the waves approach the shore (fig. 390, 1, 2, 3, 4, &c.). Since a wave is always propagated in a direction perpendicular to its crest-line, the lines of propagation, (e.g., *aA, bB, cC, dD,* fig. 390) bend towards the points and away from the heads of the bays. As the energy of a wave is transmitted in its direction of propagation, there is thus a great concentration of energy on the projecting points of the coast, which may be likened to the convergence of light through a convex lens (the energy of the portions of the waves between *c* and *d* being concentrated on the portion *CD* of the shoreline); and there is a corresponding spreading of the energy away from the heads of bays (the energy of the small portion of the wave *ab* being spread over the shore-line *AB*). Thus headlands are vigorously attacked by marine erosion, while comparatively smooth water is found at bay heads, even though the bays are open to the direction from which a swell comes. As wind-driven waves are less refracted than free waves, the concentration of energy on points is less marked with storm waves than with swell.

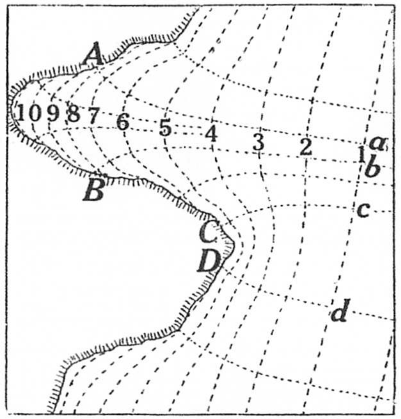

Fig. 390.—Concentration of wave-energy on headlands by refraction of waves in water of varying depth. (After Davis modified.)

Not all bay-floors have the concave shape that is required to produce refraction of waves as shown in fig. 390. Bays on the north side of Banks Peninsula, New Zealand, have quite flat floors (and steep sides), and so waves are not deflected against their sides.

Sheltered Waters.—With the exception of the influence of varying depth of water (where the water is so shallow that friction of the bottom becomes important), there is nothing that tends to change the direction of propagation of waves. They do not turn corners—in other words, they cast "shadows," just as light does. To leeward, therefore, of a promontory or island there is smooth water, though on account of the shallowness of the water in proximity to land there is a certain amount of bending around the points, and so the "shadow" is not perfectly sharp. Landlocked harbours are thus affected by no waves except those developed within their own limits; and bays that are open on one side to the sea are protected from all ocean waves except those that enter them directly, and even these, except when driven by gales, are in most cases much weakened, as previously shown, by deflection towards the sides.

Waves as Eroding Agents.—Since the strongest movements of the water (those resulting from wave action) do not extend to the bottom except in shallow water, marine erosion takes place only in shallow water and is almost confined to coast lines. In the very shallow water, where waves break, the to-and-fro movement is sufficiently energetic to move large boulders, and also the impact of the waves, sometimes amounting to several tons per square foot, may be sufficient to loosen blocks of rock, and fragments are prised off owing to the suddenly increased pressure of either water or imprisoned air in crevices as a wave strikes an exposed surface of rock. Most of the erosive work of breaking waves is done, however, with the aid of rock fragments, either derived as just described or by falling from undercut cliffs or supplied by neighbouring rivers. These are dashed against the solid rock, and drawn to and fro across it. The gravel of the beach is thus itself worn down and rounded, and where the layer of gravel is thin it abrades the solid rock beneath it, and undercuts slopes at the shoreline, causing the unsupported rock above to slip down, so as to form cliffs fronting the shore. The material thus supplied is worn down and disposed of by the waves, and thus the cliffs are further worn back and steepened.

As beach pebbles are ground down by mutual abrasion the minerals in them become reduced to fine mud. Sand grains present along with gravel are pounded into mud, removal of which leaves clean-washed gravel. Where no debris coarser than sand results from wave attack on the land or is supplied by rivers, the particles, on the other hand, after being reduced to a certain minimum size, are not worn smaller, being protected from further attrition by the surface tension of the films of water between them. Grains of sand thus remain somewhat angular. White sand is composed chiefly of grains of quartz, with some of other light-coloured minerals, along with which there is commonly a varying quantity of flakes of white mica. Black sand is composed chiefly of grains of magnetite. Grey sand is a mixture of quartz grains with magnetite and other rock-forming minerals or with rock fragments not yet broken up into their separate minerals. The longer sand remains on, and the farther it travels along, beaches, the greater becomes the concentration of relatively imperishable quartz grains in it as more destructible mineral grains decay chemically. Thus, Dr. P. Marshall has found that the proportion of quartz grains increases from one-third to two-thirds of the whole in sand of acid volcanic origin as it travels from the mouth of the Waikato River to the northern extremity of New Zealand and as feldspar grains are progressively eliminated.

