Limestone cliff morphology on Curaçao (Netherlands Antilles), with special attention to the origin of notches and vermetid/coralline algal surf benches ("cornices", "trottoirs")

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Limestone cliff morphology on Curaçao (Netherlands Antilles), with special attention to the origin of notches and vermetid/coralline algal surf benches (”cornices”,”trottoirs”)

by

JAAP W. FOCKE, Leiden

with 6 figures and 7 photos

Zusammenfassung. Die Küste von Curaçao besteht ebenso wie diejenige anderer Inseln unter dem Winde der Niederländischen Antillen vorwiegend aus Kalk-Kliffen, die in pleistozänen Riffkalken eingeschnitten sind. Es werden verschiedene Erosionskliff-Typen unterschieden als Beispiele einer kontinuierlichen Formenabfolge, deren Änderungen vor allem von dem Grad der Exposition (der Wasserturbulenz) abhängen. Die am meisten geschützte Endform dieser Abfolge zeigt nur marine Unterschneidung des Kliffs und damit grundsätzlich den Unterschied mariner und terrestischer Erosionsraten. Die am stärksten exponierte Endform ist durch eine Zone von Karren, eine gut ausgebildete Schorre und eine Kerbe unter dem Tideniveau charakterisiert. Zwischenformen zeigen Kombinationen von Kerben und Absätzen. Eines der Profile der Zwischenformen besteht aus einer Schorre und zwei getrennten Kerben, die aber beide zeitgleich sind. Die Brandungsplattformen resultieren aus dem Schutzeffekt von organischen Neubildungen, die vor allem aus vermetusartigen Gastropoden und korallinen Algen aufgebaut sind, und es wird gezeigt, daß sie genetisch weltweiten Vorkommen ähneln, die als „platforms, cornices, trottoirs etc.“ beschrieben wurden. Der Terminus „notch“ (Kerbe) wird neu definiert als eine Einbuchtung im Kliff, die genetisch mit dem Meeresspiegel verbunden ist. Kerben finden sich unter und über eher als innerhalb des Tidenhubs, daher wird der Terminus „tidal nip“ nicht beibehalten. Die Erosion des Kliffs resultiert vor allem aus der Biodegradation des Kalks, und die morphologischen Einheiten der Profile entsprechen dem zonalen Auftreten derjenigen Organismen, die entscheidend sind für die Klifferosion oder entsprechend die durch Wachstum das Kliff vor Erosion schützen.

Summary. The coast of Curaçao as well as the other leeward islands of the Netherlands Antilles, consists predominantly of limestone cliffs, cut into Pleistocene reef rock. Several erosional cliff types are distinguished as examples from a continuous range of variation, depending largely upon the degree of exposure (water turbulence). The most sheltered end member of this range shows only marine undercutting of the cliff, basically representing the difference between marine and terrestrial erosion rates. The most exposed end member is characterized by a zone of karren, a well developed surf platform, and a subtidal notch. Intermediate cliffs show combinations of notches and benches. One of the intermediate profiles consists of a surf bench and two separate notches, both of which are contemporaneous. The surf benches result from the protective effect of organic accretions, built predominantly by vermetid gastropods and coralline algae, and are shown to be genetically similar to world-wide features described as platforms, cornices, trottoirs, etc. The term notch is redefined as an indentation in a cliff, genetically related to sea level. Notches occur below and above, rather than within tidal intervals, and consequently the term tidal nip is not maintained. Erosion of the cliffs results primarily from biodegradation of limestone, and the morphological units of the profiles correspond to the zonate occurrence of those organisms which are crucial in eroding the cliff, or – reversely – protecting the cliff against erosion with accretions.

Résumé. Le littoral de l'île de Curaçao, comme des autres Iles sous le Vent (Antilles néerlandaises) est formé principalement par des falaises calcaires, incisées dans des roches récifales d'âge pleistocène. On distingue plusieurs types de falaises, montrant une série continue dépendant surtout du degré d'exposition (turbulence d'eau). L'extrême le moin agité, ne montre que des encorbellements essentiellement dûs à la différence du degré de l'érosion marine et continentale. L'autre extrême, le plus battu, est caracterisé par une zone de lapies, une corniche à vagues bien developpée, et un encorbellement. Des types intermédiaires montrent une combinaison d'encorbellements et de corniches. Un de ces types est constitué d'une corniche et deux encorbellements formés simultanément. Les corniches sont dûes à la protections des dépots organiques construits principalement par des vermets et des algues corallines. Quant à leur origine, elles correspondent à des phénomènes mondiales décrites comme des plate-formes, corniches, trottoirs, etc. Le terme « notch » est redéfini comme une incision dans une falaise, liée génétiquement au niveau de la mer. Les corniches apparaîssent plutôt au-dessous et au-dessus que dans la zone des marées, et par conséquence le terme « tidal nip » n'est pas maintenu. L'érosion des falaises est surtout le résultat de la biodégradation des calcaires. Donc les unités morphologiques des profiles correspondent à la présence étagée des organismes cruciaux pour l'érosion de la falaise, ou, à l'inverse, des organismes qui protégent la falaise contre l'érosion par leurs dépôts.

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, and at the windward side the coastal shelf is narrow, without shallow reefs or other barriers. These windward parts, i. e. the greater part of the northeast coast and some parts of the southwest coast, are therefore very exposed while other areas are relatively sheltered. The tides (De Haan & Zaneveld 1959) exhibit semi-diurnal, diurnal and seasonal variations, with an average daily tidal range of 30 cm. The islands consist roughly of a core of pre-Tertiary 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; Herweijer & Focke 1978). The morphology of the cliffs which have been eroded into this limestone has been studied by Martin (1888), De Buisonjé & Zonneveld (1960) and Focke (1977, 1978). Organism distribution on the cliffs has been described by Van den Hoek (1969) and Van Loenhoud & Van De Sande (1977). The present paper results from a study of the interrelationships between cliff morphology, organism distribution, some environmental parameters, and erosional and constructional processes. General cliff morphology and the distri-

Fig. 1. Indexmap of the Netherlands Leeward Antilles.

bution of organisms as far as relevant for the formation of the cliff profile are described elsewhere (FOCKE 1978) and to this paper the reader is referred for details.

