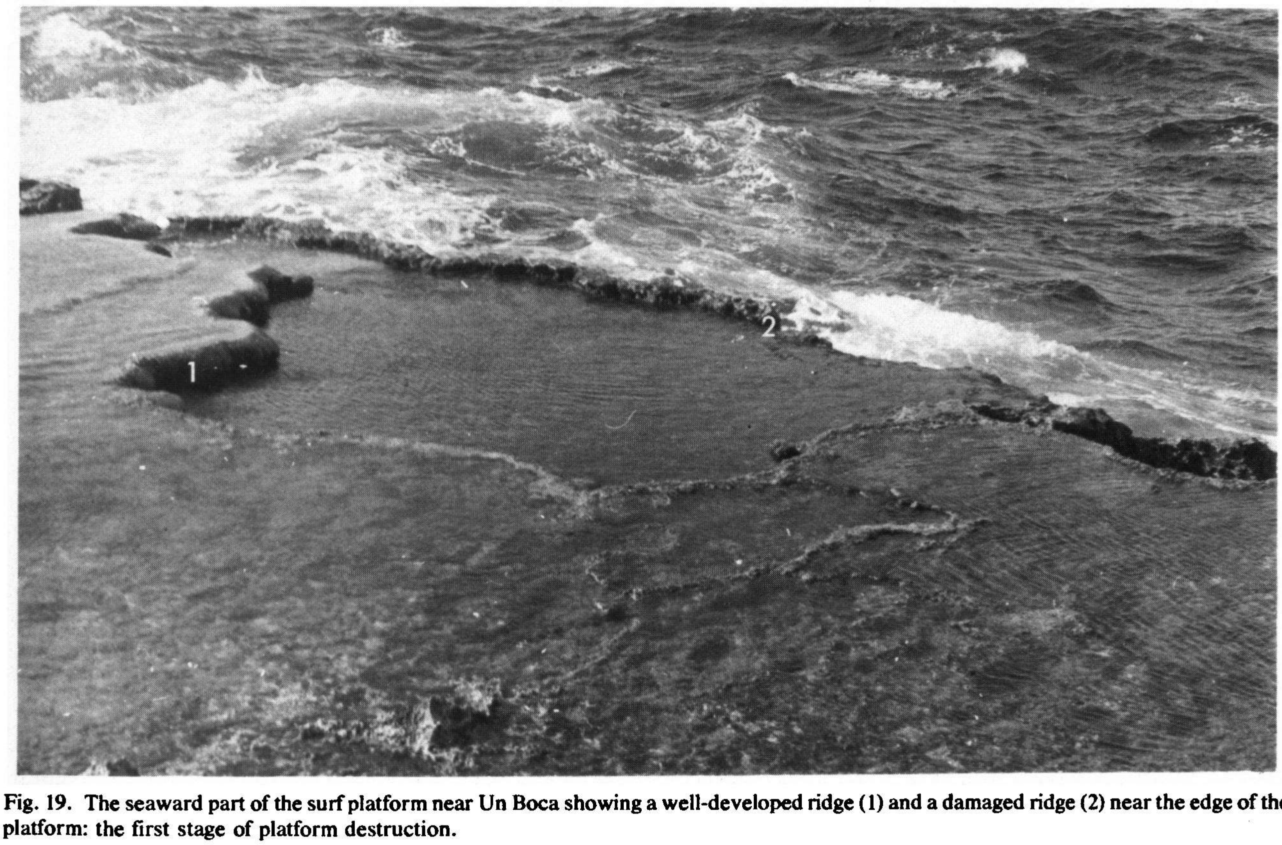

Fig. 19. The seaward part of the surf platform near Un Boca showing a well-developed ridge (1) and a damaged ridge (2) near the edge of the platform: the first stage of platform destruction.

Fig. 20. Ridges near the edge of the surf platform, showing advanced stages of breakdown; note that as a result of the damage the water level in the pool is lowered, diminishing the water flow over the remaining parts of the ridges and thus enhancing their destruction.

broken down, as evidenced by the many stages of progressive erosion found at the edge (Figs. 19, 20). On those localities which have been studied, a notch was always present underneath the surf platform (Figs. 16, 21), 1 to 2 m deep and 3 to 5 m high. The roof of the notch (Fig. 16) consists of country rock, covered with thin organic crusts and – at the same time – intensely bored by *Lithotrya* and clionid sponges. The bottom of the notch is bored by *Echinometra* on an equally large scale (Fig. 22). In between the *Echinometra* boreholes, which may be 10 to 15 cm deep, the country rock is covered with very porous accretions built by coralline algae, serpulid worms, and the sessile foraminifer *Homotrema rubrum*. The sea bottom in front of the notch is characterized by similar echinoid boreholes and porous accretions and, in addition to these, large numbers of the brown alga *Sargassum platycarpum* (van den Hoek, 1969). This algal pavement gently slopes down from approximately 5 m near the cliff to approximately 15 m, some 150 to 200 m offshore, where the bottom steeply drops off to another submarine terrace (Focke, 1978b). Boulders and other sediments in the notch and on the sea bottom, as suggested by van den Hoek (1969, fig. 3A), have not been observed except on one locality immediately west of Un

Fig. 21. The notch underneath the surf platform; dark spots are *Echinometra* boreholes, light grey patches are areas of organic crusts; the pavement on the right side of the notch is covered by *Sargassum*; note the complete absence of signs of abrasion.

