THE LESSER ANTILLES

WILLIAM MORRIS DAVIS

AMERICAN GEOGRAPHICAL SOCIETY

MAP OF HISPANIC AMERICA: PUBLICATION NO. 2

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BY

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GENERAL RELATIONS OF THE ISLANDS

The insular chain of the Lesser Antilles, including twenty-five larger islands and an uncounted number of smaller ones, forms a curve about five hundred miles in length between Porto Rico in latitude 18° and Trinidad in latitude 10°. It is interesting to note that they afford the only instance on the Atlantic side of North America of an island festoon, or arc, such as is repeated several times off the Pacific coast of Asia. These arcs undoubtedly express an important deep-seated deformation of the earth's crust. In their local structural relations the Lesser Antilles are mostly composed of volcanic rocks, and some of the islands are still afflicted with explosive eruptions. These eruptions, in spite of their destructive violence, add little to the island volume. An uncounted number of such eruptions must have taken place in the building up of the islands from their ocean-bottom foundation, which appears to have been subsiding during and after their growth and which may have long ago formed a land bridge to South America. Most of the islands show submarine enlargement in shallow banks, probably formed with the aid of coral reefs as will be explained below. Several of the lower islands consist largely or wholly of calcareous strata, which appear to represent former banks, now upraised or uptilted and more or less eroded and abraded. The islands which are most uplifted and eroded now exhibit a volcanic foundation which, originally an island, was entirely covered with calcareous strata during a long period of subsidence that preceded the later uplift. I visited the islands in October and November, 1923.

THE CLIMATE IS TROPICAL

The climate is characterized by ardent insolation and a prevailingly high temperature; yet the sensible temperature in the shade is not excessive when the northeast trade wind is blowing. The tops of fair-weather trade-wind clouds are often seen rising, far away, above the horizon. They thus, like base-down cumulus clouds over a prairie horizon, demonstrate the rotundity of the earth on a much larger scale than the familiar sight of ships hull-down at sea; for their base below the horizon may be 1000 or 2000 feet above sea level. The Lesser Antilles lie far down on the track of the Atlantic tropical hurricanes of late summer or early fall, and these scourges rival volcanic outbursts in their destructive effects. But the islands well to the southeast, by very reason of their position, are now of service to their larger neighbors on the northwest in giving early radio warning of approaching storms. The islands also show the value of land obstructions in provoking rain from the trade winds; for while the lower ones not infrequently suffer from drought, the loftier ones have a plentiful rainfall. Unfortunately, it is precisely on the lower islands, where agriculture is most extensively developed, that deficiency of rainfall is of most serious import. Yet when rain does fall there it may be heavy, because condensation begins at a high temperature, where a moderate measure of cooling precipitates a large volume of water.

THE EVENTFUL HISTORY OF THE ISLANDS

Historically and politically the Lesser Antilles are of importance because of their early discovery and settlement. Columbus came upon several of them before the end of the fifteenth century; and some were occupied by European settlers in the third or fourth decades of the sixteenth century. They have been acquired individually by several European powers; and as their value increased with the increase of population and products their ownership has often been bitterly disputed, especially among the English, Spanish, and French through the last half of the eighteenth century and the early years of the nineteenth. During these years some of the islands changed ownership several times, but they were eventually—at least until our war with Spain in 1898 and our purchase from Denmark in 1915 brought some of them into American ownership—divided among five European nations; hence nowhere else in the Western Hemisphere are so many European languages spoken in so close contiguity. The Guadeloupe group and Martinique, separated by Dominica, as well as the smaller island of St. Bartholomew and the southern half of St. Martin, are French; Statia, Anguilla, the northern half of St. Martin, and the little cone of Saba are Dutch; Vieques and Culebra, small dependencies of Porto Rico, were long under Spanish rule; and the western members of the Virgin group, including St. Croix, were Danish. The other islands, a good majority of the whole chain, are British possessions. It is curious to note that on several of the British islands formerly possessed by France nearly all the local names are still French, many of them memorializing early French governors or other officials; and that the Creoles, or whites of pure French blood, still preserve their own language and hold themselves rather aloof from the English, as if they were of a somewhat different social order. The negroes on those islands still speak a French patois; but that will probably be largely replaced in a generation or two by English through the influence of the schools as well as because of the greater value of English in official relations and business transactions.

From a literary and romantic point of view, the islands are of peculiar interest; if the question of piracy were taken up it might be shown that their insularity and their partition among several European powers promoted freebooting; but the story is too long to be entered upon here.

The small-scale manner of acquisition, in which the fate of each Lesser Antillean island seems to have been determined separately, chiefly by naval battles, affords a striking contrast to the large-scale manner in which the ownership of great continental areas has been settled; as when the whole of the St. Lawrence region and a great part of the wilderness to the north of it were transferred from French to English ownership with the fall of Quebec and Montreal after the middle of the eighteenth century, or as when the vast Louisiana territory was acquired for the United States by purchase from France early in the nineteenth century. As to the names "Leeward" and "Windward" for the two administrative divisions of the British group, no justification can be found in the relation of the islands to persistent trade winds. The Leeward Islands include Tortola and other eastern members of the Virgin group, Sombrero, St. Kitts, Nevis, Antigua, Barbuda, Montserrat, and Dominica; the Windward include St. Lucia, St. Vincent, and Grenada, with the little Grenadines. Northern and Southern islands would have been more appropriate names.

THE AMERICAN, EUROPEAN, AND AFRICAN POPULATION

The islands were originally the home of the Caribs, who in early times were almost exterminated on various islands by cruel wars, such as have often marked the encounters of civilized invaders with savage natives the world over. A small number of so-called Caribs still remain on St. Vincent; but their chief survival is in shell heaps along the shore and in such words as "Caribbean" and "cannibal." Since the aborigines have practically disappeared, the much more numerous modern inhabitants of the islands are chiefly negroes or a colored population with more or less negro blood. Whites are in largest number on Barbados, where they constitute about a fifth of the total; on Grenada they are only about a fifteenth; and on Tortola their proportion is lower still. While a small part of the colored population have acquired a considerable competence, and some of these an education, the great majority are poor and ignorant. Those on Vieques, next southeast of Porto Rico, where Spanish influence still remains, are pitiably debased in their manner of living; the contrast there to be seen between the fine residences of plantation owners or managers and the wretched hovels of the laborers is most deplorable.

The survival of superstition among the negroes is illustrated by a story told me by a recent white resident on the mountainous island of Tortola, the chief British member of the Virgin group. A young negress there was accused of murdering a child. Before going to court, she killed a lizard and placed its tongue between the sole of her foot and her shoe; when a question was about to be asked her by the magistrate, she prevented him from speaking by bearing down on the lizard's tongue; and so she was discharged. Whether or not the story is true, it was generally believed on the island by those who heard it. Such superstition, it is to be hoped, will gradually yield to education. Certainly there was an air of progress in the groups of neatly dressed and intelligent-looking children on their way to school, as I saw them

Pl. I—Barbados: rolling cane land near summit, looking south.

on a morning drive on Grenada. On Antigua, where an appearance of neatness prevails in many villages, the negro families too often live in small, one-room cottages, some of which are built of wattle. Barbados is the best cultivated and most thriving of the British islands; but from there and elsewhere there is a continuous small stream of negro emigration, mostly to New York.

Problems of island government are difficult of solution. They involve the development and maintenance of a self-supporting and contented population. Experienced officials are in charge of affairs, but their experience has perhaps been gained on other islands in other oceans; and it is to be questioned whether such experience always includes a sufficient acquaintance with West Indian psychology. For example, on one of the islands the department of Agriculture undertook a few years ago to aid the small farmers by lending them moderate sums of money to be expended in farm betterment and to be returned in small annual payments; but some of the money was spent for other objects, and in three years the returns had been so inconsiderable that legal proceedings were proposed as a means of collecting the payments then overdue. Surely the trouble here was by no means wholly financial, but largely psychological; such trouble might be better met by a psychologist trained in business administration than by an administrator untrained in psychology.

The distribution of population on certain islands presents several points of interest. It is only on the relatively low limestone islands like Antigua, Grande Terre, and Barbados that the whole surface is well enough occupied for the partition of estates and the location of villages to be developed on an areal plan. On the mountainous islands, like St. Thomas, the chief American member of the Virgin group, Guadeloupe and Martinique among the French possessions, and Dominica, St. Lucia, St. Vincent and Grenada among the British possessions, villages are almost wholly limited to the shore and plantations to the shore-facing valleys. Here, therefore, the treatment should be circumferential and radial, rather than areal. The high interior of these mountainous islands remains a forested wilderness, only here and there cultivated in small patches. On St. Lucia, St. Vincent, and Grenada, which have more indented shore lines than Dominica and Guadeloupe, shore settlements are wholly determined by the bays in front of them and by the available valley-floor areas behind them. The larger towns on all the islands are on the leeward, or western, coast, where navigation was safer for small sailing vessels on which the islands long depended for oversea transportation; consequently a visitor on a modern steamer, which touches only at the chief ports, seldom sees the windward, or eastern, side of an island.

