10

Limestone Coasts

Many workers have tried to define the elements of limestone coasts which could distinguish them from other coasts within the same climatic environments. In some parts of the world, and in some calcareous rocks, the processes and landforms are similar to those of other rock types. In the vigorous storm wave environments of the mid-latitudes of the northern hemisphere, for example, mechanical wave action plays an important role in the erosion of coasts consisting of the geologically younger, and usually physically weaker, limestones. The older, more resistant limestones, such as the British Carboniferous, however, are usually sufficiently resistant to wave action to allow other mechanisms to operate efficiently. The most characteristic features of limestone coasts are generally associated with warm climates and young calcareous rocks. Coral reef limestones occur between latitudes 30°N and S, and aeolianites (calcarenites), which are former Quaternary dune sands, between 15 and 45°N and S. Generally, weaker waves, higher temperatures, and an enormously varied marine biota favour chemical and biological activity on the calcareous rocks of the lower latitudes. Furthermore, the prevalence of magnesium-rich coral and aragonite, rather than pure calcite, may facilitate chemical action in tropical waters.

The term 'corrosion' is generally used in this discussion in preference to 'dissolution' or 'solution', to refer to the development of a variety of features which are characteristic of coastal limestone. This avoids the implication that the process involved in the formation of these features is necessarily chemical solution. As has been noted in previous chapters, there is much recent evidence to suggest that the causative mechanisms are, at least in part, salt fretting, and biochemical and bioerosional grazing and boring.

Corrosional Zones

Guilcher (1953, 1958a) proposed that the form of the littoral in limestone regions can be classified according to the temperature and tidal regime. He distinguished and described four main sequences of landforms (Fig. 10.1):

(*a*) In cool temperate regions and in limestones resistant to mechanical wave action, as on the Carboniferous Limestones of south Wales, southern Ireland, and Aran (Guilcher 1952a), the spray zone is pitted by small corrosion hollows a few millimetres in depth and less than five millimetres in width (microaveoles, vermiculations). These features are restricted to the wetter parts of the rock, and they disappear above the level which is frequently attained by spray. Lower down the platform, in the upper parts of the intertidal zone, the main feature is the presence of pools with fairly flat bottoms and overhanging edges. Sharp pinnacles or lapies (marine *karren*) coexist with these pools in the lower portions of the intertidal zone. They occur on subhorizontal as well as subvertical surfaces, but their development is best in exposed regions. Their average depth is between about 10 and 30 cm. The 'British' type of zonation has also been recognized in parts of northern Spain, northern Portugal, and western France (Guilcher 1958b), where the limestones are not too weak and wave action is strong. In parts of the northern Spanish coast, however, a platform a few metres in width slopes steeply seawards (mean slope 20°) beneath a visor and a notch at about mean sea level. The platform ends abruptly seawards in a low tidal cliff. The zonation is somewhat similar to that in tropical and subtropical waters, but although the platform has a number of deep pools with overhanging edges on it, wide shallow pools or vasques are absent. Guilcher suggested that the occurrence of this tropical-like zonation in the southeastern Bay of Biscay is a result of the higher temperatures in this area than elsewhere around the Bay. The zonation in the western Crimea is

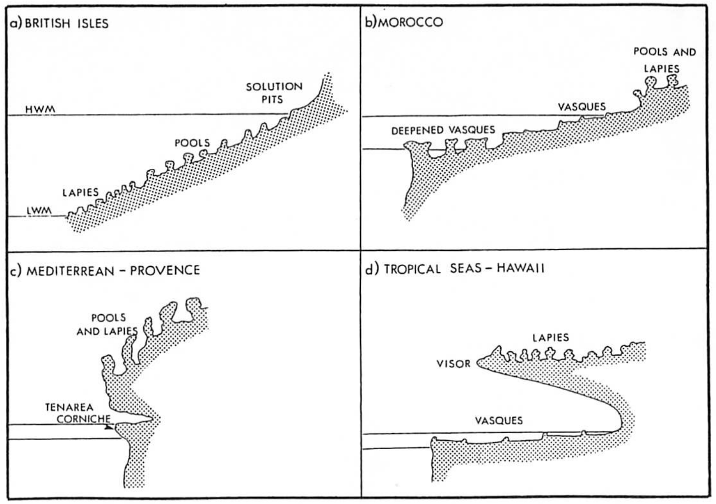

Figure 10.1. Littoral limestone zonations (according to Guilcher 1953).

similar to that in Britain, although many of the solutional hollows in this area have been modified by pothole abrasion (Givago 1950). Mechanical wave erosion is also dominant in the upper portions of the Carboniferous Limestone platforms of northern Britain, although corrosion is of more importance at lower elevations (Common 1955).

(*b*) In warm, tidal seas, jagged lapies are found further up the platform in the zone of spray and splash, as along the Atlantic coast of Morocco, southern Portugal (Guilcher 1957), and Barbados (Tricart 1972). These lapies, which are more dissected and pronounced than in Britain, are separated by small, flat-bottomed pools with overhanging rims. Vasques break the upper portions of the intertidal zone into a series of steps or terraces, each slightly lower than the preceding one. In the lower parts of the intertidal zone, the pools are much deeper (up to several decimetres), and they have overhanging sides. The intertidal zone terminates abruptly seawards in a small vertical or overhanging low tidal cliff. The upper pitted lapies zone may be separated from the vasques zone by an overhanging visor, but it is smaller than in tropical regions. A similar series of forms in aeolianite has been described by Fairbridge (1950) on Point Peron in Western Australia, and by Hills (1971, 1972) and Bird (1974) in Victoria.

(*c*) In the Mediterranean—a fairly warm sea without notable tides—lapies and pools with overhanging rims have formed in the spray and splash zones in Provence near Marseilles, and in Catalonia. There may be a notch at about the high tidal level, together with a lip or visor which can overhang by between 0.5 and 2 m. A constructional corniche of *Tenarea tortuosa* can form a second lip at lower elevations in the tidal zone (Guilcher 1953, Froget 1963, Nicod 1972). The lip-and-notch profile, however, is not always present in Mediterranean France. Near Nice, lapies and dish-shaped pools with overhanging sides dominate the spray and splash zones in dolomitic limestones. There is no corniche in this area (Debrat 1974). In Lebanon, corrosion features have been described by Dalongeville (1977) on a trottoir a few metres in width and about a quarter of a metre above sea level. The supralittoral zone is a fossil trottoir characterized by pools which are generally crater shaped, with concave bottoms and pinched-in sides. The fossil surface is separated from the contemporary trottoir by a low cliff with vermiculation-like depressions. Alveoles with overhanging rims, 5 to 8 cm in diameter and about twice as deep, occur at the back of the modern trottoir and in the lower supralittoral. Lower down the platform, the alveoles are smaller and shallower and there are some vasques, although they are not common in most parts of the Lebanon. Basins about a metre in diameter and almost as deep are found in the lower portions of the platform, where they are supplied by swash and always flooded.

(*d*) In very warm seas, as in Hawaii (Wentworth 1939), the Red Sea (Guilcher 1955), Madagascar (Battistini 1977, 1981), the Caribbean (Focke 1978), and India (Bedi and Rao 1984), the zonation in coral limestone consists of: lapies in the spray and splash zone; a lip and associated notch 1 or 2 m in depth at about the high tidal level; a platform with vasques occupying the intertidal zone; and a low tidal cliff. The lip and notch are conspicuous elements of warm seas, possibly because of high temperatures and small tidal ranges in many areas; this will be discussed later. Corrosional basins and deep notches and undercuts are found on the upper parts of the reef flats on Bikini and other nearby atolls (Revelle and Emery 1957). Residual or detrital rocks on the flats are often undercut ('negroheads'), providing convincing evidence that corrosion is effected by sea water, rather than by fresh water as was suggested by Wentworth (1939).

The degree to which variations in coastal corrosional forms in limestones can be attributed to differences in climate is still the subject of much debate. Some broad relationships between climate and landforms can be identified, such as the presence of vasques and deep corrosional notches and protruding visors in warm climates, and the generally greater efficacy of corrosional processes in these areas. Other factors, such as tidal range, the degree of exposure to wave action, and rock structure account for considerable differences in the character of limestone coasts between and within climatic regions. It is likely, for example, that the presence of deep notches and protruding visors in warm seas is at least partly a reflection of the generally low tidal range in tropical and Mediterranean areas. Furthermore, the usually more vigorous wave environments in the mid-latitudes of the northern hemisphere must exert an influence on the operation of erosional processes and on the form of the resulting landforms to a much greater degree than in tropical and Mediterranean environments.

