Davies, J.L., 1980 pp71-99

VI EROSION PROCESSES AND FORMS

Erosion along the shore produces sea cliffs and shore platforms in a wide variety of materials. Some cliffs are little more than drowned subaerial scarps or cliffs formed at Pleistocene low sea levels (Cotton, 1967), which may plunge directly into deep water without any intervening platform, but virtually all will have been modified at least in part by the action of the sea. There seem to be two basic groups of processes concerned in cliff development: on the one hand, undercutting or oversteepening by marine action and, on the other, subaerial mass movement combined with removal of waste by waves. The first is the simple case of the elementary text books in which the sea is supposed to cut into the base of the cliff and remove the material which collapses as a result (Fig. 49, 1a).

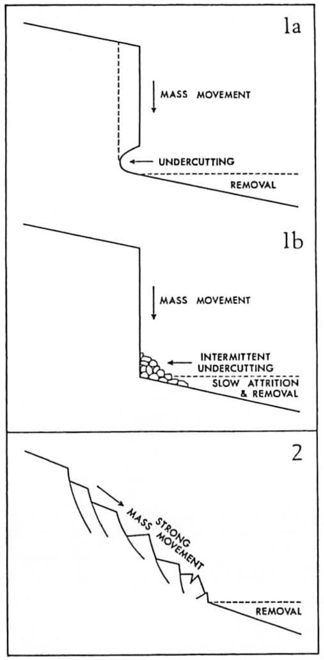

FIG. 49. Diagrammatic representation of major processes of cliff retreat and evolution.
1a: undercutting and rapid removal of collapsed material;
1b: undercutting and slow removal of collapsed material;
2: mass movement and removal of waste at various rates.

There are undoubtedly localities—particularly on unconsolidated rocks in storm wave environments—where such a simple explanation suffices, but on the vast majority of sea cliffs the sea by itself cannot cause the coast to retreat so rapidly that subaerial processes have no opportunity to contribute to morphology. The second case is that of the opposite extreme in which subaerial mass movement is so rapid in relation to wave attack that the sea has no chance of operating against the base of the cliff: its function is confined to removal with varying degrees of efficiency of what is entirely colluvial

FIG. 50. Cliffs formed by slumping and debris removal by waves, Hampshire coast of southern England. (Photo by R. J. Small.)

material (Fig. 49, 2). Examples which come to mind on a local scale are the slump cliffs of parts of the south coast of England (Fig. 50) and the mass movement dominated coast around Gisborne in the North Island of New Zealand (McLean and Davidson, 1968). The arctic coasts of Siberia, where intensive periglacial solifluction dominates, also show this condition on a large scale.

On the great majority of cliffed coasts both sets of processes operate in differing proportions, depending on the relative efficiency of subaerial and marine processes, which in turn are strongly influenced by lithology and climate.

Because most shore platforms are produced below high water mark they may be thought of as being worked on virtually entirely by marine processes. In fact, the processes that produce shore platforms are the same ones that cause undercutting of cliffs by the sea and so we can discuss them simultaneously. They may be broadly grouped into wave quarrying, wave abrasion, water layer weathering, sea water solution, frost weathering and biological erosion. The first four processes are those listed in an undeservedly neglected paper by Hoffmeister and Wentworth (1942), in which associated environmental conditions and resulting forms are set out in a table.

MARINE PROCESSES

Quarrying is the pulling away by waves of particles of material which have been prepared by some other agency. The particles may be blocks provided by jointing or cleavage, so that closely jointed rocks like some basalts (Fig. 51) and those with pronounced cleavage such as slates and schists are especially favourable to quarrying processes. Where the sea is cutting into unconsolidated materials and directly freeing pebble and sand particles it is also quarrying (Fig. 52). Quarrying would include the isolation of flint nodules from the chalk cliffs of England and France, the washing away of a

FIG. 51. Quarrying of closely jointed basalt in high wave energy environment; Giants Causeway, Northern Ireland.

weathered mantle of rotted granite in the tropics or even simply the erosion of a recently formed foredune. In all these cases the sea is disaggregating rather than disintegrating.

The processes of quarrying include the exertion of shock pressures by waves breaking against the rock and enclosing pockets of air and also the direct action of water in moving previously loosened particles. Where cliffs are cut into permafrost in the Arctic, material may be loosened by the thawing of interstitial ice (Mackay, 1963, for example). Russian workers have described this process extensively and referred to it as 'thermoabrasion' (Are, 1968, for instance) but it is more truly 'thermoquarrying'.

We have already noted that rock type is an important factor leading to variations in quarrying efficiency from place to place, but it is clear that variations in wave regime must also be important. The classic stories of the effects of big waves in moving around large chunks of material, such as those recorded by Johnson (1919) and frequently quoted, come from high energy coasts of temperate latitudes where big storm waves are a common and expectable experience. It seems self-evident that in moderate and low

energy environments quarrying is likely to be less effective, particularly on more massive materials.

Quarrying produces a platform with a general slope to seaward, because each quarried particle has to be higher than the particle to seaward of it in order that it may be removed. The resulting surface may be smooth if the dip of the rock strata coincides with the plane of quarrying: if not, then miniature cuesta and monoclinal forms develop. It seems probable that steeply dipping rocks are more susceptible to quarrying than

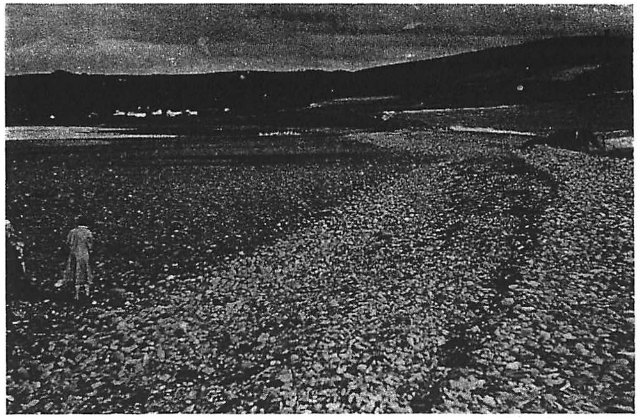

FIG. 52. Wide intertidal shore platform quarried in glacial till at Aberaeron, west Wales. Pebbles piled into a beach at the rear of the platform appear lighter in tone as a result of reworking by waves.

those which are subhorizontal because they expose more vulnerable planes of weakness over more of the platform.

Abrasion is taken to mean the wearing away or breaking up of rock material by waves—overwhelmingly by the tools which they may carry in the form of boulders, pebbles and coarse sand. As distinct from quarrying it implies actual physical breakup of cohesive rock and includes what is usually termed attrition. This distinction between quarrying and abrasion essentially parallels that made in glacial geomorphology between glacial quarrying and glacial abrasion. In the literature on coasts 'abrasion' is commonly used in a wider sense than it is here and in glacial and fluvial geomorphology, and it seems unfortunate that there should not be uniformity between different branches of the discipline in this respect.