The arrangement of highways is in accord with the distribution of population. The low islands are crossed by a network of roads, many of which are of excellent surface; the high islands are served chiefly by coastwise roads, along or near the shore, with valley roads leading inland and occasionally crossing over the axial mountain range. On several of the more embayed high islands, however, the coastwise roads are by no means level, for they lie a moderate distance inland so as to pass behind the bay heads and therefore have to make many ascents and descents over the inter-bay spurs. On Dominica and St. Lucia the coastwise roads fail to make the entire circuit of the island by reason of the boldness of parts of the coast.

Public water service is well developed on Barbados and Antigua, so that nearly every village has a supply piped to it from one or more central reservoirs; but on the mountainous islands each chief town or village has only a local water supply from its own valley. Cisterns supplied from house-roof rainfall are also largely in use on certain islands. At St. Thomas small rectangular areas on hillsides are cemented to serve as catchment surfaces; two such areas are indicated in Figure 40.

DIFFICULT ECONOMIC PROBLEMS

Economically the islands suffer from their small size; from the small variety of their products, which are almost wholly agricultural; and from the consequent limitation of their industries. The low limestone islands, the little-dissected lower slopes of the younger volcanic islands, and the delta plains in former embayments of the older volcanic islands are quite generally given over to the cultivation of sugar cane. On certain islands limes are largely grown. A curious treatment of the limes is seen when, after being gathered from the trees and heaped on the roadside, they are very gently rolled on a grater, one at a time, by negro women, to extract a valuable essence from the outermost rind. Lime-juice is an export of some importance, especially from Montserrat and Dominica. Cacao has been a profitable crop, especially on Grenada, St. Vincent, and St. Lucia; but recently the lower price of West African cacao in the London market has placed the West Indian cacao planters in a difficult position. Dominica is reputed to be an important potential producer of many kinds of fruit; but its rugged surface makes road construction difficult and transportation of fruit from tree to port without injurious bruising almost impossible. There are no mineral products worth naming, for Trinidad with its asphalt lake is not here considered. Although a number of wells have been drilled for oil on the central crest of Barbados and a pipe line twelve miles long is said to have been laid to large cisterns at Bridgetown, the chief port, petroleum is not yet an important export.

Modern methods of ocean transportation and communication have been disadvantageous to the islands in some respects. The port formally called Charlotte Amalia but generally known as St. Thomas, as it is the only town on the formerly Danish island of that name, was in the days of sailing vessels a center for distribution of European goods to other islands and for collection of their products for transport to Europe; but transshipment largely ceased with the advent of steamships. However, St. Thomas continued for a time to be a port of call for steamers to receive cable instructions from their owners; but orders are now sent by radio to passing vessels. The town remained for a time longer of some importance as a coaling station, and many workers of both sexes found intermittent occupation in carrying coal in baskets on their heads, African fashion. But this grimy work is now falling off with the arrival of fewer vessels and with the increasing replacement of coal by oil, which is pumped from supply vessels into tanks and taken aboard by gravity. The raising of sugar cane used to be profitable on St. Thomas before the abolition of slavery; but the abandoned plantations are now overgrown with bushes, and the old windmills, often set on hills the better to catch the wind, are in ruins. The best fields of St. Thomas are now planted with Guinea grass, an excellent pasturage for cattle. At Castries, the chief port of St. Lucia, the work of coaling vessels is still so eagerly sought for by the laboring population that a curious cry, begun by those on the water front and taken up by others in the streets, rises from the town when an incoming steamer is signaled from the hill at the harbor entrance.

Physiography of the Islands

A SYSTEMATIC SEQUENCE OF ISLAND DEVELOPMENT

My chief interest in the Lesser Antilles lay in their physiographic features. These I had opportunity of observing either briefly or deliberately during my voyage, when stops varying from half a day to nearly a fortnight were made on ten of the islands and views of about as many more were had from the steamer's deck. The observations thus made have been supplemented since my return by an examination of many charts and by a study of pertinent descriptions. Thus the islands have gradually come to take their place in my mind as members of a developing sequence;[1] so that, the sequence once being known, the general features of any island may be concisely learned from the stage it occupies in the sequence; and, the general features being thus learned, the special features can be easily apprehended as individual modifications of the general features.

The sequence in its simplest form begins with a volcanic island, built up from a slowly subsiding sea floor by a succession of active eruptions; after eruptive growth ceases, the island gradually diminishes by erosion as well as by subsidence, while a lagoon-

[1] See, for a brief statement of their origin, W. M. Davis: The Formation of the Lesser Antilles, *Proc. Natl. Acad. of Sci.*, Vol. 10, 1924, pp. 205–211.

enclosing barrier reef is built up around it; and finally, when the island is completely submerged, it is succeeded by an atoll, essentially as imagined by Darwin in his theory of coral reefs. But this simple sequence is affected by complications of three kinds. In the first place, an island instead of being completed in small size by a relatively short series of eruptions from a single vent, may, after subaerial erosion is more or less advanced on the earliest-formed cone, resume its eruptive growth from the same or from a new vent and become a larger composite island. In the second place, a simple or a composite island and its reef system may be uplifted or uptilted at any stage of its development by deformational forces, which thereupon interrupt the first-cycle sequence and introduce a second cycle; and the island thus upraised will then be again characterized by erosion, subsidence, and reef growth during the new cycle of development upon which it thus enters.

In the third place, on recognizing that the initial eruptive formation of different islands took place at various times from early Tertiary almost to Recent, it will be understood that, whatever the stage of either cycle reached by an island when the Glacial period intervenes, the waves of the lowered and chilled ocean, exemplifying certain postulates of the Glacial-control theory of coral reefs as stated by Daly, first truncate the encircling reef, because its corals are weakened or killed by the chilled waters; then continue their abrasive work by planing down the lagoon floor wherever it is laid bare, thus converting it into a rimless calcareous platform; and eventually, though for a short time compared to that needed for the mature dissection of an island, attack its headlands and cut them back in cliffs. Next, as the ocean rises to its normal level in Postglacial time, the abraded calcareous platform will be more or less aggraded, chiefly by organic detritus, and converted into a shoaling bank; but, inasmuch as the Lesser Antilles are believed to stand in the marginal belt of the Atlantic coral seas where, as will be explained in a later section, the ocean temperature has not been very favorable to reef growth in Postglacial time, no new bank-border reefs but only discontinuous, island-bordering reefs are developed. Coral growth in the Lesser Antillean chain is therefore now limited for the most part to discontinuous reefs along or near the island shores, well back from the bank border. The bank border, therefore, usually remains as rimless as when it was abraded. These relatively new and discontinuous bank reefs must be regarded as feeble novices compared to the stalwart veterans of the Pacific coral seas, which are now still vigorously continuing the growth that was begun in Preglacial time. They were not truncated in the Glacial period, although they were probably more or less dissected by solvent erosion when the ocean was lowered. It is only in the marginal belt of the Pacific coral seas that feeble novice reefs are found, like those of the Lesser Antilles.

Thus interpreted, the circum-insular banks of the Lesser Antilles are complex structures, as shown in

Figure 1. Their foundation must be in nearly all cases a volcanic mass, *AF*, which should include a part of the originally submarine slope, *AB*, below sea level, S_1, at the time when the volcano became ex-

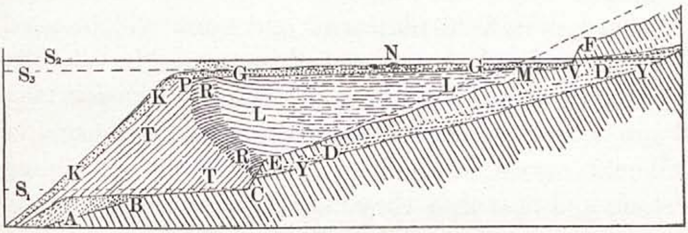


Fig. 1—Ideal section of a Lesser Antillean bank.

tinct, and a part of the originally subaerial slope, *EM*, which was more or less eroded before it was submerged, and possibly also an early-cut cliff and platform, *ECB*. The greater part of the terrace-like mass of the banks will consist of a barrier reef, *RR*, with its external talus deposits, *TT*, and its enclosed lagoon deposits, *LL*, the latter being extended inwards by the delta deposits, *DD*, in embayed valleys, *YY*. But a surface fraction of the reef and its lagoon floor will have been cut away by low-level abrasion in the Glacial epochs, with respect to the lowered ocean, S_3, and thus a gently inclined calcareous platform, *PM*, will have been produced, widened inward by a cliff-base belt of abraded volcanic rocks, *MV*, and outward by a detrital embankment, *KK*. In Postglacial time the abraded platform will have been aggraded by novice reefs, *N*, and detrital deposits, *GG*, into the present bank, over which the spurs of the island will be cut off in the plunging cliffs, *FV*. The bank alone is a matter of observation by sounding; the abraded platform at a small depth below the bank surface and the sloping volcanic foundation at a greater depth are matters of inference. The three terms, foundation, platform, and bank will be used as thus defined throughout this essay. It is easily conceivable that platforms of low-level abrasion may have been produced at successive levels in successive Glacial epochs around a progressively subsiding island and that then they may have been aggraded in successive non-Glacial epochs; but this complication of the problem is not further considered.

