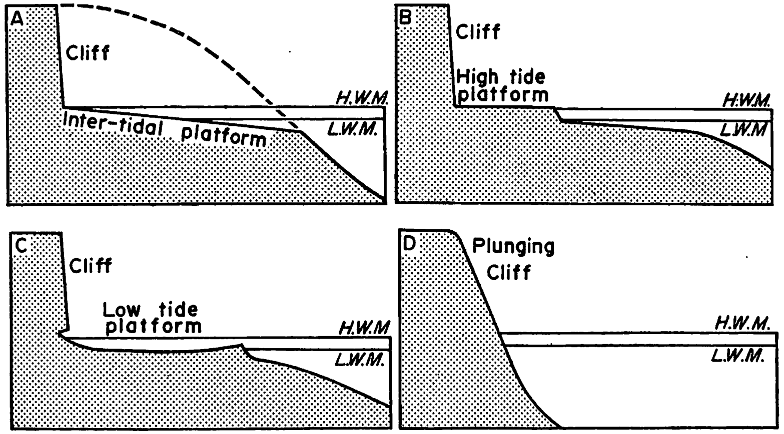
that show a more rapid rate of submergence than this indicate that the local coast has been sinking tectonically; those that show a smaller submergence, or an emergence, indicate that the land has been rising. Donn and Shaw (1963) have summarised the variations in tidal levels on the United States coast during the past century. In Britain, tide gauge records suggest uplift in the N and continuing subsidence on the E and S coasts. Repetition of precise geodetic levelling from time to time can provide an independent check on the results obtained from tide gauge records, and a means of determining areal patterns of crustal deformation more accurately than from measurements of tide levels at scattered coastal stations. Over the next century it should be possible to decide which indeed are the stable areas of the earth's crust, and to isolate more accurately the extent of eustatic sea level change.

A number of geomorphological effects have been attributed to the rise in sea level over the past century. They include the renewal of coral growth on planed-off reef surfaces off the coast of Western Australia (Fairbridge, 1947), the onset of erosion on sandy shores, notably in Australia (Chapter VI), and the prevalence of erosion on the seaward margins of many marshlands (Chapter VII). In each case it is possible to indicate other relevant factors and processes, but the continuance of a slow marine transgression should be borne in mind in considering the dynamics of existing coastal features.

IV

CLIFFED COASTS

Marine erosion of cliffed coasts takes place mainly during storms, and is achieved largely by wave action: the hydraulic pressure of impact and withdrawal, and the abrasive action of water laden with rock fragments (sand and shingle) hurled repeatedly at the cliff base. After a storm the backshore is littered with debris eroded from the cliff. Much of this becomes broken and worn down by wave action (a process known as attrition), and is either retained as a beach, or carried away along the shore or out to sea by the action of waves and currents. The simplest type of cliffed coast is found where marine erosion has attacked the margins of a stable land mass of homogeneous and relatively resistant rocks, removing a wedge of material to leave a steep cliff at the back of a gently-sloping platform, which extends from high tide level to beneath low tide level (Fig. 13A). There are, however, many variants of this simple form, for complications are introduced by the lithology and structure of coastal rock formations, the degree of exposure to wave attack, the effects of subaerial processes of denudation on the coast,

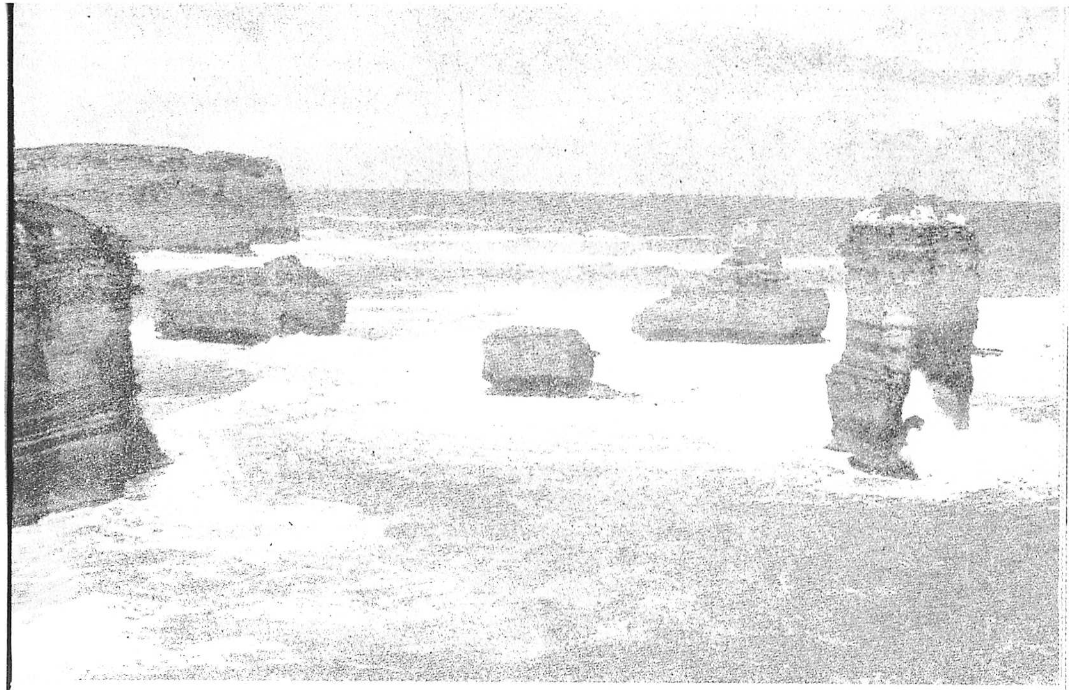


13A *Cliffed coast with an inter-tidal shore platform*
B *Cliffed coast with a shore platform at about high tide level*
C *Cliffed coast with a shore platform at about low tide level*
D *Plunging cliff form, with no shore platform*

and the history of changing land and sea levels. The platform is often termed a wave-cut, or abrasion platform, but these generic terms can be misleading and the purely descriptive term, shore platform, is preferred here. A misconception repeated in many textbooks is that the platform extending beneath low tide level is continued by a wave-built terrace constructed by deposition at its outer margin. There is little evidence that such a terrace actually exists on sea coasts (Dietz, 1963).