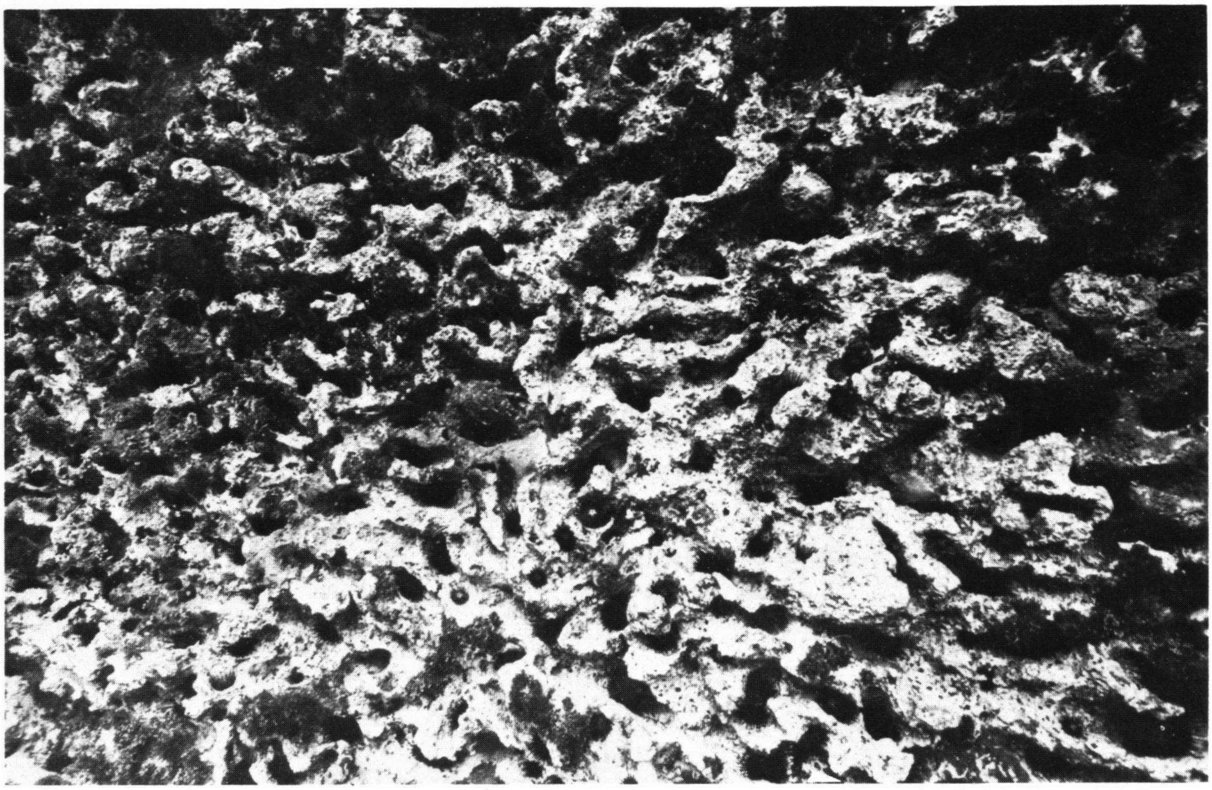

Fig. 22. Detail of the surface of the windward notch; white areas show accretions (living crusts), dark areas are *Echinometra* boreholes.

Boca, where this sediment occurred in shallow grooves, a few meters wide, 1 or 2 m deep and several tens of meters long, perpendicular to the shore (Fig. 23). The bottom of the grooves was very smooth, with a polished bluish-grey nature, quite different from the surface of the spurs which showed the mixture of boreholes and living crusts so characteristic for the bottom of the notch and the greater part of the sea bottom (Fig. 22). Evidence of mechanical abrasion such as is obviously taking place on the bottom of the grooves has not been found anywhere else on the windward coast of Curaçao. The boulders were very well rounded, similar to those found on the beach of the nearby inlet (Un Boca), and are obviously derived from the interior parts of the island.