The easy possibility of thus imagining the inferred complex structure of the submarine banks around the Lesser Antilles has of course nothing to do with the truth of the theory from which the structure is deduced; but the truth of the theory can be better tested if these and all its other consequences are clearly imagined.

In order to give fuller warrant for certain statements made in the preceding paragraphs, several sections of a general nature will be here introduced. The first sets forth in brief form a climatic classification of volcanic islands, so that the larger relations of the islands belonging in the above-mentioned "marginal belt" of the coral seas may be better understood; another describes the position and breadth of the marginal belts of the Pacific and Atlantic oceans as defined by their islands; a third shows that oceanic volcanic islands usually exhibit the effects of subsidence; and a fourth qualifies a broad statement made in the first regarding the absence of cliffed islands from the coral seas.

A CLIMATIC CLASSIFICATION OF ISLANDS

If volcanic islands are formed in the frigid seas they will bear glaciers; if in the warmer parts of the torrid seas they will be encircled by coral reefs; if in the intermediate cool seas they will neither bear glaciers nor be encircled by coral reefs. The limits of these seas are subject to change in consequence of geological changes of climate. Thus if islands are formed in the cold seas adjoining the frigid seas, they will, like the Faroes, show the effects of glacial erosion during the Glacial period, although they bear no glaciers today. Similarly, islands that stand near the margin of the warm seas and are today more or less completely reef-encircled will show the effects of having lost their reefs during the Glacial epochs of the Glacial period when the ocean was somewhat chilled and its surface was somewhat lowered. Just as the islands of the cold seas should exhibit forms due to normal erosion in Preglacial or Interglacial epochs, modified by glacial erosion in the Glacial epochs and little affected by Postglacial changes, so the islands in the marginal belt of the warm or coral seas should exhibit forms due to Preglacial or Interglacial erosion, similar to those of reef-encircled, coral-sea islands, but modified by low-level abrasion and by erosion with respect to the lowered ocean in the Glacial epochs when reef protection was withdrawn; and the latest abrasional modifications thus introduced should be little modified by Postglacial changes.

Islands in the frigid and the cold seas need not be further considered here; but the features of those in the three other seas demand attention. St. Helena in the South Atlantic, recently examined by Daly,[2] is a typical example of a maturely sculptured island in the cool seas. It has been elaborately dissected by its short but steep streams and severely abraded on all sides by the unobstructed ocean waves. The work done by the streams in eroding their radial valleys appears to be comparable with that of the waves in cutting back the shore cliffs, as if both destructive processes had been at work continuously since the island was formed. Various reef-encircled islands in the torrid Pacific are equally typical of the true coral seas, for the absence of cliffs on their spur ends shows that they have long been reef-protected.

On the other hand, certain islands standing farther from the equator show features that in part resemble those of the always-reef-encircled islands of the true coral seas and in part resemble those of the never-reef-encircled islands of the cool seas. The most significant feature of the first kind is a circuminsular submarine bank, so like the lagoon floor of reef-encircled islands that it may be regarded as having been formed as such a floor and only subordinately modified by low-level abrasion in the Glacial epochs and by aggradation in Postglacial

[2] R. A. Daly: The Geology of Ascension and St. Helena Islands, *Geol. Mag.*, Vol. 59, 1922, pp. 146–156.

time. The most significant features of the second kind are the plunging cliffs around the island shore, the base line of which appears to lie at or a little below the inner margin of the submarine bank. These cliffs may be of greater or less dimensions according as their islands were exposed for a longer or shorter period to low-level abrasion; that is, according as the islands stand on the polar or the equatorial side of their marginal belt. Postglacial features include only small changes due to wave work along the present or normal shore line, to bank aggradation, and to reef upgrowth. It is noteworthy, however, that apart from shore fringing reefs, the reefs associated with the banks of cliffed, marginal-belt islands today are more or less discontinuous and that, instead of being built up from the outer margin of the bank, they rise toward or to sea level from the middle or inner part of the bank; they will therefore be called bank reefs, as above noted, to distinguish them from true barrier reefs of the coral seas. The fact that the discontinuous reefs of marginal-belt islands thus stand, like timid novices, well back from the outer edge of the bank, instead of rising, like the stalwart veterans of the true coral seas, from the edge of the bank suggests that the ocean temperature of the marginal belts has been less favorable to reef growth in Postglacial time than it was in Preglacial and Interglacial time. It is as if the temperature of the water did not become high enough for reef growth until after the ocean surface had risen so much as to leave the outer border of the abraded platform at a depth where reef-building corals could not establish themselves. A contributing cause to the delay in reef growth is found in certain islands, to be mentioned below, in the eastern part of the marginal belts where the dominant ocean currents come from cooler latitudes and are therefore unprovided with floating coral larvae. This cause of delay would not be present in the western part of the marginal belts, where the dominant currents come from the coral seas and should therefore be well charged with coral larvae: there, the delay in reef establishment and the resultant location of reefs well back from the margin of their banks, as well as their frequent failure to reach present ocean level, appear to be due wholly to the failure of the Postglacial ocean to rise to as high a temperature around these islands as it had in Preglacial and Interglacial times.

THE MARGINAL BELTS OF THE CORAL SEAS

Although islands with cliffed shores and submarine banks are not numerous enough to define the marginal belts of the Pacific precisely, they indicate that the belts have a width of about 5° of latitude between 23° and 28° north and 28° and 32° south latitudes in the western and central parts of the Pacific and that they become confluent by looping across the equator in the neighborhood of the Marquesas Islands in the eastern half of the ocean. The most remarkable series of such islands and banks is found in the northwestern extension of the Hawaiian chain. The banks are from 10 to 30 miles in diameter and are seldom over 30 or 40 fathoms in depth. The reefs, so far as they occur, stand back from the edge of the banks; they may be called bank atolls if no central island occurs, or bank barriers if a central island survives. This series includes six bank atolls, three banks without conspicuous reefs but with cliffed central islands or pinnacles, five banks without reefs or central islands, and two intermediate forms. The facts that some of these banks have no reefs and that all the central islands are reduced to so small a size that they have a continuously cliffed shore line without embayments place these examples on the polar side of their marginal belt. In the western North Pacific, several islands south of Japan have well embayed shore lines and cliffed inter-bay spurs with fringing reefs and rather extensive reefless submarine banks.[3] These islands presumably stand near the equatorial side of their belt.

In the South Pacific, Norfolk Island, northwest of New Zealand in latitude 29°, is about 13 square miles in area and 1050 feet in height; it is strongly cliffed and is partly bordered by a small fringing reef; the smaller Phillip Island, also strongly cliffed, is three miles away: both islands rise near the center of a vast bank, 60 by 20 miles in extent, with depths of 20 fathoms near the island and of 40 or 50 fathoms near the bank edge. Lord Howe Island, between Norfolk Island and Australia in latitude 32° S., is smaller, with cliffs 800 feet high; it rises from a bank 12 by 8

[3] W. M. Davis: Drowned Coral Reefs South of Japan, *Proc. Natl. Acad. of Sci.*, Vol. 9, 1923, pp. 58–62.

miles in extent and as deep as the Norfolk Island bank. Balls Pyramid, not far away, is an extraordinary stack or pinnacle, its height of 1816 feet being greater than its shorter sea-level diameter; it stands on a bank three by seven miles in extent. Middleton and Elizabeth Reefs are small bank atolls, north of Lord Howe Island in latitude 29°. The reduction of these high islands to continuously cliffed shores suggests that, as in the case of the Hawaiian examples, low-level abrasion has here been repeatedly at work and that the islands therefore stand near the polar side of their marginal belt. Raoul Island, in the Kermadec group, is embayed with cliffed spur ends and is surrounded by a submarine bank: it probably belongs in the marginal belt.

The Marquesas Islands are cliffed and embayed, and the few soundings that are charted near them suggest the presence of circuminsular banks of moderate depth; hence the members of this group are provisionally regarded as standing in the cross-equator loop of the Pacific marginal belts, between the cool seas on the east where currents come from the temperate zones of both hemisphere and the true coral seas farther west where the same currents have become warm enough for reef formation by their long and slow passage through the torrid zone. The delay in the establishment of reefs around these islands may be due largely, as above noted, to the absence of coral larvae in the great ocean current that approaches the islands from the cool seas.