The effect of variations in tidal range and exposure to wave action is manifested on the limestone coasts of Bermuda (Taillefer 1957, Neumann 1966). Two profiles can be distinguished. On the sheltered Harrington Sound coast, where tidal range is only 15 to 20 cm, the profile consists of a single notch, and a narrow and deep visor in the spray zone, finely sculptured with alveoles and lapies. On the more exposed northern and southern coasts, where the tidal range is 1 to 2 m, notches are found at a variety of elevations. On the southern coasts, notches have formed at the high and the low tidal levels, where they define the upper and lower limits of a platform of lapies and pools. The intertidal lapies become deeper and more evolved towards the sea, but they are less angular and the ridges are less sharp than those in the spray zone. There are also two types of profile on Oahu, Hawaii (Wentworth 1939). The bench profile consists of a level corrosional bench, up to 1 m above mean sea level, terminating abruptly seawards in a low tidal cliff. The bench is between 1.5 and 15 m wide, and its passes inland into a gradually rising pitted zone. In some places an abrasion ramp, a moat, or a quarried surface is found at the landward margin of corrosional benches. The second major type of profile, also described by Guilcher (1953), consists of a notch and an accompanying visor protruding outwards by up to 3 m. The top surface of the visor is pitted. A seaward-sloping platform or corrosional bench can extend for a metre or so from the base of the notch.

A particularly interesting study has been made of the effects of wave action on coastal lapies in the Bristol Channel in southwestern Britain (Ley 1977, 1979). Solutional relief is greatest in this area just below the mid-tidal level. Near the high tidal level the rock is pitted, joints have been partially enlarged, and there are some small, shallow pools with flat bottoms and extensive divides. Near to the low tidal level, the platform surface is flat and quite smooth, apart from the overdeepening and widening of joint and bedding planes. Ley (1979) proposed that the relief or surface area of the solutional features is proportional to the wave energy expended within the intertidal zone. Relief is greatest between the neap tidal levels, where the greatest amounts of energy are expended (see Chapter 1), and it declines with the reduction in wave energy towards the spring tidal extremes. As the platform is lowered by erosion, the surface area above the mid-tidal level increases as it becomes exposed to a zone of higher wave energy. Below the mid-tidal level, platform lowering causes a decline in wave energy, progressive removal of the lapies, and a reduction in surface area. Ley considered, therefore, that a state of dynamic equilibrium exists, in which a constant amount of erosive energy is expended per unit area. As the tidal range increases, the degree of concentration of wave energy between the neap tidal levels decreases, so that the degree of microrelief about the mid-tidal level must also decline; this occurs towards the eastern parts of the Bristol Channel. Alternatively, increasing wave fetch increases the energy expended between the neap tidal levels, and therefore the degree of microrelief. Ley found that the degree of development of the lapies increases with the purity of the limestones.

Some typical corrosional features of limestone regions are also well developed in calcareous aeolianites, but in the calcareous sandstones of southern California, the dominant elements are shallow tidal pools, many of which have flat bottoms and raised rims (Emery 1946). Similar forms have been reported from other areas (see Chapter 2). It should also be noted that features such as aveoles, lapies, and shallow pools are produced in non-calcareous rocks (such as basalts, granites, and other igneous lithologies) by salt fretting, particularly but not exclusively in the low latitudes (Guilcher *et al.* 1962, Tricart 1972, Consentius 1975, Guilcher and Bodere 1975).

Plates-formes à Vasques

The term *plates-formes à vasques* originates from the work of Guilcher (1953) and Guilcher and Joly (1954) in Morocco, although it describes a feature which is essentially analogous to the solution benches of Hawaii, previously described by Wentworth (1939). Vasques are wide (up to several decimetres), shallow pools with flat bottoms, which form a network consisting of a tiered, terrace-like series of steps on limestone, and particularly aeolianite, platforms. The pools are separated from each other by sinuous, narrow, lobed ridges, between 1 and 20 cm in height, running continuously for dozens of metres (Fig. 10.2). Vasques can develop on trottoirs which are fronted by vermetids. The *plates-formes à vasques* develop between the high and the low tidal levels. They are submerged at high tide, but fed by breaking waves at the low tidal level, with the return flow cascading down into the successively lower pools.

The rims surrounding each pool can be residual corrosion features marked by the pinnacles of lapies; built by organisms such as calcareous algae, vermetids, or even serpulids; or a combination of the two (Guilcher 1958a). Guilcher (1953) suggested that the pools are more corroded than the rims, which are partly protected by organic growths; although in southern and southeastern Madagascar, some vasques have developed on the lower portions of trottoirs as a result of the enlargement of boreholes (Battistini 1980). True *plates-formes à vasques* have only been recorded from intertropical and Mediterranean climatic regions. Battistini and Guilcher (1982) and Dalongeville and Guilcher (1982) made a survey of

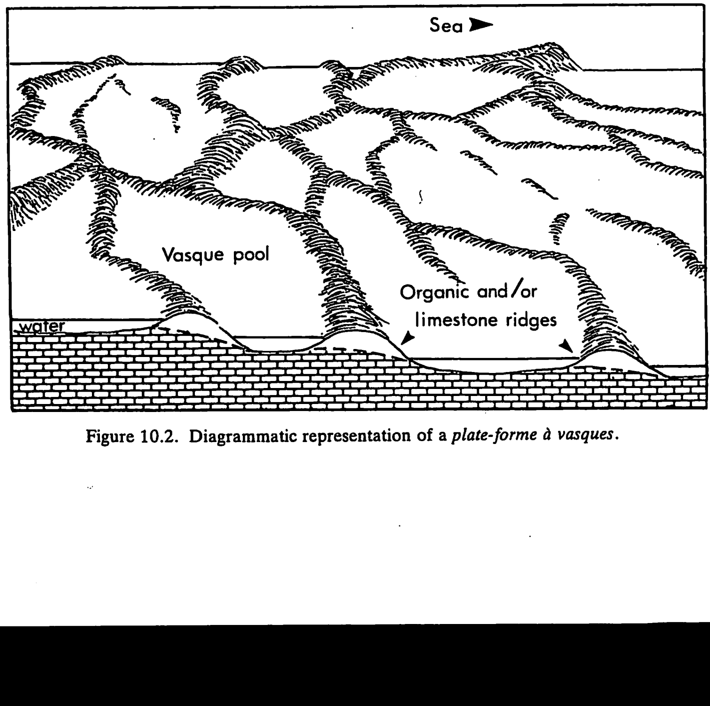

Figure 10.2. Diagrammatic representation of a *plate-forme à vasques*.

the literature to determine their occurrence, and the nature of the intervening rims. In the Mediterranean, the platforms occur as far as 40°N. in Italy and in Sardinia, which is further north than in the Atlantic. They have been reported from Syria, Lebanon (Dalongeville 1977), Israel (Safriel 1966), Cyprus, Crete, Turkey, Morocco (Guilcher 1953), Malta (Paskoff and Sanlaville 1978), Tunisia, Algeria (Guilcher 1954), Spain, Italy, and Sardinia. As elsewhere, there are rims which are constructed and others which are non-constructed, as well as ridges consisting of country rock with a cover of organic material. These various forms can coexist in the same areas. Exposed environments appear to facilitate the development of these platforms (Dalongeville and Guilcher 1982). Outside the Mediterranean (Battistini and Guilcher 1982), vasques have been described in Hawaii (Wentworth 1939), Guam (Emery 1962, Tracey *et al.* 1964), New Caledonia, the New Hebrides (Guilcher 1974b), Tonga, western and southeastern Australia (Fairbridge 1950, Hills 1971), Puerto Rico (Kaye 1959), Desirade in the Lesser Antilles, Barbados (Tricart 1972), the Netherlands Antilles (Focke 1978), Costa Rica, northeastern Brazil, Madagascar (Battistini 1980, 1981), Inhaca off Mozambique, Kenya (Bird and Guilcher 1982), the Red Sea (Guilcher 1952b, 1955), and in southern Portugal (Guilcher 1957).

Corniches and Trottoirs

Organogenic formations assume an important role in the development of calcareous coasts in warm climates. The terms 'trottoir' and 'corniche' have been used to describe organic protrusions which grow out from steep rock surfaces at about sea level, as well as rock ledges which are cut into the littoral rock and coated with a thin crust of organic material (Molinier 1955a, Pérès 1968). Although both phenomena provide narrow pavement or sidewalk-like paths at the foot of marine cliffs, in this chapter, 'corniche' will be used to describe the former situation, and, in accordance with the original definition of Quatrafages (1854), 'trottoir' (literally, footpath or pavement) will be used to refer to the erosional rock ledges and their organic veneers (Fig. 10.3).

Three major types of organic reef have been distinguished in the western Mediterranean (Pérès and Picard 1952, 1964, Molinier and Picard 1953, 1954). They are:

1. reefs formed of calcareous red algae at about the mean sea level;
2. corniche composed of polychaete worms (Serpulidae), which develop below mean sea level and are usually submerged—Folke (1978) has argued that these deposits often turn out to be misidentified Vermetid tubes; and
3. erosional ledges, slightly below mean sea level, with a veneer of sessile Vermetid gastropod tubes.