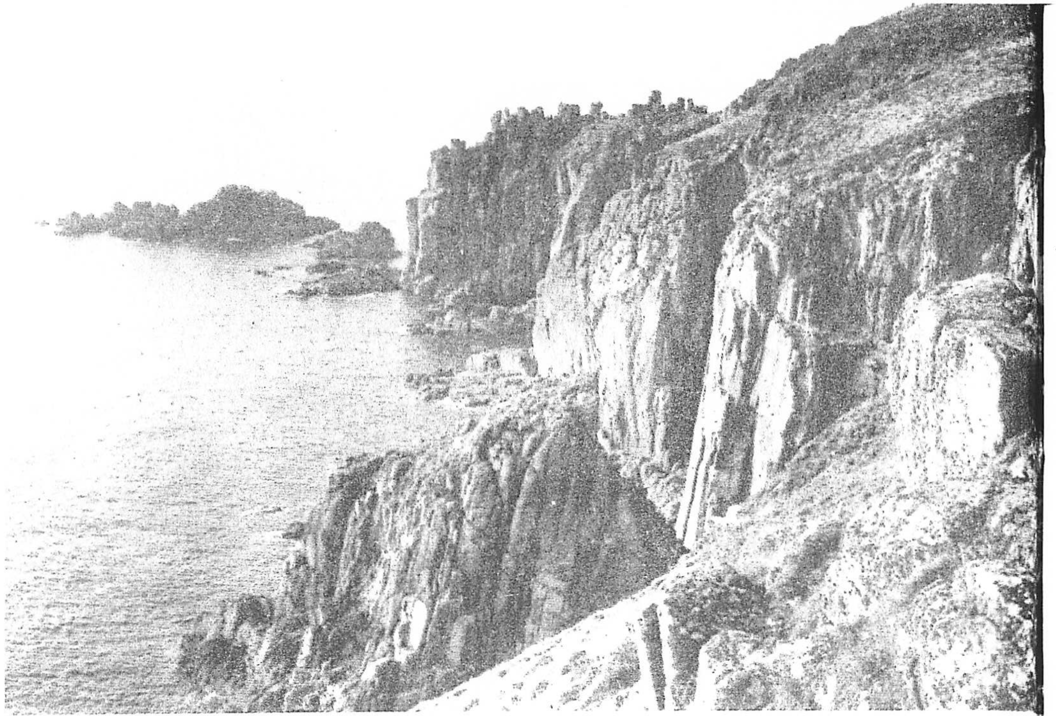
The morphology of cliffs

Examination of almost any section of cliffed coast soon reveals features that are related to variations in lithology and structure, picked out by marine erosion. It is obvious that the more resistant parts of coastal rock formations protrude as headlands, or persist as rocky stacks and islands offshore, whereas the weaker elements are cut back as coves and embayments. Resistance in this context means the hardness of rocks attacked by the physical forces of marine erosion, or their durability in face of other processes at work on the coast, including the physical and chemical effects of repeated wetting and drying of rock surfaces, and the purely chemical effects of solution by sea water, notably on limestone coasts. Solid and massive formations are generally eroded more slowly than formations that disintegrate readily, such as friable sandstones, or rocks with closely-spaced joints and bedding-planes, or rock formations shattered by faulting. Weathering and marine erosion penetrate these lines of weakness, excavating caves and coves, so that patterns of jointing and faulting influence the outline in plan of a cliffed coast. Natural arches, formed where less resistant rock has been excavated from a promontory or islet, are exemplified by the Green Bridge of Wales on the S Wales coast which consists of massive Carboniferous Limestone beneath which thinly-bedded strata have been cut out along joint planes, and various 'London Bridges', notably at Torquay in Devon and Portsea on the Victorian coast in Australia. Where the forces produced by the hydraulic action of waves and the compression of trapped air puncture the roof of a cave, water and spray are driven up through blowholes, as on Porth Island, near Newquay in Cornwall, and on the Old Red Sandstone coast near Arbroath in eastern Scotland. An Australian example is shown in Plate 2. Spectacular steep-sided clefts are produced where the roofs of caves collapse, or



3 *The Twelve Apostles, stacks bordering the cliffed coast near Port Campbell, Victoria*

4 *The Needles, stacks in hard Upper Chalk at the W end of the Isle of Wight, England. The promontory is a ridge of steeply-dipping Chalk, with fresh cliffs on the side exposed to predominant SW waves (Scratchells Bay, right) and partly degraded cliffs on the more sheltered side, bordering Alum Bay (left). (Aerofilms Ltd)*



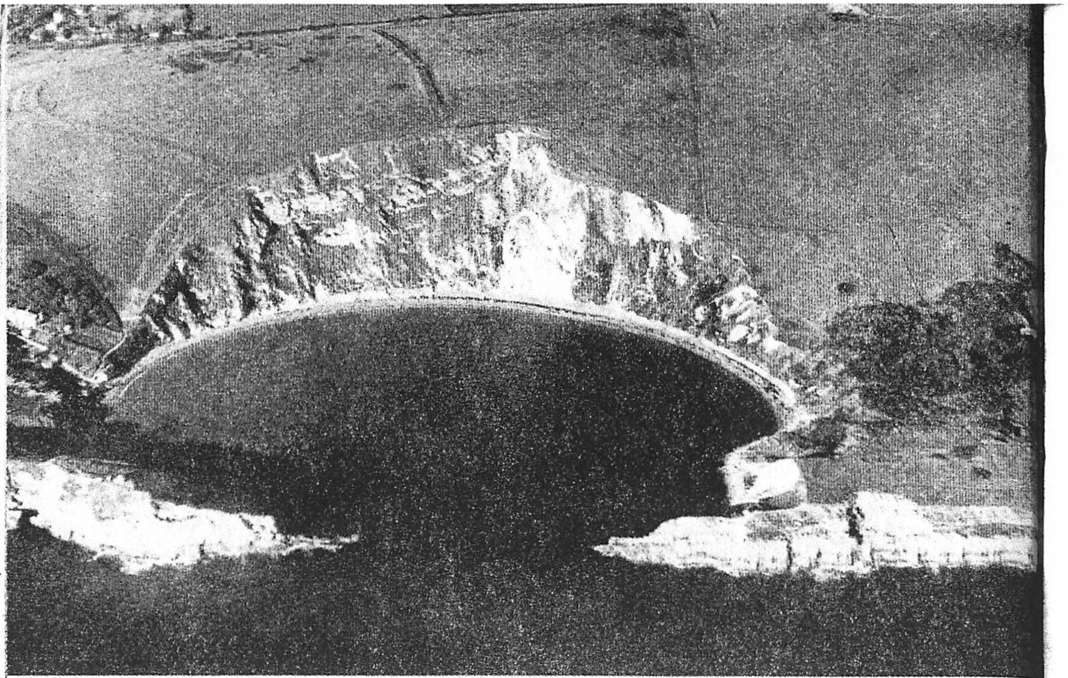
5 *Castellated cliffs in granite at Lands End, England (Aerofilms Ltd)*

6 *Cliffs of columnar dolerite near Cape Pillar in SE Tasmania (Australian Tourist Commission)*

where rock is excavated along lines of weakness at an angle to the shore. Examples can be found on many cliffed coasts: they are known as geos or yawns on the coast of Scotland, and zawns in Cornwall, and local place names commonly credit them with some diabolical function. Gorges of this kind are found on the bold sandstone cliffs of the Jervis Bay district in New South Wales, and near Port Campbell in Victoria, where powerful wave action has penetrated joints and bedding-planes to sculpture a variety of forms, including stacks and natural arches (Plate 3). Similar coastal topography is found on the red sandstones of the Devon coast, notably at Ladram Bay, and in northernmost Scotland, where huge cliffs of Old Red Sandstone face powerful wave action from the north Atlantic. The Old Man of Hoy is a spectacular stack in front of towering cliffs of Old Red Sandstone on the west coast of the Orkneys, but probably the best known stacks are the Needles, residual ridges of hard chalk at the W end of the Isle of Wight (Plate 4).

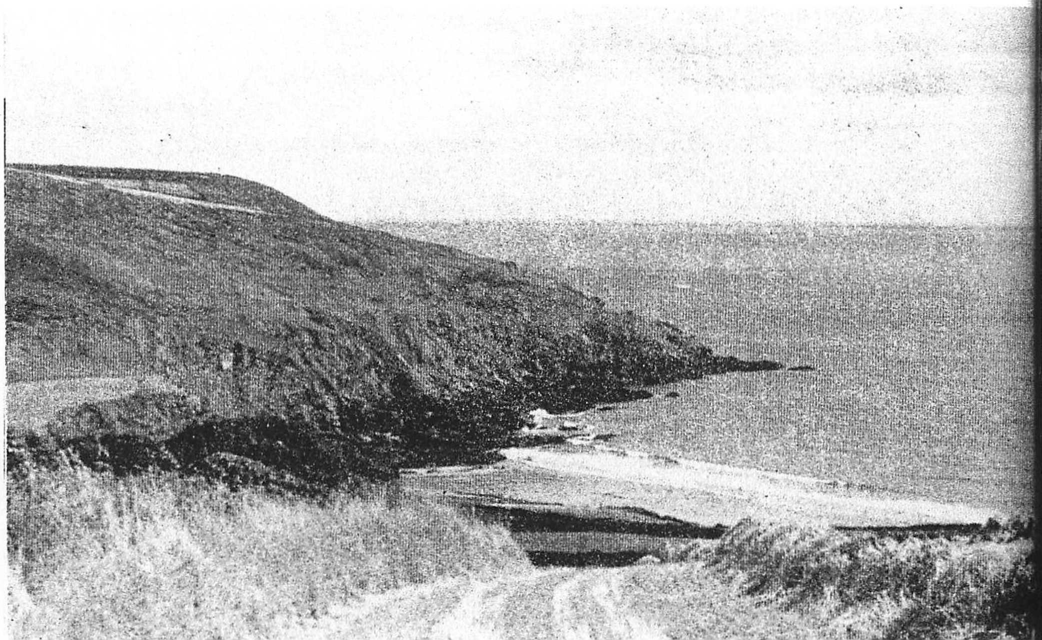
Certain kinds of lithology yield characteristic cliff forms. The castellated granite cliffs of the Lands End peninsula in Britain are related to cuboid jointing (Plate 5), and the columnar basalt cliffs of N Ireland and the similar columnar dolerites on the high cliffs of SE Tasmania (Plate 6) result from pronounced vertical jointing. In limestone areas the sea may penetrate and widen caves that originated as subterranean solution passages: the caves of Bonifacio, in S Corsica, are believed to have formed in this way.