Abrasion at the foot of a cliff may cause notching (Fig. 53): it will also smooth the surface of shore platforms as abrasive materials are moved backwards and forwards across them (Fig. 54). A real variation in its efficiency depends essentially on wave energy and the availability of tools. In particular, effectiveness is much increased by the presence of pebbles and small boulders and the occurrence of waves large enough to throw this material against the cliff and move it repeatedly over the platform. Both these requirements are satisfied in storm wave environments of temperate latitudes, where not only is wave energy high, but shorter period waves give a greater frequency of back and fore movement and, as we have seen (Ch. II) and shall see later (Ch. VIII), pebbles are especially abundant. It should be noted too that there is a connection

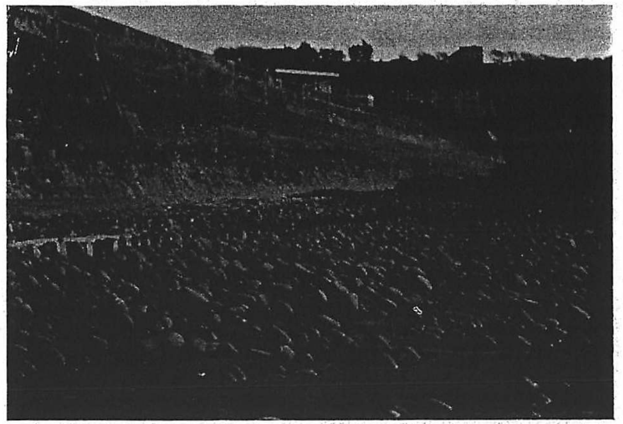

FIG. 53. Formation of a high shallow notch by abrasion on a man-made cliff at Westward Ho!, southwest England, in a high wave energy environment with abundant pebble and boulder tools.

FIG. 54. Effect of abrasion on platform in steeply dipping slates near Staunton, southwest England. Wave energy is high and coarse sand and pebbles abundant.

between abrasion and quarrying in that greater quarrying means more tools for abrading waves: there are several reasons therefore why both are encouraged in the same environment.

Abrasion is associated with a general slope to seaward, which seems necessary in order that boulders, pebbles and sand may move up and down over the platform. Wave uprush pushes material upward but it returns by gravity with the help of backwash and becomes available once more as an abrading tool. On horizontal platforms, such as those produced mainly by water layer weathering and solution, loose particles tend to be pushed to the rear of the platform and to remain there in storage (Fig. 55).

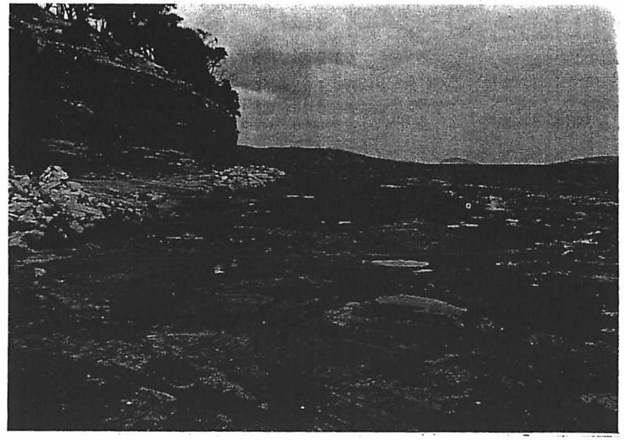

FIG. 55. High tide platform near Hobart, Tasmania. The cliffs retreat by quarrying and are fronted by a narrow 'abrasion ramp' and a wide nearly horizontal surface formed by water layer weathering processes. Boulders remain on the abrasion ramp and do not move back and fore on the high tide platform proper.

Sloping platforms with strong wave backwash commonly develop rills or gullies, which in unconsolidated rocks such as glacial tills are subparallel to the direction of steepest slope but in consolidated rocks usually take advantage of structural lineations.

Abrasion and quarrying together produce the type of shore platform often called an abrasion platform or wave cut platform. In the early literature emanating from around the North Atlantic, this was the only shore platform recognized and these were virtually the only processes acknowledged. However later workers, on warmer, lower energy coasts have showed that there are other important processes and platform types.

Water layer weathering is meant to include all those weathering processes which operate when rock is alternately wetted and dried by sea water. Wentworth (1938) first used the term 'water level weathering' in relation to platform development, but Hills (1949) suggested the term 'water layer weathering' as being less ambiguous. However the same processes also seem to operate against the cliff face as a result of the action of surging waves and spray. The effect on the cliff may be concentrated at lower levels so as to form a notch or it may be sufficiently distributed that a distinct notch does not eventuate.

Alternate wetting and drying promotes a whole complex of weathering processes. Some, such as salt crystallization pressure (Tricart, 1960) are mechanical, but the great majority are probably the result of chemical reaction between rock minerals and the periodically arriving sea water. The zone through which these processes operate extends from the highest limit of wave spray down to a level below which the rock is permanently saturated. Depending on lithology different varieties of pitting and fluting on lower cliff and incipient platform surfaces are produced (Fig. 56), but the ultimate landform is a platform which is often remarkably smooth and horizontal and which lies somewhere around high tide level (Fig. 55). This surface seems to represent the upper level of permanent rock saturation.

Fig. 56. Cavernous weathering in phyllite as a result of wetting and drying by spray near high water mark south of Cairns, Queensland. (Photo by E. C. F. Bird.)

Water layer weathering processes vary in importance as platform producers according to rock type and structure, for they are aided by permeability of the rock and also by low angles of dip. A low angle of dip promotes homogeneity of lithology and therefore a uniformly developing surface: high angles of dip encourage quarrying instead. These weathering processes are also strongly influenced by climatic factors, both those controlling the wave regime and those controlling the contiguous atmosphere. For weathering to become important in fashioning coastal landforms it seems necessary that wave energy should not be high, because big waves promote rapid quarrying and abrasion so that weathering features do not survive. This can be demonstrated repeatedly on a small scale and there are plenty of places in Tasmania where platforms produced by weathering grade into platforms dominated by abrasion and quarrying as exposure changes and wave energy increases. On the larger scale this is undoubtedly one reason why platforms produced by water layer weathering have not been recognized from storm wave environments such as those of the North Atlantic.

The significance of the local subaerial climate lies mainly in the way in which different rates of evaporation must lead to differences in the effectiveness of wetting and drying. It is very unlikely that water layer weathering can be very effective in wet climates with low evaporation rates, particularly where the tidal type is semi-diurnal. The most effective weathering is likely to be associated with high evaporation and diurnal or mixed tides, and published records to date seem to support this deduction.

Within the tropics, where higher temperatures could be expected to encourage high weathering rates, Tricart has noted that wetting and drying effects are prominent on drier coasts, such as in Brazil near Bahia and north-east of Rio de Janeiro, but are not found in the wet tropics, such as on the Ivory Coast. In favourable environments, like southern California, rock reduction rates of about 30 cm in 600 years have been estimated (Emery, 1960).