THE ACCRETIONS OF THE WINDWARD CLIFF

As indicated above, accretions are important on and below the surf platform. High on the surface of the surf platform the vermetid *Spiroglyphus irregularis* is the most important framebuilder (Fig. 24). Going down, the contribution of the vermetids gradually decreases, while *Porolithon* takes over as primary framebuilder (Fig. 25). On the lowest parts of the platform edge the vermetids are virtually absent. On those parts of the edge which are slightly more protected against the full impact of the waves (the morphology of the edge is very irregular), the knobby coralline alga *Lithophyllum congestum* may predominate. The framebuilders create a wide variety of porespace, both inside and in between their skeletons. The intraskeletal pores become open to circulating sea water after decay of the organisms, while interskeletal pores are usually open from the beginning. A variety of coelobites (cavity dwellers, see Ginsburg & Schroeder, 1973) lives in these pores. The encrusting foraminifer *Homotrema* is the most conspicuous coelobite and may be very important by volume (Fig. 26). To a lesser extent, other organisms contribute to filling the pores, either directly or as producers of (internal) sediment. Free-living coelobites are equally abundant, particularly porcellanoid crabs. Very small pores, or pores with only small apertures, are filled with silt or mud, while coarser sediment is deposited in larger and better permeable pores. Often distinct generations of internal sediment can be distinguished; younger generations are generally finer grained and less well cemented as compared to older generations. The general trend of fining upwards probably represents the decrease in permeability in the structure as more and more pores (and apertures) are filled by coelobites, internal sediment and cement. Fragments of coralline algae and foraminifera make up the majority of recognizable particles of the internal sediment, with smaller amounts of mollusc and echinoid fragments. Fragments of corals and calcareous green algae are notably absent. Most of the sediment must

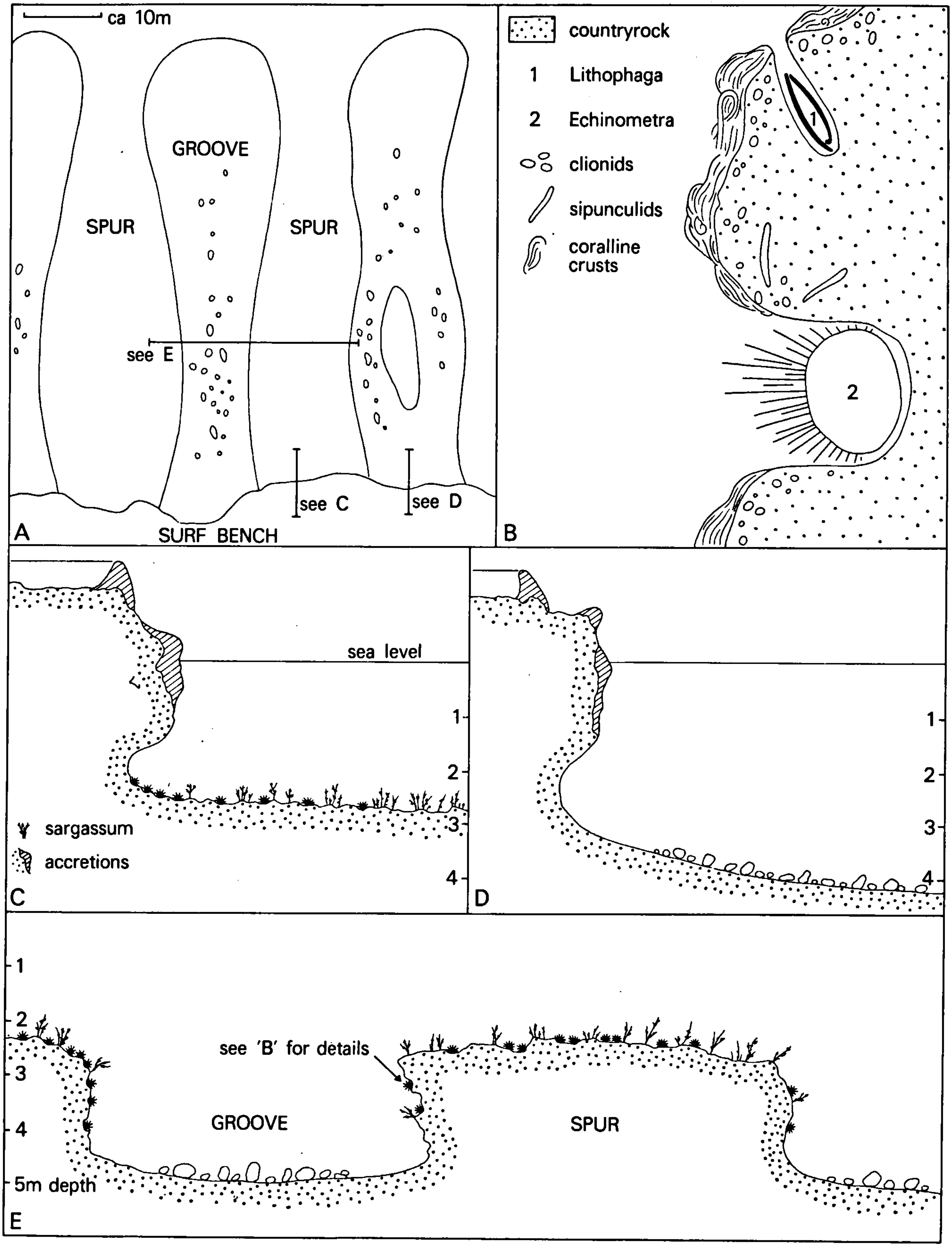

Fig. 23. The occurrence of an erosional spur and groove system near Un Boca.