Where the dip of coastal rock formations is seaward, undercutting by marine erosion often leads to landslips and rock falls, the undercut rock sliding down bedding-planes into the sea, leaving the exhumed bedding-planes as a coastal slope. On the S coast of England, coastal landslips are common where the permeable Chalk and Upper Greensand formations dip seaward, resting on impermeable Gault Clay. Water seeping through the permeable rocks moves down the clay plane, and if marine erosion has exposed the junction at or above sea level, lubrication of the interface leads to slipping of the overlying rocks. A spectacular landslip occurred in this situation on the E Devon coast near Axmouth in 1839 (Arber, 1940), and similar slides have occurred on the S side of the Isle of Wight, and between Folkstone and Dover, where a railway built along the undercliff is damaged from time to time by falling rock. It is probable that the physical effects of wetting and lubrica-



7 *Lulworth Cove, on the Dorset coast, S England, a cove excavated in Wealden sands and clays behind a breached wall of strongly-folded Jurassic limestone and backed by a high ridge of Chalk (Aerofilms Ltd)*

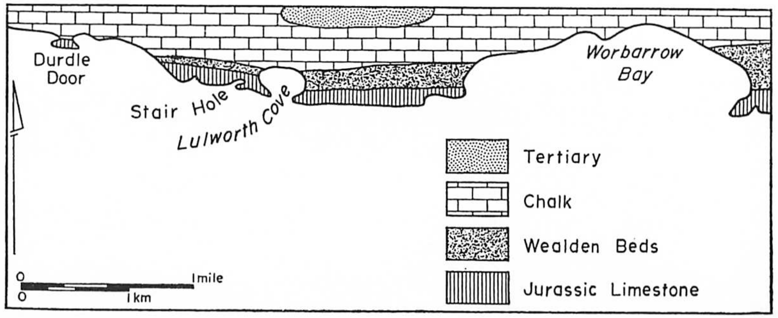
8 *Slope-over-wall cliff topography on the W side of Dodman Point, Cornwall, England. The promontory consists of intensely folded slates and phyllites, exposed in the lower part of the cliff, but mantled by periglacial rubble in the upper slope. (C. T. Bird)*



tion of the Gault Clay surface are accompanied by chemical processes, involving base exchange. The seeping water is rich in dissolved calcium carbonate, and when it reaches the glauconitic Gault Clay, calcium ions displace potassium ions from the clay, alkalinity increases, and the clay is deflocculated (Varnes, 1950). Conversion of the upper layers of Gault Clay into a soft wet slurry which flows out at the base of the cliff hastens the undermining of the Chalk and Upper Greensand beds. Cliffs on soft clay formations in Bournemouth Bay, and on parts of the East Anglian and Yorkshire coasts, are subject to recurrent slumping, particularly after wet weather. Subsequent removal of slumped material by waves and currents at the base of the cliff then rejuvenates the profile, preparing the way for further slumping, so that the cliffs recede as the result of alternating marine and subaerial effects.

Where relatively resistant coastal rock formations are backed by weak outcrops, penetration of the outer wall by marine erosion is followed by the excavation of coves and embayments. The classic example of this is on the Dorset coast E of Weymouth, where several stages can be seen. Stair Hole, near Lulworth, is an early stage, a narrow breach in the outer wall of steeply-dipping Jurassic limestone. Close by, Lulworth Cove has a wider entrance through the limestone wall, and an almost circular bay carved out of Cretaceous sands and clays, backed by a high ridge of Chalk (Plate 7). Farther E a much broader embayment has developed, opening up the clay lowland corridor in front of the Chalk ridge at Worbarrow Bay (Fig. 14).

Cliffs exposed to powerful wave action are often shaped entirely by marine erosion. This is true of the high wave energy coast near



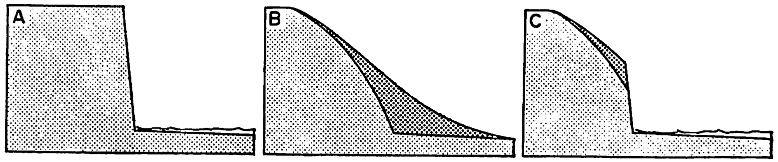
14 *Configuration of part of the Dorset coast, in S England.*

Port Campbell, in W Victoria, where steep cliffs have been cut by marine erosion in horizontal stratified Miocene sedimentary rocks, and the huge waves that break against these during storms have cut out ledges along the bedding-planes at various levels up to 60 m above high tide mark (Baker, 1958). The ledges are rarely more than 3–6 m wide, and it is important to note that they are the product of present-day storm wave erosion; they should not be confused with coastal terraces that bear 'raised beach' deposits indicative of emerged shorelines.

Cliffs on more sheltered sections of the coast, where strong wave action is intercepted by headlands, islands, or reefs offshore, or attenuated by a gentle offshore slope, may show features that have been formed by subaerial denudation as well as those shaped by marine attack. Cliffs in these situations often consist of a coastal slope shaped by rainwash and soil creep, the lower part of which is kept steep and fresh by wave attack. It is instructive to compare the bold profiles of cliffs of massive sandstone facing the ocean in the Sydney district with the gentler, often vegetated, slopes on the same geological formation on the sheltered shores of Sydney Harbour and Broken Bay. The degree of cliffing developed in these situations is closely related to the local fetch, which limits the strength of attack by local wind-generated waves.

Where beaches or barriers have been built up in front of a former cliffed coast, protecting it from marine erosion, subaerial processes become dominant and the steep sea cliff is 'degraded' to a coastal slope of gentler inclination, comparable with escarpment and valley-side slopes inland. In humid regions these slopes acquire a soil and vegetation cover. On the shores of Carmarthen Bay, in S Wales, growth of the Laugharne spit has cut off a former cliffed coast E of Pendine, and the subaerial evolution of slope forms on the abandoned cliffs has been studied by Savigear (1952). On the N Norfolk coast a line of bluffs, formerly cliffs, were cut off in a similar way by the development of spits, barrier islands, and marshlands (Fig. 30, p. 109). In this case the sea reached the cliffs in late Pleistocene times, the raised beach at Stiffkey dating from a late interglacial or interstadial phase, and deposition in front of them took place during and since the Holocene marine transgression, which reworked glacial drift deposits left behind on what is now the floor of the North Sea. In Australia, enclosure of former embayments by the growth of coastal barriers has been followed by the degradation of the former sea cliffs on the enclosed coast, as in the Gippsland Lakes region in Victoria (Bird, 1965).

The active cliffs that we now see on the coast have assumed their present form only since the Holocene marine transgression brought the sea to its present general level within the last 6000 years. Cliffed coasts undoubtedly existed before the Last Glacial phase of low sea level, but during that phase, in the absence of marine attack, they were degraded by subaerial denudation. In high latitudes this degradation took place partly under periglacial conditions, when the cliff became a slope mantled by frost-shattered debris. Since the Holocene transgression, periglaciated slopes of this kind have been undercut by marine erosion, but some coasts retain part of the periglaciated slope, the lower part having been cut back by wave attack to produce a 'slope-over-wall' profile (Plate 8). The slope, mantled by frost-shattered debris, is clearly a legacy of past periglacial conditions; it cannot be explained in terms of processes now at work. Coastal landforms of this type are well developed on the coasts of Devon and Cornwall, in SW England, where the proportion of relict periglaciated slope to actively-receding wall depends on the degree of exposure of a coastal sector to storm wave attack. On sheltered sectors of the S coast of Cornwall and Devon, the relict slope is well preserved, extending down almost to high tide level, but on the more exposed north coast of Cornwall, open to Atlantic storm waves, the relict slope has been largely, and on some sectors (e.g. Watergate Bay, N of Newquay) completely destroyed by Recent marine erosion. The inferred sequence of cliff forms is shown in Fig. 15. Similar features are found in Brittany and S Ireland, on parts of the coast of Washington and Oregon, and on the shores of islands in the Southern Ocean, notably on Auckland Island (Fleming, 1965).



15 *Evolution of slope-over-wall cliffs on coasts subjected to Pleistocene periglaciation. A, pre-periglacial sea cliff; B, cliff degraded under periglacial conditions and mantled by rubble drift (shaded black) during Pleistocene glacial phases of low sea level; C, 'slope-over-wall' form produced by marine erosion of the base of the cliff after the sea rose to its present level in Recent times.*

On rocky sectors of the Antarctic coast the formation of degraded slopes by periglacial activity still continues.

The influence of subaerial denudation on the form of cliffed coasts is also important in humid tropical regions, where many coastal rock formations, weakened as the result of decomposition by chemical weathering, do not form steep cliffs. Yampi Sound in N Australia is bordered by low crumbling cliffs of deeply-weathered metamorphic rocks, from which protrude bolder promontories of quartzite, a type of rock less readily modified by chemical weathering (Edwards, 1958). Marine erosion therefore works upon coastal rock formations, the resistance of which is more a function of their response to weathering under humid tropical conditions than of their original lithology. Tricart (1962) has described the persistence of a dolerite headland at Mamba Point in Liberia, where adjacent outcrops of thoroughly weathered granite and gneiss do not form bold cliffs, and the rarity of cliffed coasts in the humid tropics is also apparent in E Brazil (Tricart, 1959).