The marginal belt of the Atlantic will be more fully described in a later section. Suffice it to state here that the temperate and torrid Atlantic as a whole appears to be a cool reefless ocean, corresponding to the reefless eastern Pacific; that the coral seas of the Atlantic are limited to the Caribbean Sea and part of the Gulf of Mexico; and that the marginal belt of the Atlantic seems to pass from the eastern coast of equatorial Brazil to the Lesser Antilles, with an abnormal northeastward loop that takes in Bermuda. Like the Marquesas Islands, the Lesser Antilles are approached by an ocean current that comes from the cool seas, where no reefs are present to furnish floating coral larvae.

STABLE AND UNSTABLE VOLCANIC ISLANDS

It has been briefly stated in a preceding section that the submarine banks which occur around the cliffed islands of the marginal belts resemble the lagoon floors of reef-encircled islands, modified by low-level abrasion in the Glacial epochs and by subsequent aggradation and reef growth. It may now be added that the formation of such lagoon floors is believed to be due to the slow accumulation of deposits, largely of organic origin, upon slowly sinking foundations—usually volcanic islands—from which the enclosing reefs have maintained themselves at sea level by upgrowth, essentially according to Darwin's theory of coral reefs. The main reasons for this belief are found by comparing the expectable features of stable and of unstable islands with the features of actual islands in the coral seas, the cooler seas, and the marginal belts, in brief as follows.

Stable islands in the cool seas will, in their maturity, be commensurably eroded and abraded, like St. Helena; but in their later stages, when the streams are shortened by the recession of the cliffs, abrasion will gain the upper hand; the uplands of subaerial erosion will become smaller; when they disappear the island will be a cliff-rimmed stack or pinnacle and eventually will be cut down to a shallow submarine platform by normal abrasion, or to a somewhat deeper platform by low-level abrasion or to a shallow normal platform rimmed around by a low-level platform. A fair number of partly dissected and abraded volcanic islands, with shallow banks of slightly different depths around them, and hence such as might be produced around slowly subsiding islands better than around stable islands, are known in the cool seas, especially in association with the volcanic groups of the eastern North Atlantic; but practically no examples of shallow banks of uniform depth, representing the platforms of completely truncated stable islands are charted in the cool seas. Inasmuch as volcanic islands, however ancient, would if stable remain perpetually as shallow banks, the rarity of such forms in the cool seas is noteworthy. The various banks of the North Atlantic have different depths, usually greater than 50 fathoms.

Among unstable islands of the cool seas, two classes must be distinguished—rising islands and sinking islands. Rising islands would present a succession of wave-cut benches. If such islands occur, they are rare. Sinking islands would be benched and reduced in size as they sank, and their diminished summits would eventually disappear. Just before their disappearance, they might show as slender stacks rising over submerged platforms of less or greater depth. Two remarkable examples of this kind are believed to occur south of Japan: One is Sumisu-shima, or Smith Island, 31½° N., 140° E., consisting of two pinnacles, the larger one having a smaller sea-level diameter than its height of 445 feet; soundings of 147 and 306 fathoms are charted within three miles. The other is Sofu-gan, or Lot's Wife, 30° N., 140½° E., which is again of less sea-level diameter than its height of 326 feet; soundings of 105 and 110 fathoms are charted two miles away. This rock was first reported in 1788; hence it cannot be a spine of the temporary kind that rose above Mt. Pelé; it must be the result of advanced abrasion.

After subsiding islands have disappeared in the cool seas, they might long escape discovery, except where many soundings are taken. A few rather deeply submerged cones are known in the Pacific; and, as above noted, a considerable number of small banks at depths of 50 or more fathoms are charted in the North Atlantic; but all these submarine eminences may be growing or extinct volcanoes not built up to sea level, instead of former islands submerged. Hence their bearing on the problem here considered is uncertain.

THE FORMATION OF ATOLLS

The possible occurrence of stable islands in the coral seas is of especial interest in connection with the formation of atolls. Such islands could serve as atoll foundations only if, as has been stated by Daly,[4] they are of so ancient origin as to have been worn down to low relief with deeply weathered soils when the Glacial period supervened and only if they were reefless in the Glacial period,[5] so that after being reduced to submarine platforms by low-level abrasion, reefs might grow up around the platform borders and enclose lagoon floors of very accordant depths. But if all the numerous Pacific atolls have been thus produced, it would be natural to expect that some islands of less ancient origin would have been less completely peneplained in Preglacial time and therefore less completely truncated by low-level abrasion in the Glacial epochs; and these residual islands would today survive in the center of barrier-reef and almost-atoll lagoons; they would be cliff-rimmed, and they could have no embayments of greater width or of greater rock-bottom depth than could have been excavated by low-level erosion in the Glacial epochs. As the actual reef-encircled islands of the coral seas do not present such features, and as the lagoon floors they enclose show significant variations in

[4] R. A. Daly: The Glacial-control Theory of Coral Reefs, *Proc. Amer. Acad. of Arts and Sci.*, Vol. 51, 1915, pp. 157–251.

[5] According to Daly, the absence of reefs in the Glacial epochs would be due, in part at least, to the lowered temperature of the ocean; but, under the conditions here assumed, that cause of reeflessness would be inoperative in the true coral seas.

depth,[6] long enduring stability of reef foundations is to be doubted.

On the other hand, if the volcanic islands of the coral seas are unstable, some might rise and others sink. The rising islands would bear reef benches of less or greater width at various altitudes. A fair number of such benched islands are known, especially among the non-volcanic islands of the Australasian archipelago. It is highly significant of the origin of the reef benches that their limestones rest, in all cases that have been closely studied, unconformably upon the underlying foundation rocks; thus proving an earlier episode of subsidence and reef formation before the later episode of elevation and reef emergence.

Other unstable islands in the coral seas might subside either at a nearly uniform rate or intermittently. If the subsidence were not too rapid, an up-growing reef would be formed around an aggrading lagoon floor; the subsiding island would diminish in size; its increasingly mature valleys would become well embayed; the rock-bottom depth of the embayment would come to be much greater than the measure of ocean lowering in the Glacial epochs; and the inter-embayment spur ends would not be cliffed. Raiatea and Borabora, Matuku and Totoya, which may be cited as typical islands of the coral seas, as well as various others that might be named, exemplify these features in a striking manner. With further subsidence an island would be reduced to one or

[6] W. M. Davis: Coral Reefs and Submarine Banks, *Journ. of Geol.*, Vol. 26, 1918, pp. 198–223, 289–309, and 385–41.1

more non-cliffed mountain-top islets, encircled by an almost-atoll reef. The islets of Truk in the western part of the Carolines and of Mangareva, or Gambier, south of the Paumotus are of this nature;[7] the absence of cliffs on their shores, in contrast to the strongly cliffed little islands of the marginal belts, confirms the view that the reduction of good-sized volcanic islands to the present small size of almost-atoll islets is due to subsidence of unstable volcanic cones and not to the abrasion of stable cones.

After an island disappears by subsidence in the coral seas, its former presence is still indicated by an atoll. Herein lies one of the chief differences between the coral seas and the cool seas; for in the cool seas a sunken island leaves no memorial. The rarity of volcanic islands in the cool seas of the Pacific in contrast to the abundance of atolls in the Pacific coral seas may perhaps be thus explained; but as the contrast may also be explained by an original difference in the number of volcanic islands formed in those seas, no demonstration of subsidence is thus provided; nevertheless, the contrast is still worthy of consideration. If subsidence be accelerated after a barrier reef has been formed, it will be drowned and be succeeded by a fringing reef on the new shore line, as was long ago perceived by Darwin although he then knew of no actual fringing reefs thus associated with subsidence. They are, however, abundant in the Philip-

[7] *Idem:* The Small Islands of Almost-Atolls, *Nature*, Vol. 105, 1920, pp. 292–293.

pine Islands.[8] One of the best examples is along the west side of the non-volcanic island of Palawan, where the drowned barrier reef and the unusually deep lagoon behind it are both well defined by numerous soundings.[9] If rapid subsidence take place after the atoll stage of reef upgrowth has been reached, the atoll reef will be submerged. The reef may again grow up the surface if its submergence is small; it will be permanently drowned if the submergence is greater. A remarkable group of submerged atolls lies north of Fiji; some of their reefs may again reach the surface.