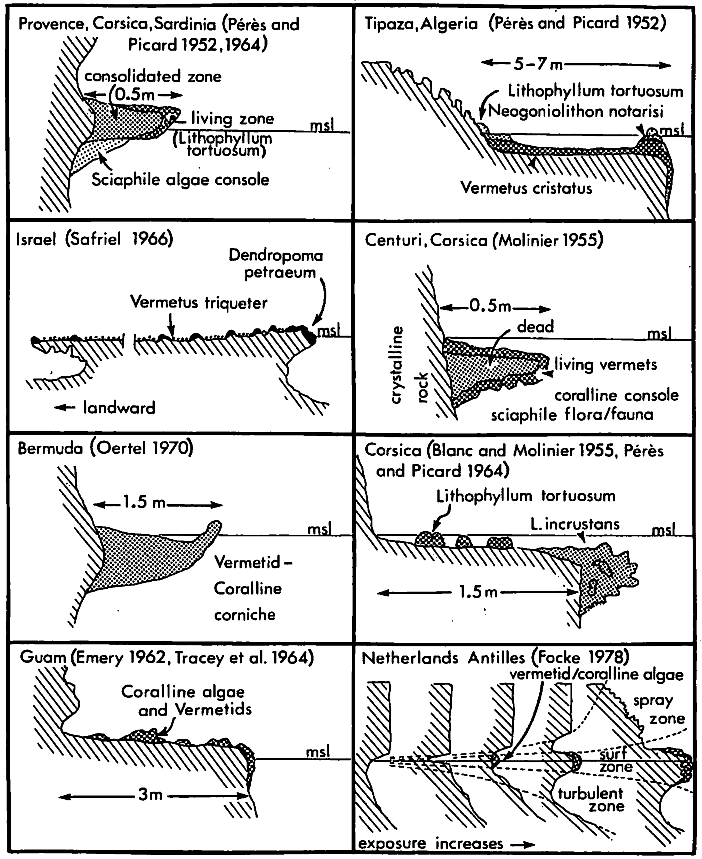

Figure 10.3. Examples of coastal corniche and trottoir.

In the Mediterranean, corniches are usually composed of the calcareous alga *Tenarea tortuosa* (= *Lithophyllum tortuosum*), and other diverse Melobesieae algae, such as *Neogoniolithon notarisi.* They are oranic accumulations, which protrude out about 0.5 to 2 m from steep coastal slopes, at about the mean sea level (Guilcher 1953, 1958a, Froget 1963, Nicod

1972). Corniches are essentially intertidal structures which are absent in calm, sheltered areas. They cannot withstand the impact of the strongest waves, however, and are therefore best developed in the inlets of exposed coasts (Pérès and Picard 1952, 1964). Although *T. tortuosa* can survive in areas where it is subject to direct sunshine, it seems to prefer less insolation. This could explain why corniches develop better on very steep slopes than on gentle gradients, and particularly why they favour north-facing surfaces (Pérès and Picard 1952). The outer portion of corniches consist of living algae, but diagenesis of the interior makes the formation very resistant to wave attack.

The growth of algal corniches also provides suitable environments for a variety of fauna and flora. On the surface of well-developed corniches are populations which are tolerant of strong insolation and prolonged periods of emersion. On the lower face, there is usually a population of overhanging sciaphiles (Blanc and Molinier 1955). Cavities within the formation are filled by a variety of bivalves, gastropods, spiders, mites, crustaceans, and worms (Pérès and Picard 1952, 1964, Guilcher 1953, Pérès 1968). Molinier (1955b) and Blanc and Molinier (1955) have described massive corniches 20 to 30 cm in width in Corsica composed of the Melobesieae *Lithophyllum incrustans* mixed with some *Corallina mediterranea*, and on the lower face *Lithothamnium lenormandi*. These accumulations are largely infralittoral, although the upper portions can extend into the lower mesolittoral. They form projecting corniches bordering a small erosive terrace about 1.5 m in width, cut in sandstones. The terrace itself has pads of *T. tortuosa* in semi-shaded hollows. Where the rock is subjected to strong insolation, however, the battered edge of the terrace is densely populated by species of the brown algae *Cystoseira*, and the surface by isolated, thin crusts of *Vermetus cristatus*. Molinier (1955b) and Blanc and Molinier (1955) have also discussed the occurrence, in Corsica and near Marseilles, of fist-sized *bourrelets* or pads of *C. mediterranea* and *L. lenormandi*. They develop in a shaded environment in the infralittoral zone, below a *T. tortuosa* corniche. The coralline algae trap detrital material carried by the sea, which is then cemented by the encrusting *L. lenormandi*. It therefore grows in thickness, always covered by the coralline algae. Sipunculids and foraminifera also contribute to their development.

Corniches of *Tenarea* are not restricted to calcareous substrates. In Catalonia, for example, they have developed on crystalline rocks (Barbaza 1970), but they do not form on friable rocks, presumably because the *Tenarea* thalli need rocks of a certain hardness to become fixed (Pérès and Picard 1952). They are nevertheless usually larger and more regular on limestones and calcareous sandstones, where a notch can develop in the supralittoral zone which is exposed to the physical and chemical effects of spray.

In several parts of the western Mediterranean, as in Corsica and the south of France, there are corniches or 'balconies' composed of Serpulid worms and Melobesieae algae (Pérès and Picard 1952, 1964). They are found on resistant rocks in sheltered environments, below mean sea level in the upper part of the infralittoral. In Corsica, a reef on granite is composed of Melobesieae algae, and several Serpulid species, *Protula* sp., *Serpula vermicularis, S. concharum, Vermiliopsis multicristata*, and particularly, *Pomatostegus polytrema*.

Vermetids do not generally flourish in the northern parts of the western Mediterranean, where most organic reefs consist of calcareous algae and Serpulid worms. Temperatures are more favourable for large Vermetid populations in the southern parts of the Mediterranean, where they grow vigorously on narrow ledges cut into the littoral rock (Safriel 1966). Quatrefages (1854) first mentioned the occurrence, in Sicily, of a trottoir just below mean sea level; although he failed to realize that the Vermetid tubes only provide a thin veneer to an eroded rock surface below. Purely constructional Vermetid and coralline algae corniches can form on fairly resistant, even non-calcareous, substrates. Trottoir platforms, however, develop where the rock is fairly easily eroded, as in weak limestones and sandstones. Erosion occurs in the spray zone, forming an eroded, subhorizontal platform which is quickly covered by Vermetid tubes, especially on the wave-battered fringes of the platform. Continued erosion of the cliff slowly widens the platform, which is protected by the Vermetid encrustations. These platforms are up to 7 to 8 m in width in Sicily and Algeria (Pérès and Picard 1952, Molinier and Picard 1953).

Vermetid encrustations (Keen 1961) have been reported from around the western Mediterranean, in France (Molinier 1955a,b, Debrat 1974), the Balearic Islands (Molinier 1954, Molinier and Picard 1957), Italy (Molinier and Picard 1953), Algeria (Pérès and Picard 1952), and Tunisia (Molinier and Picard 1954). Trottoirs are usually associated with thin crusts (several centimetres thick) of *Vermetus cristatus* Biondi (= *Dendropoma petraeum*) below mid-tidal level in the infralittoral zone. In Algeria and Sicily, the Vermetid crust attains its greatest thickness on the seaward margins of the platform, where the water is most agitated. It is also thicker, however, along the edges of fractures, which may correspond to fissures in the underlying rock. This produces a *plate-forme à vasques* consisting of broad shallow pools separated by elevated Vermetid ridges (Molinier and Picard 1953). At Tipaza in Algeria, *V. cristatus* only occupies the back of the platform, whereas the rest of the platform and the seaward terminus carries *V. triqueter* (Pérès and Picard 1952). If the Vermetid crust is sufficiently built up, it may become covered by *Tenarea* and *Lithothamnium* algae in the lower portions of the mesolittoral zone (Molinier and Picard 1953, Molinier 1954). This generally occurs at the seaward and landward margins of the platform. In Majorca, for example, limestone ledges in the lower mesolittoral zone are partially protected from corrosion by *Tenarea* and *Neogoniolithon notarisi* (Molinier and Picard 1957). In the Balearic Islands, the infralittoral platform is covered by thin veneers of *Vermetus cristatus*, interdispersed with *Laurencia popillosa*, the coralline algae *Jania rubens*, and the calcium-depositing Phaeophyta *Padina* (Molinier 1954). In some semi-shaded places in Corsica, Vermetids have been replaced by *Tenarea* algae on narrow terraces in the infralittoral zone (Molinier 1955b).