Solution is a process which is strongly tied to lithology, because carbonate-rich rocks or those with carbonate cements are by far the most vulnerable, published rates of erosion in coastal limestones being generally in the range of 0·5 to 1·0 mm per year (Hodgkin, 1964). Solution is assisted by the considerable agitation and flow of water in the surf zone (Kaye, 1957). Any broad scale distributional factors must work by varying the dissolving capacity of seawater in various parts of the world ocean, but unfortunately we do not yet know enough of how seawater dissolves to be able to say with any certainty how this capacity varies. It has already been noted that seawater is normally saturated or supersaturated with calcium carbonate and that this supersaturation increases in the tropics (Fig. 35, p. 53). This, together with the decrease in solubility of carbon dioxide in the water of warmer seas, should lead to the deduction that solution must be most effective in colder waters and it is difficult to explain how it can take place at all in the tropics. Attempts to overcome this difficulty have been made by a number of workers. Fairbridge (1948) invoked nocturnal temperature lowering in rock pools and a resulting local short-term increase in carbon dioxide intake by seawater. Revelle and Emery (1957) also concluded that solution in the tropics must be related to local nocturnal increases in the carbon dioxide content of the water, but probably mainly associated with a surplus in the biological balance of carbon dioxide as photosynthesis by marine plants ceases during the hours of darkness. In this connection it is noteworthy that the green algae, in which photosynthesis is most rapid and which Guilcher (1953) considered particularly important in giving a high diurnal pH change, are more abundant in warmer seas. According to Guilcher and Pont (1957), above certain temperatures silica is liberated by decomposition of silicates in sand freed by solution of rock cements. This silica recombines with limestone in a silicate of calcium and liberates carbon dioxide, which attacks the remaining limestone. All these suggestions seem to require isolated or semi-isolated bodies of water in which the processes can operate and they largely envisage rock reduction by the formation and enlargement of rock pools of varying sorts (Fig. 57). Because the lower limit of such pools must lie close to low-

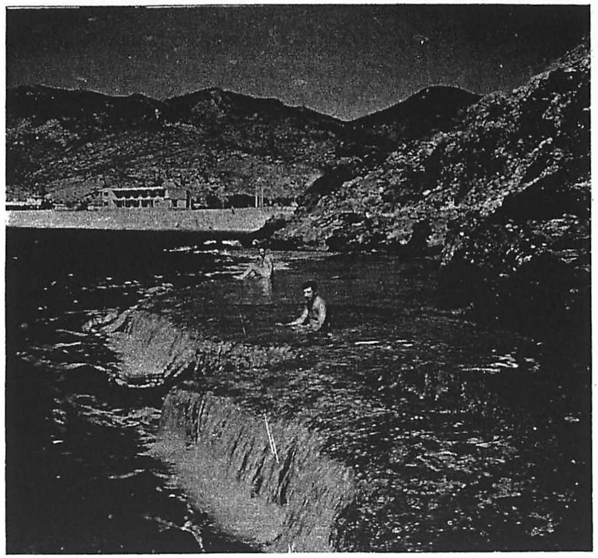

FIG. 57. Shore platform in limestone at Alanya, Turkey, formed by enlargement and coalescence of rock mills and solution pools (Photo by J. N. Jennings.)

water mark, this must also constitute the lower limit of these solution processes, and resulting platforms must form near this level. Revelle and Emery, for instance, considered that 'the very existence of the broad and dead reef flat just below low-tide level indicates the efficacy of erosion of limestone in the intertidal zone'. Above this ultimate low limit, solution pitting and fluting may occur to the upper level reached by wave spray.

Although it may be possible to explain how seawater solution can occur in tropical seas, it still remains probable that it is potentially more efficient in colder waters. Its apparently greater significance in the tropics stems from the much more extensive occurrence of coastal limestones, many of them poorly cemented and susceptible to disaggregation, from the lower wave energy in these latitudes which means that solution effects are not masked by those of quarrying and abrasion, from the lower rates of subaerial solution in the drier tropics, which accentuate the relative effects of marine solution, and from the greater effect of biological solution in the tropics, the results of which are difficult to separate from those of seawater. Cloud (1965), in a review of carbonate precipitation and dissolution in the marine environment, concluded that more and better evidence was required before notching and pitting features of limestones, equally well explained as the work of intertidal organisms, were attributed to seawater solution.

Frost weathering. Some authors, for instance Aufrère (1934) seem to have thought of icebound coasts as being in a state approaching suspended development because of the absence of wave attack. Others such as Nansen (1922) attributed to frost action along the shore the major part in the formation of the high latitude platform complex known as the strandflat. Most present-day opinion would lie between these two extremes. Guilcher (1958) pointed to the relative lack of effectiveness of ice crystallization from seawater, because salts isolated on freezing tend to make the ice cellular and comparatively soft. Presumably this is why those who have written on icefoot phenomena (Chapter IV) rarely seem to mention their association with platform production. Priestley (1922), for example, remarked in reference to the Antarctic that 'the chief geological effect of the icefoot is undoubtedly the cônservation of the coast to which it is attached.' However, there are many ways in which freshwater may be brought into this situation in both liquid and solid form. Certain types of icefoot consist primarily of frozen precipitation, and Nichols (1968) recorded and illustrated 'snowdrift-ice slabs' occupying sub-cliff positions along the Antarctic coast. He considered that their low surface slope of about 15° and lack of crevasses indicated an absence of movement and did not suggest their possible geomorphic effect, but, by analogy with what is known of the operation of subaerial transverse snowpatches, it would be surprising if they were entirely passive. Russian writing, summarized by Zenkovich (1967) has described how blown snow may accumulate at the foot of cliffs along sections of the Siberian coast. As reported by Zenkovich the general Russian view seems to favour the efficiency of frost action in cliff recession.

There seem to be three main factors influencing the effectiveness of freezing as a destructive agent. One of these—that of lithology and the distribution of frost susceptible rocks—is likely to vary over short distances. The other two are the supply of freshwater, desirable for maximum effectiveness of ice crystal growth, and the periodic wave action necessary in order that frost weathering residues may be removed. Both of these factors are potentially of regional significance in that they are connected with climatic controls. Perhaps this would help to explain the absence or poor development of platforms on the main coast of Antarctica, with its low precipitation, limited snow and ice melt, low wave energy and essentially marine icefoot. In immediate contrast Fleming (1940) reported strandflat forms from the warmer, wetter and more wave susceptible west coast of the Antarctic peninsula, and Flores Silva (1952) described vertical cliffs cut in granite.