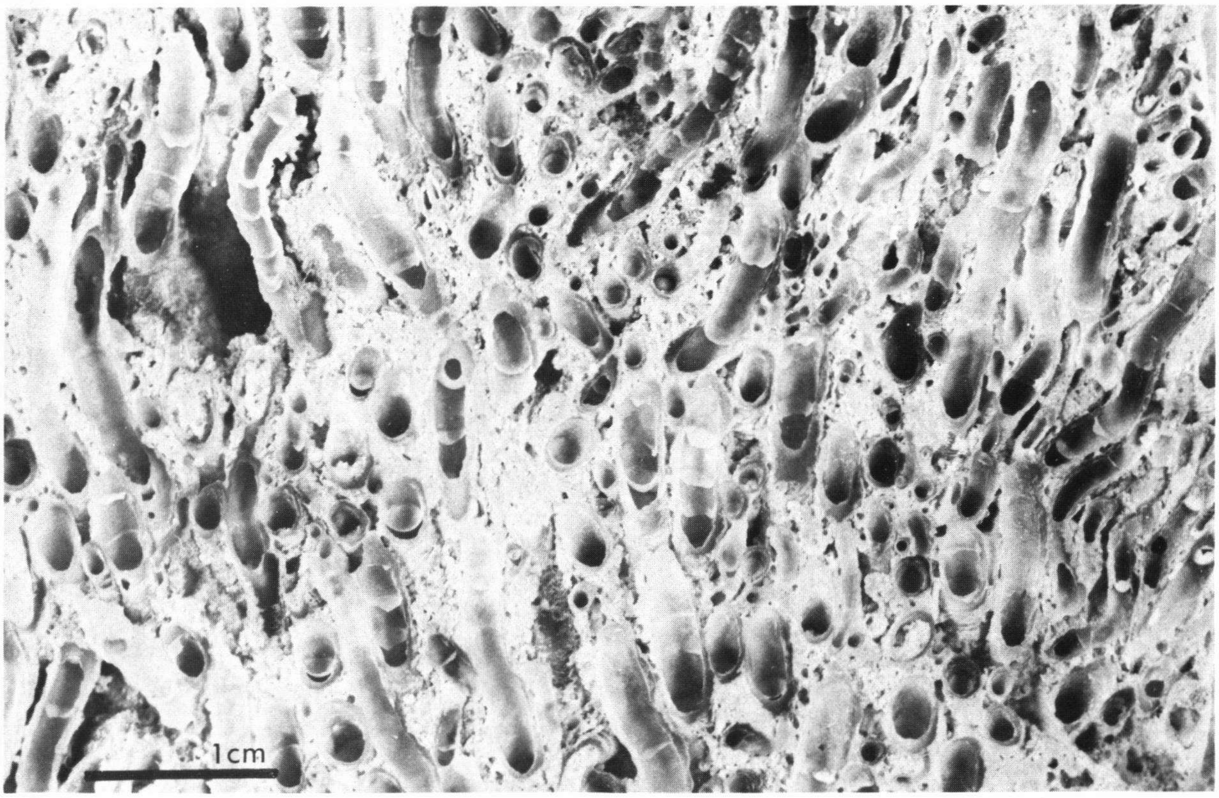

Fig. 24. Section through accretions from the highest parts of the surf platform showing an exclusively vermetid framework with friably lithified interskeletal sediment; the sample was taken just below the living surface of the accretions.