Blanc and Molinier (1955) and Molinier (1960) also identified Vermetid *mergelles* or curbs in Corsica. Unlike the true Vermetid trottoir, they are not formed in crusts or pads, but as projecting bulges at the wave-battered fringes of beds of schist which dip slightly seawards. They are cemented on the surface in the lower mesolittoral by the calcareous alga *N. notarisi*, and sciaphile flora develop below the overhang. Vermetid corniches can develop on hard substrates which are resistant to marine erosion. On the island of Centuri, northwest of Cape Corsica, Vermetid tubes have accumulated on the battered fringes of metamorphic rock slabs, forming structures which are similar to projecting *Tenarea* corniches. The presence of Vermetids in the mesolittoral zone on Centuri and in parts of Corsica may be related to particularly intense wave action, which shifts their habitat upwards (Molinier 1955a).

Vermetid trottoirs are also common in the eastern Mediterranean (eg. Safriel 1966, Sanlaville 1972). They are usually quite narrow, but they can be dozens of metres in width in aeolianites (Fevret and Sanlaville 1966, Dalongeville 1977). Safriel (1966) suggested that differences in the form of Vermetid platforms in the western and eastern Mediterranean reflect the slightly higher temperatures in the east, where subtropical conditions may prevail in summer. In northern Israel, horizontal Vermetid-encrusted ledges attached to the land, similar to those in the western Mediterranean and in Lebanon (Fevret and Sanlaville 1966, Dalongeville 1977), were considered to represent immature forms. Mature Israeli platforms on the other hand, are broad, flat, round or elliptical, surf swept and awash at low tide, and possibly separated from the coast by hundreds of metres of water. They have overhanging edges and raised margins. *Dendropoma petraeum* (= *V. cristatus*) occupies the raised platform margins and the edges of the terraced pools, where wave action is strongest. *Vermetus triqueter* (= *V. gregarius*) is found on the platform surface, as it only thrives in areas which are underwater, or sheltered from direct surf action. Safriel (1966) proposed that in Israel, the Vermetid communities develop simultaneously with the formation of the platform, rather than after the platform has been formed. He proposed the following sequence of development:

1. the formation of corrosion basins in limestones or aeolianites;

2. barnacles first colonize the rims of these basins, but *Vermetus* arrives when the basins become deep enough to be permanently filled with water;
3. *Dendropoma* replaces the barnacles on the basin rims when they have been lowered to an appropriate level, and further lowering then almost ceases, because of the protection afforded by this cover; and
4. ledges form as the basins coalesce, as *Dendropoma* fails to protect the increasingly sheltered internal rims.

Trottoirs are also common in tropical seas, in Cape Verde, Senegal, Ghana, and Barbados. The 'boilers', which resemble microatolls, are related forms in Florida and Bermuda (Prat 1935, Guilcher 1953, Laborel 1966).

Safriel (1974) compared the atoll-like reefs of Israel and Bermuda. In both areas, the circular platforms have raised, overhanging rims, and they retard the erosion of exposed promontories. In Israel, however, the Vermetids, cemented by coralline algae, form a thin crust over the underlying limestone, whereas in Bermuda, the reefs are growing, wave-resistant, biogenic structures. The lower interiors of the reefs in Israel are the result of erosion, but in Bermuda they are the result of differential growth. In Bermuda, calcareous algae cement the tubes of *Dendropoma irregulare* and *Petaloconchus nigricans*. On the exposed, tidal southern coast, Vermetids develop between the visor and notch in the mesolittoral and the overhang created by infralittoral erosion below. In sheltered Harrington Sound with its very small tidal range, the Vermetids are less abundant, although they are at the same level as on the southern coast. This area has little biological erosion in the mesolittoral, but much more in the infralittoral (Laborel 1966).

Throughout the tropical Atlantic, a well-developed surf platform occurs within the range of encrusting coralline algae (*Porolithon, Lithophyllum* etc.) and Vermetids. *Millepora*, gargonians, corals, and sponges play a similar but less effective role in some areas (Newell 1961). They have been reported from Brazil (Kempf and Laborel 1968, Delibrias and Laborel 1971), west Africa (Laborel and Delibrias 1976), Puerto Rico (Kaye 1959), Barbados (Newell and Imbrie 1955, Newell 1956, Tricart 1972), the Bahamas (Newell 1961), the Netherlands Antilles (Focke 1978), the Cayman Islands (Woodroffe *et al*. 1983), and Venezuela (Gessner 1970).

Concretionary formations occur in a number of areas in Brazil (Kempf and Laborel 1968). They are composed of calcareous algae (Melobesieae) and *Petalonconchus varians* and *Dendropoma irregulare* Vermetids. They are found on igneous rocks as well as on sandstones and coral limestones, but always in the upper infralittoral, in areas exposed to strong wave action. A recent change in environmental conditions may be responsible for the replacement of *Petalonconchus* by *Dendropoma*, and the Vermetid in general by calcareous algae. On the weaker rocks (aeolianite, silaceous marine sandstones, dead coral), horizontal platforms have formed in exposed environments at the boundary between the meso- and infralittoral zones. These can be covered by Vermetids as in Sicily (Molinier and Picard 1953), but boilers develop if they only form on the outer edge. On hard rocks, *bourrelets* or flanges form a type of corniche on steep rock surfaces in Brazil and Corsica (Molinier 1955b).

Focke (1977, 1978) has described the development of limestone cliffs in Curaçao and elsewhere in the Netherlands Antilles (Figs 10.4 and 10.5). Rapid bioerosion occurs in the intertidal zone. The form of the coastal profile is dependent upon the degree of exposure (Fig. 10.3). In sheltered areas, notch profiles predominate, but without significant organic accumulations. Accretions are common in more exposed areas, but they are restricted to a narrow vertical zone in the middle of the cliff notch, at about the mid-tidal level. In the most exposed areas, the coralline algae and the Vermetid accretions become thicker, better lithified, and higher, and they have given rise to protruding surf benches (trottoirs) up to 10 m wide, and as much as 2 m above mean sea level. These accretions are primarily constructed by the Vermetid gastropod *Spiroglyphus irregularis* (= *Dendropoma irr.*) and the coralline algae *Lithophyllum congestum* and *Porolithon pachydermum*. Sessile foraminifera and internal sediment help to fill the cavities. The level of the platforms is determined by the highest point at which the Vermetids are able to build accretions. Focke noted that there may be just as many frame-building organisms in sheltered as in exposed coastal regions. The occurrence of accretions in exposed areas is therefore apparently related to water turbulence, possibly because of its positive effect upon the supply of nutrients to the organisms, or possibly because lithication is facilitated by the large amounts of water pumped through the accretions. Lithication, by aragonite and magnesian calcite cements, strengthens the accumulations against wave attack and seals the substrates, protecting them from biodegradation. Fevret and Sanlaville (1966) and Focke (1977, 1978) have suggested that as platforms widen they retard erosion in the spray zone and notch, until eventually a state of dynamic equilibrium must be attained. On the Cayman Islands, it has been proposed that the surf benches, which are slightly above mean sea level, are in equilibrium with the present sea level and with wave energy conditions. In one area, for example, the rate of platform lowering is only 0.2 mm yr^{-1} (Woodroffe *et al*. 1983). It has also been argued that other types of shore platforms are in equilibrium with their environments (see Chapter 9).

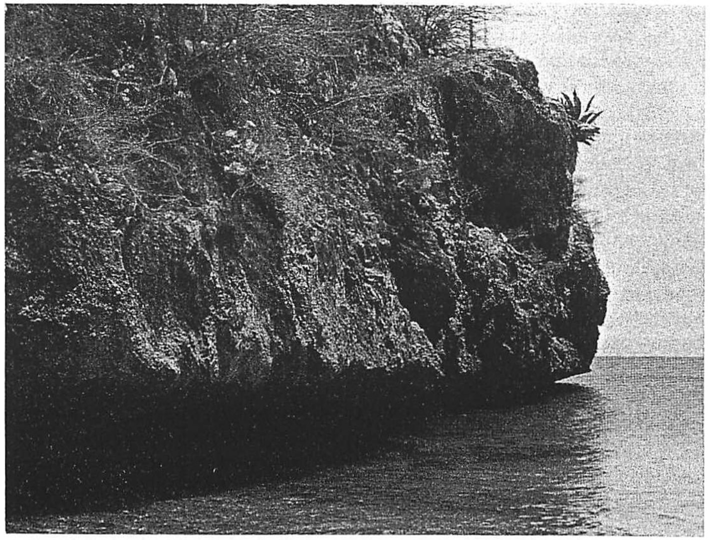

Figure 10.4. Notch in coral limestone on the sheltered southern coast of Curaçao, Netherlands Antilles.

Figure 10.5 Surf bench with vasques on the exposed northern coast of Curaçao, Netherlands Antilles. Benches in this area are backed by lapies and pools and occasionally by a notch in the spray zone. The outer portions of these benches are undercut by a subtidal notch.