All these features appear to me to contradict the view that volcanic islands are as a rule stable and to confirm the view that they are prevailingly unstable and exhibit a decided tendency to subsidence. The only fact which gives support to the view that such islands are prevailingly stable is the moderate variation in the depth of reef-enclosed lagoons; this being explained under the Glacial-control theory of coral reefs by the assumption that, even in the region here called the coral seas, Preglacial reefs were cut away and their lagoon floors were reduced to a standard depth by low-level abrasion in the Glacial epochs. That explanation is unacceptable because the absence of cliffed spur ends on the reef-encircled islands of the coral seas makes it unreasonable; and it is also unnecessary, because the variation of lagoon

[8] *Idem:* The Fringing Reefs of the Philippine Islands, *Proc. Natl. Acad. of Sci.*, Vol. 4, 1918, pp. 197–204.

[9] *Idem:* Subsidence of Reef-encircled Islands, *Bull. Geol. Soc. of Amer.*, Vol. 29, 1918, pp. 489–574.

depths, although moderate in comparison with ocean depths, is actually considerable; and in certain large lagoons the present depth is, in spite of Postglacial aggradation, even greater than the liberal measure of ocean lowering in the Glacial epochs adopted in the Glacial-control theory. The great lagoon enclosed by the magnificent barrier reef around the island of Tagula, east of New Guinea, is a striking instance of this kind.[10]

If the marginal-belt islands are considered alone, most of their features may be explained by assuming the islands to be either stable or unstable; but in view of the evidence for their subsidence given by the estimated rock-bottom depth of some of their embayments and in view also of the more general evidence given for prevalent subsidence by the islands of the coral seas proper, the stability of the marginal-belt islands seems improbable. It is made still more so when the persistent occurrence of extensive shallow banks around them is contrasted with the extreme rarity of such banks in the cool seas; for if the marginal-bank islands were stable and their banks were based chiefly on platforms produced by the abrasion of formerly larger islands, then the cool seas, being of vastly greater area than the marginal belts, ought to contain at least a fair number of similar banks based on platforms produced by the abrasional truncation of large stable islands there situated; but the cool seas do not contain such banks. Hence

[10] *Idem:* The Barrier Reef of Tagula, New Guinea, *Annals Assoc. of Amer. Geogrs.*, Vol. 12, 1922, pp. 97–151.

the banks around the marginal belts must be otherwise explained; and they are best explained as chiefly formed by upgrowing reefs and accumulated lagoon deposits around islands originally about as large as the banks but much reduced in size by subsidence; the reefs, the lagoon floors, and the island shores being brought to their present form by low-level abrasion in the last Glacial epoch, with small Postglacial modifications. It is certainly a remarkable feature of the oceans that shallow banks of fairly accordant depths, after being practically absent from the vast areas of the cooler seas, are suddenly found to be prevalent in association with the relatively small number of islands that stand on the border of the coral seas; and it is also highly significant that the islands which rise within these banks are cliffed, while the islands of the coral seas are not. When all these considerations are viewed together, the evidence for the prevalent, long-continued, and slow subsidence of marginal islands and for the former upgrowth of lagoon-enclosing coral reefs around them gains much strength.

CLIFFED ISLANDS IN THE CORAL SEAS

It has been briefly stated in an earlier paragraph that the islands of the true coral seas are not cliffed and that cliffed islands are found only in the marginal belts of those seas and in the cooler seas. This statement must now be modified; for it appears that volcanic islands in the coral seas also are usually cliffed in their youth before protecting reefs are established round them. The reason appears to be that the active outwash of detritus from the deepening valleys of young non-embayed islands furnishes an abundant supply of cobbles, gravel, and sand by which beaches are formed all around the island shore. Any incipient fringing reefs are thus smothered, the attack of the waves on the shore is unobstructed, and cliffs fronted by gently sloping rock platforms a little below sea level are produced. The rock platforms are extended a little seaward by detrital embankments, and the width of a platform is usually five or six times as great as the height of the cliff behind it.

Abrasion will continue as long as the island stands still; but as soon as it subsides enough to embay the valley mouths, the stream detritus will be pocketed there; and then the firm face of the partly submerged, or "plunging," cliffs will afford a fitting support for corals to grow upon and in time to form a fringing reef. If subsidence then ceases, the little bays will soon be filled with deltas, and thereafter the detritus will again tend to form circuminsular beaches and to smother the reefs; whereupon the abrasion of a platform backed by cliffs will again be instituted but at a somewhat higher level with respect to the island mass than before. On the other hand, if subsidence continues at a rate rapid enough to prevent the filling of the valley-mouth bays and yet not rapid enough to drown the corals, the fringing reefs will grow up as the island diminishes in size and form an offshore barrier reef, and the enclosed lagoon will be more or less aggraded. After the island sinks below sea level the reef will be an atoll.

Reunion, in the southern Indian Ocean, is a good example of a cliffed and beach-begirt island, out from whose deep valleys an immense volume of detritus is washed and offshore from which only a few small reef patches are charted.[11] Tutuila, the chief American member of the Samoan group in the Pacific, appears to have had its slopes deeply dissected by streams and to have had its shore cut back in high cliffs fronted by a wide platform while it stood in its reefless youth several hundred feet higher than now. The absence of portecting reefs at that time cannot be explained by a lowering of ocean temperature, because in that case many other islands in the coral seas of the Pacific ought also to be cliffed, and they are not. The absence of reefs around Tutuila then, as around Reunion now, is best explained by the formation of beaches composed of outwashed detritus. After extensive cliffing a slight submergence appears to have embayed the valleys a little and thus permitted the upgrowth of an offshore reef, now recognized by shallower soundings on the outer part of the broad circuminsular bank; but soon an acceleration of the submergence drowned that reef, embayed the valleys more deeply than before, and determined the occurrence of a fringing reef of later generation at the higher level of the present shore line. The submergence thus indicated cannot be advisedly explained by Postglacial ocean rise, because the present bank, which is undoubtedly aggraded to a less depth than

[11] *Idem:* Clift Islands in the Coral Seas, *Proc. Natl. Acad. of Sci.*, Vol. 2, 1916, pp. 283–288.

the supposed underlying rock platform, has soundings of 60 fathoms or more back of the drowned reef.[12]

Tahiti was sharply dissected and even more strongly cliffed in its youth, especially on its windward coast, than Tutuila; but there the offshore reef, which appears to have been established, like the now drowned reef of Tutuila, on the cliff-base platform when subsidence set in, has continued its upgrowth with continued subsidence, so that now, when the measure of subsidence as indicated by the inferred rock-bottom depth of the larger embayed valleys has reached 600 or 800 feet, it is a typical barrier reef. Here again the absence of reefs during the former higher stand of the island cannot be explained by a lowering of ocean temperature, because in that case the other islands not far away in the Society group should also be cliffed, and they are not. Recently a pause in the subsidence of Tahiti appears to have taken place; for the formerly embayed valley mouths are at present nearly all delta-filled, and the delta fronts have advanced into the lagoon and thus formed a confluent belt of alluvial lowlands fronting the plunging cliffs nearly all around the island.[13]

It thus appears reasonable to conclude that young volcanic islands even in the warm coral seas experience cliff cutting during a part of their youth, before subsidence sets in. A corollary of this conclusion is that the maturely dissected, reef-encircled islands of

[12] *Idem:* The Coral Reefs of Tutuila, *Science*, Vol. 53, 1921, pp. 559–565.

[13] *Idem:* Les falaises et les récifs coralliens de Tahiti, *Ann. de Géogr.*, Vol. 27, 1918, pp. 241–284.

the coral seas, which today have non-cliffed spur ends between their well developed embayments, were exposed to abrasion when they were younger and stood higher and that the cliffs then cut are now invisible because they are completely submerged. It may strain a reader's credulity to accept, even provisionally, so surprising a corollary; but that measure of reason-guided credulity is more consistent with what is now known of volcanic islands and the reefs that encircle them than an unreasoned incredulity.

If the facts and arguments and conclusions presented in these four intercalated sections are now borne in mind, the relations of the Lesser Antilles to the coral-reef problem as a whole may be much better apprehended than if those islands, to the description of which we now return, are studied alone.