It is not only immediately at the shoreline that there is sufficient motion to cause erosion. As explained above, the orbital motion of the water in waves is interfered with by the bottom even at considerable depths, and converted into a to-and-fro movement. On a coast exposed to full-sized ocean waves this movement is sufficiently strong at depths of 10 and 20 fathoms or more to move to and fro coarse sand and even gravel,[1] and cause it to erode, or *abrade,* the bottom if bare rock is exposed, as is the case off the coast of Otago Peninsula, New Zealand. This is the process of *marine abrasion.* Though abrasion of a rock bottom may take place at these depths, it is possible only if the layer of waste on the bottom is thin and may be all moved. If the waste is at all thick, then only the upper layer of it can be stirred, and no abrasion of bedrock can take place.

The thickness of the waste layer on the bottom, which determines whether abrasion shall or shall not take place, is governed by the supply of waste, which in turn depends on the nature of the rocks and the energy with which the waves break at the shoreline, and also to a large extent on the loads brought down by neighbouring rivers. It is related also, of course, to the rate of removal of waste. Waste broken at the shoreline is removed in two directions—offshore and alongshore. Removal

offshore is effected by the to-and-fro component of wave motion, assisted by the undertow and rip currents, while movement alongshore is partly due to the zigzag path followed by the swash on the beach (p. 403). Alongshore movement is not confined, however, to the beach zone; it is also assisted by currents.

Transportation by Currents.—Ocean currents and tidal currents, though only rarely sufficiently rapid to erode even newly deposited sediment, actively transport fine silt that is held in suspension, and also coarser material such as sand and even gravel, when it is occasionally lifted clear of the bottom by wave action. Strong currents thus maintain a considerable depth of water by preventing accumulation of silt.

Tidal and ocean currents flowing along a coast attain their full velocity only at some distance offshore. Inshore they are much impeded by friction of the bottom and by irregularities of the shoreline which their momentum does not permit them to follow. A slower current following the shoreline more closely is dragged along, however, by the offshore current. The configuration of the coast determines whether this *littoral current* (as it is termed by Gilbert) shall follow the shoreline around the heads of open bays or sweep across bay mouths from headland to headland, leaving the water of the bay still, or perhaps generating an eddy in it.

While the offshore current can move the finer waste on the continental shelf when it is stirred by storm waves, it is the littoral current only which effects transportation of the coarser waste in the more agitated water of the littoral zone. The material thus moved, together with the gravel or coarse sand swept along (as explained above) by wave action within the breaker line, is the *shore drift,* which is built into beaches, spits, and bars when it reaches places favourable to accumulation (Chapter XXXIII).

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[1] Some occurrences of gravel on the bottom under rather deep water have been explained as ancient beaches submerged by rise of sea-level. Such gravel must obviously now lie at a depth greater than that at which it can be moved about by wave motion.

CHAPTER XXIX

COASTAL PROFILES

Initial coastal profiles. Steep initial profile. Sea cliffs and the cut platform. Profile of equilibrium. High-water or shore platform. Profile and width of the graded platform. Marine terraces. Cover head. Profiles of progressively uplifted coasts.

Initial Coastal Profiles.—The initial forms on which the marine forces—waves and currents—begin to work are very varied in profile. The cycle of marine erosion may be initiated, for example, by a movement of regional subsidence or of regional uplift, in the former case a land surface being submerged to form the new sea floor in the shallow water zone, and in the latter case a portion of the floor of the deeper sea being brought into this position. In place of simple vertical movement there may be warping or faulting along the new shoreline. Thus the initial coast profile (including the portions above and below sea-level) may have any slope, from almost vertical to nearly horizontal and may be either smooth or irregular.

Steep Initial Profile.—The initial profile is rarely so steep that waves are reflected from the shore, but where it is vertical or nearly so waves have little or no erosive effect, partly because they are reflected without breaking, and partly because there is no resting-place for loose material at a convenient depth to allow it to be picked up and used by waves as tools, or weapons, in their attack on solid rock at the shoreline. Such material as is dislodged by the impact of waves on the initial shore slips immediately into deep water.