In the tropical Pacific, the lime-secreting algae, particularly *Porolithon onkodes* (Newell and Imbrie 1955), have greater durability and possibly faster growth rates. This results in the development of algal ridges near the seaward ends of reef flats (Newell 1961). Vermetid-rimmed terraces up to 6 m in width and 3 m above mean sea level have been reported on Guam (Emery 1963, Tracey *et al*. 1964).

Notches

Deeply undercut cliffs, platforms, and reef flat boulders are prominent features of limestone coasts in tropical regions, but notches are found in other climatic environments, and in other types of rock (see for example, Kelletat 1982). Near Tokyo, Japan, the formation of a notch in tuffs has been attributed to solution, hydration, alternate wetting and drying, and organic acids released by attached organisms (Emery and Foster 1956). Wave-cut notches have been produced in homogeneous cement and plaster blocks in wave flumes (Sanders 1968b, Sunamura 1973). In Britain, chalk and limestone notches have been cut by wave action (Common 1955, Wood 1968, Trenhaile 1969). In cool regions, however, notches are generally poorly defined in fairly homogeneous rocks, and locally restricted where they are associated with lithological and structural variations. On Hudson Bay, for example, angular notches have developed along structural planes of weakness, as a result of the effects of waves, the ice foot, and gelifraction (Allard and Tremblay 1983).

Deep, narrow notches in warm seas are usually found in areas with a very low tidal range, probably because the erosive processes are concentrated within a narrow range of elevations. The effects of tidal range and exposure on the development of limestone coasts in Bermuda have been considered by Taillefer (1957) and Neumann (1966). Taillefer compared the sheltered, inland sea coast of Harrington Sound, which has a tidal range of only 15 to 20 cm, with the more exposed southern coast of the island, where the tidal range is 1 to 2 m. Neumann made a similar comparison between the northern coast and the Harrington Sound coast. On the southern coast, Taillefer found that a well-developed notch has formed at the high tidal level, as well as a less continuous one at the low tidal level; these notches are separated by a surf bench. A visor above the high tidal notch was attributed to induration of the aeolianite at the level at which sea water inhibits the downward percolation of fresh water charged with calcium carbonate. Hodgkin (1970), however, has argued that the visor in coral limestones is a residual feature, restricted to areas backed by a low cliff. Neumann found notches above, within, and below the intertidal zone on the northern coast, although there is no continuous intertidal notch in this area. In Harrington Sound, however, the limestone cliffs are usually deeply undercut, overhanging by as much as 3 to 4.6 m. Taillefer reported that this notch is intertidal, but Neumann found that it developed just below the low tidal level, although it is exposed for a few weeks each year during extreme tidal periods. The notch has a flat roof, corresponding to the low tidal level, and is independent of variations in rock structure. Neumann considered the notch to be the result of rock borers, such as sponges, pelecypods, and worms, which are particularly active near the water level, where wave agitation provides a regular supply of nutrients and aids in the removal of the weakened rock particles.

Focke (1977, 1978) showed that the degree of exposure also has a profound effect upon the form of limestone notches in Curaçao in the Netherlands Antilles (Figs. 10.3, 10.4 and 10.5). In sheltered areas, notches have developed about the mid-tidal level, but where the waves are more vigorous the increased turbulence of the water facilitates the accumulation of organic material, largely consisting of Vermetids and calcareous algae. These crusts develop in the centre of the notch and protect the underlying rock, dividing the original notch into two sections, one above, and another below a protruberance. In the most exposed areas, the spray zone reaches up to the top of the cliff, and the upper notch is generally replaced by a corroded slope. Progressing seawards, the coastal profile then consists of this slope, a trottoir, and the lower notch. This relationship between the form of the coastal profile and the exposure to wave action has also been noted on Grand Cayman (Woodroffe *et al*. 1983). A similar organically induced division of a notch into two sections occurs in Puerto Rico (Kaye 1957). These notches are contemporary, but other workers believed that double or multiple notches are evidence of changes in sea level, or intermittent tectonic events.

Double notches are very common in a number of areas, as in the Ryukyu Islands (Takenaga 1968), Borneo and Malaysia (Hodgkin 1970), eastern Indonesia (Verstappen 1960), Guam, Puerto Rico (Kaye 1957, 1959), and Barbados (Tricart 1972). Fairbridge (1948, 1950, 1968b) considered that notches form at about mean sea level, so that those which are now below the low tidal level must reflect former lower sea levels. If Holocene sea levels have been higher than today (Chapter 7), then the contemporary notch may be found a little below a notch or notches formed during recent stillstands of the sea (Tricart 1972). In the Bismarck Archipelago, the presence of a higher notch has been attributed to the sea level responsible for a 1.5 m terrace found throughout the Pacific and Western Australia (Christiansen 1963) (see Chapter 7). MacFadyen (1930) and Guilcher (1952b) have reported the presence of double notches around the Red Sea. Guilcher found that double notches, 1.2 to 1.4 m apart, only exist in sheltered areas, and are replaced by a single notch in exposed sites. The higher notch was attributed to the maximum of the Dunkerkian sea level.

Notch levels are similar to those reported in Western Australia (Teichert 1950).

There are undoubtedly many reasons other than changes in relative sea level, which might account for the formation of multiple notches on limestone coasts—for example, because of variations in rock structure and lithology, and possibly because different notch-forming mechanisms operate most efficiently at different elevations. Some workers have found that the main intertidal notch develops at or close to the high tidal level (Wentworth 1939, Guilcher 1953, 1958a, Newell 1956, Verstappen 1960, Christiansen 1963, Takenaga 1968, Hills 1971, Tricart 1972, Nicod 1972), although notches are frequently found at other elevations. On the northern Adriatic coast of Yugoslavia, for example, the notch is always below the mean high water level (Schneider 1976, Torunski 1979). Several workers in different areas have found that the notch normally develops at or close to the mid-tidal level (Ginsburg 1953b, Guilcher 1958b, Hodgkin 1964, Teichert 1947, 1950, Fairbridge 1948, 1968b, Sweeting 1973, Debrat 1974, Trudgill 1976b, Bird *et al.* 1979, Woodroffe *et al.* 1983). Kaye (1957, 1959) placed the formation of notches in Puerto Rico in the zone extending from the level of the low tidal wave trough up to the level of mean high waves; that is, the upper and lower limits of the notch are determined by mean wave height. On sheltered coasts, he found that the deepest part of the notch is at the mid-tidal level. A different type of notch forms just below the intertidal zone, as in sheltered regions of Bermuda (Neumann 1966, 1968), Curaçao (Focke 1978), and elsewhere in the humid tropics (Tricart 1972).

The debate over the precise level of formation of notches in the mesolittoral zone partly reflects the very small tidal range in nearly all the regions in which the notches are found. Determining the elevation of a notch relative, for example, to the high or mid-tidal level requires decisions involving vertical intervals of fractions of a metre in many areas. Given the general lack of precise measurement and the poor reliability of tidal data in relation to terrestrial bench-mark elevations in many regions, it is difficult at present to confidently determine the levels of notch development in relation to tidal levels. Notch formation seems to be facilitated by a very small tidal range. Distinct notches appear to be associated with warm, microtidal coasts, and they are usually difficult to discern when tidal ranges are greater. As the tidal range increases, notches can develop close to both the high and the low tidal levels (Taillefer 1957, Flemming 1965, Hills 1971, Battistini 1980, 1981).

The tidal range and the degree of exposure affect the morphology of notches. In general, the higher the amplitude of the waves and the higher the tidal range, the greater is the difference in elevation between the notch roof and floor (Newell 1961, Butzer 1962, Christiansen 1963, Neumann 1966, Hodgkin 1970, Focke 1978, Torunski 1979). Takenaga (1968), for example, measured and classified aspects of the morphology of 139 notches on the Ryukyu Islands, Japan. He found that the height of the notch roof corresponds to the upper limit of sea spray, and is therefore greatest on open coasts. Verstappen (1960), and later Russell (1963), concluded that notches on exposed coasts have flat floors and often steeply inclined roofs, caused by the effects of surf and spray, but in sheltered areas they are essentially horizontal incisions with nearly flat roofs. The vertical height range of these notches increases with tidal range (Fig. 10.6*a*).