A Simple Sequence of First-Cycle Islands

SABA, A YOUNG VOLCANIC ISLAND

Three small members of the Lesser Antilles in different stages of a simple sequence of first-cycle development may be first presented. I saw them only from passing steamers. Saba (Fig. 2), the simplest island in the whole chain, represents an early stage: it is a young volcanic cone, from two to two and a half nautical miles in diameter and 2820 feet high. As yet it is little dissected by streams but rather sharply cliffed by waves around the shore and bordered by a narrow submarine shelf, hardly wide enough to be called a bank. It naturally shows no signs of subsidence in the way of embayments even if

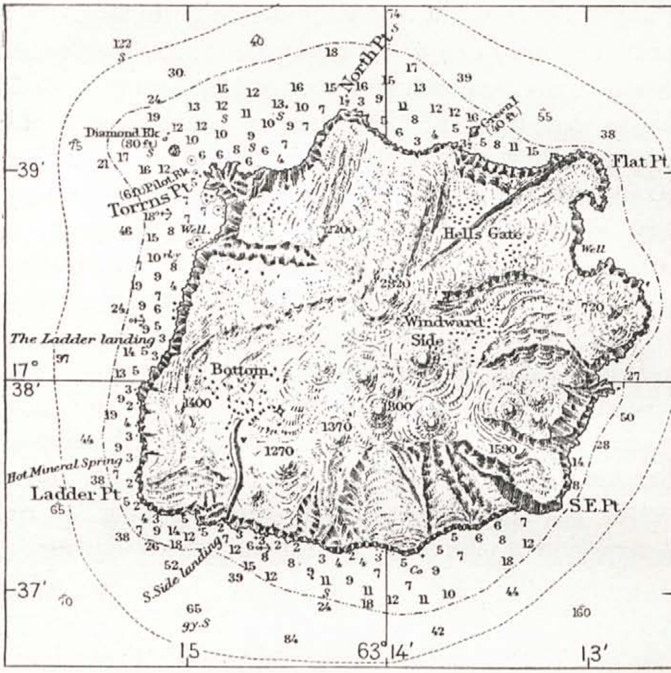


Fig. 2—Saba Island (from U. S. Hydrogr. Office Chart No. 1011).

its subsidence has begun, for its little valleys all have hanging mouths in the cliff face, well above the sea level. Naturally it has no coral reefs, because, as has just been explained, they cannot be established on a detritus-covered, cliff-base shelf. The inhabitants, of Dutch descent, have learned to speak English rather than their forefathers' tongue; they cultivate the uplands and also build small boats which are lowered down the cliffs to the harborless shore and sold for inter-island traffic.

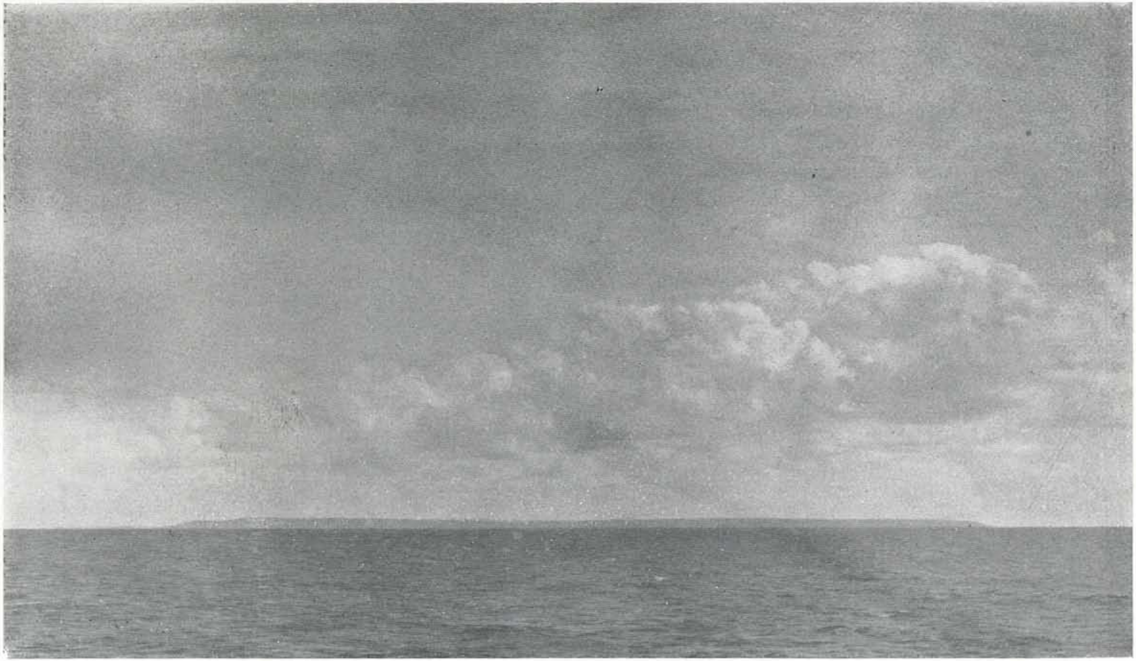
THE SAINTS, EMBAYED AND CLIFFED RESIDUALS

The Saints, south of the lofty island of Guadeloupe, represent a well advanced stage in the first-cycle sequence of small-island development. They are the separated residual summits, one of which is shown in Figure 3, of an elaborately dissected and partly submerged volcanic mass about five miles across over all, which rise with cliffed head-

Fig. 3—One of the Saints, south of Guadeloupe, with moderately cliffed headlands between well-developed drowned-valley embayments; looking west.

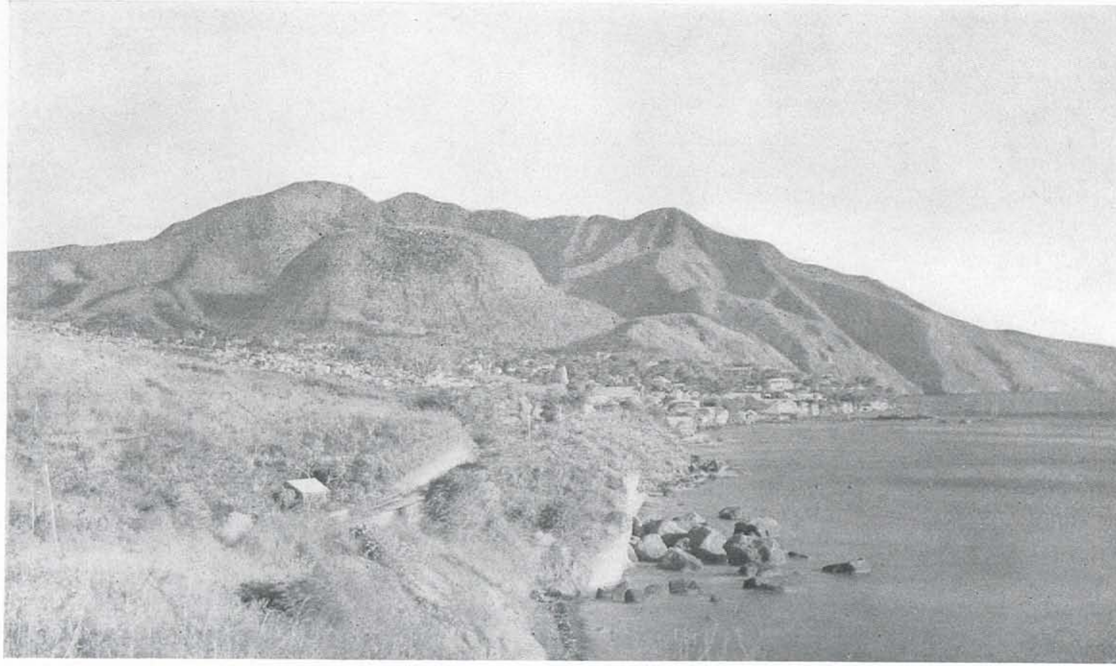
lands from a rimless bank eight or ten miles in diameter and from 30 to 40 fathoms in depth at its outer border. Part of one of the islands is mapped in Figure 4. Here the mature subaerial sculpturing of the residuals is manifestly the work of a much longer period than that required for the abrasion of the immature headland cliffs. It is therefore believed that the Saints show in their well carved summits and slopes the work of a long continued interval of subaerial erosion on a slowly subsiding island, which was protected from wave attack during nearly all of that interval by an upgrowing barrier reef; and that the rimless bank which now extends around them represents the reef and its enclosed lagoon floor, as modified during the Glacial epochs by low-level abrasion, which also accounts for the immature head-

Fig. 4—Part of one of the Saints (from U. S. Hydrogr. Office Chart No. 362).



Pl. II—The uplifted limestone island of Marie Galante.

Pl. III—The younger volcanic cones of Montserrat.



PL. IV—The southern part of Statia, looking east by south. Orangetown lies at the foot of the volcano.

land cliffs, and during Postglacial time by aggradation. The fact that the cliffs plunge somewhat below present sea level, as shown by the charted depths near them, gives support to this view. The submergence of the carved island and the conversion of its summits into separate islets are ascribed to subsidence, not to Postglacial ocean rise, because the amount of carving and probably the depth of carving also—for the slopes of the islets have the appearance of pitching down to a considerable depth below sea level—seem to be much too great to have been accomplished by low-level erosion during the Glacial epochs.