The cliff profiles

The morphology of a cliff *(i. e.* its profile) naturally depends heavily on its basic properties: lithology, height, stratification, etc. The study on Curaçao however focussed on cliffs which were all similar in this respect. Within this framework, several different profiles have been distinguished (FOCKE 1978) which proved to be part of a continuous range of variation, with the degree of exposure as main controlling parameter. This range of variation may be visualized by correlating the profiles on the basis of hydrographic regime and organism zonation (fig. 2),

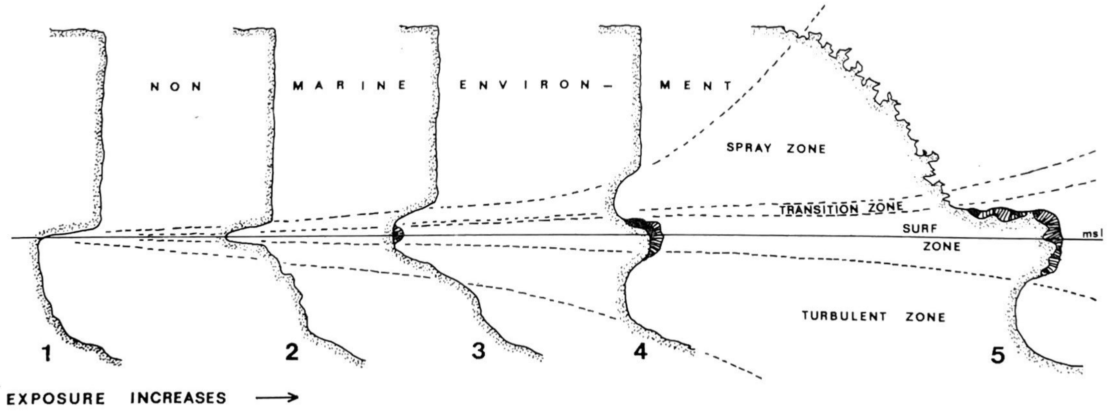

Fig. 2. Morphological variation of limestone cliffs as a function of water turbulence (degree of exposure); see text.

but can also be directly observed in the field where a curved coastline gradually changes its orientation towards the prevailing wind direction or wave front, thus showing a gradually changing degree of exposure.

Limestone cliffs confronted with open marine but very quiet seawater are simply undercut (fig. 2: 1), without the development of pronounced indentations (a true indentation having penetration into the cliff relative to the cliff part below as well as above the indentation). This undercutting has been defined as a notch by Neumann (1966). Essentially, it represents the difference (more than an order of magnitude) between marine and terrestrial erosion rates.

As water turbulence increases, organism zonation becomes more pronounced, and a true indentation developes at sea level (fig. 2: 2; photo 1). This indentation has been defined by Neumann (1966) as a tidal nip, but is redefined as a notch in this paper (see below). The higher the wave amplitude, the wider (in a vertical sense) the notch will be. These observations suggest that the development and the dimensions of the sea level indentation are controlled by turbulence, rather than by tidal oscillations (which are similar for all the profiles).

As turbulence increases further, organic accretions appear in the middle of the notch, i. e. in its most turbulent, surf-beaten part (fig. 2: 3). These accretions become more and more pronounced and eventually form a seaward protruding bench (surf platform), dividing the notch into two seperate features (fig. 2: 4). The presence of two notches has led many authors to the conclusion

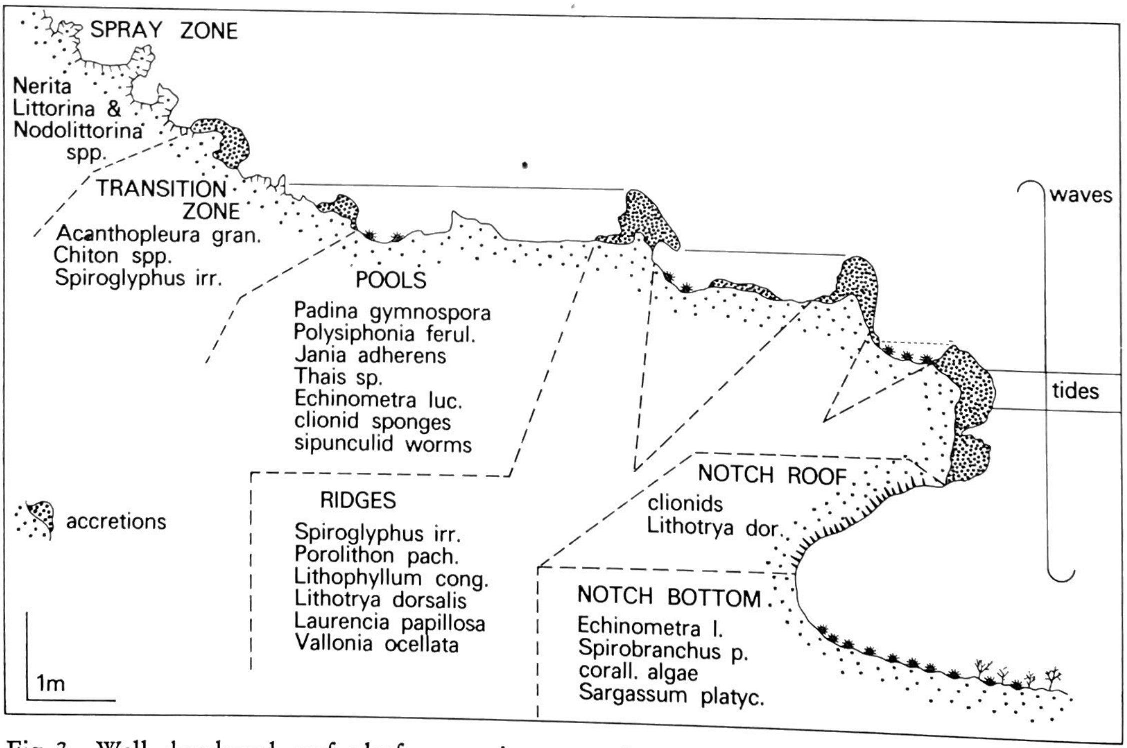

Fig. 3. Well developed surf platform as it commonly occurs on the most exposed shores of Curaçao (see fig. 2: 5).