The enormous width of strandflats in some places makes it difficult to conceive of them as extraordinarily extensive shore platforms and their origin remains obscure. Tricart (1967) has noted that the Norwegian strandflat does not appear to be in process of formation today and yet was covered by glaciers during Pleistocene glacial stages. Most present-day opinion would probably be that strandflats are glacial or glacio-coastal features and Tietze (1962) has interpreted them as being due to freeze–thaw processes underneath Pleistocene shelf ice as it rose and fell with the tide.

Biological erosion. The important part played by marine organisms in rock destruction has been referred to in Chapter V. The efficiency of biological erosion, particularly in the tropics and on lime-rich rocks, is not in doubt and several writers, notably Emery

(1962) have considered it to be one of the most rapid ways in which the intertidal zone may be reduced, given the right conditions. A more difficult question concerns the extent to which the action of animals and plants produces recognizable landforms. The voluminous literature on intertidal zonation in marine organisms attests to the close relationship between habitat limits and levels reached by wave action, so that one would expect any topographic modification which they were able to attain also to have a zonal relationship with water level. Putting it at its simplest, a particular organism could be expected to erode down to its lowest potential level of existence and then stop. In turn this should produce notches coinciding roughly with the upper and lower limits of the eroding organism and platforms at the lower limit. One could also deduce complications due to the variety of organisms involved, each with different tolerances, and the width of the developing platform which adds another dimension to the zonation picture.

By and large such deductions are not substantiated by field observation in the high energy storm wave environment of temperate latitudes, where notches and platforms are demonstrably due to quarrying and abrasion by waves, but in the low wave energy microtidal tropics and especially on limestone or lime-cemented rocks they may have much more validity. A very good case can be made out for the contention that

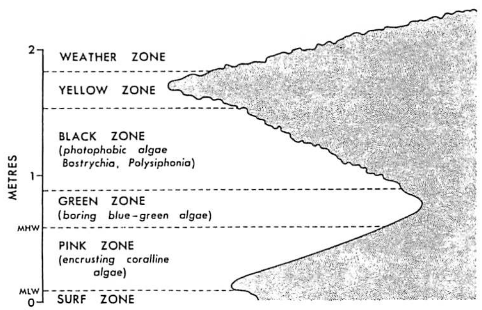

FIG. 58. Biological zonation on coral cliffs in Barbados. (After Lewis, 1960.)

'solution benches' and 'solution nips' in tropical limestones are produced not by seawater solution but by the action of intertidal organisms (for example, Ginsburg, 1953; Newell and Imbrie, 1955). The most important organisms from the point of view of notch development in limestone are almost certainly the blue-green algae. Newell (1956) regarded notches in the Tuamotus as the result of leaching below a film of blue-green algae and mechanical rasping and boring by animals. He felt there was no compelling evidence that it is the result of solution of the rock by seawater. On coral limestone shores around Barbados blue-green algae are particularly concentrated in the major undercut approximating to high tide mark; this is the 'green zone' of Lewis (1960), usually about 15 to 45 cm wide (Fig. 58). The notch seems due to loosening of the

surface rock by algae and attendant herbivorous invertebrates, coupled with removal of loosened particles by waves. That blue-green algae are also found at higher levels where cliff retreat is not so rapid suggests that their effectiveness depends in part on the quarrying action of waves on a surface prepared by the algae, and this is essentially the conclusion reached by Hodgkin (1970) from a study of notch formation on limestone coasts in Malaysia.

Whereas seawater solution may be an effective process in the development of platforms by the enlargement of tidal pools, it seems probable that where a notch occurs in relatively deep water biological agencies are mainly, if not entirely, responsible.

BIOLOGICAL CONSTRUCTION

It may seem anomalous at first sight to be discussing processes of construction in a chapter headed 'Erosion Processes', but in the tropics it is quite impossible to consider the evolution of cliffs and platforms without reference to ways in which animals and plants build or protect. Herein lies a major difference between tropical and temperate

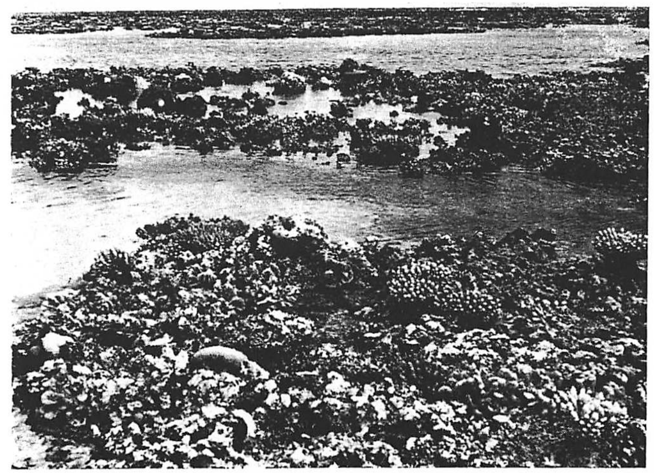

FIG. 59. Constructional coral surface exposed by an exceptionally low spring tide on Keeper Reef, a platform reef among the Great Barrier Reefs of Queensland.

latitudes. Indeed, if the term 'shore platform' is interpreted, as it is here, in a descriptive and non-genetic way, most if not all coral reef flats must be thought of as shore platforms. Reef flats arise in a number of ways. Some appear purely constructional and represent the upper level to which the reef complex has been able to grow (Fig. 59): others seem to be the surface of agglomerations of boulders and pebbles filling what had

FIG. 60. Low-tide platform at Eclipse Island, Halifax Bay, Queensland. The platform is of complex origin; partly cut into beach conglomerate, partly cut into coral and partly built by coral into a fringing reef.

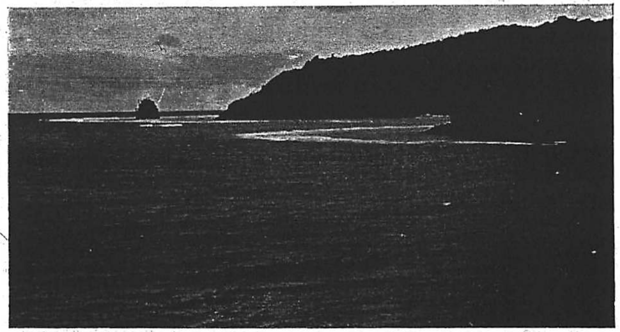

FIG. 61. Fringing reefs on the south coast of Tutuila, Samoa. The presence of the stack suggests a composite origin, due to erosion as well as construction.

previously been a depression: yet others can be shown to have been truncated near low-tide mark by some erosion process and are the end result of lowering rather than building. A clear example of this last case is that of the reef flats on Okinawa described and figured by MacNeil (1950). Many present-day reefs are shore platforms cut into older coral (Fig. 60) and on which a veneer of modern coral has accumulated (Stoddart, 1969c). Most reefs have gone through more or less complicated histories of alternate

erosion and construction, so that historically and geographically, the line between eroded and constructed forms is difficult to draw (Fig. 61).