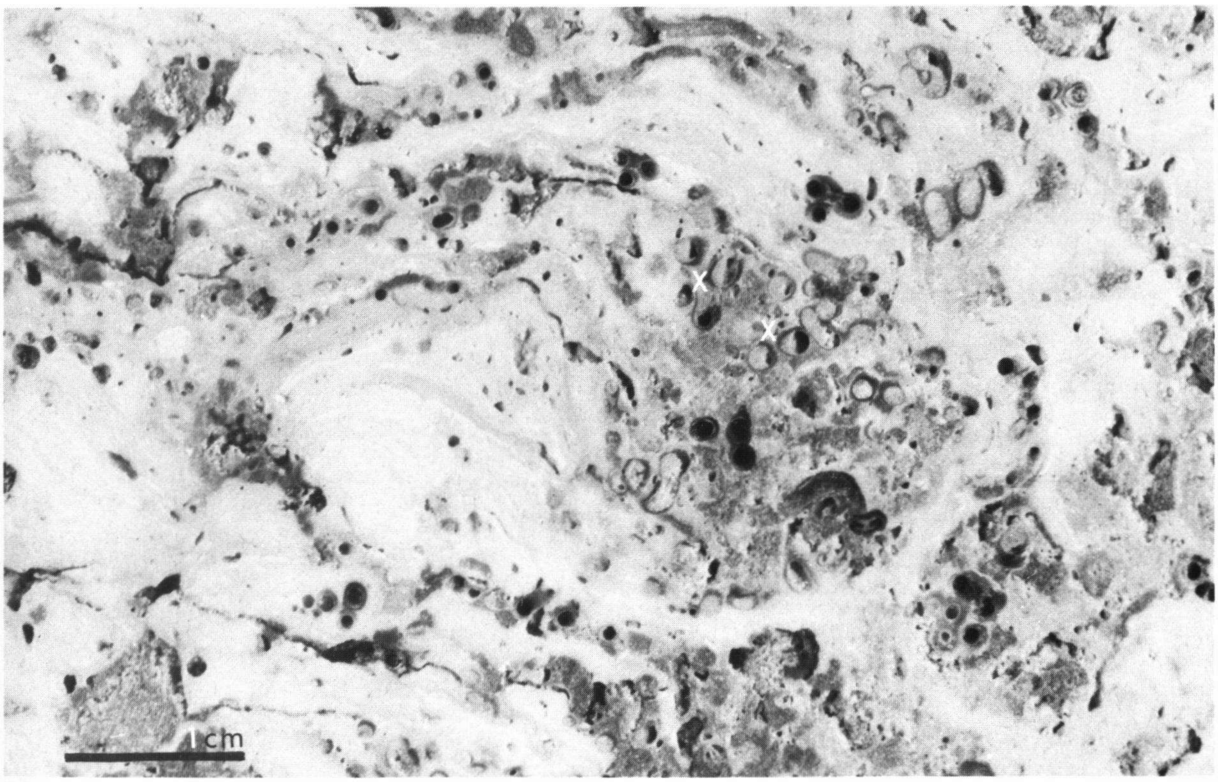

Fig. 25. Section through accretions from lower parts of the surf platform, showing a predominant coralline algal framework (white areas) with patches of vermetids and forams; note geopetal structures inside vermetid tubes around 'x', top is to the right of the picture, and the algae grew sideways.

therefore have been produced in situ by breakdown of skeletal material in the littoral zone.

In the accretions, lithification is a pervasive phenomenon. Sand-sized sediment becomes lithified already a few millimeters below the living surface (Fig. 24), and approximately a decimeter below the surface the accretions form a dense, well-lithified rock (Figs. 25, 26). The lithification is produced by two types of cement: aragonite needle and magnesian calcite micrite. Aragonite needle cement is very rare and was observed only on aragonitic skeletal substrates inside the primary framework (Fig. 27). Aragonitic substrates of the internal sediment were always overlain by calcitic cements. If aragonite cement and internal sediment occur together in a single framework void (usually a vermetid chamber, Fig. 27), the cement is clearly overlain by the sediment. Also, in spite of the close association with the aragonite cement, the sediment itself is cemented with magnesian calcite. This type of cement distribution suggests that the aragonite cement predates the magnesian calcite cement, and indicates that the precipitation of the two cements is controlled by different processes (Macintyre, 1977). The accretions occur up to 1.5 m above mean sea level, but it is clear that, apart from a few calm days per year, large amounts of sea water are continuously percolating through the structures. A marine origin of the cements is also indicated by their nature (see Alexandersson, 1972; Schroeder, 1972) and their association with other marine processes such as boring and internal sedimentation. Support is further provided by scanning electron micrographs (Fig. 28), although care must be taken in identifying cement on the basis of crystal morphology alone.

ZONAL DISTRIBUTION OF ORGANISMS AND THE CORRELATION OF PROFILES

Littoral regions, and rocky shores in particular, are characterized by pronounced zonal distributions of organisms (see Stephenson & Stephenson, 1972; Connell, 1972; Menge, 1976). On steep cliffs the environmental conditions change sharply over short distances, resulting in small, well-defined zones. This zoning has a significant influence on the cliff profile. The profile results from the net effect of degradational and constructional organisms (Focke, 1978a), and since these organisms occur in well-defined, vertically restricted intervals (zones), the net erosional effect also varies in a vertical sense. It has been pointed out that, reversely, the profile has a significant influence on the distribution of organisms. This is obviously correct. Deteriorating light conditions in a notch for example control the distribution of epiphytes. Yet this reversed influence is of secondary importance only, because it is clear that the same profile will develop on an at first undifferentiated cliff, a situation which frequently occurs after collapse of a cliff. Rather, the influence of the profile on organism distribution is a matter of adaptation, of evolving equilibrium, as the profile develops.