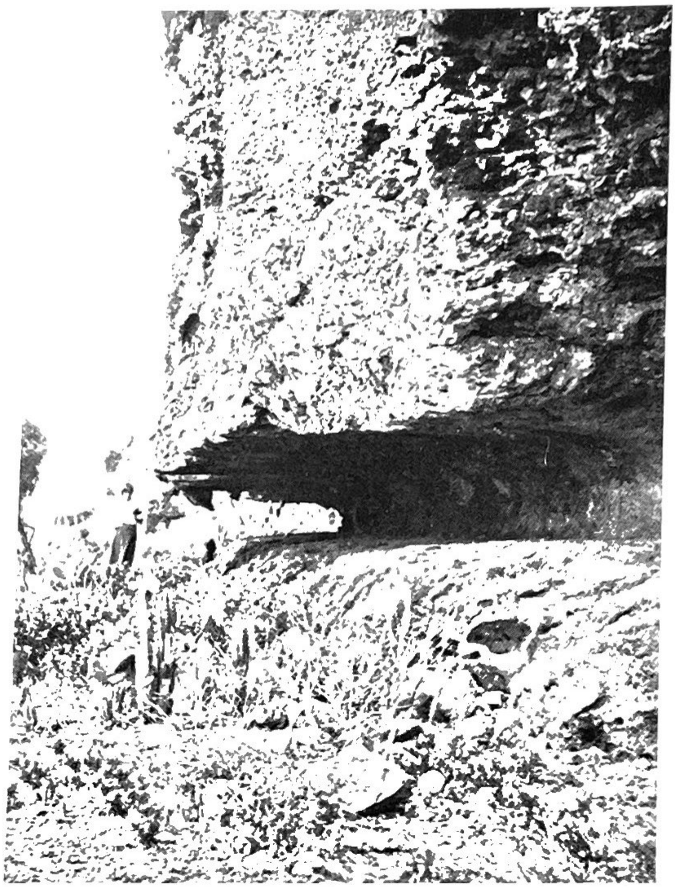

Photo 1. A single notch such as shown in fig. 2: 2; example from the Pleistocene (10 m above present sealevel).

Photo 2. 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); second (subtidal) notch not visible (cf. fig. 2: 4).

Photo 3

Photo 4

Photo 3. 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.

Photo 4. Surf platform near Boca Wandomi, showing the great impact of the surf (foreground).

Photo 5

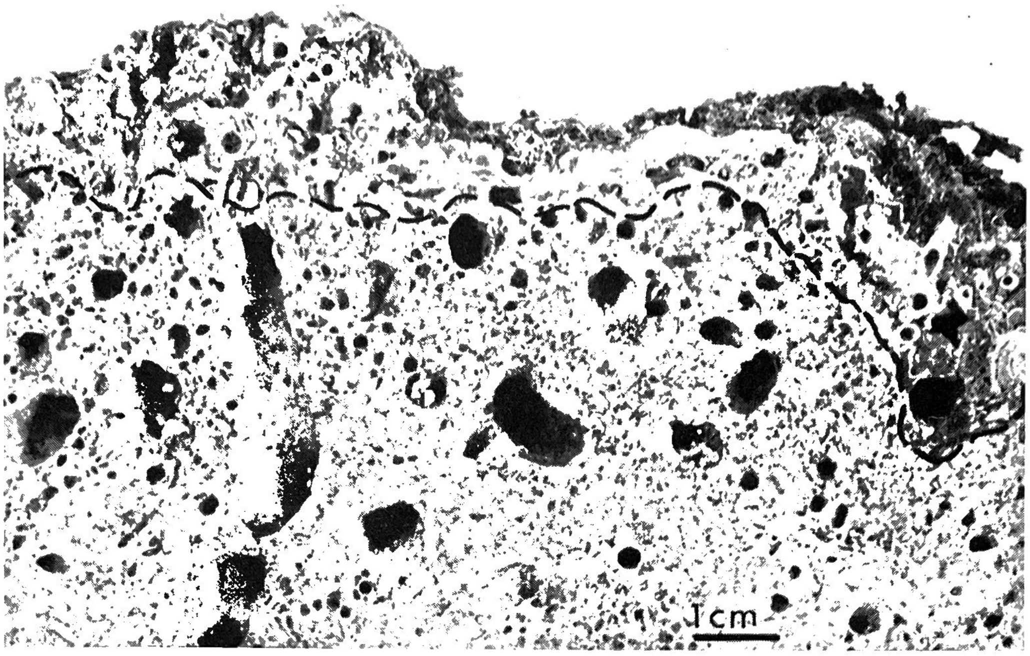

Photo 6

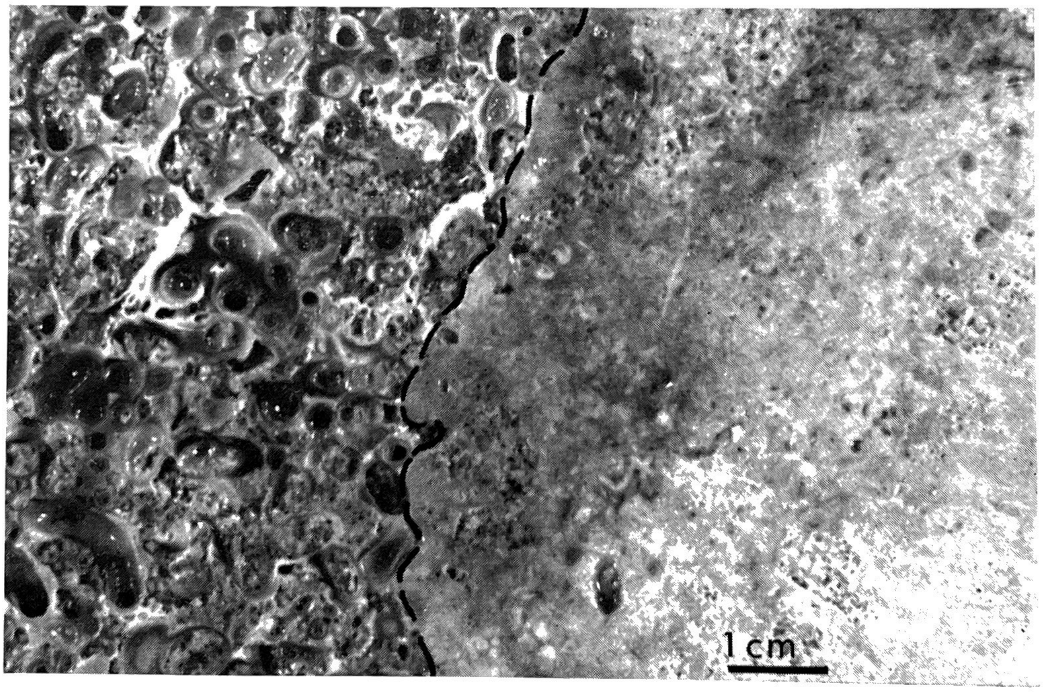

Photo 5. Pleistocene limestone covered by recent (living) encrustations of algae, foraminifera, worms etc., in spite of these crusts the limestone is infested with boring organisms (bivalves, sponges, sipunculids, etc.); compare photo 6.

Photo 6. Pleistocene limestone covered by thick, lithified accretions (left hand side of photo); the Pleistocene limestone is virtually free of boreholes.