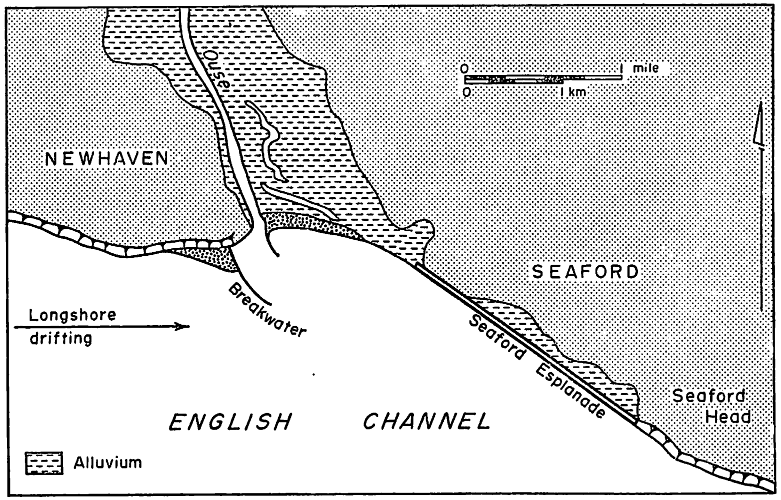
Cliff forms are also influenced by the geomorphology of the immediate hinterland, in particular the topography which is intersected as the cliff recedes. Other things being equal, cliffs that intersect high ground recede more slowly than cliffs cut into low-lying topography, so that interfluves tend to become promontories between valley-mouth embayments. This has happened on the coast near San Remo, Victoria, where a crenulate coastal outline has developed on the margins of hilly dissected country on Jurassic formations, and rather similar terrain has been sculptured in the same way on the Yorkshire coast N of Flamborough Head. Streams which drain valleys truncated by cliff recession pour out as waterfalls cascading on to the shore, as at Ecclesbourne Glen, on the Sussex coast near Hastings, and deep coastal ravines known as chines in the Isle of Wight and Bournemouth Bay have been cut by runoff from land adjacent to rapidly-receding cliffs. Dry valleys truncated by recession of chalk cliffs on the Sussex coast produce the undulating crest line of the Seven Sisters (Plate 9); locally, valleys that ran parallel to the coast have been dismembered by cliff recession, as in the vicinity of Beachy Head. Recession of cliffs is often measured in linear terms, but it is more useful to take account of variations in cliff height. Williams (1956) recorded 12 m of recession on cliffs 12 m high and 27 m of recession on cliffs 3 m high on a mile-long sector of the Suffolk coast at

9 *Chalk cliffs at Seven Sisters on the Sussex coast, England. The cliffs truncate ridges and valleys on the coastal margin of the South Downs, and there is an inter-tidal shore platform at their base. In the foreground the Cuckmere River has built a small delta of sand and gravel, exposed at low tide. (C. T. Bird)*

10 *The ruined village at Hallsands on the S Devon coast, England. The village was built on a coastal ledge (an emerged shore platform) 4–5 m above mean sea level. A broad shingle beach formerly stood in front of it, but removal of shingle resulted in accentuated erosion at the cliff base. (C. T. Bird)*

Covehithe during the 1953 storm surge, when the loss of material over a 24-hour period amounted to about 300,000 metric tons.

Accumulation of large quantities of beach material on the backshore serves to protect the base of a cliff from wave attack, storm wave energy being expended upon the beach. Smaller quantities of beach material that can be mobilised and hurled on the cliff base during storms accentuate abrasion by waves. Herein lies the risk of removing beach material from the shore. Removal of shingle from the foreshore at Hallsands, in S Devon, for construction work at Plymouth during the eighteen-nineties, has led to accentuated cliff erosion and the destruction of the fishing village of Hallsands, which used to stand on a coastal terrace near the base of the cliffs (Robinson, 1961) (Plate 10). Complete absence of rock material in front of cliffs would leave waves unarmed with abrasive material and capable only of hydraulic action at the cliff base, but as a rule some beach sediment is present, and one way of halting recession of cliffs on weak outcrops is to build and maintain a broad beach by constructing groynes to intercept longshore drifting, augmented if necessary by the dumping of supplementary beach material on the foreshore or updrift. Groynes which intercept longshore drifting may starve the coast downdrift of sediment, accentuating erosion there. This has happened on the Sussex coast since the building of Newhaven breakwater intercepted eastward shingle drift, leading to depletion of beaches at Seaford, where the seafront is repeatedly damaged in storms, and under Seaford Head where the chalk cliffs are now receding rapidly (Fig. 16). Sea walls may stabilise a shore, but unless a protective beach is maintained in front of them they will need frequent repair.



16 *At Newhaven, on the S coast of England, the construction of a breakwater W of the harbour interrupted the eastward shingle drift, so that only a narrow fringe of shingle persists from Seaford Esplanade eastwards*

The outline in plan of a cliffed coast often becomes simplified and smoothed with the passage of time, except where there are marked contrasts in the structure and lithology of coastal rock formations, which may perpetuate irregular outlines as the cliff recedes. Where the coastal outcrops are comparatively uniform, a receding cliffed coast tends to develop an outline in plan related to the prevailing wave patterns, although it is possible for crenulations to develop and persist even on receding cliffs of generally homogeneous material, as on sectors of the Nullarbor coast in S Australia (Plate 11). Where the predominant wave patterns are refracted by offshore topography or adjacent headlands, the cliffed coasts develop gently-curved outlines in plan, much like those on depositional coasts (Chapter V); indeed a curved cliffed sector may pass smoothly into a curved depositional sector, as in some of the asymmetrical embayments on the Victorian coast, notably Waratah Bay W of Wilsons Promontory. Similar curved outlines have developed on the Tertiary cliffs of Bournemouth Bay, in S England, in relation to refracted waves approaching from the SW.

Shore platforms

On the simplest form of cliffed coast, the cliffs are bordered by platforms extending across the shore zone and sloping gently, but not always uniformly, to pass beneath the sea. These platforms are evidently developed and widened as the cliffs recede, and shaped by the action of waves and other marine processes. They extend from high tide mark, at the base of the receding cliff, to a level below and beyond low tide mark, in the nearshore zone, and it is convenient, though not strictly accurate, to describe them as inter-tidal shore platforms (Fig. 13A).

Such platforms are best developed where the coastal rock formations are homogeneous, without structural or lithological variations, but it is difficult to find ideal examples. Vertical cliffs and sloping inter-tidal platforms are found on the Chalk coasts of

11 *Cliffs near the Head of the Bight, in South Australia. The coast consists of almost horizontal Eocene and Miocene limestones. (Australian Tourist Commission)*

12 *Serrated foreshore topography on Palaeozoic rocks at Barraga Point, New South Wales, showing shore platform development along corridors of less resistant rock (O. F. Dent)*

S England and N France (Prêcheur, 1960), but these are not simply the product of wave abrasion (see below, p. 65). The ideal form is sometimes found where structureless sandstone or shale formations have been eroded by wave action, but its development requires a delicate balance between rock resistance and the intensity of wave attack. If the rocks are too resistant, the cliff and the inter-tidal shore platform will not have developed in the time available since the sea reached its present level; if they are too weak they will be unable to sustain a steep cliff profile, and will either show recurrent landslides or will recede until they are reached by the sea only briefly at the highest tides and develop subaerially degraded profiles. Relatively resistant formations may be eroded into steep cliffs and inter-tidal shore platforms on a high wave energy coast, and relatively weak formations may develop these features on a low wave energy coast; under such a balance of conditions, a dynamic equilibrium may be attained, the coastal morphology persisting with parallel recession of cliffs and inter-tidal platforms. In practice there are usually several complicating factors, but the balance of these may sometimes yield a deceptively simple cliff-and-platform profile, as on certain Chalk coasts. More often, variations in structure and lithology in the shore zone persist in irregularities of profile with tracts of platform locally developed, between ridges of harder rock and channels where less resistant outcrops have been excavated (Plate 12).