When, however, a slope initially too steep to cause waves to break has had its steepness reduced by slumping and subaerial erosion accompanied by accumulation of talus at the base (fig. 391, *b* and *b′*), waves will no longer be reflected, but will break, and will dislodge by their impact weathered and joint-bounded blocks of unweathered rock. This takes place also without any delay on shores which, though steep, have yet sufficiently gentle slopes initially to cause waves to break upon them.

Waves encountering a steep shore have lost but little energy owing to friction of the bottom before they reach the shoreline. They expend their energy at the breaker line. Most of this energy moreover, is available for the attack on the land, comparatively little being used up in grinding waste, for a steep coast is not encumbered with waste. Sufficient is present to act as tools with which the rushing and swirling water may batter and rasp the shore, but the bulk of the broken material is quickly drawn out into deep water and deposited there. Under these conditions wave action has its maximum efficiency as a destructive agency, and the shoreline recedes as a line of sea cliffs of increasing height.

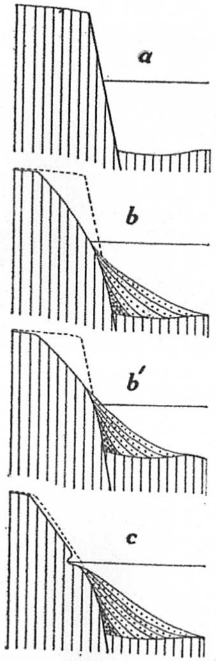

Fig. 391. — To illustrate the beginning of wave attack on a very steep initial coast. *a*, initial form; *b*, *b′*, forms after the profile is rendered less steep by accumulation of talus; *c*, sequential form, showing the beginning of wave work.

Sea Cliffs and the Cut Platform.—Erosion may be so rapid that cliffs of tough, unjointed rock are undercut, a notch being cut along the base, above which the cliff overhangs (figs. 391, 393). The material above slips down, however, before long, and the cliffs recede as the fallen blocks are themselves attacked by the waves, broken up, and removed, and the attack on the base of the cliff continues.

At this early stage in the development of the wave-cut profile, at which the shoreline is still rapidly receding, all cliffs are steep; but the steepness of any particular cliff depends largely on its structure. Cliffs may be vertical (fig. 392) or may overhang a notch (fig. 393), or, if a system of division-planes—stratification or joints—dipping inland is the only one present, they may slant outward for their full height. The presence of a notch indicates absence of joints in the rock of a cliff rather than any excess of vigour in the attack by waves; for jointless rocks overhang a notch even on the shores of landlocked waters (fig. 394).

Fig. 392.—Vertical cliffs and stack determined by the presence of vertical joints in horizontal stratified rocks ("flagstones"), Holborn Head, Caithness, Scotland. The cut platform developed by marine erosion is here far below high-water level.

H.M. Geol. Survey, photo.

The retreat of young and steep cliffs takes place as a succession of rock falls and slides, which are particularly large where resistant strata overlie easily eroded formations along the shore.

At the foot of a line of receding sea cliffs there may be a gently-sloping wave-cut platform, in some cases smoothly worn, but in others accidented by many small unconsumed *stacks* (fig. 395). The base of the cliff is then generally at or near high-water level,

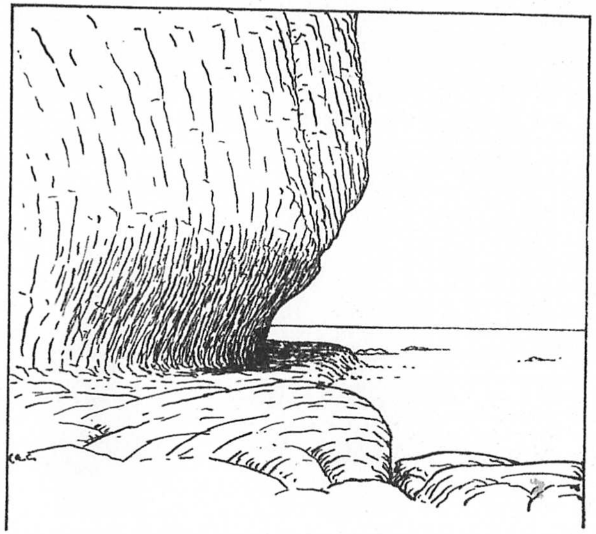

Fig. 393.—Notch at the base of a wave-cut sea cliff. Pillar Point, Washington, U.S.