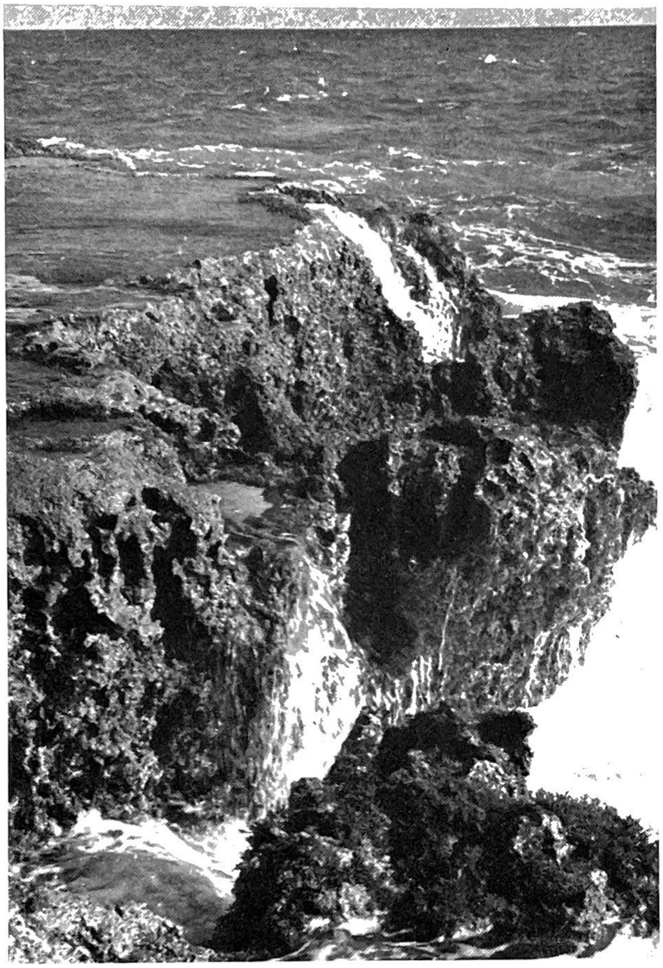

Photo 7. The edge of the surf platform, showing stages of breakdown, indicating that the accretions may retard erosion, but do not prevent it; see Focke (1978) for details.

that only one of them could be contemporaneous, the other being an ancient feature related to some other sea level event (see for example Fairbridge 1968, p. 864, fig. 9 B). Viewed in the context of fig. 2 however, it is evident that such notches, especially when separated by a "*Lithothamnium* rim" or other organic bench, are both contemporaneous, being in fact a single notch with a surf bench growing in the middle (see photo 2). Eventually the upper limit of the spray zone, determining the upper limit of the notch on the other profiles, is raised so high (fig. 2: 5) as to bring the entire cliff face within the marine environment. The presence of a notch depends in part on the upper cliff part being outside the marine environment, because only then the erosion of this part lags behind, forming the overhang which is the roof of the notch. Thus, when the entire cliff face comes within reach of the sea-water, the notch is replaced by the rugged karren zone of the windward profile (fig. 3; photo 3).

At first (fig. 2: 3), the accretions are inconspicuous, but as surf action increases they become bigger and better lithified, forming sizable platforms up to 2 m above mean sea level and up to 10 m wide (photos 3 and 4). The thickness of the accretions however seldomly exceeds 50 cm, and country rock (in this case Pleistocene limestone) is invariably found to underly the accretions (fig. 3). Detailed descriptions of surf benches and accretions are given by Focke (1977, 1978).

The erosional agents

The nature of marine littoral erosion of limestones has been a controversial matter for many years (see Fairbridge 1968). Three main types of erosion have traditionally been recognized. *Mechanical erosion* (Fairbridge 1952; Revelle & Emery 1957) includes processes as corrosion and abrasion (provided that there is a supply of sand or pebbles), hydraulic fracturing (Fairbridge 1968) and collapse of overhanging cliffs. Several authors advocated *physico-chemical solution* as an important erosional agent in the littoral region (Wentworth 1939; Kuenen 1950; Fairbridge 1952; Revelle & Emery 1957; Kaye 1957, 1959; Hodgkin 1964). The importance of *biodegradation* has also been stressed (Emery 1946; Ginsburg 1953; Newell & Imbrie 1955; Newell 1956; Kaye 1959; Neumann 1966). In a classic paper on the boring activities of clionid sponges, Neumann (1966) was able to rule out mechanical wave action completely (for very sheltered cliffs, fig. 2: 1) and indicate biodegradation as predominant if not only erosional mechanism. Strikingly, on the very exposed windward side of Curaçao, mechanical erosion is equally insignificant (Focke 1978). The role of chemical erosion on the cliffs of Curaçao is difficult to assess. It has been pointed out that sea-water must be undersaturated with respect to calcium carbonate for solution to take place (Pytkowicz 1969), while generally the surface water in the area is supersaturated in this respect (*ibid.;* Lisitzin 1970). This supersaturation is also indicated by the ubiquitous presence of carbonate cements in the littoral zone. The role of complex-ion formation however is not clear (see Fairbridge 1948; Revelle & emery 1957). A possible, though minor, role of chemical solution, related to the presence of instable minerals as aragonite in the cliff, is suggested by Trudgill (1976). On the other hand, data from regions with undersaturated sea-water indicate that chemical solution leaves specific leaching marks on carbonate substrates (Alexandersson 1972, 1974, 1975, 1976). Such leaching marks, which are easily distinguished from marks left by boring micro-organisms (see Golubic et al. 1975; Schneider 1976, 1977), have not been observed in this study. Biodegradation is indeed the only erosional process which is evident on the cliffs. An amazingly wide variety of organisms is boring into the cliffs. The potential of these organisms to effectively remove limestone from the cliff has been well documented (*inter alia* Ginsburg 1953; Newell et al. 1955; Neumann 1966; Schneider 1976; Trudgill 1976). Carricker & Smith (1969) tabulate organisms and erosion rates as far as known at the time. A recent review is given by McLean (1974). An echinoid such as *Echinometra lucuntur,* extremely abundant on the cliffs, is able to remove 14 cm^3 limestone per individual per year (McLEAN 1974). For a dense *Echinometra* field of ca 100 individuals per square meter this amounts to a total removal of 1400 cm^3 per year or an erosion rate of 1.4 mm per year, for the echinoids alone. Zones of evident erosion and zones of evident erosion-retardation correlate well with zones of major eroding and constructing organisms (FOCKE 1978). In conclusion, it seems that, at least on Curaçao, the littoral erosion of limestone is predominantly the result of biological breakdown.