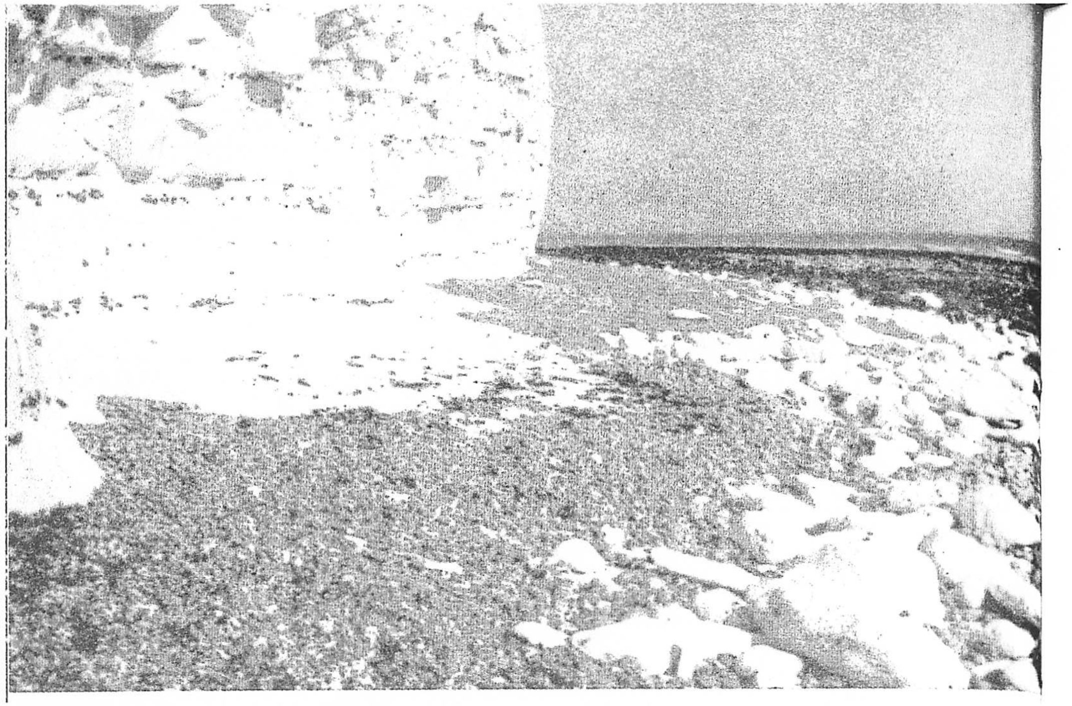
Waves armed with rock fragments (sand, shingle, cobbles) are undoubtedly powerful agents of abrasion. Without such fragments, waves are capable of only limited abrasion, mainly on soft clay and shale formations. Rock fragments may be of local derivation, eroded from the cliff or the shore platform, or they may have been brought in by longshore drifting from adjacent sectors of the coast, or shoreward drifting from the sea floor. Evidence of wave abrasion can be seen on shore platforms where the more resistant elements of rock persist as reefs and stacks and intervening areas have been scoured out as pools and clefts. Debris used by the waves as an abrasive tool is found littered on the shore platform, particularly after stormy periods; the rock fragments are generally smooth and round as the result of abrasion. Smoothed and scoured abrasion ramps slope gently upward to the base of the receding cliff, which has sometimes been undercut to form a definite abrasion notch. Rock fragments that become trapped in a crevice on a shore platform may be repeatedly moved by wave action in such a way as to excavate circular potholes, smoothly-worn basins containing smoothed and rounded pebbles—clear evidence of the potency of waves armed with abrasive debris.

The depth to which abrasion is active is an important factor in the evolution of shore topography. Sand grains in sea floor sediments off the Californian coast have been shown to become well worn and rounded in depths of less than 10 m below low tide level; in deeper water they show less evidence of wear, and often remain angular. As the wearing of these particles implies the abrasion of the rock surface upon which they rest, this evidence suggests that on coasts exposed to ocean swell, abrasion of the platforms is effective only to a depth of 10 m (Bradley, 1958). On a tideless coast, wave-cut platforms can develop from the water's edge seawards to a depth of 10 m, and with an average inclination of 1° such a platform would be about one-third of a mile (0·5 km) wide. The possible width increases with tide range, and would be about half a mile (0·8 km) with an average slope of 1° where the tide range is 5 m. Where very broad shore platforms are found, they can only be explained as wave-cut platforms if they have developed during a phase of slow marine transgression, the land margin being planed off by waves as the sea rose.

The Chalk cliffs and inter-tidal shore platforms on the English and French coasts bordering the English Channel are to some extent the product of wave abrasion, the waves being armed with flint nodules eroded out of the Chalk (Prêcheur, 1960). Chalk is a relatively homogeneous limestone formation. The best development of vertical cliffs and sloping inter-tidal shore platforms is on the Kent coast near Dover and the Sussex coast E of Brighton, where stratified chalk dips gently seaward. Fresh white chalk exposed on the shore platform and at the base of the cliff after stormy periods is evidence of the wearing and scouring of chalk by waves armed with flints, but other processes are also at work. Cliff recession is marked by recurrent rock falls, particularly after wet weather, or when a spring thaw releases rock masses that had been loosened by frost action along vertical joints and horizontal bedding-planes during the preceding winter. Fans of chalk and flint talus thus produced are subsequently dispersed or consumed by the sea. Examination of boulders that have fallen in this way shows that the chalk surface is pitted by solution, and that the rock has been modified by the physical and biochemical effects of shore flora (chiefly marine algae) and fauna (limpets, mussels, and winkles). These processes play an important part in the reduction and eventual disappearance of the chalk, releasing unworn flint nodules which can then be used in abrasion. Wave action contributes to the wearing and reduction of rock debris and also clears away material that has fallen from the cliffs, thereby ensuring continued recession at the cliff base (Plate 13).

Structural and lithological variations in coastal rock formations can strongly influence the development of cliff and shore platform profiles. In the Sydney district, on the coast of New South Wales, stepped profiles have developed on the outcrops of Triassic sandstones, the steps being 'structural' in the sense that they coincide with the upper surfaces of resistant strata: they are horizontal where the bedding is flat, and inclined where the rocks are dipping (Plate 14). It is possible to follow a particular bench along the shore, down the dip of a resistant sandstone layer, until it passes below sea level, when the bench on the next higher resistant rock outcrop begins to dominate the shore profile (Johnson, 1931; Jutson, 1939). This kind of coastal topography results from storm wave activity, with erosion along bedding-planes and joints and the removal of dislocated rock masses to lay bare a structural bench. Where the rock formations dip gently seaward the profile may resemble an inter-tidal shore platform, passing below low water mark. Where benches or platforms have developed on flat or gently dipping formations above high tide level, it may be tempting to regard them as emerged features, developed during an earlier phase of higher relative sea level, but on high wave energy coasts storm waves may develop 'structural' benches as much as 60 m above present sea level on horizontal or gently-dipping stratified formations (p. 56). A platform above high tide level is more likely to indicate an earlier phase of higher relative sea level if it is cut *across* the local structures of coastal rock formations, and, even then, confirmatory evidence of associated 'raised beach' materials is desirable.

Structural benches of the kind found on the Sydney coast are developed elsewhere on horizontal or gently-dipping sandstones, and occasionally on stratified limestone formations. In Britain, the Old Red Sandstone of northernmost Scotland has benches of this kind, and they are also found locally on the Triassic sandstones of the S Devon coast between Torquay and Sidmouth.



13 *Base of Chalk cliff near Birling Gap, Sussex, England, showing flint shingle and rounded boulders of chalk on the beach and layers of flint in the face of the cliff (C. T. Bird)*

14 *Structural benches on bedded sandstone in the cliffs at Cape Solander, New South Wales (O. F. Dent)*

Much attention has been given in coastal geomorphological literature to horizontal, or nearly horizontal, shore platforms found on many coasts, which truncate local geological structures and cannot be explained in terms of lithological control. Originally observed and studied in New Zealand, Hawaii, and Australia, these are in fact of widespread occurrence on the islands and shores of the Pacific and Indian Oceans, and have also been noted locally on the Atlantic coast. They fall into two main categories: those developed at, or slightly above, mean high tide level ('high tide shore platforms') (Fig. 13B), and those developed slightly above mean low tide level ('low tide shore platforms') (Fig. 13C).

Shore platforms at relatively high levels have been interpreted in various ways (Cotton, 1963). In SE Australia they are typically submerged at high spring tide, and when storms drive waves across them, but on calm days they remain dry at high neap tide (Plate 15). It has been suggested that they are essentially 'storm wave platforms' produced by waves driven across them during storms when the cliff at the rear is cut back; in calmer weather, wave action is limited to the outer edge, which gradually recedes, the width of the platform being a function of the relative rates of front and rear recession. It is difficult to accept this as an explanation for horizontal shore platforms, except in the special case where the platform coincides with the upper surface of a horizontal rock stratum. Attempts to argue that storm waves achieve planation by concentrating their energy at a particular level (Edwards, 1941) are not convincing, since storm waves come in a variety of dimensions, and operate over a height range related to the rise and fall of tides. High tide shore platforms are often as well, or better, developed on sectors of the coast that are sheltered from strong storm wave activity as on the New South Wales coast, where the strongest storm waves arrive from the SE, but the high tide shore platforms are at least as broad and often better developed on the northern sides of headlands and offshore islands. On the more exposed southern sides the platforms show evidence of dissection and destruction at their outer margin and along joints and bedding-planes, and there is evidence that this recession accompanies the development of an inclined platform at a lower level (Bird and Dent, 1966). It appears that wave abrasion, operating alone, tends to develop the simple profile of steep cliff, bordered by 'inter-tidal' shore platform, within restraints imposed by the structure and

15 *High tide shore platforms on the New South Wales coast near Scarborough*

16 *Inner margin of high tide shore platform cut in basalt on Broulee Island, New South Wales, showing the degraded bluff*