REDONDA, A SOLITARY REMNANT

A solitary and uninhabited islet known as Redonda (Fig. 5) between Nevis and Montserrat, less than

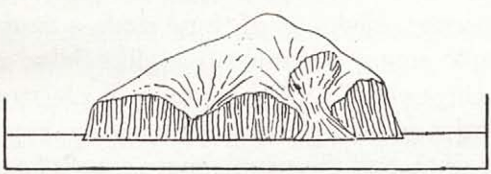


Fig. 5—A rough outline of the residual island of Redonda, north of Montserrat; looking north.

a mile in diameter and about 1000 feet in height, rises from an imperfectly charted bank, several miles across, with depths of 30, 40, or 50 fathoms. This little remnant appears to represent a penultimate stage in the first-cycle sequence of insular forms; that is it is the central islet of an almost-atoll, the atoll reef having been cut away and the central islet having been modified by the waves of the lowered and chilled Glacial ocean. The scar of a landslide, about 700 feet high at the top, and a heap of fallen detritus are seen on the southeastern slope. Manganese ore is said to have been quarried here.

SUBMARINE BANKS OR ABRADED ATOLLS

Finally, the ultimate stage of the first cycle is exemplified by several small, rimless and island-free banks, which appear to be true atolls modified, like the forms of earlier stages, by low-level abrasion. One, three miles across, lies some miles to the east of Redonda, with depths of from 43 to 86 fathoms; another, to the north of Redonda, is five miles long, with depths of 25 or 30 fathoms. A few others of similar size and depth are charted elsewhere in the chain. Evidently, if this schematic interpretation is correct, each one of these rimless banks began as a simple young volcanic island, like Saba, and then passed through the mature stage of elaborate subaerial sculpture and partial submergence, represented by the Saints, and the penultimate stage of approaching extinction, represented by Redonda, before reaching the ultimate stage of atoll development, with its episodes of low-level abrasion followed by imperfect reef growth and aggradation.

A Simple Sequence of Second-Cycle Islands

MARIE GALANTE, AN UPLIFTED ATOLL

Two simple examples of second-cycle islands may be adduced. The first is Marie Galante, a limestone island in the Guadeloupe group, nine miles in diameter, with a remarkably even profile at a height of 670 feet. As represented on H. O. Chart 363, the relief seems stronger than it would be inferred to be from the view of the island (Pl. II) reproduced from a recent photograph by Mr. G. S. Miller, Jr., of Washington.

This island was seen only in the distance: no detailed studies have been made of it. It appears to be an upraised atoll, somewhat benched during and moderately dissected since its recent emergence, not yet provided with a bank of second generation.

SOMBRERO, AN UPLIFTED AND CLIFFED ATOLL

The second example I did not see at all; it is Sombrero, southeast of the Virgin group, a narrow limestone island a mile long and from 25 to 40 feet high. Its shore cliffs plunge to depths of 8 to 14 fathoms, and it is surrounded by a bank three by four miles across and 30 or 40 fathoms deep at the outer edge. Julien spent several months on the island nearly half a century ago,[14] and gave an excellent account of it as an uplifted atoll, originally about as large as the bank of second generation that now surrounds it, but reduced to its present size by wave attack. He concluded that its "marine deposits appear to have been formed upon the area, oscillating vertically, of the bottom of a lagoon, more or less inclosed," as if it had the basin form peculiar to

[14] A. A. Julien: On the Geology of the Key of Sombrero, *Annals Lyceum of Nat. Hist. of New York*, Vol. 8, 1867, pp. 251–278

atolls. The rarity of atolls in the West Indies is recognized, but it is held that Sombrero must have been one, because of the repeated occurrence of lagoon-like limestones upon it; and it is added that "many of the isolated keys and banks with which its [the West Indian] archipelagoes abound, may reveal to future examination the possession (in their former history if not at present) of a true atoll construction." The parenthetical remark here included is, in my opinion, fully justified by the features of Antigua, to be described below. Six beds of limestone were recognized on Sombrero, bearing many fossils like the forms now living on the bank around the abraded island, and indicating as many subsidences with deposition followed by emergences with erosion.

The following extracts from Julien's account illustrate the detailed analysis of the island's history that he felt warranted in making. At an early stage in its growth "the whole subsiding area was covered with a close and uninterrupted madrepore reef. From the few species and individuals of the shells in the coral-bed, from their fragility and that of the corals, and from the absence of fragments, it may be inferred that the reef grew in comparatively quiet water. . . . The quietness of the locality could not have been due simply to great depth. We are forced to believe . . . that some barrier encircled the reef . . . varying at different periods in height relative to the bottom of the lagoon. Indeed such a barrier must necessarily have been formed on the outer edge of the oscillating area, on the first occasion that the superincumbent sea was sufficiently shallow to support coral life, creating an atoll when it reached the sea level. . . . Coral life ceased over the central area, with the exception of many scattered clumps and the frequent superposition of a more delicate species. These remnants were next overlaid with coarse sand from the shore of the lagoon and the barrier islets, and thereby killed. The greater quietness and depth of the water favored the abundant growth of a few species of fragile shells, whose unbroken condition proves that they grew where they now lie.'' Similar inferences are presented regarding the several overlying limestone beds. The formation of the sixth bed was followed by two oscillations of level without submergence; the guano deposits which then accumulated in crevices in the limestone have been quarried and shipped away. ''Thus then this little rocky islet stands out in the open ocean, a solitary pillar, like those of the Temple of Serapis, marking old convulsive throbs and prolonged oscillations of the deep-sea bottom.''

Sombrero must have had, according to the scheme of development proposed in the present essay, a somewhat more extended experience than the small rimless banks which represent the ultimate stage of one-cycle islands; for after passing through the first-cycle stages represented by Saba, the Saints, Redonda, and an atoll, it appears to have been introduced into a second cycle by a moderate uplift and then to have passed through the young second-cycle stage of Marie Galante, preparatory to reaching its own mature stage of advanced abrasion. Its emergence would therefore seem to have been early enough for it to have suffered low-level abrasion in at least one Glacial epoch, while the emergence of Marie Galante appears to have been so recent that it hardly bears the marks of even the latest Glacial epoch of low-level abrasion.

This interpretation is necessarily in large measure hypothetical, for most of the conditions and processes it involves are lost in the past. Nevertheless, in so far as the interpretation is correct, the past conditions and processes involved in the interpretation were facts in their own time just as truly as are the observable conditions and processes of today. That the hypothetical interpretation may be accepted as essentially correct appears from the simple manner in which it assembles and correlates a variety of insular features which at first sight seem to have little in common.

A More Complicated Sequence of First-Cycle Islands

EARLY STAGE: MONTSERRAT, A COMPOSITE ISLAND

Several examples belonging in a more complicated sequence may now be presented, beginning with a composite island of easy analysis. Montserrat (Fig. 7), nine by five miles across, was seen only from a

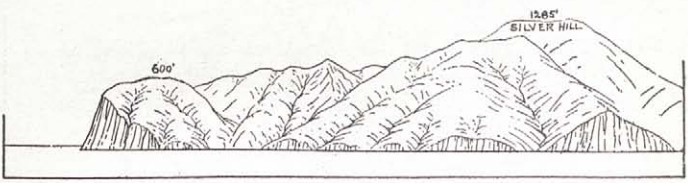


Fig. 6—Silver Hill, a maturely dissected volcanic mass at the northern angle of Montserrat. The cliff of the most exposed headland is about 450 feet high and is one of the highest cliffs seen on any island.

steamer that passed near its western and northern coast; but five or six cones in different stages of erosion and hence of different dates of eruption were recognized. It has therefore had a more complicated history than the small, one-cone island of Saba. Its oldest cone, Silver Hill (Fig. 6), occupies the northern corner of the island, with a height of 1285 feet; it is a cone no longer but is so maturely eroded as to have lost all its initial form; its exposed shore is cliffed, and it is fronted by a two-mile rimless bank. Center Hill (Fig. 8), a few miles to the southwest, about five miles in diameter and 2450 feet in