The accretions and their relation with surf platforms

Encrusting organisms are abundant on all cliffs which have been studied. Generally, in spite of the organic crusts at the surface, the underlying limestone is riddled with boring organisms (photo 5). Usually little is to be seen of these borers on the surface and only after fracturing the devastating effect on the limestone is evident. The crusts, even when relatively thick, do not effectively prevent the breakdown of the country rock. In this respect the effect of the accretions, occurring on the more exposed cliffs, is markedly different. They are much thicker than the usual crusts described above, and in addition they are intensely altered by marine diagenesis. Particularly the lithification (FOCKE 1978) adds greatly to the strength, the density and the wave resistance of the structures. The similarity of the accretions with reef rock is remarkable. The vermetid/coralline algal accretions found on the higher parts of the most exposed surf platforms have fabrics which are very similar to those of the algal cup reefs (boilers) of Bermuda (see GINSBURG & SCHROEDER 1973). The accretions found on the other surf platforms and which are mainly built by coralline algae are comparable to algal reefs (algal ridges) reported from the northeastern Caribbean (ADEY 1975; ADEY & BURKE 1976). In view of this it is not surprising that the presence of the accretions does have a significant effect on the cliff. As a rule no signs of biodegradation were found in country rock covered with accretions (photo 6), and obviously the accretions do protect the limestone against bioerosion. The surf benches on which the accretions occur obviously result from this protective influence; on an otherwise rapidly eroding cliff the interval which is protected by accretions lags behind, thus forming a seaward protruding feature (see fig. 5).

The occurrence of the accretions, and therefore also the benches, is positively related to water turbulence (fig. 2). According as wave action increases, the accretions become thicker and better lithified, and the benches become higher and wider. The occurence of the primary framebuilders, however, is not in the same way related to turbulence; on sheltered shores they are often just as abundant as on exposed shores, only without producing accretions. Although it is known that wave action is a very important parameter in littoral species composition (CONNELL 1972; LEWIS 1968), it does not directly explain why the accretions and the benches are related to high turbulence. Since most of the framebuilders depend on water circulation for their supply of nutrients, it may be that they benefit from the increased turbulence, possibly resulting in higher growth rates. Similar theories have been advanced for reef-like structures in general. An additional or even alternative explanation, however, may be found in the distribution of marine lithification. The intense wave action on the surf benches provides the driving mechanism to pump large quantities of sea-water through the accretions and is thus one of the main reasons for the pervasiveness of lithification. Consequently there is no doubt that the occurrence of marine lithification is directly related to the degree of exposure. This lithification is furthermore essential in maintaining the accretions. Without it, the crusts would be easily stripped off the substrate. It is postulated that marine lithification explains the relation of surf benches with high turbulence in two ways: 1) lithification greatly strengthens the structure, enabling it to withstand the force of the waves and fixing it strongly to the country rock, and 2) it seals the substrate from circulating water, thus protecting it against biodegradation.

The mechanisms of profile formation

All the limestone cliffs which have been discussed are being eroded. Many stages in the erosional process can be seen, and there is ample historical evidence for the receding nature of the cliffs.

The very sheltered cliff (fig. 2: 1) represents the most simple mechanism of profile formation: the cliff is undercut by marine erosion untill the overhang collapses. The undercutting represents the difference between marine littoral erosion rates, estimated at 1 mm/yr by HODGKIN (1964) and 1 to 1.5 mm/yr by TRUDGILL (for sheltered coasts; 1976) and terrestrial erosion rates, estimated at 0.01 to 0.02 mm/yr, no less than two orders of magnitude slower (GINSBURG 1953; LADD et al. 1967).

The somewhat more exposed profiles form in a similar way: marine undercutting of the cliff with periodic collapse of the overhang, except that now the notch is better defined and more sharply related to sea level (fig. 2: 2–3), indicating increased erosion as a result of sea-level turbulence with surf and spray action. As we have seen (see above; also FOCKE 1978), this increased erosion reflects increased biodegradation, rather than the effect of mechanical erosion as suggested by TRUDGILL (1976). Maximum notch depth on Curaçao is 3 to 4 m, largely depending on the mechanical properties of the cliff limestone. Periodic collapse is a common feature of all cliffs of which the upper part is outside the marine environment (fig. 2: 1—4).

The most exposed profile however (fig. 2: 5) seems to have a different mechanism of formation. The entire cliff is within the marine environment, and collapse does not occur unless in exceptional circumstances (FOCKE 1978). The profile consists of two major zones of rapid erosion: spray zone (karren zone) and notch (fig. 3), separated by a zone of retardation: the surf bench. All three zones, now representing a vertical interval of more than 15 meter, are together equivalent to the single notch of more sheltered cliffs (fig. 2). In the spray zone the limestone is eroded untill the level has been lowered so much as to bring the limestone within reach of the surf. Then vermetids start building accretions. These accretions effectively retard erosion at this upper, vermetid determined, level. In the spray zone however, erosion continues, and so a horizontal plat-

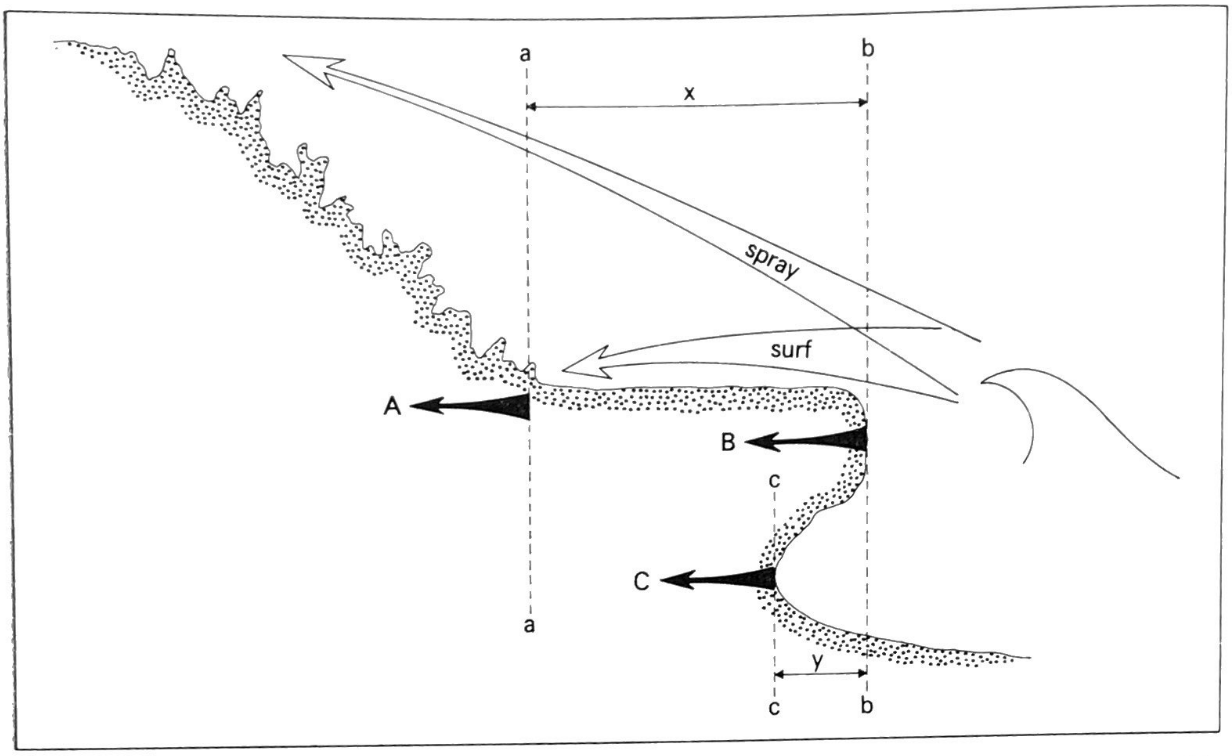

Fig. 4. Parameters controlling the erosional equilibrium of the windward profile; *x* = width of surf bench; *y* = depth of notch; A, B and C are the rates of landward displacement of the lines aa, bb and cc; see text.