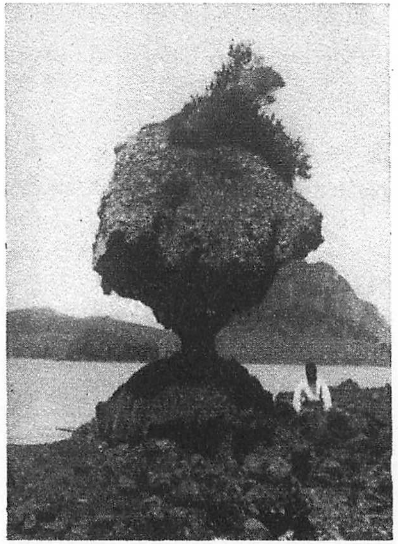

Fig. 394.—Stack reduced to a mushroom shape by development of a notch in well-cemented jointless rock in the landlocked Whangaroa Harbour, New Zealand.

F. G. Radcliffe, photo.

for the material above that level is to some extent loosened by subaerial weathering, and thus prepared for ready removal even by weak waves. In some cases, however, where steep coasts are subject to very violent wave attack, the cliff base is below high-water level and the landward edge of the wave-cut platform is covered at high water to a considerable depth, which may be taken as an indication that subaerial weathering has failed to keep pace with marine erosion (fig. 392). On the other hand, the base of the cliff may retreat under the combined attack of weathering and the swash of breaking waves at some height above high-water mark (p. 413).

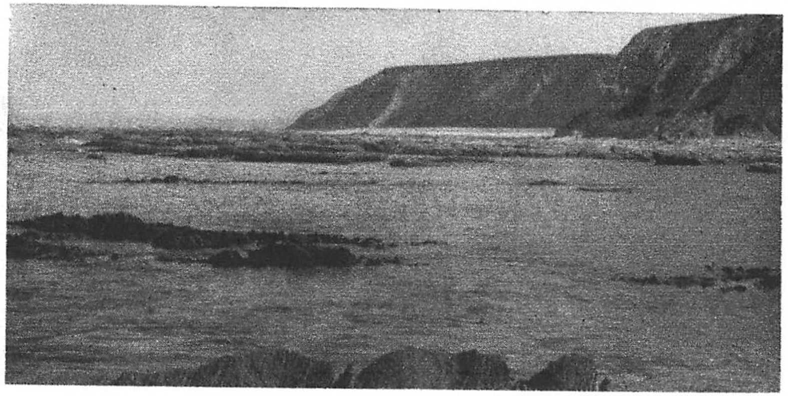

Fig. 395.—Sea cliffs with wave-cut rock platform at their base, East Head, Kaikoura Peninsula, New Zealand. Above the general level stand numerous low stacks.

R. Speight, photo.

Farther out, at the line of breakers, where waves expend most of their energy, there is sufficient movement of the water to keep very coarse waste in motion. This material—boulders, gravel, and coarse sand—is dragged to and fro over the bedrock bottom, unless the supply of waste is excessive, in which case only the upper layers of waste will be moved and ground. The abrasive action of this material is such that a bottom consisting of solid unweathered and even unjointed rock may be rapidly worn down.

Still farther seaward to a considerable depth wave motion drags finer waste to and fro, and so abrasion continues, though less vigorously, on such parts of the rock floor as remain bare or are occasionally swept clear of protective waste. This continued offshore deepening by marine abrasion accounts for the fact that a cut platform generally slopes rather uniformly seaward; for the outer part, having been longest subject to wave action, has been most deeply abraded. The wearing down of the outer part of a broad platform from sea-level has taken a long time; but its abrasion will continue (though more and more slowly) as long as the waste on it continues to be moved to and fro over bare rock.

Profile of Equilibrium.—At an early stage in the erosion of a steep coast, after a certain amount of cliffing and platform-cutting has taken place and this has been accompanied by some seaward extension of the platform by deposit of rock waste as sediment, the slope of the platform to its outer edge becomes smooth and nearly uniform owing to attainment of a state of balance between erosion and deposition at all points on it (fig. 396). The profile of the off-shore platform is now *graded*, or a *profile of equilibrium* has been developed across it. Landward the profile is concave and steepens considerably at the inner margin, which may be (but is not necessarily) at the base of the land cliff.