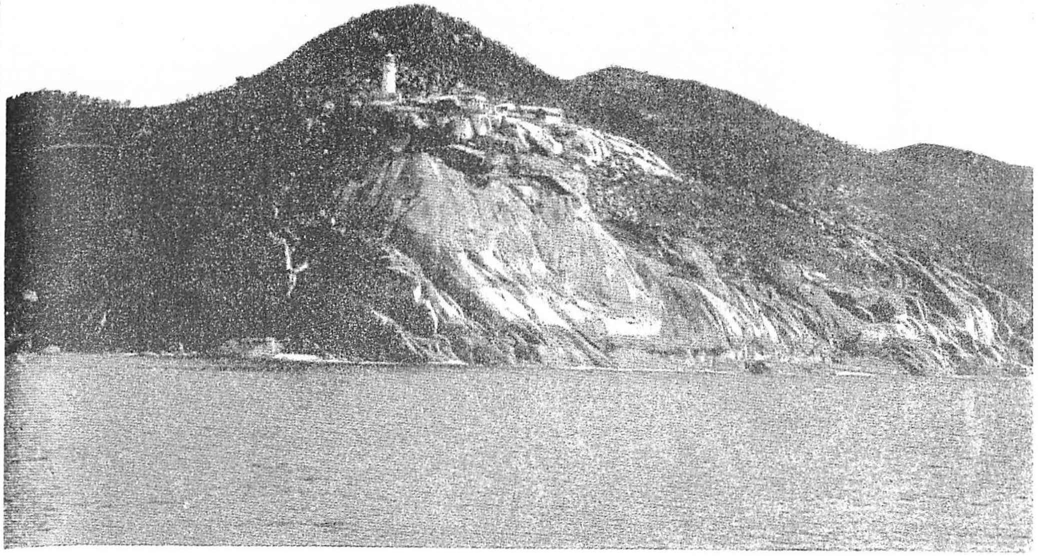
lithology of coastal outcrops. Horizontal platforms truncating local geological structures cannot be explained in terms of storm wave attack, which appears to have a secondary and modifying influence on these features.

It has been suggested that shore platforms at or slightly above mean high tide level are the product of wave abrasion at an earlier phase when sea level was higher (Fairbridge, 1961), the platforms merely being kept fresh by the surf that washes over them at high spring tides and during storms. The hypothesis accords with the idea that the Holocene marine transgression attained a maximum a few feet above present sea level before dropping back during a phase of 'Recent emergence', and, where high tide shore platforms are backed by degraded cliffs which have not been kept fresh by marine attack, the evidence for this view appears strong (Plate 16); dissection of the outer edge of the platforms can then be interpreted as the result of the cutting of a new platform by wave abrasion at a lower level following emergence. However, it is difficult to explain why high tide shore platforms are horizontal, or nearly so, whereas the platform being cut by wave abrasion at a lower level has a seaward inclination. Moreover, the cliffs behind high tide platforms are not always degraded. Some are clearly active and receding, but the degradation of others could be simply a function of intermittency of storm wave attack, and a relatively long phase of quiescence since they were last trimmed back by the sea. It is necessary to consider what other processes are at work on these cliffs and platforms before deciding if it is necessary to invoke an episode of higher sea level in Recent times to account for their development.

Examination of shore features in the vicinity of high tide shore platforms yields evidence that weathering processes are at work on coastal rock outcrops unprotected by a soil or vegetation cover in the zone at and above mean high tide level. Superficial decomposition of exposed rock surfaces results from repeated wetting and drying, accompanied by salt crystallisation, in the zone subject to the action of spray. Tricart (1959) claimed that salt spray weathering is a dominant process in shore platform development on the tropical coast of Brazil, where absence of coarse detritus impedes abrasion by waves and high insolation rapidly dries off rock surfaces wetted by saline spray. It is, however, difficult to dissociate the physical effects of wetting and drying from the physicochemical effects of crystallisation from drying spray. Salt crystallisation probably has specific corrosive effects, and may accelerate weathering compared with wetting and drying in freshwater environments: laboratory tests suggest that this is so, but the problem requires further investigation in the field.

Sandstone outcrops subject to wetting by seaspray and rainfall, and subsequent drying, become pitted and honeycombed as sand grains are loosened by the decomposition of the cementing material that formerly bound them. Other fine-grained rock formations, such as siltstones, mudstones, shales, schists, phyllites, and basalts, are subject to similar superficial decomposition and weathering effects. This kind of weathering is not effective at lower levels, where rock formations are permanently saturated by sea water, and so wave action washes away the disintegrating material above a certain level, gradually laying bare a platform which coincides with the upper level of permanent saturation. On the coast of SE Australia it is the fine-grained rock outcrops, which show evidence of pitting and cavity formation indicating that the exposed rock is gradually being disintegrated by weathering processes, that have shore platforms developed at or slightly above mean high tide level. Pools and channels on the platform surface become enlarged and integrated as their overhanging rims recede, and gradually the rock surface is 'peeled off' down to a level which remains intact because it is permanently saturated (Plate 16). The process has been described as 'water-layer weathering', and as the level of saturation need not coincide with bedding-planes it offers a mechanism by which coastal planation may operate, forming platforms which may transgress local geological structures (Hills, 1949). It also accounts for the fact that high tide shore platforms are almost horizontal, often with a raised rim at the outer edge which is permanently saturated by breaking waves. Finally, this type of weathering is less effective on massive coastal outcrops of granite and quartzite on the SE coast of Australia, which explains why some headlands, such as the granite mass of Wilsons Promontory in Victoria, are not bordered by high tide shore platforms (Plate 17).

Water-layer weathering explains many features of high tide shore platforms, but it cannot explain them entirely. Occasional storm wave activity is necessary to sweep away the disintegrated rock material, and to attack and rejuvenate the base of the cliff at the rear of these platforms. On extremely sheltered sectors of the



17 *Plunging cliffs of granite at the southern end of Wilsons Promontory, Victoria (Australian News and Information Bureau)*

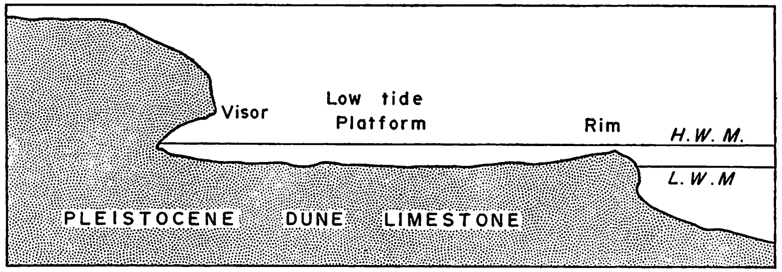
18 *Part of the low tide shore platform cut in Pleistocene calcarenite on the Victorian coast near Portsea, showing the notch and overhanging visor at the base of stacks*

coast it is possible that the weathered material would not be carried away sufficiently for the high tide shore platform to develop, and on sectors exposed to very frequent storms it is possible that abrasion would be sufficiently rapid to destroy the high tide platform as quickly as the removal of weathered debris laid it bare. The width of such a platform is determined by the relative rates of recession of the cliff at the rear (by removal of weathered material and occasional storm wave abrasion) and the frontal margin (by more continuous wave action on permanently saturated and unweathered rock). Where nearshore rock debris is available, accelerated dissection of the frontal margin may lead to the development of an inter-tidal shore platform. On the New South Wales coast high tide shore platforms give place to inter-tidal platforms on exposed sectors where wave abrasion is facilitated by the presence of locally-derived shingle (Bird and Dent, 1966). The nature and extent of shore platforms on such a coast vary in relation to a number of factors: lithology, structure, weathering processes, nearshore topography, wave régime, tidal range, and the availability of abrasive debris—factors that vary intricately on a coast of irregular configuration, with local variations in aspect. As the sea stood at higher levels relative to the land at certain phases during Quaternary times, existing shore platforms have evidently developed as the result of down-wasting and planation of presumably similar features that developed earlier at higher levels. Locally, fragments of older and higher platforms may persist as emerged terraces. High tide shore platforms on the SE coast of Australia are related to present sea level and wave conditions and it is not necessary to invoke an episode of higher sea level to account for them; on the other hand they cannot be taken as evidence that a higher stillstand did not occur in Recent times.

The development of shore platforms by the washing away of disintegrated material where rock formations have been weathered down to a certain level was described by Bartrum who termed these platforms of 'Old Hat' type, with reference to an island off the NE coast of New Zealand (Cotton, 1963). In N Australia, Edwards (1958) similarly explained broad platforms on the shores of Yampi Sound in terms of removal by wave action of rock that had been deeply weathered, under tropical humid conditions, to expose a shore platform of unweathered rock. Climatic factors may also have influenced the development of strandflats, the

extensive shallow-water and partly emerged platforms of problematical origin found on the fiord coasts of Norway, Spitzbergen, Iceland, and Greenland. They are up to 64 km wide locally, and numerous rocky islands rise above them. It is possible that they developed as the result of plucking and disintegration of coastal rock outcrops by shelf ice, followed by the sweeping away of debris by wave action when the ice melted. Alternatively, they may be the outcome of prolonged coastal periglaciation. The Norwegian strandflat appears to be a relict feature (Tietze, 1962), but the processes which produced it have not yet been identified on actively glaciated or periglaciated Arctic or Antarctic rocky coasts.