form is created, the upper surface of which is determined by the highest level at which the vermetids are able to build accretions. Underneath the platform, unhindered by accretions, a notch is formed (fig. 3). The width of the surf platform, *x* (fig. 4) and the depth of the notch, *y*, are rather constant along those parts of the windward coast which have similar orientations towards the wind and the wave front. This observation indicates that an equilibrium exists in which the rates of landward movement of the vertical dotted lines: A, B and C, are equal (fig. 4). In such a situation the form of the profile will not change as the cliff recedes landward. The distances *x* and *y* are crucial in maintaining this equilibrium. The regression of the platform edge, B, represents the slowest erosion rate, obviously as a result of the accretions (erosion is retarded, not prevented, by the accretions; see photo 7). The erosion rate in the notch, C, potentially faster, is probably slowed down by the depth of penetration, *y*. Probably the conditions in the back of the notch change sufficiently as the notch deepens to slow down biodegradation and decrease other erosional effects, until C equals B. If C were slower than B, then of course the notch would disappear. If C were faster than B, then the notch would undermine the surf bench by growing too deep. Only very rarely however have collapsed parts of surf platforms been observed on the sea-bottom in front of the cliff. Also, the rather constant dimensions of the notch argue strongly against the occurrence of collapse. Indeed the depth of penetration of notches of the other cliff types varies from almost nothing to several meters, depending on how long ago collapse took place.

To understand the supposed equilibrium between B and A (*i. e.* the rate of landward displacement of the boundary between the surf bench and the spray zone), it should be realized that the spray originates at the seaward edge of the surf bench and is then transported across the platform to the higher parts of the cliff (fig. 4). Part of the spray is lost by precipitation on the platform, and the amount of spray which eventually reaches the spray zone will diminish if the platform width (x) increases. The breakdown of the spray zone depends however on the amount of water reaching the zone. Similar relations between humidity and intensity of biodegradation have been described by SCHNEIDER (1976, 1977). Increasing platform width will therefore slow down the erosion rate of the spray zone, until B equals A. Any changes in x and y will thus cause changes in A and C in such a way to restore the equilibrium situation. Figure 5 shows how the windward profile as we now know it would form from an initially undifferentiated vertical cliff wall. It also illustrates the relation between the double notch profile (fig. 2: 4) and the windward profile: if the upper part of the cliff can not be reached by the spray, an overhang will form and thus a notch (fig. 5, phase 2). Phase 4 is the assumed equilibrium situation in which the profile will remain essentially the same as the cliff recedes landward. Have the cliffs reached such an equilibrium already? TRUDGILL (1976) measured erosion rates of 2 to 4 mm/yr, with extremes of 7 mm/yr for exposed coasts. In view of these rates, and considering that the cliffs have been subjected to marine influence at least a few thousand years, it may be assumed that the notch of the windward cliff would have been considerably deeper if the equilibrium did not exist.

Comparable features in other parts of the world

Limestone cliffs with notches at sea level are very common in tropical seas, and although the relative importance given to biodegradational, mechanical or chemical processes may differ (see for example TRUDGILL 1976), there is little doubt that most of them are comparable to those described in this paper. Organic accretions associated with surf platforms similar to the benches of Curaçao have also been reported from all over the world. One of the oldest reports seems to be that of Quatrefages (1854, *fide* MOLINIER 1955 a), who noted the importance of vermetid accretions on the coast of Sicily. Vermetid accretions have been reported since from many Mediterranean coasts, including France (MOLINIER 1955 b, 1960), Spain (MOLINIER 1954; MOLINIER & PICARD 1957), Algeria PÉRÈS & PICARD 1952), Italy (MOLINIER & PICARD 1953), Tunesia (MOLINIER & PICARD 1954), Israel (SAFRIEL 1966, 1974) and Lebanon (SANLAVILLE 1972). GUILCHER (1953) compared shore benches from Marocco and Hawaii. MOLINIER (1955 a) stressed the significance of the vermetids in protecting the country rock against erosion, the role of water turbulence and the fact that the zone of vermetids may extend higher in the littoral region than the zone of coralline algae. Surf benches with accretions in which serpulid worms are important have been reported by PÉRÈS & PICARD (1952) and many others, but often the worms prove to be misidentified vermetids. Much attention has been given to benches which are primarily associated with coralline algae. Where such benches occur