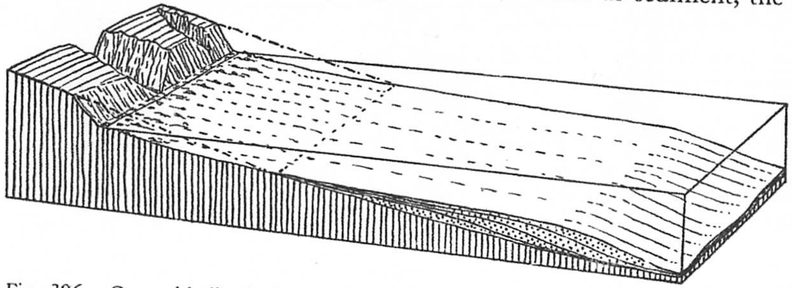

Fig. 396.—Cut-and-built platform, or continental shelf, with graded profile, in front of wave-cut cliffs developed from the initial profile indicated.

High-water or Shore Platform.—Between the shore end of the concave profile of equilibrium and the base of the cliff there is quite commonly present a level bench, the *high-water* or *shore platform*, the origin of which is distinct from that of the graded surface farther seaward. From this it may be separated by a steep descent, just as another nick or even notch may be present in its rear at the cliff base (fig. 397).

At first sight it would appear that a shore such as that shown in fig. 397 had been uplifted and that the higher-level bench was a remnant of an older graded platform in course of removal and

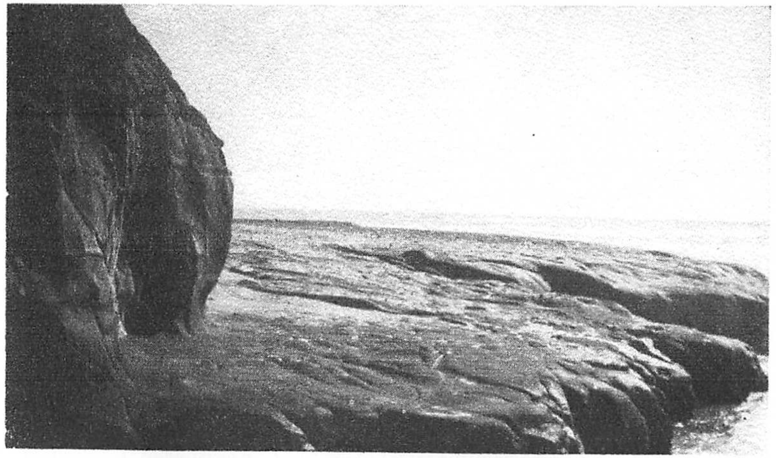

Fig. 397.—An unusually broad high-water rock platform, separated by a scarped descent from the off-shore graded profile, at Muriwai, Auckland, New Zealand.

Douglas Johnson, photo.

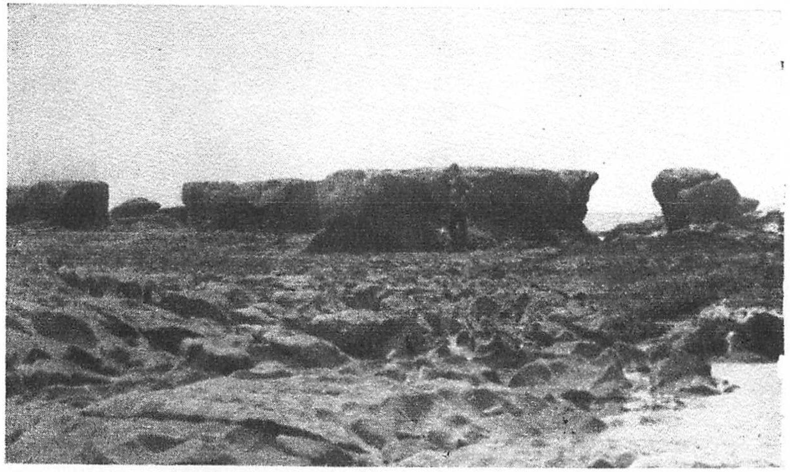

Fig. 398.—Destruction of a probably older and uplifted rock platform is in progress and a newer platform is developing. East coast of Marlborough, New Zealand.

C. A. Cotton, photo.

replacement by a newer one adjusted to the present sea-level. Such may well be the correct interpretation of the history of the two platforms shown in fig. 398. High-water rock platforms, however, are still in course of development as is indicated by the bare, freshly worn rock surface and the cleanly scoured nature of the cliff-base angle or notch at the rear (fig. 397). The feature is distinct from the graded profile of equilibrium, which is developed mainly under water.

Apparently there are various ways in which erosion may make a horizontal "saw cut" into the land at or about high-water level which is able to keep ahead of the general process of marine erosion.