Even more difficult to separate in nature from processes of platform and cliff development are the constructional activities of calcareous algae. In warm seas where there is only a small tidal range, intergrowth of algae with marine invertebrates may build a projecting rim on vertical rock faces round about mean tide mark—the '*trottoir*' of French writers who have described it from many parts of the Mediterranean. Johnson (1961) recorded having observed these features rimming narrow rock terraces on rocky coasts on Guam, Tinian and Saipan in the Mariana Islands of the western Pacific. The *trottoir* is limited in outward growth by the varying propensity of waves to break off the extremity.

Much more significant than *trottoir* building is the way in which calcareous algae modify the development of shore platforms in the tropics by the construction of algal flats and rims. Some algal flats seem almost entirely constructional and are the algal equivalents of fringing coral reefs: in other cases the algae form a crust of varying thickness on a rock platform and whether their role is predominantly constructive or protective is arguable. In either case they commonly form rimmed terracettes descending in height from the zone of greatest water supply by waves. While on narrow platforms this gives an overall slope seaward or sideways, if the platform is broad the resulting gradient may be inward.

CLIFF MORPHOLOGY

On many rocky coasts the sea has done relatively little to modify morphology. Coastal outlines have been etched by subaerial weathering, especially between 100 000 and 10 000 years ago when sea levels were low, and the waves have washed away the waste mantle to expose the weathering front. Massively jointed and impermeable crystalline rocks resistant to all processes of marine attack particularly answer this description. In other cases minor amounts of quarrying may have taken place as a result of wave action, without imposing clearly defined forms of marine origin.

Plunging cliffs have also been thought of as largely inherited and little modified by the Holocene Sea. The primarily hydrostatic forces imposed by non-breaking waves in the deep water at their foot are relatively small and much wave energy is likely to be reflected. Other cliffs have narrow, poorly defined platforms at their foot, often covered by talus which acts as an efficient absorber of wave energy.

The most spectacular free-face cliffs are generally associated with conditions of maximum marine attack with waves able to break directly on the lower face and impose dynamic forces of great intensity (Fig. 62). Free-face cliffs are also associated with easily quarried rock producing easily removed detritus, low rates of subaerial weathering and mass movement so that sloping sections are poorly developed, and landward dipping or horizontal structures (Fig. 63). Seaward dipping rocks tend to produce bare slopes. Limestones are particularly favourable for the production of free faces but horizontally bedded, strongly cemented, sandstones and coarsely jointed basalts and dolerites are also frequently associated with near-vertical cliffing.

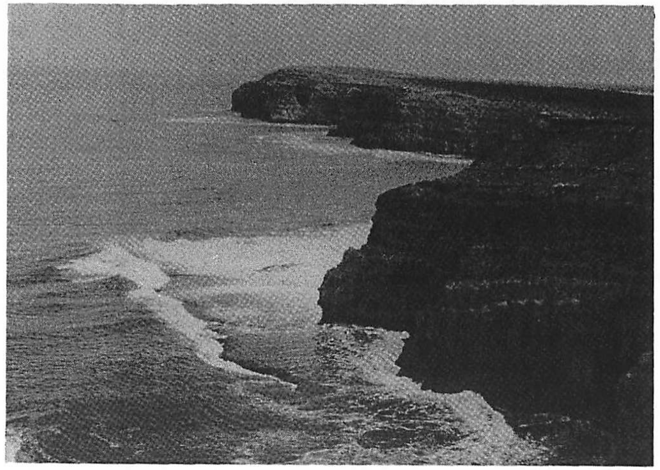

FIG. 62. Cliffs and low-tide shore platforms in dune rock, Elliston, South Australia.

Where wave attack is weak or has been weakened by talus accumulation or platform extension, steep coastal slopes may develop and assume a cover of vegetation. In the first case the slope may have developed as the original form because of a strong

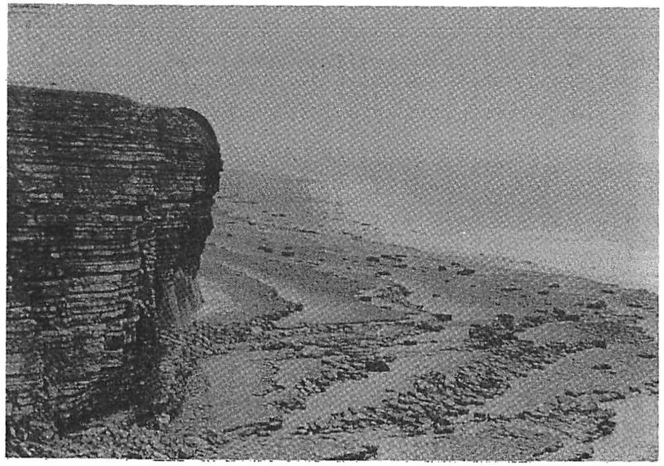

FIG. 63. Cliff and sloping shore platforms in subhorizontal flaggy sandstones, Nash Pt, South Wales.

FIG. 64 Degraded cliff forming steep coastal slope, Sydney, New South Wales.

preponderance of mass movement over wave attack: in the second case it may have resulted from degradation of a steeper pre-existing cliff (Fig. 64).

The intimate relationship of cliff form with rock type and the frequent appearance of features inherited from past denudation systems make geographical generalizations

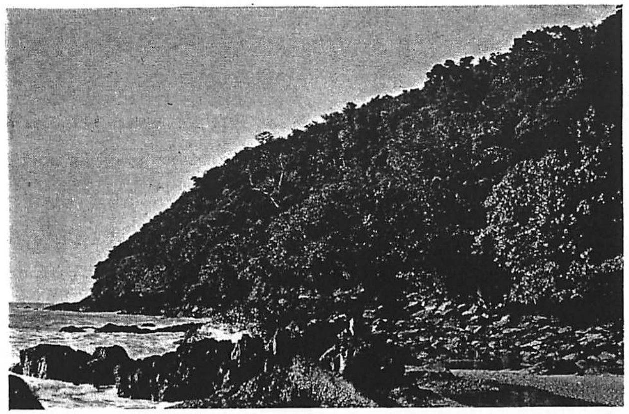

FIG. 65. Tropical rain forest coming down to an almost uncliffed rocky shore south of Cairns, Queensland. The environment is one of low wave energy and perennial rainfall of about 2500 mm a year. (Photo by E. C. F. Bird.)

difficult and some would say impossible. A survey, such as that for the British Isles in Chapter 5 of Steers (1953), exemplifies the way in which a large variety of forms may exist within a relatively limited area. Even so, some broad conclusions seem possible from a consideration of the way in which the relative efficiency of mass wasting and wave attack vary in different parts of the world. Tricart and Cailleux (1965) for instance have suggested that within the tropics a significant difference exists between humid and arid coasts. On hot, wet shores, such as those of the Pacific coast of Colombia and the coast of Liberia, cliffs recede slowly and at relatively low angles by mass wasting. There is almost continuous vegetation cover and only the lowest few metres are bare (Fig. 65). Landslips may produce amphitheatre-like bays as described by Tricart (1957) from the Ivory Coast of West Africa. On hot, dry shores plant and regolith cover is limited and steeper angles are encouraged by marine attack. This tends to be more effective than mass wasting, even though marine attack is still relatively weak and largely in the form of seawater weathering and solution. The main lithological factor which upsets the general relationship is the occurrence of limestones, including corals and aeolianites, which tend to produce 'arid' type cliffs throughout the tropics because of their failure to generate substantial waste mantles of weathered material (Fig. 66).