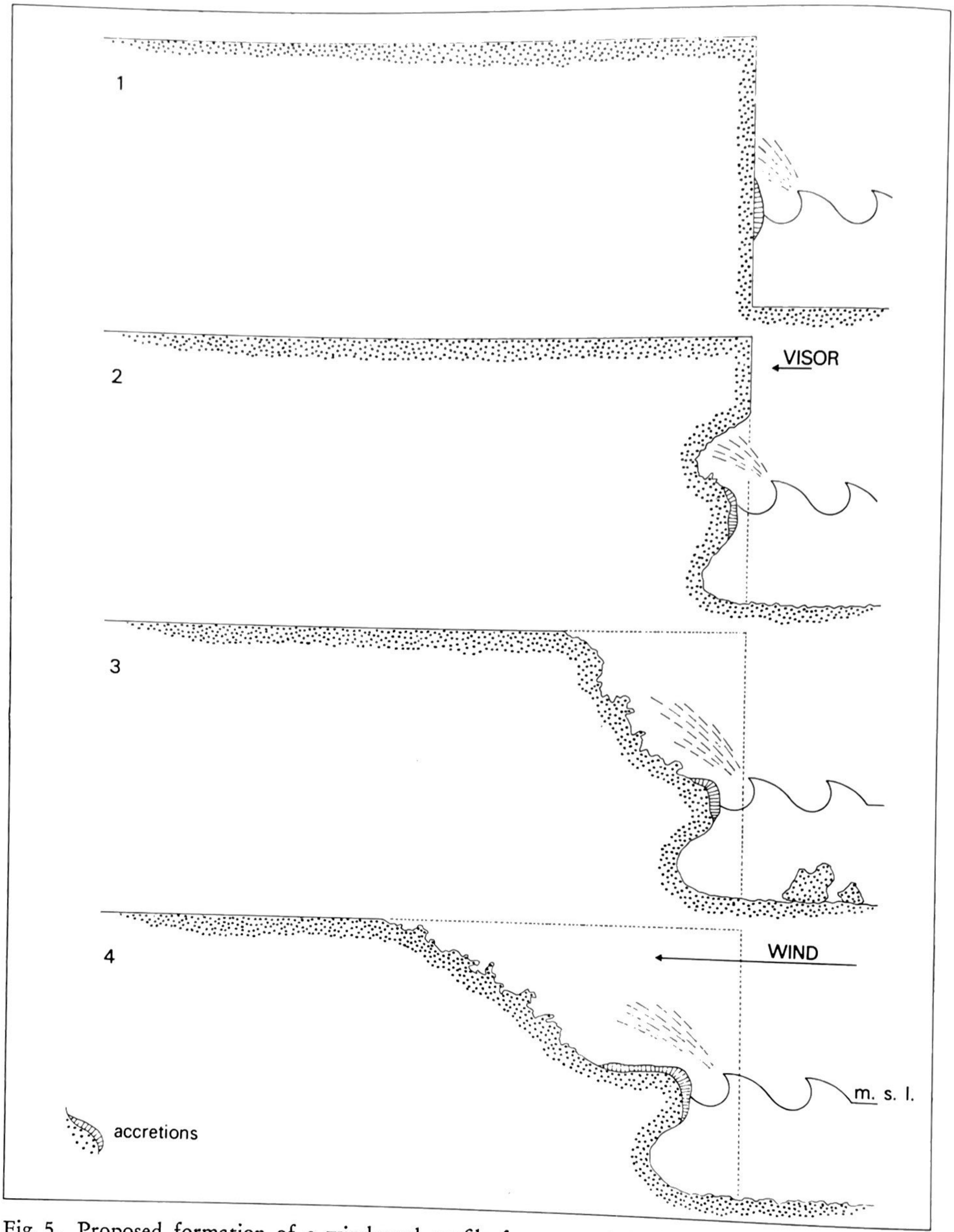

Fig. 5. Proposed formation of a windward profile from an originally undifferentiated vertical cliff wall; phase one, if arrested (for example when the cliff itself is too resistant to allow significant erosion), would yield a cornice such as shown in fig. 6: 1; phase 2, if arrested (for example when the wind, which carries the spray, is not strong enough in relation to the height of the cliff), would yield a "double notch profile" such as shown in fig. 2: 4 and photo 2.

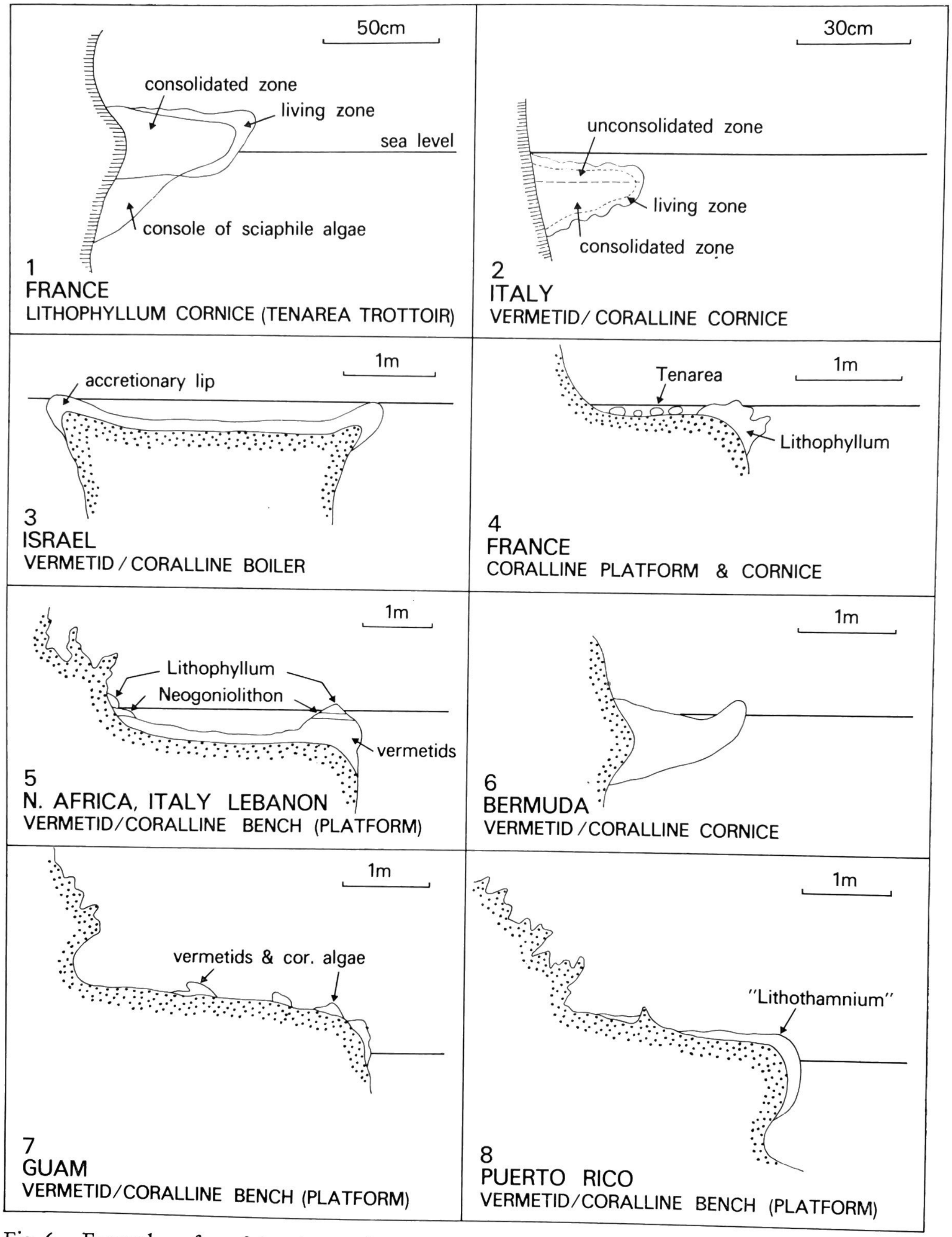

Fig. 6. Examples of surf benches and comparable features described from the Mediterranean, the Pacific and the Atlantic, after 1: Pérès & Picard 1952, 1964; Guilcher 1953; 2: Molinier 1954, 1955 a; Pérès & Picard 1964; 3: Safriel 1966, 1974; Blanc & Molinier 1955; 5: Molinier 1955 a, Pérès & Picard 1964; Sanlaville 1972; 6: Oertel 1970; 7: Emery 1962; Tracey et al. 1964; 8: Kaye 1959.

on resistant cliffs, often being entirely constructional (fig. 6: 1), they have become well known as *Tenarea cornice* or *Lithophyllum trottoir* (PÉRÈS & PICARD 1964).