Notches in the humid tropics typically range from 1 to 5 m in depth (Tricart 1972), but they are considerably deeper under favourable circumstances. In western Barbados, for example, notches in soft coral marl are more than 30 m in depth. Deep notches in Barbados form where the coral lacks joints and other fissures which promote cliff collapse, the debris is quickly removed from the cliff base, and sand is available for abrasion. There is little relationship here between notch depth and wave energy (Bird *et al.* 1979). Notches have formed in sheltered as well as in exposed areas (Wentworth 1939, Guilcher 1953, 1958a, Emery and Foster 1956, Christiansen 1963), but in some places, notch depth does appear to be related in a complex way to the exposure to wave action. In the French Mediterranean, notches have attained their best development on the

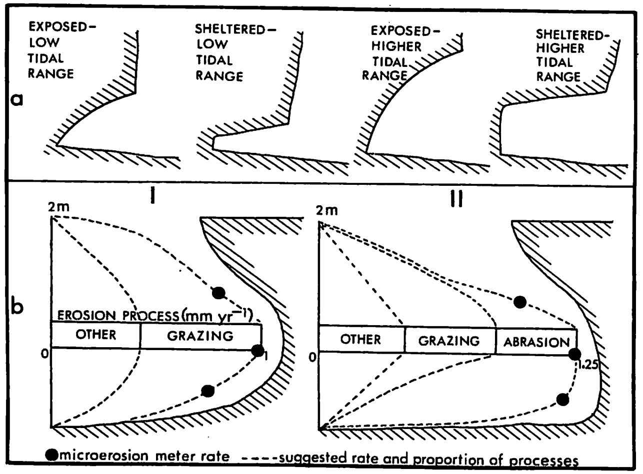

Figure 10.6. (*a*) The effect of tidal range and exposure on the form of the notch in eastern Indonesia (after Verstappen 1960). (*b*) Erosion rates and processes in notches on Aldabra Atoll, where I) sand is absent; and II) sand is present (Trudgill 1976b).

extremities of headlands (Froget 1963, Debrat 1974), and they are absent from the most sheltered areas in Borneo and northwestern Malaysia (Hodgkin 1970). In the western Atlantic (Newell 1961), the Red Sea (MacFadyen 1930), and Oman (Vita-Finzi and Cornelius 1973) the most deeply cut notches are often found in sheltered areas (Fig. 10.4). On the Ryukyu Islands there appears to be a negative relationship between notch depth and the strength of the waves (Takenaga 1968). This is consistent with Trudgill's (1976b) observation that coastal profiles around Aldabra Atoll change from notch to cliff to ramp as the degree of exposure increases. The depth of the notch is also probably related to numerous other aspects of the morphology of the littoral zone. In eastern Indonesia, tidal currents generated in the narrow entrances to bays produce particularly deep notches (Verstappen 1960). In Curaçao (Focke 1978) and elsewhere, it has been suggested that the surf platform is in a state of equilibrium on exposed, windward coasts; this may control the depth of the notch by determining the amount of spray and splash which can reach it, and therefore prevent marked variations in its morphology through time.

The controversy over the origin of notches in warm seas is essentially a specific aspect of the larger debate over the origin of coastal limestone features in general (see Chapters 3 and 4). It was formerly believed that notches are produced by mechanical wave erosion (Agassiz 1895, Prat 1935), but most investigators now consider that chemical or biochemical corrosion, or biological grazing and boring activities, are dominant. This view is partly a response to the observation that notches are often well developed in sheltered locations. MacFadyen (1930) suggested that deep undercuts in Red Sea corals were produced by seawater solution and organic boring, but he was unable to determine which is the more important. Wentworth (1939) thought that notches are formed where fresh groundwater emerges, and below which the rock is saturated with seawater. This theory was devised to circumvent the difficulty of accounting for limestone solution features around the shores of lime-saturated seas. Notches, however, have formed around the base of mushroom-shaped rocks on reef flats ('negroheads') (Umbgrove 1931, Revelle and Emery 1957, Russell 1963), where there can be very little groundwater seepage from the base (Panzer 1949). Furthermore, as Guilcher (1953, 1955) has noted, notches have also developed in arid areas such as the Red Sea, where there is little fresh water. Panzer (1933) considered that notches are formed by seawater solution, and this view has been supported by many other workers (Fairbridge 1948, Kuenen 1950, Guilcher 1953, 1958a, Revelle and Emery 1957, Kaye 1957, Taillefer 1957, Verstappen 1960, Christiansen 1963, Russell 1963, Tricart 1972), although the mechanism is poorly understood. Corbel (1954, 1956) proposed that deep notches in the limestones of Spitsbergen and the Gulf of St Lawrence were produced by solution related to sea water and the presence of snow on the ice foot; it is likely, however, that wave action and frost play an important role in the undercutting of the coastal cliffs in these areas.

Many other workers have emphasized the work of organisms in the development of limestone notches (Newell 1956, 1961, Hodgkin 1964, 1970, Neumann 1966, 1968, Debrat 1974, Focke 1978, Torunski 1979, Schneider and Torunski 1983). Endolithic algae, browsing gastropods, the *Cliona* sponge, and boring pelecypods are often mentioned as being active in the notch zone. Schneider (1976), for example, recognized the polychaete *Polydora ciliata*, the sponge *Cliona vastifica*, and the pelecypods *Lithophaga lithophaga* and *Gastrochaena dubia* in a notch in the northern Adriatic. In this area, the intertidal notch on limestone coasts is thought to be completely biogenic in origin (Schneider and Torunski 1983). In support of the bioerosional origin of notches, it has been observed that they develop in turbulent water, which increases the supply of nutrients to the organisms and helps to remove the weakened rock particles (Neumann 1966). Alternatively, it has been argued that this association is because turbulent water flows quickly, or because it is charged with air bubbles and carbon dioxide, making the water aggressive and facilitating the formation of notches by chemical solution (Guilcher 1953, Kaye 1957, Nicod 1972, Tricart 1972). Some workers have insisted that abrasion and other forms of mechanical wave erosion play a significant role in notch development (Froget 1963, Takenaga 1968). The absence of notches in sheltered areas and the occurrence of smooth forms at exposed sites in the Langkawi Islands in Malaysia, convinced Tjia (1985) that they are the result of abrasion. In Oman, notches are cut by wave action in rocks which have been weakened by the borings of *Lithophaga* (Vita-Finzi and Cornelius 1973). According to Bird *et al.* (1979), solution plays a minor role in western Barbados, where the notch is largely the result of physical processes, increasing in depth where sand is available. Trudgill (1976b) made a detailed investigation of the rates and mechanisms of limestone erosion on Aldabra Atoll in the Indian Ocean (Fig. 10.6*b*). He found that chemical solution by sea water is possible in this area, although it is of minor significance. Where sand is absent, grazing organisms account for between one-third and one-half of the notch erosion on Aldabra. Where there is sand at the foot of the notch, abrasion assumes a major role, accounting for about one-third of the notch erosion. Concentration of abrasion at the base of the cliff forms notches which have much flatter floors and less concave profiles than in areas where sand is absent. Trudgill emphasized that physical processes such as abrasion and other mechanisms of wave action account for a large proportion of the erosion of limestone shores.

Several estimates have been made of the rate of notch erosion and of the contributions of single erosive agencies, but few reliable measurements of the overall rate have been made (Saumell *et al.* 1982). In Oman, the boring rate of *Lithophaga* in notches was judged to be about 9 mm yr^{-1} (Vita-Finzi and Cornelius 1973). Neumann (1966) obtained a figure of 14 mm yr^{-1} for *Cliona lampa*, but this is the maximum obtainable under experimental conditions, and a range of 0.1 to 1 mm yr^{-1} for this species, as measured by Rutzler (1975), seems to be more reasonable. There have been several estimates of the overall erosion rate, which is the result of the contribution of many mechanisms. Verstappen (1960) calculated a rate of 5 mm yr^{-1} on an island in eastern Indonesia, based upon the occurrence of a notch at the foot of a boulder which was presumed to have fallen onto the reef at the time of the Krakatau eruption. Taillefer (1957) considered that notch erosion in sheltered Harrington Sound, Bermuda, is about 10 mm yr^{-1}, but Kaye (1959) thought that in Puerto Rico it is only 1.6 mm yr^{-1}. In Barbados, steel rods placed into the notch recorded rates of erosion of between 0.23 and 2 mm yr^{-1} (Bird *et al.* 1979). In the cool, stormy waters of the St Lawrence estuary, Corbel (1958) estimated that the limestone cliffs are corroded at the rate of 2 to 3 mm yr^{-1}. Hodgkin's (1964) figure of 1 mm yr^{-1}, obtained using steel rods driven into an aeolianite notch in Western Australia, has been widely quoted, and is often used as being representative of limestone erosion rates in warm climates (see Chapter 4). Fairbridge (1968b) considered this figure to be typical of erosion rates in coral. He thought that the harder Mesozoic limestones of the Mediterranean probably erode at about one-tenth that rate, although rates of erosion similar to those in Western Australia have recently been measured in the northern Adriatic (Torunski 1979). Very similar rates of erosion to those in Western Australia, were recorded with a microerosion meter in the notches of Aldabra Atoll (Trudgill 1976b). They suggest that the 2 to 3 m deep notches on Aldabra could have formed within the last 2–3,000 years. On an island in the southern Great Barrier Reef of Australia, the surface in the upper part of the notch, at about the mid-tidal level, has been lowered around pedestals of sedentary rock oysters at the rate of 2.04 mm yr^{-1}. Chiton grazing and excavation of a 'home site' probably accounts for much of this erosion (Trudgill 1983).