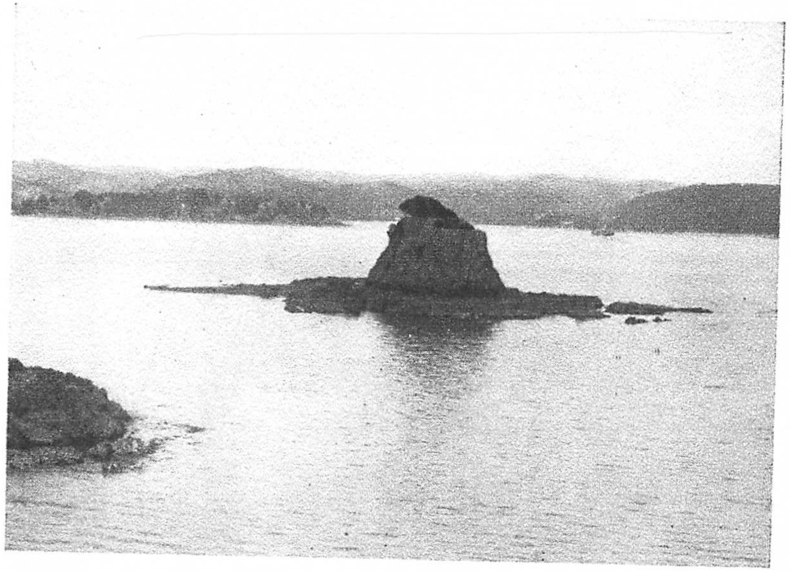

Fig. 399.—The "Old Hat," Bay of Islands, New Zealand. A small island of a drowned landscape reduced to a stack by development of cliffs and a high-water platform around it.

F. G. Radcliffe, photo.

Within landlocked embayments, where wave action is feeble and inefficient in its attack on solid rock, a high-water platform of considerable breadth may be developed as practically the only modification of the steep initial profile that has resulted from drowning of land slopes (figs. 399, 400). In such cases feeble wave action has removed the products of rock-decay (chemical weathering), which has affected the rocks only above the level of saturation —that is, high-water level. This plane, therefore determines a surface of fresh rock exposed in the platform.

The foregoing is not applicable, on the other hand, to coasts exposed to heavy surf (that shown in fig. 397, for example) and fringed by broad platforms farther seaward that have evidently been worn by vigorous marine erosion. Yet a platform even *above* high-water level is so commonly present that it must be regarded as a normal feature developed by the cliff-making processes. A horizontal "saw cut" above high-water level may or may not keep ahead of the general process of platform-cutting and grading going on in the zone of breakers and farther seaward. If it keeps well ahead, a cut rock platform of considerable breadth is developed and maintained; if it fails to keep ahead at all, the high-water platform has zero width—that is, is locally absent. As for the origin of the "saw cut" in this case, it may be in part similar to that described above in the case of sheltered waters; but it appears also that the swirling impact of masses of water driven landward when great waves break in severe storms is particularly effective in developing a cliff at the rear of the higher platform and in cleanly scouring this platform itself. The landward part of this platform, moreover, is frequently dry and is subject to disintegration at the surface owing to wetting and drying. When storm waves wash away rock debris thus loosened they sometimes even hollow out a landward strip of a high-water platform to some extent, leaving a residual rampart at the seaward edge.

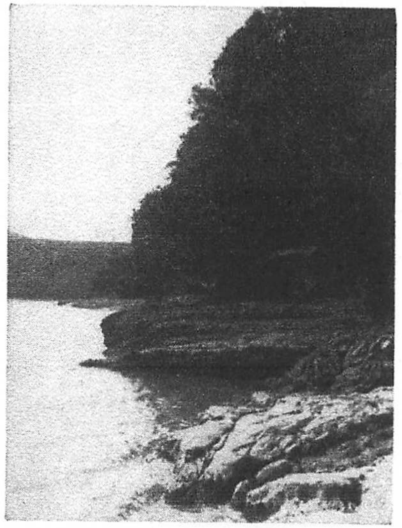

Fig. 400.—High-water rock platform at Greenhithe, upper reaches of Auckland Harbour, New Zealand.
C. A. Cotton, photo.