Low tide shore platforms may be defined as horizontal, or almost horizontal platforms exposed only for a relatively brief period when the sea falls below mean mid-tide level. They are best developed on certain limestone coasts, where they are broad and almost flat, except for an inclined ramp towards the rear, leading up to the cliff base, which frequently has a notch overhung by a visor (Plate 18). There is sometimes a slightly higher rim at the outer edge formed by an encrustation of algae (chiefly *Lithothamnion* species) in a zone that is kept wet by wave splashing even at low tide (Fig. 17).



17 *Low tide shore platform, as developed on Pleistocene dune limestone (aeolian calcarenite) on the S and W coasts of Australia*

As low tide shore platforms of this kind are typically developed on limestone formations, it is evident that solution of limestone (chiefly calcium carbonate) by water, in the presence of carbon dioxide, is an important factor in their formation (Wentworth, 1939). The dissolving of limestone is represented by the equation:

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca(HCO_3)_2$$

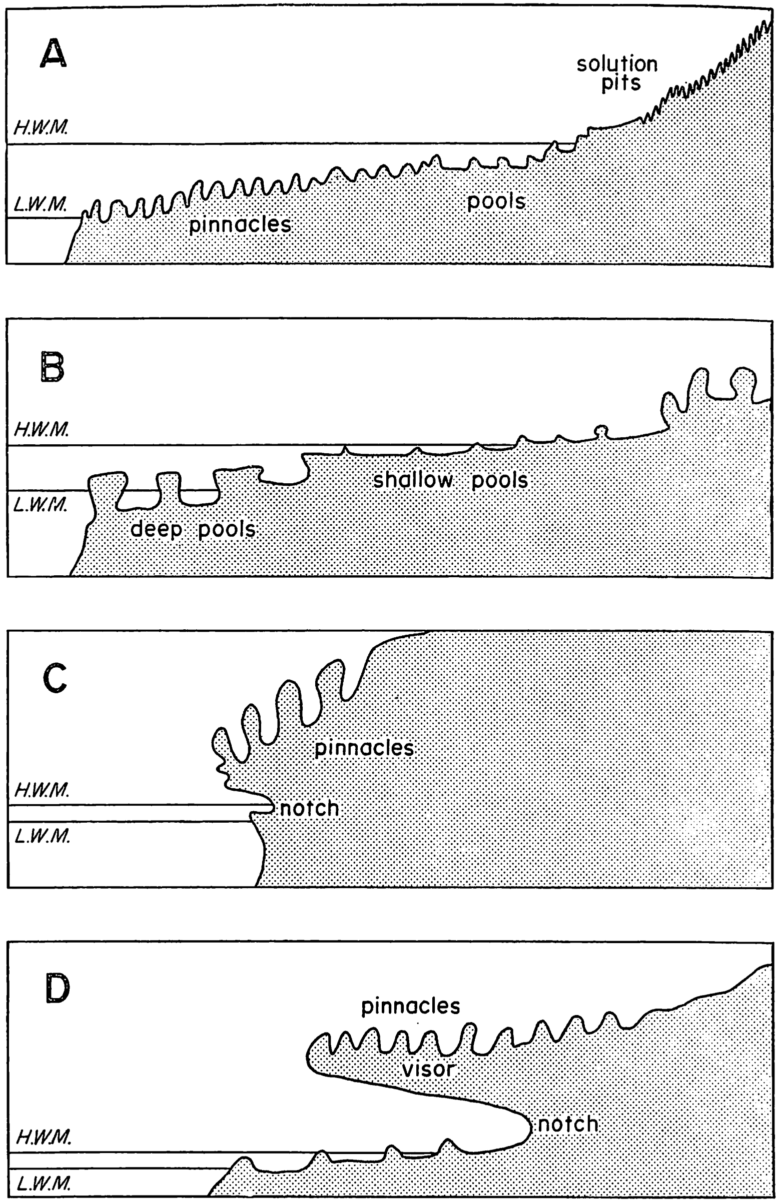
the rock passing into solution as calcium bicarbonate, $Ca(HCO_3)_2$. Solution of limestone can also be accomplished by rainwater and by ground-water seepage provided that the water contains dissolved carbon dioxide and is not already saturated with calcium bicarbonate in solution. In fact, sea water off limestone coasts and ground water emerging from limestone cliffs is normally saturated with dissolved calcium bicarbonate, and thus incapable of dissolving more limestone on the shore. Rain water, on the other hand, is rich in dissolved atmospheric carbon dioxide, and is capable of dissolving away a limestone surface. This is a contributory factor in the development of limestone shores exposed to rainfall at low tide, but the fact that low tide platforms are at least as well developed on the coasts of arid regions indicates that some other factor must be dominant.

The problem of how sea water, already saturated with calcium bicarbonate, can achieve further solution of limestone in the shore zone was analysed by Revelle and Emery (1957) on Bikini Atoll. They found that there were marked diurnal variations in the dissolving capacity of sea water, related in part to variations in the temperature and carbon dioxide content of water in the shore zone. Nocturnal cooling of sea water increases its capacity to take up carbon dioxide (which is more soluble in water at lower temperatures), permitting it to dissolve more limestone, and the biochemical activities of marine organisms lead to the production of carbon dioxide (from plant and animal respiration) which is used by the plants (chiefly algae) in photosynthesis by day but which accumulates at night when the absence of sunlight halts photosynthesis. The nocturnal increase in the acidity of coastal water permits limestone to be taken into solution. Additional calcium carbonate dissolved during the night will be precipitated by day, when temperature rises and photosynthesis revives, but the precipitated sediment is likely to be carried away from the limestone shore by waves and currents. As the nocturnal solution processes operate mainly within the tidal zone, they will remove calcium carbonate in solution down to a level at which permanently saturated and submerged limestone is evidently dissolved more slowly, if at all, by sea water, so that a low tide platform tends to develop. According to Hills (1949), shore platforms developed on calcarenites coincide with a horizon of secondary induration, where cementing calcite has been precipitated from percolating ground water encountering

carbonate-saturated sea water: the calcarenite is less resistant both above and below this horizon, which thus becomes a structural factor in shore platform evolution.

As with the water-layer weathering process effective on the coastal rock formations where high tide shore platforms have developed, solution processes are accompanied by occasional storm wave activity, which sweeps away precipitated calcium carbonate, and, if armed with suitable rock fragments, achieves abrasion of the outer margin of the platform and of the ramp and cliff at the rear. Chalk coasts, discussed previously, would evidently have developed similar low tide shore platforms, were it not for the availability of associated flints, which have been used in wave abrasion, leading to the development of a broad inter-tidal platform. The notch and visor feature typical of many limestone coasts is evidently not simply an abrasion notch; it is as well developed on sheltered sectors of the coast as on sectors exposed to strong wave action, and extends uniformly around the stacks in the foreground of Plate 18. Exposure to strong storm wave activity is evidently inimical to the development of this feature, for storm waves have been observed to snap off visors that had developed under quieter conditions. Hodgkin (1964) found that maximum solution of coastal calcarenites (about 1 mm/year) takes place just above mean sea level, where the notch develops, indicating that it is essentially the outcome of solution processes. Marine organisms also contribute to the etching away of limestone in the shore zone, and Emery (1960) has indicated that in favourable conditions biochemical processes can consume rock at least as quickly as physical and purely chemical erosion. Some would go as far as to suggest that the notch has been almost literally eaten out by the shore fauna that occupies this horizon.

Shore morphology on limestone coasts shows variations related to zonal climatic factors. Guilcher (1953) has outlined the characteristic features of limestone (excluding Chalk) coasts in the cool temperate, warm temperate, and tropical zones. In cool temperate regions (S Ireland, S Wales) limestones show pitting and honeycombing in the upper (spray) zone, shallow flat-floored pools with overhanging rims, tending to widen and coalesce as a platform, in the shore zone, and a more irregular network of ridges and pinnacles (coastal lapies) in the lower part of the shore zone (Fig. 18A). These predominantly solution forms are obliterated where waves



18 *Typical zonation of corrosion forms on coastal limestone (after Guilcher, 1958): A, cool temperate regions (British Isles); B, warm temperate regions, microtidal (Mediterranean); C, warm temperate regions, mesotidal (Morocco); D, tropical regions (Pacific atolls)*

armed with rock debris abrade the shore zone, and lithological variations introduce further complications, as on the stratified Jurassic limestones of the Dorset coast. In warm temperate regions Guilcher recognised two kinds of zonation, both with coastal lapies in the upper (spray) zone (Plate 19). On mesotidal coasts (Morocco, Portugal) the shore zone consists of flat-floored pools becoming larger and deeper towards low tide mark; on microtidal coasts (Mediterranean) there is a notch, with an overhanging visor, and a narrow shore ledge exposed at low tide (Fig. 18 B and C). The zonation on Australian calcarenite shores in a warm temperate environment is similar except that the shore platform is somewhat broader. Guilcher (1958b) found that the warm temperate zonation gave place to the cold temperate zonation from S to N around the Bay of Biscay. In tropical regions, especially on emerged coral, the pinnacles are developed on top of an overhanging visor, and the flat-bottomed pools occupy a ledge exposed at low tide (Fig. 18D).