Coastal and Submerged Terrestrial Karst

The form of some limestone coasts is determined by the presence of terrestrial karstic features which have been inherited and modified by marine processes, as a result of coastal retreat and changes in the relative level of the sea. In southern Pembrokeshire, Wales, for example, cliff detail in the Carboniferous Limestones has been determined by the sea cutting back into dry karstic water courses, and into caves and grottoes previously formed by terrestrial corrosion (Leach 1933, Steers 1962a).

The interaction between marine and terrestrial processes is exemplified on the Port Campbell coast of Victoria, Australia (Baker 1943). Mechanical wave action in the Miocene limestones, clays, and shales assumes the dominant role in the marine domain in this region, but its efficacy is increased by terrestrial corrosion. The cliff tops on this exposed coast consist of limestone stripped of its vegetation, soil, and clay cover. These bare surfaces, which extend up to 55 m from the cliff edge, have subsequently become zones of small-scale sinkholes and basin-like solutional features (Baker 1958). The area contains a number of streams which flow into sinkholes near to the cliff edge, and then reappear at the cliff base. Caves have been cut by wave action from subterranean, karstic cavities and stalactites and other speleothems give a fluted appearance to the cliff face. Blowholes develop in sinkholes which are connected to the sea through narrow, wave-modified conduits. Particularly spectacular blowholes have developed in similar circumstances in very thinly bedded limestones at Punakaiki, near Greymouth, New Zealand. Narrow geos or long gorges, often associated with joints, are created by the collapse of the roofs of the subterranean stream courses. At Port Campbell, narrow, wave-cut gorges may also be traced back into stream valleys which terminate at sinkholes, or into hanging valleys on the cliff face (Baker 1943). Coastal erosion has also exposed cylindrical hollows, several metres in depth, which were originally solution pipes. Similar features in aeolianite have been reported south of Melbourne (Bird 1970) and in western Australia (Fairbridge 1950).

On the Houtman's Abrolhos Islands off western Australia, sinkholes 1–100 m or more in diameter are found on the reef flats, although some have been filled by sediment. They have been attributed to deep dissection when sea level was low during the last glacial period. These subaerial channels, caves, and potholes were later drowned by the postglacial transgression, and planated by marine processes (Fairbridge 1948). A similar situation occurs in aeolianite on Point Peron, near Fremantle, Western Australia, where numerous sinkholes are connected to the sea through submarine caves and channels, which were formed during a glacial period when sea level was low (Fairbridge 1950).

Marine dolines are common in limestone regions. In Asturias, Spain, Mensching (1965) has described the occurrence of doline valleys, doline bays, and blowholes, as well as marine lapies (see also Guilcher 1958b). Schulke (1968) described five types of marine dolines in Asturias, which are representative of those found in many other areas (see, for example, Baulig 1930):

(*a*) Submarine dolines are essentially subaerial features which are now continuously under water. Sea water corrosion may have played some role in their formation just before they were submerged by the postglacial transgression, but they are presently inactive unless they contain a submarine resergence.

(*b*) Inundated dolines have floors below sea level, and they are continuously, but only partially, submerged. They are not very common in Asturias, but are encountered more frequently in areas where the tidal range is very small, as in the Dinaric coast in the Mediterranean (Cvijic 1902, Baulig 1930, Milojevic 1952). Similar dolines connected to the sea through conduits occur in coral in the Maltese islands, forming semicircular bays where they have been breached by the sea (Paskoff and Sanlaville 1978).

(*c*) Intertidal/tidal dolines have floors which are within the intertidal zone, and they are therefore periodically partially submerged, according to tidal ebb and flow. They were deepened during glacial periods when sea level was low, and widened by lateral corrosion during transgressions.

(*d*) Other dolines have floors which are above the high tidal level, so that they are never completely submerged. They are, however, episodically and partially or totally washed by spray, and they are connected to the sea through vents. Fountains or blowholes can occur in these dolines when sea water is forced through the conduits during storms.

(*e*) The last category includes dolines which lie above the spray zone, although sea water impregnates the rock below, forming the karst base. Tidal oscillations therefore facilitate the enlargement and extension of conduits in the rock, and place limits on the depth to which they develop.

Schulke (1968) thought that marine dolines develop best where (*a*) coasts are not too high, and are well fissured but resistant to wave attack; (*b*) strong tides and frequent storms displace water in the karst network, and induce regular alternations of wetting and drying; and (*c*) high precipitation aids limestone solution.

Coastal scenery is, in some cases, almost totally dependent upon the character of submerged dolines and other elements of karstic landscapes. In northwestern Yugoslavia, marine invasion has produced a tortuous coastline consisting of rounded bays, peninsulas, coves, and small, elliptical or circular island-hillocks with rounded slopes (George 1948). Cavern collapse and marine invasion has produced most of the harbours, sounds and bays on Bermuda (Bretz 1960), and the drowning of a karst landscape is responsible for much of the form of the sheltered limestone coast of western Florida (Shepard and Wanless 1971). Tower karst has been submerged in parts of Java (Quinif and Dupuis 1985), Vietnam, and Malaysia, possibly as a result of changes in sea level. The coastal landscape in parts of Vietnam consists of a series of enclosed seawater lakes, which may be reached by boat through caves in the surrounding slopes (Jennings 1971).

The presence of partially or totally submerged karst caves influences the development of coastal scenery in many areas. In Malta, semi-circular coves have been formed by the collapse of these caves and their occupation by the sea. Invasion of subterranean caves as a result of wave erosion and cliff retreat was responsible, for example, for the formation of a 'Blue Grotto' in southern Malta (Paskoff and Sanlaville 1978). Submarine caves are particularly numerous in Provence, in the vicinity of Marseilles (Froget 1963). Some of these caves are only partially submerged, containing a lake of sea water on their floors, and communicating with the sea through narrow conduits or siphons. One cave contains cemented, pre-Flandrian sand deposits. Several caves have formed along fault planes, and in calanques. Fragile speleothems have been able to survive in some of the submarine caves because of weak wave action, although it has apparently been strong enough in other cases to clear out loose rubble. Froget also described the network of karstic galleries in the submarine Veyron Bank, an offshore limestone outcrop lying at depths of between −13 and −25 m. Wave action is more important here, and the caves are in a poor state of preservation, often having fractured roofs. Froget attributed the formation of the submarine caves of Provence to a sea level less than 50 m below today's. The pre-Flandrian regression, which was more than 40 m in this area, may explain the formation of most of the caves. In the case of the Veyron Bank, however, a fall of this magnitude would have left it as a small island, with little fresh water for the formation of extensive subterranean karst systems. Froget believed that the Veyron Bank karst was either formed at some time before the pre-Flandrian and followed by land subsidence, or that it is even more ancient. Submerged sinkholes, caves and terraces occur in the Caribbean and on Pacific atolls. Corrosion caves are largely submerged on Bermuda, where they extend down to depths of −24 m (Bretz 1960). The Blue Holes of Belize and the Bahamas are submerged sink holes formed during periods of lower sea level in the Pleistocene. Stalagmites and stalactites are common in the submarine caves of Honduras, but are absent where there are strong currents (Benjamin 1970, Dill 1977).

Submarine springs or resurgences have been described near Dubrovnik, Yugoslavia (Baulig 1930), and on the island of Kefallinia (Cephalonie) in southwestern Greece (Nicod 1963). The karst on this island was forced more deeply during periods of low glacial sea level, and it was invaded by the sea during the Flandrian transgression. Speleothems at a depth of −26 m have been dated to 20 ka BP, and at −3 m they have been dated to 16 ka BP. Submarine springs have also been described on the island of Tavolara, northeast of Sardinia (Siffre 1961). All the littoral limestones of Provence have active and abandoned submarine resurgences, often associated with marine caves, as on Capri (Nicod 1972). Conduits at depths of −30 and −45 m have been found in submarine talus, which suggest that they were emergent during cold periods, when there was active karst circulation Nicod (1967) rejected the alternate hypothesis that attributes the formation of these conduits to the circulation of phreatic water under pressure, during a period of submergence. If the flow of water from the resurgence is more powerful than the hydrostatic pressure of the sea, then the fresh water escapes quite easily. If the pressure of the sea is more powerful, as in deep water, and the flow of fresh water is weak, then the sea invades the main submarine cavities, forcing the fresh water to escape through the narrowest cracks.