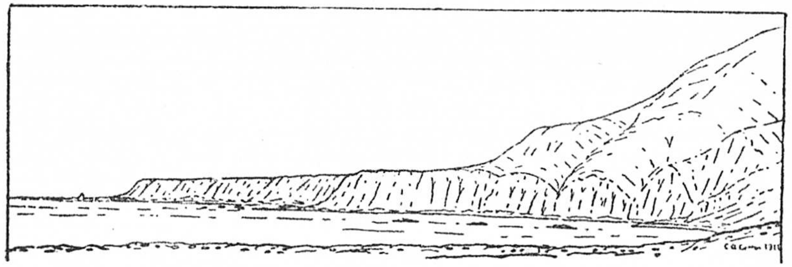

Fig. 401.—Remnants of uplifted marine platforms forming a narrow, upper, dissected bench and a broad, well-preserved, lower marine terrace at Tongue Point, Wellington, New Zealand. The lower bench exhibits the profile of a graded off-shore platform sloping rather steeply seaward.

Profile and Width of the Graded Platform.—A seaward slope developed under water on a cut platform is shown in fig. 401. Two uplifted benches are here seen, but the upper one is narrow and is dissected. The lower bench displays its broadest remnant at this point, which is seen again in fig. 402 and (along with the west-

Fig. 402.—The Tongue Point marine terrace, Wellington, New Zealand, showing thin beach deposits over a cut surface of bedrock.
C. A. Cotton, photo.

ward continuation of the terrace) in figs. 403, 404. It is smoothly graded, but slopes somewhat steeply.

Marine Terraces.—The platform referred to above has emerged to become the Tongue Point *marine terrace.* Because of warping which has taken place since the emergence its elevation varies from point to point along the coast, but at Tongue Point the ancient shoreline is about 220 feet above sea-level. The terrace is everywhere strongly cliffed at the margin by modern marine erosion. It is such cliffing that converts a narrow coastal plain or emergent platform into a terrace. This bench, like most marine terraces, is discontinuous along the shore, having been cut away altogether by modern marine erosion at some places.

Fig. 403.—View westward along the Tongue Point marine terrace, Cook Strait, New Zealand. *V. C. Browne, photo.*

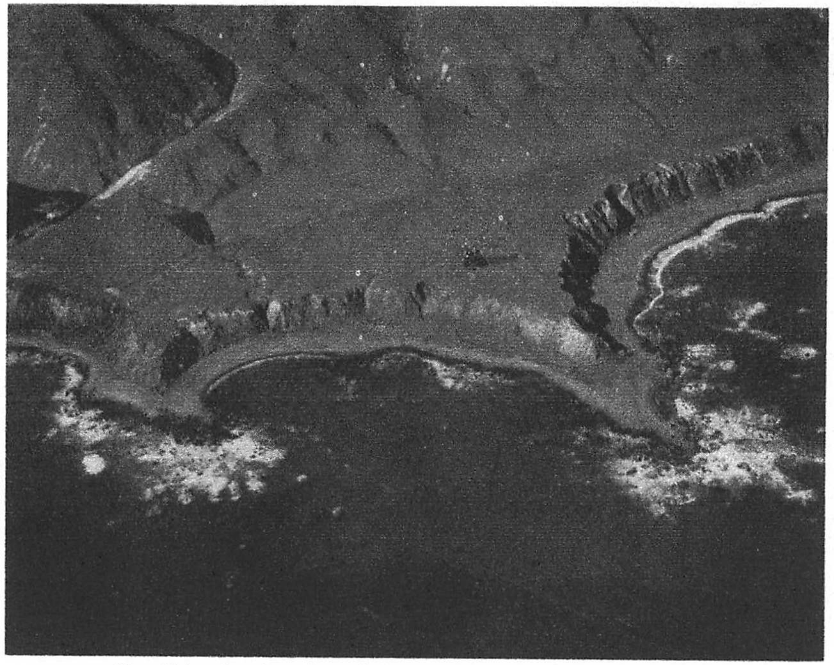

Fig. 404.—Another view of the marine terrace shown in fig. 403.
N.Z. Ministry of Works, photo.

Fig. 405.—A boulder-covered and very recently emerged cut platform forming a narrow coastal plain at Cape Turakirae, near Wellington, New Zealand. (A beach ridge appears in the left upper corner of this view.)
C. A. Cotton, photo.

Such benches are generally thinly veneered with beach gravel. During slow emergence deposits that have been laid down in rather deep water far out on a platform are liable to be reworked, largely removed, and replaced by beach material. This is not invariably the case, however, and the thin landward edge of a wedge of "coastal-plain" marine deposits containing fossil shells may be present. It is found on a marine terrace at Motunau, for example, on the east coast of the South Island of New Zealand. This terrace was cut rapidly on soft rocks, and slopes very gently seaward.