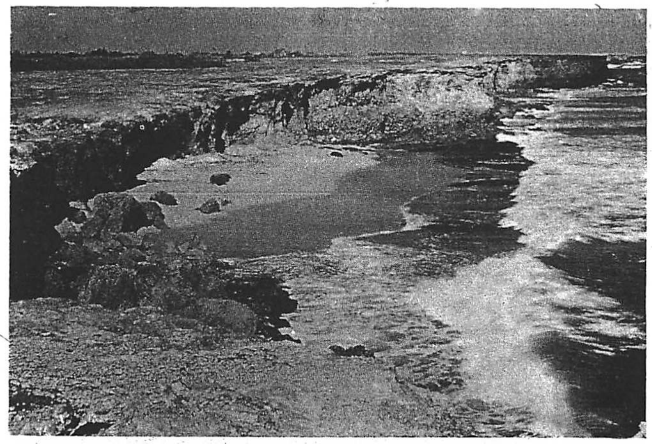

FIG. 66. Near vertical cliffs in coral limestone on the east coast of Barbados. Strong trade wind controlled waves with abundant spray produce a saline cliff top environment in which plant growth is limited.

As one moves poleward from the tropics into high wave energy latitudes where quarrying by big waves becomes proportionately more effective, marine attack tends to dominate on all rock types and to evolve steeper, more spectacular cliffs. Further poleward still, along Arctic and Antarctic shores, wave energy decreases once more and periglacial mass movement processes maintain relatively low angle slopes.

In temperate latitudes the existence of two-cycle slope-over-wall cliffs has been

thought to reflect strong degradation of older cliffs by Pleistocene periglacial mass movement and subsequent steepening of their lower section by the postglacial sea (Cotton, 1952; Bird, 1968). Slope-over-wall cliffs occur in many parts of the world and some of them may result from a kind of balance between terrestrial processes acting from above and marine processes acting from below: but in the main they probably reflect the intervention of a low sea-level phase in which marine attack was removed and subaerial processes held full sway. However, where both marine and subaerial processes were in turn particularly effective, such as in western Europe, where periglacial solifluction extended below present sea level during glacials and wave energy was high during interglacials, the slope-over-wall form seems especially well marked (Fig. 67). In the

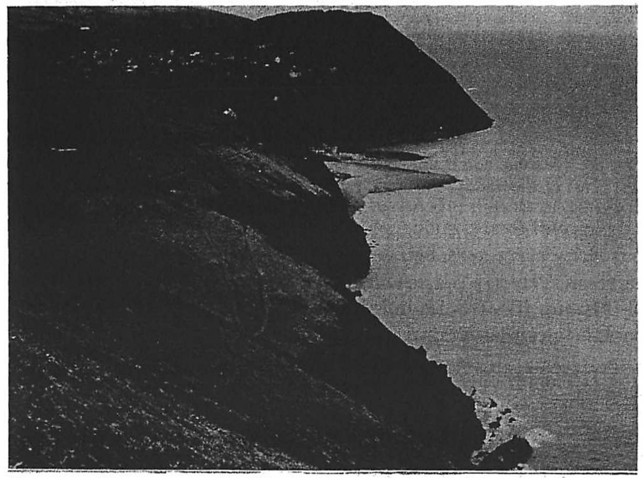

FIG. 67. Slope-over-wall cliffs near Lynmouth, southwest England.

Southern hemisphere only relatively small sections of coast are comparable in their Pleistocene history to those of western Britain for instance, but Fleming (1965) has described and illustrated strongly developed slope-over-wall cliffs at the Auckland Islands in latitude 51°S.

On cliffs where marine processes dominate, a notch may form at the base, but it is now widely recognized that this is best developed in low energy environments where weathering, solution and biological processes are more effective in cliff retreat than wave quarrying and abrasion. This is because the big waves tend to destroy the upper limb of the notch and the varying wave height gives rise to a broad, relatively shallow indentation. The extreme of notch development is found on tropical limestone coasts where exaggerated visors are produced as a result of various solution processes and relatively weak wave attack within a limited vertical range (Figs 68 and 69). A low tidal range is of great importance and the best notch and visor cliffing is to be found on microtidal coasts.

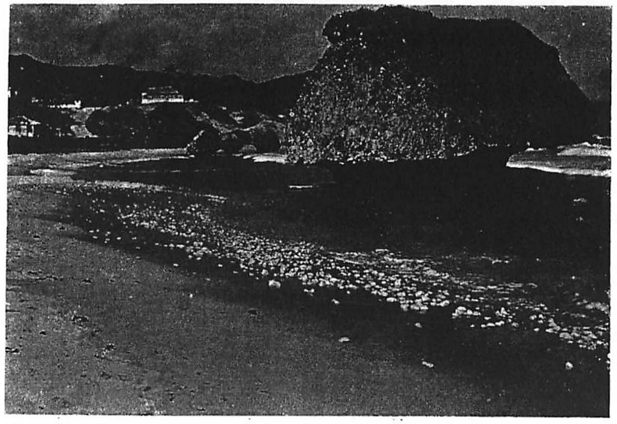

FIG. 68. Strong notch and visor formation in an erratic coral block, east coast of Barbados.

The spectacular cliff forms, such as arches, stacks, geos and blowholes which figure prominently in elementary text books are relatively rare in nature and are largely confined to high wave energy coasts where structure and lithology are suitable for their development. Within the tropics minor examples occur on limestone coasts and particularly in association with coral but otherwise they are uncommon.

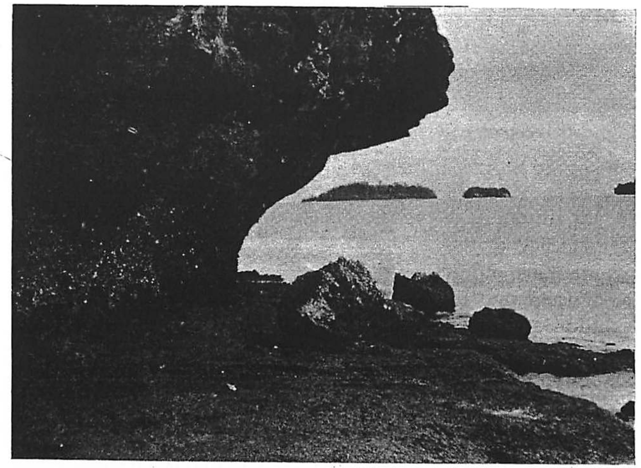

FIG. 69. Notch and platform in Ordovician limestone near Kua, Langkawi Island, Malaya (Photo by J. N. Jennings.)