An excellent summary on the Mediterranean shore benches is given by BLANC & MOLINIER (1955), including descriptions of the different bench types as well as the accretions. They agree that well agitated, turbulent water is a prerequisite of all bench types, and that the elevation of the benches is related to the degree of exposure. They conclude that the term intertidal, often used with respect to the benches, is not correct. This conclusion is strongly supported by the result of the present study, and a similar conclusion is reached for the term tidal nip (see below). Lithification is reported to be pervasive; quartz and other non-carbonate minerals which were reported as cement in older reports, were later demonstrated to be of detrital origin (BLANC & MOLINIER 1955). Magnesian calcite cement is the predominant lithifying agent (*ibid.*). Clearly these lithified accretions, when occurring on otherwise easily erodable country rock, have a protective effect on this rock, such as described on Curaçao. The truely constructional vermetid and coralline algal cornices (trottoirs) seem to occur on resistant, often non-calcareous country rock, while benches (platforms) more like the ones described in this paper are generally found on easily erodable country rock. Probably, on resistant cliffs, accretions form in the surf zone, build the cornice, and then just "sit there", not causing the formation of a wider platform simply because the other parts of the cliff do not rapidly erode. In other words, the cliff is already so resistant by itself that protection by the accretions does not result in different erosion rates. Thus the cornices may be thought of as the arrested first phase of platform development as proposed in fig. 5. It seems therefore that, in spite of considerable morphological variation and differences in framebuilding organisms, the mechanism of formation such as proposed for the benches of Curaçao (fig. 5) may be equally well applied to the variety of benches reported from other areas (fig. 6).

From the Pacific surf benches have been reported, among others, by STEARNS (1941). EMERY (1962) described in some detail benches with rimmed terraces (ridges) from Guam (fig. 6: 7), up to 6 m wide and 3 m above mean sealevel, but always within reach of the surf. He considered a constructional approach (*sensu* LISTER 1891) as opposed to an erosional approach (*sensu* KUENEN 1933; UMBGROVE 1947), and concluded that the benches of Guam were erosional. Nevertheless he recognized (*ibid.*, p. 68) that the benches owed their form and very existence directly to the presence of the accretions. Vermetids are the chief rock building organisms in the rims. TRACEY et al. (1964) further documented the benches of Guam, showing the striking similarity with the platforms of Curaçao (*ibid.*, fig. 43). Again the relation of bench elevation and degree of exposure is noted, and there is little doubt that the benches are genetically similar.

In the Atlantic-Caribbean area vermetid/coralline algal communities are well known as important reef builders (SHIER 1969; GINSBURG & SCHROEDER 1973; LABOREL & DELIBRIAS 1976). No explanation seems to be available for the fact that in some cases truely constructional bioherms are formed and in other cases the more restricted features as cornices and platforms. Algal lips have been reported by NEWELL et al. (1959) and others; 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 however certainly not correct. Benches which are controlled by vermetid gastropods extend significantly above the upper limit of coralline algae. Surf benches are further described from Brazil (KEMPF & LABOREL 1968; DELIBRIAS & LABOREL 1971), West Africa (LABOREL & DELIBRIAS 1976), Venezuela (GESSNER 1970), Bermuda (OERTEL 1970), Puerto Rico (KAYE 1959) and the Dutch leeward Antilles (DE BUISONJÉ & ZONNEVELD 1960).

Pleistocene or Holocene fossil vermetid/coralline algal structures are known from many raised coasts (LABOREL 1969); some of them have been used to date old sea levels (DELIBRIAS & LABOREL 1971; SANLAVILLE 1972). Carboniferous vermetid/coralline algal structures, possibly more similar to the intertidal biostromes described form Florida (SHIER 1969), have been reported by BURCHETTE & RIDING (1977).

Definition of terms

The terms boring and burrowing are being used with varying implications in the biological and geological literature. Summarizing the results of a symposium which dealt specifically with the excavation of limestone by organisms, CARRICKER & SMITH (1969) proposed to restrict the term *burrow* for excavations made only with the purpose of living inside the excavation, and *boring* for excavations of skeletons with the purpose of obtaining food. Etymologically a burrow is a hole made in unconsolidated material ("earth"), while with boring a hard substrate is usually implicated, and this distinction, based on the substrate being unconsolidated or lithified, seems to be widely accepted (see GOLUBIC et al. 1975), especially in the geological literature where it has been fruitfully used, for example in recognizing the occurrence of marine lithification. This paper conforms to this original distinction and uses the term boring for all organic excavations in consolidated material, regardless of its purpose.

NEUMANN (1966) distinguished a *notch* as a subtidal, and *nip* as an intertidal feature. As we have seen however, the position of the indentation is gradually raised according as the turbulence increases, and the tidal oscillation has little to do with it. Where tidal oscillations are more pronounced, vertical ranges will increase, but without affecting the basic relation between profile morphology and water turbulence. Notches may occur below as well as far above tidal levels, never being really intertidal. For these reasons the term notch is used for all more or less V-shaped indentations in a cliff, related to sealevel, while the term tidal nip is not used at all. The term surf bench or platform is used in this paper for all relatively narrow and more or less horizontal ridges protruding seaward from the cliff wall (the reverse of a notch), and associated with organic accretionary activity. Many other terms have been used: ledge, terrace, ridge, cornice, trottoir, balcon etc. MOLINIER (1955) proposed to restrict trottoir to the small, entirely constructional features (fig. 6: 1). Pérès (1968) agrees, reserving the term platform for the erosive features (fig. 6: 5), but prefers the term cornice rather than trottoir. Since, as proposed in this paper, most of these structures are genetically similar, it seems not too important which of the names is used.

For other terms reference is made to Fairbridge (1968).

Conclusions

Although several well defined types of limestone cliff profiles can be distinguished it is clear that they form part of a continuous range of variation which can best be described as a function of water turbulence. Notches are zones of increased bioerosion (not excluding mechanical breakdown), platforms (benches) are zones of increased bioconstruction. Both phenomena depend on water turbulence, and both are therefore directly related to sea level, rather than to the tidal interval. Some profiles have two separate notches which are both contemporaneous. The term tidal nip is not maintained. Surf benches are very common throughout the world, and result primarily from the retarding effect on littoral erosion of organic accretions. Vermetid gastropods and coralline algae are among the most important framebuilders.

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