Calanques

Calanques are coastal inlets which can be of a gorge-like nature. They have been described in a number of areas in the Mediterranean, including Yugoslavia (George 1948), Malta (Paskoff and Sanlaville 1978), and Majorca, where they are known as *calas* (Butzer 1962), and especially from the limestone coast of Provence. Several types have been identified. According to most investigators, the true calanques or *calanques–rias*, are karstic dry valleys which have been partially drowned. The valleys were deepened during periods of low glacial sea level, and then submerged by the transgression of the Flandrian or Holocene period (De Martonne 1909, Blanchard 1911, Johnson 1919, Butzer 1962, Froget 1963). In Provence, Denizot (1934) distinguished between calanques consisting of short ravines with steep slopes and well defined thalwegs, and less common, wider forms with poorly defined thalwegs. In Malta, the calanques–rias are fault controlled (Paskoff and Sanlaville 1978). Calanques–criques (Berard 1927, Chardonnet 1948, Nicod 1951) are simply an expression of anfractuous coastlines. They seem to be the result of selective wave erosion of fault zones or other areas of weak rock, and are not usually associated with significant terrestrial valleys. Berard (1927) believed that a large proportion of the calanques between Marseilles and Toulon are of this type. Chardonnet also recognized the occurrence in Provence of ancient or fossil calanques consisting of narrow, boxed-in, upstream areas, and wide downstream plains (1 to 3 km) with marine deposits of Pliocene age. He considered that they are former rias which have been fossilized by recent warping. In Malta, a calanque is being created by the marine exhumation of an ancient valley from beneath fossilized materials (Paskoff and Sanlaville 1978).

Chardonnet (1948, 1950) has argued that most calanques are not the result of ria-like invasions of stream valleys. In Provence and in Corsica, he noted that some calanques are not related to a well-developed valley, nor can they be attributed to a recent marine transgression; the evidence, at least between Marseille and Menton, being of recent emergence. Because calanques–rias, unlike some other types, are restricted to limestone regions, he concluded that they must be strongly associated with karst processes. Furthermore, he noted that calanques are best developed in the thickest and most homogeneous limestone formations. He recognized two generations of landforms within the calanques. The first corresponds to an initial period of subaerial erosion, whereas the second commenced when the streams began flowing below the surface. The subterranean systems developed so that parts of the streams flowed in caves which extended below sea level. Eventually, hydrostatic pressure from the marine waters and pressures exerted by the underground streams forced the removal of the rock partitions between the marine and freshwater domains. The rushing of marine water into the subterranean systems then caused the roofs to collapse. Although the sea was thought to have invaded the lower parts of the subterranean systems, this theory does not depend upon the occurrence of a marine transgression. Corbel (1956) proposed that stream waters in a humid, periglacial climate flowed over the frozen ground surface until it came within 500 to 1,000 m of the coast. In this littoral zone the ground was not frozen, and stream flow was underground. Subsequent marine transgression then caused the invasion of the subterranean system, collapsing the roof and forming a ria inlet. Denizot (1934) and Froget (1963) recognized 'false' calanques which are not related to thalweg courses, but appear to be the result of the destruction and retreat of coastal karst. In one case, a submarine cave occurs in the central part of a calanque in Provence. Similar forms can be attributed to the presence of faults.

Calanques–rias and calanques produced by the collapse of subterranean systems have also been identified on the Maltese Islands (Paskoff and Sanlaville 1978). One example consists of a dry valley which has been enlarged downstream by the wave-induced collapse of cave roofs beneath the thalweg. Deep karst has developed to such an extent in Malta, that the collapse of these subterranean systems has formed islands from the side slopes of some calanques. Nicod (1967, 1972) acknowledged the occurrence of calanque-like forms related to the wave excavation of karst cavities and conduits, and also of fault zones and other areas of geologically induced weaknesses, but he did not consider this a satisfactory explanation for calanques–rias. Nicod (1951) believed that the glacial climate of Provence was very damp, which facilitated the cutting of ravines by stream action when sea level was low. The lower portions of these ravines were then invaded as sea level rose in the postglacial period. Further upstream the valleys are dry, and obstructed by material which slid and fell from the sides at the end of the Würm, which was cold and dry in this area.

The Geomorphology of Rock Coasts

ALAN S. TRENHAILE

CLARENDON PRESS · OXFORD
1987

Oxford University Press, Walton Street, Oxford OX2 6DP
Oxford New York Toronto
Delhi Bombay Calcutta Madras Karachi
Petaling Jaya Singapore Hong Kong Tokyo
Nairobi Dar es Salaam Cape Town
Melbourne Auckland
and associated companies in
Beirut Berlin Ibadan Nicosia

Oxford is a trade mark of Oxford University Press

Published in the United States
by Oxford University Press, New York

British Library Cataloguing in Publication Data

Trenhaile, Alan S.
The geomorphology of rock coasts.
—(Oxford research studies in geography)
1. Coasts 1. Title
551.4'57 GB451.2
ISBN 0-19-823279-9

Library of Congress Cataloging in Publication Data

Trenhaile, Alan S.
The geomorphology of rock coasts.
(Oxford research studies in geography)
Bibliography: p. Includes index.
1. Coasts. 2. Erosion. 3. Petrology.
I. Title. II. Series.
GV451.2.T74 1987 551.4'57 8-21695
ISBN 0-19-823279-9

Set by Spire Print Services, Ltd
Printed in Great Britain
by Butler and Tanner Ltd
Frome, Somerset

Preface

A large proportion of the coasts of the world is rocky, and even many sandy and stony beaches are backed by rock cliffs and underlain by shore platforms. Nevertheless, there is a growing tendency for books, book chapters, and review articles, purporting to represent all types of coasts, to be primarily or exclusively concerned with depositional landforms. There has been a great deal of research on, or relevant to, various aspects of rock coasts, but the literature is widely scattered among the journals of numerous disciplines. Valuable contributions have been made, for example, by marine biologists, engineers, geologists, phyical geographers and oceanographers. A great deal of this work is not specifically concerned with rock coasts, but it can be interpreted in a geomorphological context.

Despite the use of sophisticated methods of chemical and physical analysis, geochronometric dating, computers, physical and theoretical models, and the careful study and measurement of processes and erosion rates, we can still only speculate on the mode of development of rock coasts. This is partly because of the importance of events of high intensity and low frequency, which makes it particularly difficult to determine the relative significance of the various erosional processes. In any case, even if the most important processes could be identified and measured, they are not necessarily the same, or of the same intensity, as those which sculptured the coast in the past. This is because the nature and relative importance of erosive processes change with variations in relative sea level, climate, geology, and coastal gradient. Most rock coasts change very slowly, retaining vestiges of former sea levels and environmental conditions. Nevertheless, it needs to be emphasized that they are dynamic elements of a landscape, in the process of adjusting to the contemporary morphogenic environment.

There has been no comprehensive survey of the current state of knowledge on rock coasts. Furthermore, some important topics have not been discussed in any detail in the English language. In writing this book, I became aware not only of the enormous amount of work which has been done on rock coasts, but also of the vast amount which remains to be done. This book was written to provide a convenient source of reference for researchers, senior students, and instructors, to identify deficiencies in our knowledge, and to encourage and facilitate new investigation.

I thank my parents and friends for their encouragement in writing this

6 **Mass Movement** 104
Free Falls and Topples 104
Landslips 109

7 **Changes in Relative Sea Level** 122
The Mediterranean 123
The Cretaceous and Tertiary 126
The Last Interglacial and the Early Wisconsin/Weichselian Glacial Period 129
Pre-Sangamon/Eemian Levels 131
Wisconsin/Weichselian Sea Levels 132
Low Pleistocene Sea Levels 134
The Postglacial Period 135
The Oxygen Isotopic Record 145
The Trend of Falling Sea Level 151
Mechanisms of Sea Level Change 152
The Origin of the Ice Ages 157
Models of Sea Level Change 161

II. LANDFORMS 167

8 **Coastal Cliffs** 169
Global Characteristics 170
Geology and Cliff Type 172
Composite Cliffs 178
Plunging Cliffs 187
Cliff Erosion 188

9 **Shore Platforms** 192
Cliff Weathering 194
Platform Weathering 198
Weathering: The Evidence 199
Frost and Ice 203
Wave Erosion 205
Platform Morphology and the Morphogenic Environment 206
Platform Morphology and the Effect of Geological Factors 216

Models of Platform Development 225
Inheritance 231
Rates of Erosion 235
Submarine Erosion 237

10 **Limestone Coasts** 240
Corrosional Zones 240
Plates-formes à Vasques 245
Corniches and Trottoirs 246
Notches 254
Coastal and Submerged Terrestrial Karst 260
Calanques 264

11 **Some Aspects of Coastal Scenery** 266
The Geotectonic Classification 266
Bays and Headlands 267
Caves, Arches, Stacks, and Related Features 271
Elevated Marine Erosion Surfaces 279
Strandflats 291

References 296

Index 371