Tidal oscillations are very small, and on most cliffs the

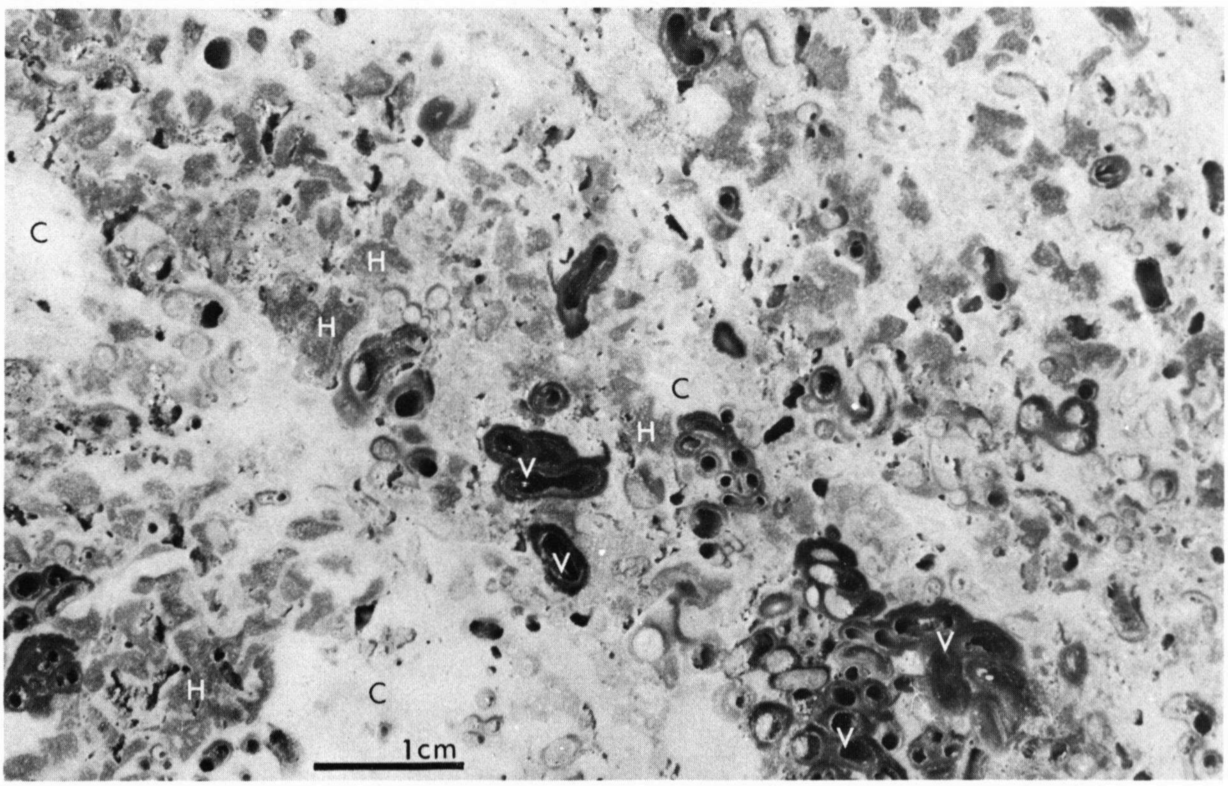

Fig. 26. Section through well-lithified accretions in which the foraminifer *Homotrema* is an important element; black tubes (V): vermetids white areas (C): coralline algae, grey dots (H): *Homotrema*; note lithified internal sediment, particularly inside vermetid tubes.

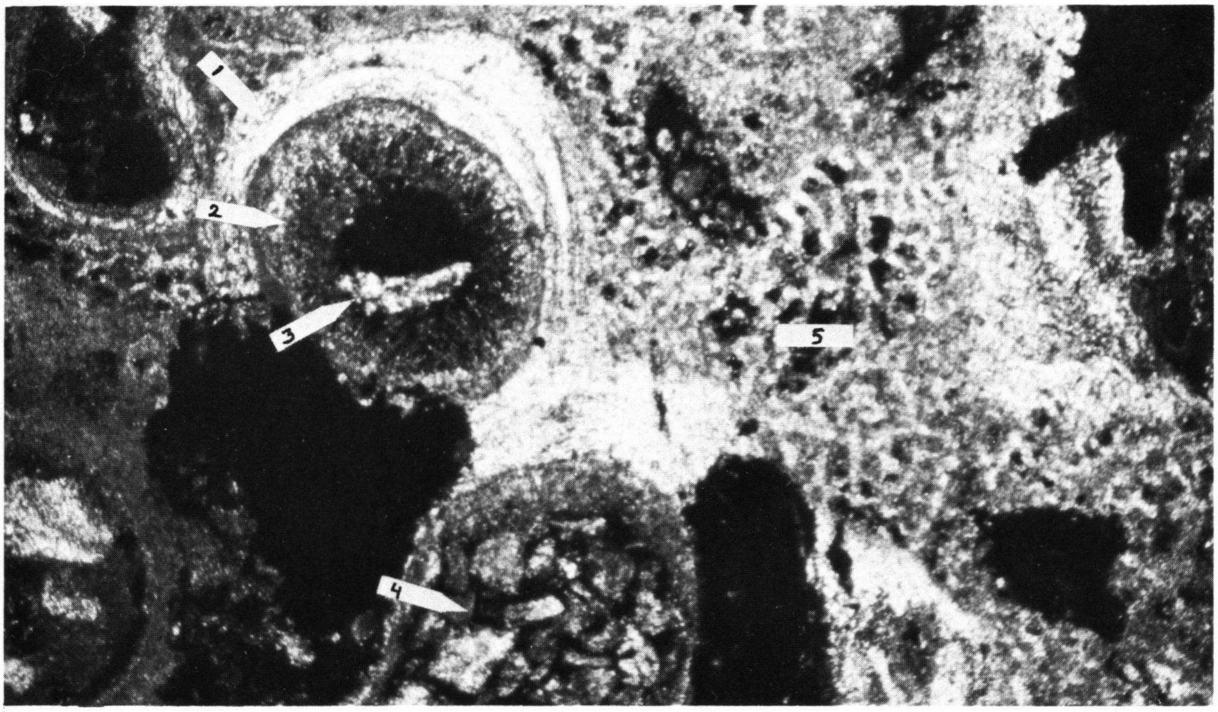

Fig. 27. Thin section of accretions showing vermetid tubes (1), aragonitic needle cement (2), overlain by internal sediment (3) which in its turn has been cemented with magnesian calcite (3 and 4); skeletal voids of coelobitic *Homotrema* (5) have also partially been filled with magnesian calcite.