The form of cliffs may also owe at least something to the detailed history of sea level change along a particular stretch of coast. A number of authors (King, 1963, for instance) have concluded that a long phase of active marine erosion requires one or more periods of gradual submergence, so that the sea may continue to eat into the cliff base across a progressively wider shore platform. Cotton (1969), while agreeing with this conclusion and suggesting that existing high cliffs are probably the product of repeated periods of submergence in the Pleistocene, has pointed out that there must in fact be an optimum rate for such submergence because, if it proceeds too quickly in relation to the rate of erosion, a plunging cliff will develop, after which it will be difficult to restart erosion because of increased reflection of wave energy and a lack of tools for abrasion. If, as seems likely, the exact rate of submergence and the length of time over which it operates are of critical importance, then the factors which operate to vary such rates and times as between one coast and another must also be taken into account in explaining cliff morphology.

SHORE PLATFORM MORPHOLOGY

As in the case of cliffs, the close association between the details of platform morphology and the nature of the country rock has inhibited attempts at classification. Such attempts have also been inhibited by the apparent absence of some important types from the North Atlantic region within which earlier workers operated. The most useful simple classification may be the tripartite division by Bird (1968) into intertidal, high tide and low tide platforms (Fig. 70). These appear to represent three broad

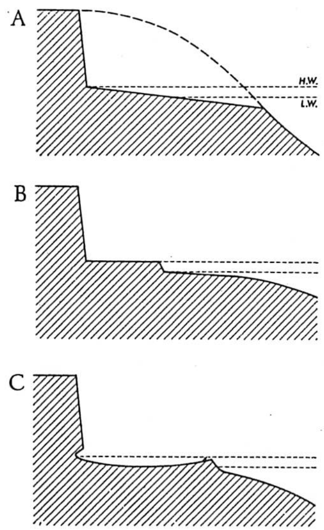

FIG. 70. The three major shore platform types of Bird (1968). A: intertidal; B: high tide; C: low tide.

themes upon which numerous variations may occur and their usefulness probably stems from the way in which they represent the basic forms which major groups of processes tend to develop. As already indicated, quarrying and abrasion produce sloping surfaces; water layer weathering produces subhorizontal surfaces related to high tide mark; solution and biological destruction produce subhorizontal surfaces with a lower limit somewhere around low tide. On shores where one of these groups of processes is completely dominant, platforms will approach closely one of Bird's three basic models, provided lithology is favourable. Where process regimes are complex, intermediate or compound forms will develop, and morphology becomes further complicated where lithology and structure are complex as well, but the three models may profitably be regarded as norms from which various departures occur in different environments. The factors affecting their distribution are therefore important in any consideration of the geography of shore platforms.

Unfortunately the terminology relating to forms has become confused. Some writers have used 'intertidal' in a different sense, not necessarily implying a slope. The terms 'high tide' and 'low tide' also may cause uncertainty because 'high tide' platforms in particular have very varied relationships to tide levels. In the short discussion which follows treatment is in terms of process rather than form.

PLATFORMS PRODUCED BY QUARRYING AND ABRASION

These are basically the intertidal platforms of Bird, which slope from about high water mark to somewhere below low water mark and are the traditional 'wave cut' or 'abrasion' platforms of earlier European and North American writers (Fig. 63). The development of such platforms is encouraged by the same factors which favour maximum quarrying and abrasion—high wave energy, easily quarried rocks and an abundance of rock tools. They are therefore virtually universal within the storm wave environments of temperate coasts, but in lower energy environments nearer the equator they occur only where local lithology or tidal conditions are especially favourable. One of the commonest of such situations in the tropics is where deeply weathered rocks outcrop on the shore and quarrying is possible even by small waves.

The height of the inner edge of the platform is mainly related to wave exposure (Wright, 1970) and that of the outer edge to the greatest depth at which waves can quarry and abrade. This depth is certainly less than surf base (see p. 102) and probably in most cases a great deal less. Depending on the degree of difference between platform gradient and overall coastal ramp angle, there may be a distinguishable break of slope forming a low tide cliff, but this is submerged at most if not all stages of the tide.

In a number of studies, Trenhaile (1978) has demonstrated a relationship between platform gradient and tidal range: as tidal range decreases platform gradient also becomes lower, presumably because wave attack is concentrated on a more uniform horizontal plane. There may be other factors operating such as the ratio of wave energy to the size of quarried particles but data relating to these are lacking up to the present.

Sloping platforms due basically to quarrying by waves may have considerable internal relief because of lithological variation and consequent resistance to erosion

structural lineations may lead to preferred quarrying along certain vertical planes and the excavation of gullies along which strong water and sediment movement occurs. On weaker, poorly consolidated rocks such as clays the platform is often cut by shallow semi-parallel rills down which backwash is preferentially channelled.

PLATFORMS PRODUCED BY WATER LAYER WEATHERING

The second group of platforms result from weathering processes associated with the alternate wetting and drying of rocks. As a result they tend to develop to the highest level of permanent saturation which is most nearly related to high water mark (Fig. 71). In practice, the height of prevailing waves may be at least as important as tidal amplitude in determining the effective level. Rock permeability and atmospheric climate also have an effect. The conditions which favour formation are those which favour water layer weathering—permeable, coarsely bedded rocks with low dips, high evaporation and mixed or diurnal tides to facilitate drying, high temperatures to speed chemical reaction rates and a low tidal range facilitating the maintenance of a well defined horizontal upper level of saturation. But also important are conditions discouraging abrasion and rapid quarrying which tend to destroy the effects of weathering (Fig. 72). To date almost all high tide platforms seem to have been recorded from low to moderate wave energy, microtidal, high evaporation regions such as Hawaii, Peru, Brazil, Madagascar, Senegal, Sicily, southern California, Australia and New Zealand.

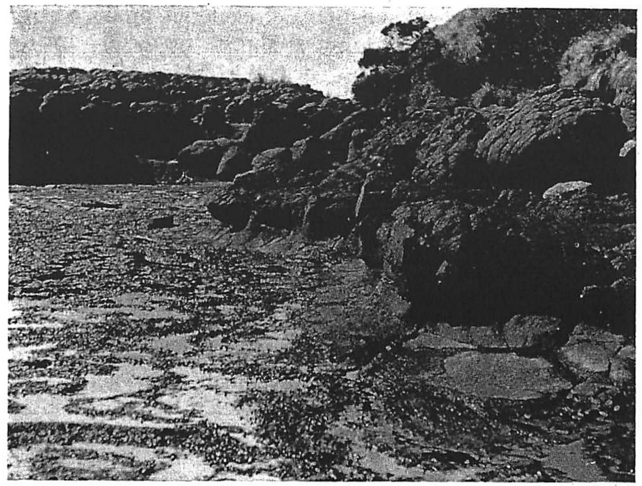

FIG. 71. Rear of a high tide platform cut into massively jointed basalt by water layer weathering on the north coast of Tasmania. The modern platform is forming at the expense of older higher platforms.