There are similar variations in the characteristic forms of cliffed coast on granites and basalts, related to the weathering régime under different climatic conditions, but the details of these have not yet been worked out.

Plunging cliffs

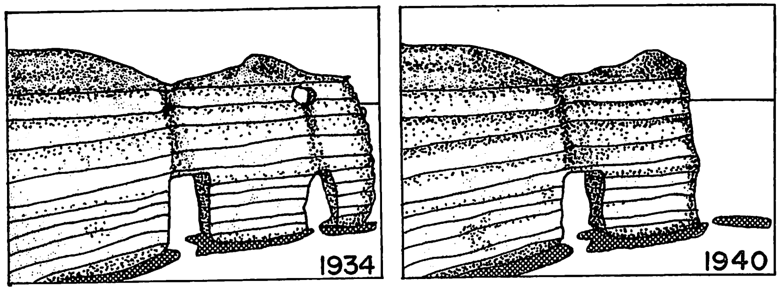
Plunging cliffs (Fig. 13D) are cliffs that pass steeply beneath low tide level without any development of shore platforms. These have several possible explanations. Plunging cliffs can be produced by Recent faulting, the cliff being the exposed plane of the fault on the up-throw side, the down-thrown block having subsided beneath the sea. The cliffs along the line of the Wellington fault, on the W shore of Port Nicholson in New Zealand, have been explained in this way (Cotton, 1952); they slope at about 55°, show little evidence of marine modification at the shore level, and descend to the 12 fathom (about 22 m) submarine contour, close inshore and parallel to the coastline. Tectonic subsidence of coasts may lead to the development of plunging cliffs, possibly with former shore platforms submerged beneath low tide level; Cotton (1951b) suggested that the plunging cliffs of Lyttleton Harbour and Banks peninsula (Fig. 45, p. 123) originated as the result of continuing subsidence of this area during and since the Holocene marine transgression. Coasts built up recently by volcanic activity,

19 *Coastal lapies on a limestone shore at Two Mile Bay, Victoria*

as on the island of Hawaii, show plunging cliffs on sectors where there has not yet been time for shore platforms to develop. Absence of shore platforms on very sheltered sectors of coast bordering rias and fiords, and on sectors where the coastal rock outcrops are extremely resistant, may simply be due to the fact that the period of up to 6000 years since the sea attained its present level has been too brief for marine processes to develop platforms. In Australia the plunging granite cliffs of Wilsons Promontory (Plate 17) are evidently too resistant for shore platforms to have developed within this relatively short period; the cliffs are the partly-submerged slopes of granite hills and mountains. On the Nullarbor coast, there are sectors where the vertical cliffs of homogeneous Eocene and Miocene limestones pass beneath low tide level without shore platforms, possibly because the great vigour of storm wave activity on this coast is achieving abrasion down to a level below low tide level as these cliffs recede (Plate 11).

The morphogenic system leading to the evolution of cliffed coasts can be analysed in terms of the effects of geological structure and lithology, the action of marine and subaerial processes, tidal conditions, and the inheritance of changing levels of land and sea and changing climatic conditions. The tempo of change on a cliffed coast shows marked variations from place to place, even on adjacent flanks of an embayment or headland, according to rock resistance and degree of exposure to marine attack. At one extreme there are sections of coast, like Wilsons Promontory, which have changed very little in the period since the Holocene marine transgression brought the sea to its present general level. At the other extreme there are sections of rapid cliff recession, as on the coast of W Victoria, near Port Campbell, and sectors of the E and S coasts of England, where relatively weak Tertiary formations confront stormy seas, and changes can be measured by referring to old maps and photographs (Fig. 19). Between these extremes there are many sections of cliffed coast that are developing slowly and showing variations which can be analysed to show the respective roles of rock resistance, wave attack, and coastal weathering processes in their developing morphology.

Studies of the evolution of cliffed coasts have generally been largely qualitative, concerned with identifying and attempting to evaluate the various factors and processes that have been at work. In quantitative terms it would be possible, given adequate data on



19 *The betrunking of Elephant Rock, near Port Campbell, Victoria (after Baker, 1958)*

wave direction and height in relation to tidal levels, to derive a time-integrated expression of the wave energy profile on a cliffed coast. Profiles of this kind have been used in engineering studies, notably in the design of sea walls, but there are difficulties in attempting to use such data to explain the configuration of a cliffed coast. Existing configuration is one of the important factors determining the wave energy profile so that there is a danger of circular argument. Moreover, as has been indicated, erosion of cliffed coasts is the outcome of a variety of processes, including weathering, solution, and biochemical activity, which are largely independent of wave energy profiles. It is perhaps because of these difficulties that satisfactory quantitative appraisals of the evolution of cliffed coasts have yet to be made.

V

BEACHES, SPITS, AND BARRIERS

Beaches are accumulations of sediment deposited by waves and currents in the shore zone. In terms of the Wentworth scale of particle diameters (Table 1) they are typically composed of sand or shingle. The proportions of each grain size can be determined by mechanical analysis, when a known weight of dried beach sediment is passed through a succession of sieves of diminishing mesh diameter, and divided into size grades which are weighed separately. As a rule, samples of beach sediment are well sorted, in the sense that the bulk of a sample falls within a particular size grade, as indicated by the graph in Fig. 20. Statistical parameters based on mechanical analysis indicate that the grain size distribution of beach sediment is commonly asymmetrical, and negatively-skewed, the mean grain size being coarser than the median; evidently the winnowing effect of wave action reduces the relative proportion of fine particles (Mason and Folk, 1958). Such parameters may assist in the identification of former beach deposits, permitting a distinction from positively-skewed grain size distributions typical of fluvial, aeolian, and lagoonal deposits (Fried-

TABLE 1

Wentworth size class	*Particle diameter*	*φ scale*
Boulders	> 256 mm	below -8φ
Cobbles	64 mm — 256 mm	-6φ to -8φ
Pebbles	4 mm — 64 mm	-2φ to -6φ
Granules	2 mm — 4 mm	-1φ to -2φ
Very coarse sand	1 mm — 2 mm	0φ to -1φ
Coarse sand	$\frac{1}{2}$ mm — 1 mm	1φ to 0φ
Medium sand	$\frac{1}{4}$ mm — $\frac{1}{2}$ mm	2φ to 1φ
Fine sand	$\frac{1}{8}$ mm — $\frac{1}{4}$ mm	3φ to 2φ
Very fine sand	$\frac{1}{16}$ mm — $\frac{1}{8}$ mm	4φ to 3φ
Silt	$\frac{1}{256}$ mm — $\frac{1}{16}$ mm	8φ to 4φ
Clay	< $\frac{1}{256}$ mm	above 8φ

Note: The φ (phi) scale is a logarithmic scale of particle diameters defined by Krumbein as the negative logarithm to base 2 of the particle diameter in millimetres: $\varphi = -\log_2 d$

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INTRODUCTION TO THE SERIES

This series is conceived as a systematic geomorphology at university level. It will have a role also in high school education and it is hoped the books will appeal as well to many in the community at large who find an interest in the why and wherefore of the natural scenery around them.

The point of view adopted by the authors is that the central themes of geomorphology are the characterisation, origin, and evolution of landforms. The study of processes that make landscapes is properly a part of geomorphology, but within the present framework process will be dealt with only in so far as it elucidates the nature and history of the landforms under discussion. Certain other fields such as submarine geomorphology and a survey of general principles and methods are also not covered in the volumes as yet planned. Some knowledge of the elements of geology is presumed.

Four volumes will approach landforms as parts of systems in which the interacting processes are almost completely motored by solar energy. In humid climates (Volume One) rivers dominate the systems. Fluvial action, operating differently in some ways, is largely responsible for the landscapes of deserts and savanas also (Volume Two), though winds can become preponderant in some deserts. In cold climates, snow, glacier ice, and ground ice come to the fore in morphogenesis (Volume Three). On coasts (Volume Four), waves, currents, and wind are the prime agents in the complex of processes fashioning the edge of the land.

Three further volumes will consider the parts played passively by the attributes of the earth's crust and actively by processes deriving energy from its interior. Under structural landforms (Volume Five), features immediately consequent on earth movements and those resulting from tectonic and lithologic guidance of denudation are considered. Landforms directly the product of volcanic activity and those created by erosion working on volcanic materials are sufficiently distinctive to warrant separate treatment (Volume Six). Though karst is undoubtedly delimited lithologically,