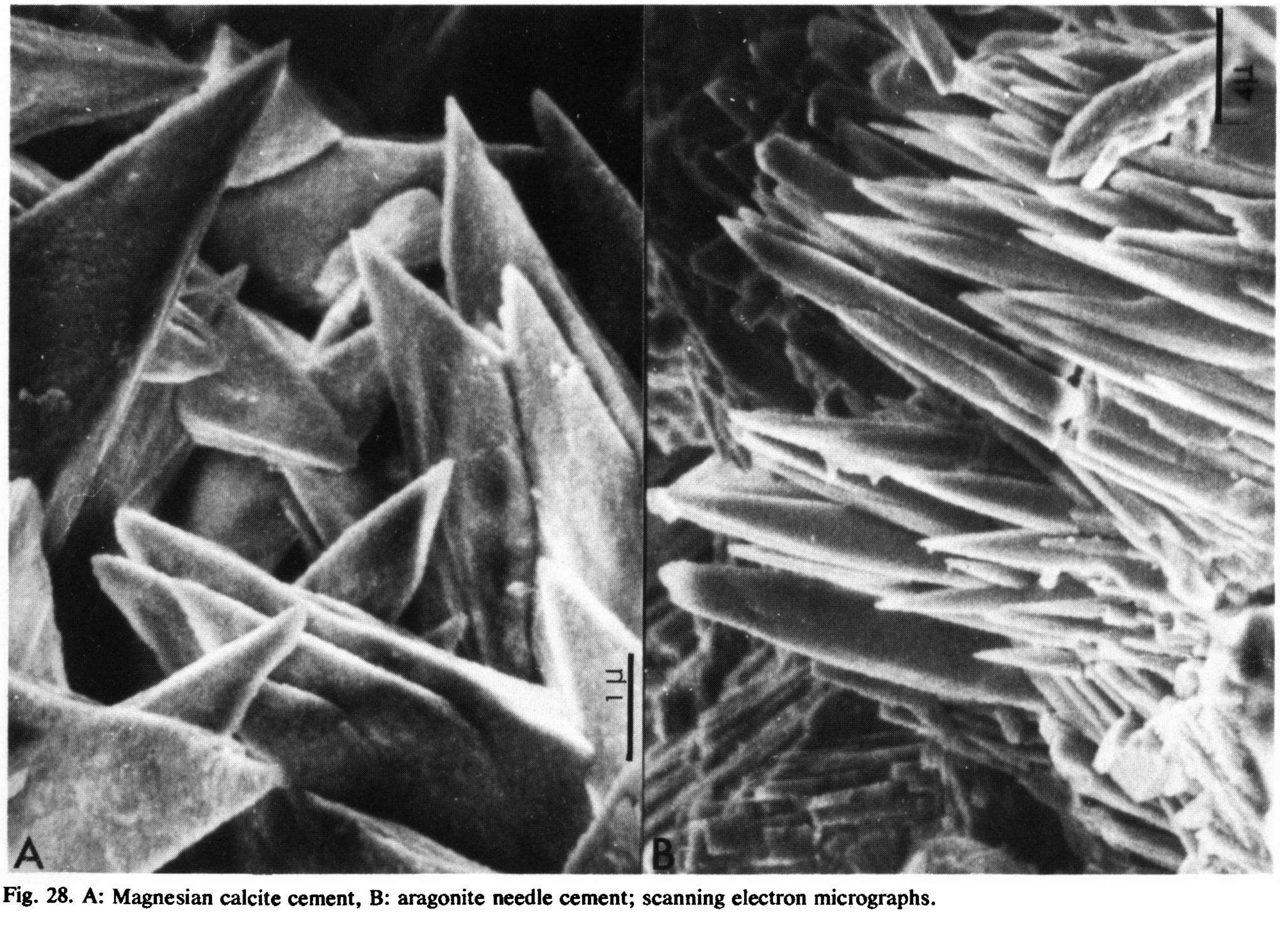

Fig. 28. A: Magnesian calcite cement, B: aragonite needle cement; scanning electron micrographs.

influence of exposure (waves, splash, spray) is far greater. Consequently the zonal distribution of organisms is related to the degree of exposure rather than to the tides (Focke, 1977b; van Loenhoud & van de Sande, 1977). Fig. 29 shows that the zones become wider and higher as turbulence increases. The spray zone, which is the roof of the leeward notch, becomes the rugged, 10 m high karren zone on the windward cliff maintaining the same endolithic algae and rasping snails as most important inhabitants. Similar correlations can be made for the other zones. The surf zone, on the more sheltered cliffs the zone of most rapid erosion, becomes the site of accretionary retardation as exposure increases further.