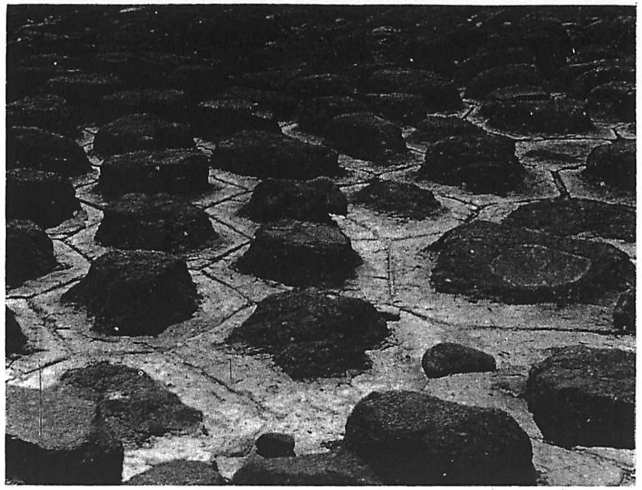

FIG. 72. Water layer weathering in massively jointed basalt with moderate wave energy, north coast of Tasmania. The waves are too weak to quarry the massive joint blocks (compare with Fig. 51).

There seem to be two broad subgroups of platforms produced by wetting and drying. In the first the platform has resulted directly from cliff retreat, with the cliff being sapped by weathering in a narrow zone at its foot. The 'old hat' platform of Bartrum (1926) is a good example of this. Such platforms are not strictly horizontal, but have very slight slopes to seaward which may be of the same magnitude as the flattest platforms produced by quarrying. They do not have ramparts and their surface is relatively continuous, but like all high tide platforms, they have well marked low tide cliffs.

The second subgroup contains platforms produced by downwasting, probably nearly always from older platforms (Figs 71, 72). New platform surfaces form by successive extension of permanently saturated level sections as rock around their edges is alternately wetted and dried. This is the water layer weathering process in the strict sense and the surfaces so developed are absolutely horizontal. Because the process may begin at a number of levels, surfaces may develop at different heights and be separated by minor rock dams or scarps. Eventually however these tend to coalesce at the lowest level. Developing platforms may therefore have varied internal relief and they commonly have ramparts at their outer edge.

PLATFORMS PRODUCED BY SOLUTION AND BIOLOGICAL EROSION

Bird described his low tide platforms as developed typically on the Pleistocene dune limestones of southern and western Australia, and they seem generally to be associated

with solution or biological erosion of calcareous rocks in low wave energy, microtidal conditions. They lie somewhat above low tide mark and the highest examples appear to approach in altitude the lowest high tide platforms. If, as suggested previously, constructional, destructional and composite reef flats have to be considered as types of shore platforms, then it is in this category that they have to be placed, because the upper limit of coral growth and the lower limit of its destruction generally occur near to low tide level. Platforms constructed by calcareous algae show more complicated relationships with sea level. At one extreme they may modify low tide platforms to only a slight extent by encrustation or rim building: at the other extreme they may build massive platforms close to high water mark. Russell (1967) has observed that the height of algal flats or reefs is strongly correlated with exposure to wave action and that they commonly reach higher elevations on headlands than in embayments.

Low tide platforms thus include a multiplicity of genetic types, but they are all overwhelmingly characteristic of warmer waters, particularly where Pleistocene beach, dune and reef rocks form the shore.

Again it seems useful to distinguish platforms produced by cliff retreat from those produced by downwasting of a pre-existing higher surface. Examples of the first subgroup have been described and illustrated by Hills (1971). They are commonly associated with notches and visors at their inner edge; they slope very gently and smoothly seaward; and their outer edge has no rampart but is often undercut by the sea. As concluded earlier in this chapter, the most important formative agents are blue-green algae operating in the notch, but calcareous algae and a range of other organisms are important in protecting the developing platform. The other subgroup is best developed on harder limestones in higher latitudes where biological erosion is relatively slow and seawater solution may be more effective. These platforms often display complex microrelief forms such as lapies with intricate intertidal pools around which solution is presumed to take place. Where tidal range is considerable the pools are characteristically stepped so that as they coalesce to form the ultimate smoother surface it may slope strongly seaward. Examples of such platforms have been described by Guilcher in a number of publications and summarized in his book (Guilcher, 1958).

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PREFACE

In this book I have tried to assess the present state of knowledge on how and why the morphology of coasts varies from place to place, and in writing it, I am aware of metaphorically swimming against the present geomorphological tide in at least two respects. In the first place it is a book full of attempted synthesis and generalization in which words such as 'probably' and 'likely' occur with more than commendable frequency and in which very few statements are made in adequately quantified fashion. I have conceived it as an effort at stocktaking, in which the generalizations represent hypotheses erected with varying degrees of confidence on the basis of available fact and needing critical examination. I hope that I have managed to convey something of the degree of confidence which seems applicable in individual instances. It will be a long time before a definitive work on this theme is written: in the meantime a first attempt at assessing present knowledge and thought and pointing to 'probabilities' and 'likelihoods' seemed a worthwhile project. The 'probabilities' and 'likelihoods' will disappear only when we have far more data and can quantify the inputs and outputs of the world's coastal systems.

The book also deals with a topic which has become rather unfashionable in subaerial geomorphology, where the trend in recent years has been to be increasingly sceptical of many ideas on the climatic zonation of landforms. Until quite recently, coastal processes and forms were thought of as being essentially azonal and attempts, particularly by French geomorphologists, to introduce the idea of climatically controlled distributions have come comparatively late. It is to be hoped that this will enable climatic coastal geomorphology to profit from the mistakes of climatic subaerial geomorphology and in the discussion which follows I have tried to give due weight to all factors of locational variation.

Because it is part of my thesis that the development of thought on coastal processes and forms has been strongly influenced by the location of authoritative workers, it is desirable that I declare my own experience. Although I have seen at least something of the coast of every continent except Antarctica, and have visited extensive stretches of the North American coast, I am most familiar with the shores of Europe and Australia and this familiarity has possibly coloured some subjective judgements which are made in what follows. The Australian coast in particular, incorporating as it does a very wide range of environments, is a very profitable field for the study of coastal variation. Within the tropics I can claim only to have worked for short periods in Ceylon and Barbados and to have made more fleeting visits to other low-latitude shores in Australia, the West Indies, Malaya, Hawaii, Samoa and Fiji. I have not seen coasts in the Arctic or Antarctic and my only experience of ice action has been during a winter and spring spent on the shores of Lake Huron.

Much of the discussion in this book is based on map and air photo work and on a reading of the now very extensive literature in coastal studies, but for practical reasons