Minor irregularities, including prominent stacks, were probably very numerous originally on the Tongue Point platform (shown in figs. 401-404) if one may judge from the rough relief of reefs of rocks now fringing the adjacent shoreline. The smoothness of the terrace surface in its present condition indicates that such stacks have crumbled down and been destroyed by subaerial weathering. A recently emerged cut platform, or narrow coastal plain not yet cliffed to convert it into a terrace, at Cape Turakirae, which is also near Wellington, New Zealand, has an extremely rough floor of stacks and large boulders as yet unaffected by weathering (fig. 405). During very recent retreat of the sea from this platform several successive beach ridges were piled in parallel lines along the emerging sea-floor. The retreat continues intermittently.

A pavement of fresh boulders indicates very recent emergence in the case of the Hawaiian uplifted platform shown in fig. 406.

Head and Cover Head.—Along the south coast of England, then a periglacial region, sea cliffs were broken down during the last ice age by solifluxion (p. 28), and the debris thus streaming from them accumulated thickly as solifluxion head, or simply "head", over a formerly wave-cut platform and raised beach now preserved in a marine terrace (fig. 407). Such cover obscures the cliff-base angle behind the terrace.

Some marine terraces have a very thick *cover head* over them, consisting of talus cones and alluvial fans spread during and after emergence (fig. 408). Such cover head on a marine abraded platform of vast extent forms a very extensive piedmont alluvial plain fringing the Santa Monica Mountains at Los Angeles, California; and its margin, cliffed now by the sea, forms the "Palisades" (fig. 409). Similar but less thick cover head is present over an extensive platform at the head of Palliser Bay, in New Zealand (fig. 410).

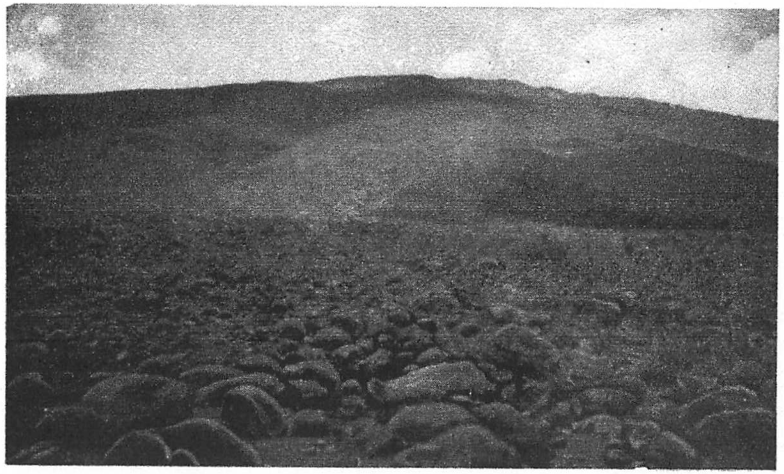

Fig. 406.—Sea cliff and fresh boulder-strewn rock platform upraised 550 feet on the island of Lanai, Hawaiian group.

H. T. Stearns, photo.

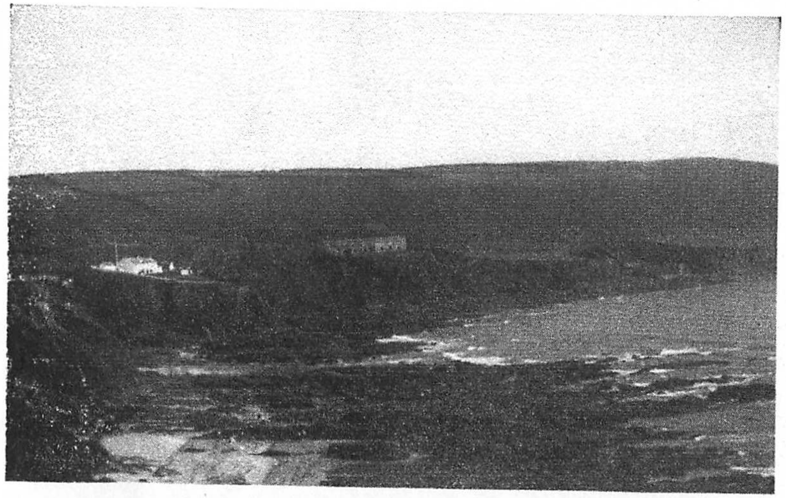

Fig. 407.—A cut platform, new cliff, and marine terrace covered by solifluction head, which obscures the form of an ancient cliff, Polhawn Cove, Whitsand Bay, Cornwall.