The raising and widening of the equivalent zones applies to the accretionary organisms as well as to the borers and epibionts. This is well illustrated by the sides of the inlets at the windward coast which display a lateral profile (Fig. 10). Going inshore, the force of the waves gradually decreases, and consequently the surf bench as well as the two notches become lower and smaller. Apart from this gradual lowering there is an abrupt lowering at or near the corner of the inlet (Fig. 11), coinciding with the disappearance of the vermetids as primary framebuilders. Van den Hoek noted (1969, pp. 555–558) that the windward bench is in fact higher than the upper limit of *Porolithon*, the coralline alga which was supposed to be responsible for the bench (de Buisonjé & Zonneveld, 1960), and concluded that this casts doubt on this relation. The answer to this is certainly that the upper limit of the surf platform is, on Curaçao, determined by the upper limit of *Spiroglyphus* rather than the upper limit of *Porolithon*. Obviously, in the same environment, the first occurs at a higher level than the second, which also explains the abrupt lowering coinciding with the disappearance of the vermetids. Oertel (1970) shortly described surf benches from Bermuda, and observed a similar decrease of vermetid framework relative to coralline algae from higher to lower parts of the rims. In this respect the statement by Newell (1961, p. 98) that "where ever a well defined, more or less continuous tidal bench occurs in the tropical Atlantic, it lies within the vertical range of the zone of incrusting coralline algae, and corresponds to the upper surface of the algal cornice" is certainly not correct.

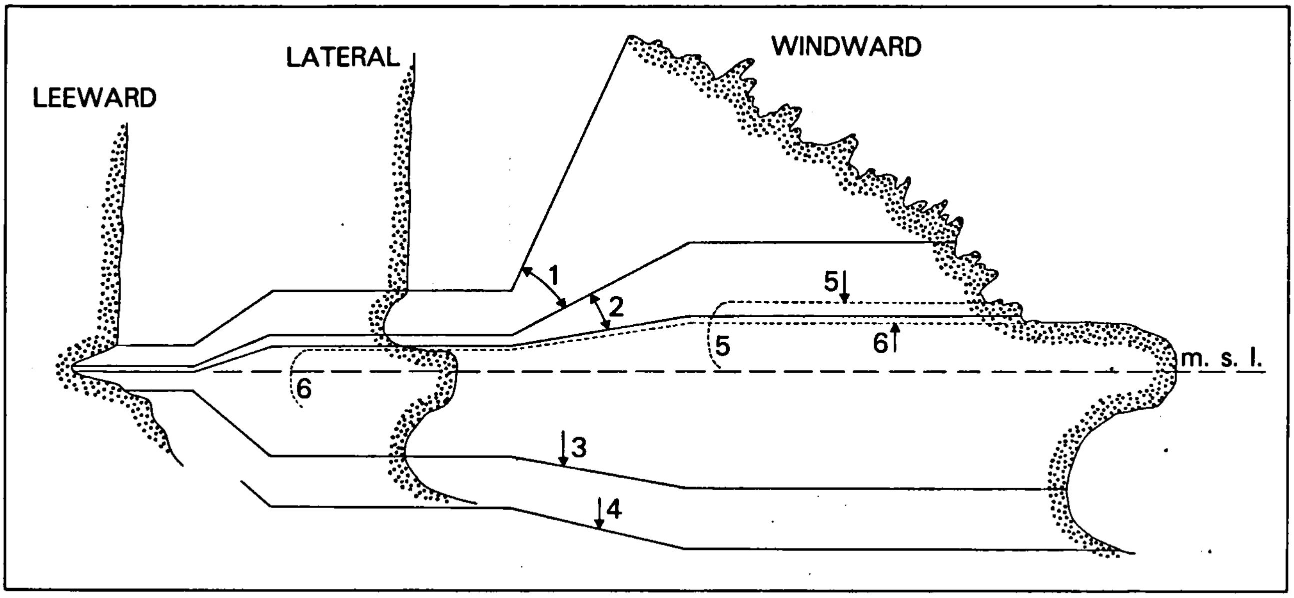

Fig. 29. Correlation of profiles, based on a selected number of organisms; the sheltered profile is not included because zoning is relatively poorly developed; 1: spray zone with endolithic algae (e.g. *Entophysalis deusta*) and rasping snails (e.g. *Littorina* etc.); 2: transition zone with *Chiton* and *Acanthopleura*; 3: lower limit of *Lithotrya*; 4: lower limit of *Echinometra*; 5: upper and lateral limit of vermetid accretions; 6: upper limit of coralline algal accretions; *Lithotrya* and *Echinometra* do occur below the limits indicated, but in significantly lower numbers; the correlation shows the raising and widening effect of increasing exposure, and exemplifies that the profiles are comparable as suggested in the text.

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