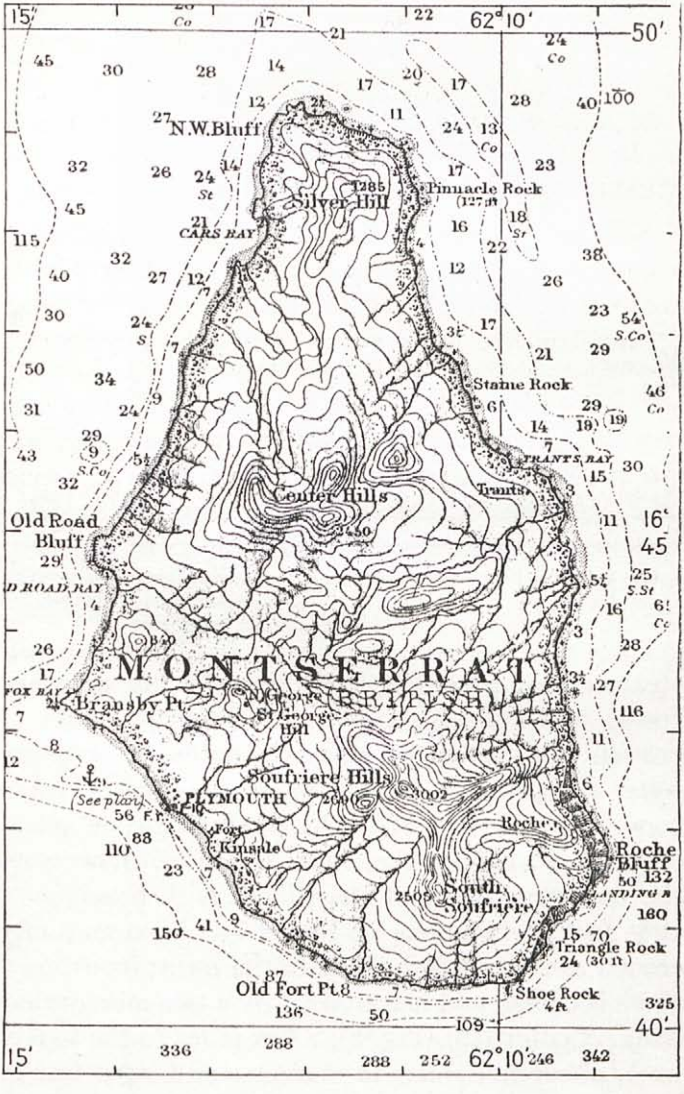


Fig. 7—Montserrat (from U. S. Hydrogr. Office Chart No. 1011).

height, is much less eroded; for, while its loftier slopes are sharply incised by deep, close-set, steep-sided valleys between which the original upper surface of the cone is reduced to acutely serrated ridges, its

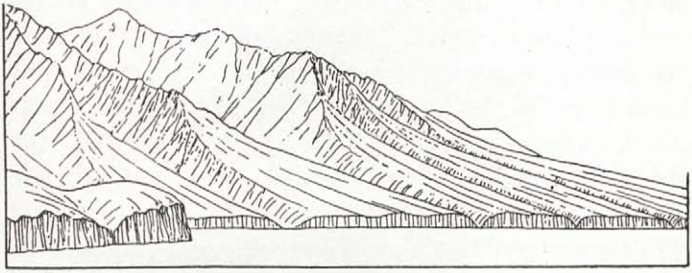


Fig. 8—Center Hill, on the northwest coast of Montserrat, showing the deeply incised inner valleys between sharply serrated ridges, the moderately dissected lower slopes, and the low cliffs of the shore. The higher cliffs in the left foreground are part of Silver Hill, Fig. 6.

lower and gentler slopes still preserve their initial form little changed between the same valleys, which are there wider spaced and much less deep; its shore line is moderately cliffed. The Soufrières, a compact group of the youngest and loftiest cones, 3002 feet at the highest point, still smoking and little trenched, occupy the southern part of the island with low, beach-based bluffs along the shore and with no submarine bank offshore; their southeastern slope pitches down at an angle of 35° or 40°, as if part of the cone there had slipped into the sea. This young cone does not therefore possess the long basal slope of very gentle declivity seen on Nevis, to be described below, and it thus gives support to the idea shortly to be presented that the gentle basal slope of Nevis is a consequence of the growth of its young cone on a preëxistent bank of moderate depth, while the steeper slopes of the Soufrières on Montserrat result from their descent into deep water. On the other hand, Center Hill descends by gentler slopes northwestward and eastward to its bluffed shore, as if its volcanic beds were there spread out on a bank now buried on the south of Silver Hill, like the bank that is not buried to the north of it. Only Silver Hill, the oldest, maturely dissected cone at the northern angle of Montserrat, shows signs of submergence in its slightly embayed valleys. No reefs occur around this island; those that are believed to have once rimmed the bank in front of Silver Hill have been cut away; and none can yet have been formed on the beached shores of the younger cones. Plymouth, the chief town of Montserrat, lies where, in consequence of the projection of a low lava point a little farther north, the shore is moderately concave on the bluffed slope of a young cone of small size on the west coast. The smooth lower slopes of Center Hill and other similar cones are cultivated. The saddles between adjacent cones guide cross-island roads.

A MORE ADVANCED STAGE: STATIA, ST. KITTS, AND NEVIS ON ONE BANK

The next example includes three composite islands that rise from a single bank, 47 miles in length. I landed on the middle member, St. Kitts, and drove around its younger cones; the southern member, Nevis, was well seen from passing steamers:

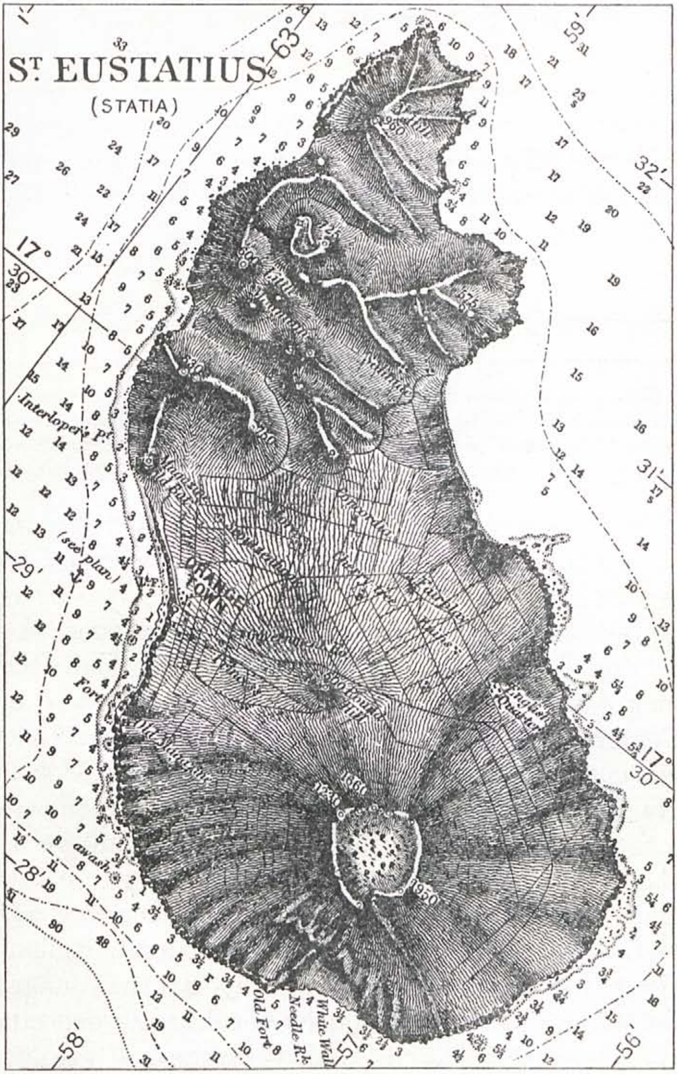


Fig. 9—Statia (from British Admiralty Chart No. 487).

the northwestern member, Statia, properly St. Eustatius, was seen only in the distance. The last-named island (Fig. 9) is a volcanic doublet consisting of two cones of unlike age. A sketch made from St. Kitts through very hazy air is given too definite an expression in Figure 10. The older cone

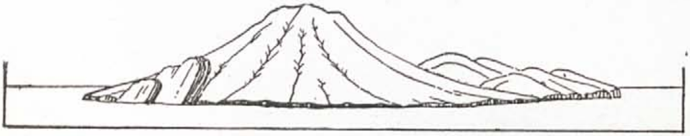


Fig. 10—A rough outline of Statia, as seen through hazy air from the northwest end of St. Kitts: the huge inclined slabs of limestone, known as the "White Wall," on the shore of the cone, appear to have been lifted up from a preëxistent submarine bank when the volcano was formed.

of Statia is now a well dissected mass, a mile or more in diameter and 960 feet high, with a somewhat irregular and moderately cliffed shore line. It is overlapped on the southern side by the younger cone, two or three miles in diameter and 1950 feet high; the long concave slopes of this cone resemble those of Center Hill on Montserrat but are less dissected and less cut back along their shore. According to Molengraaff,[15] the younger cone bears on its southern side some huge monoclinal slabs of limestone, known as the "White Wall," containing shallow-water fossils and rising with strong inclination to a height of 900 feet. From this as well as from the moderate inclination of its basal slopes, one may infer that the younger volcano was built up on a bank of calcareous deposits

[15] G. A. F. Molengraaff: De geologie van het eiland St. Eustatius, Leiden, 1886.

that had already been formed in association with the older volcano.

Similarly, St. Kitts (Figs. 12 and 13), formally named St. Christopher and colloquially reduced to "Singkits," consists in its older southeastern part of six or eight small volcanic residuals, whose area is too

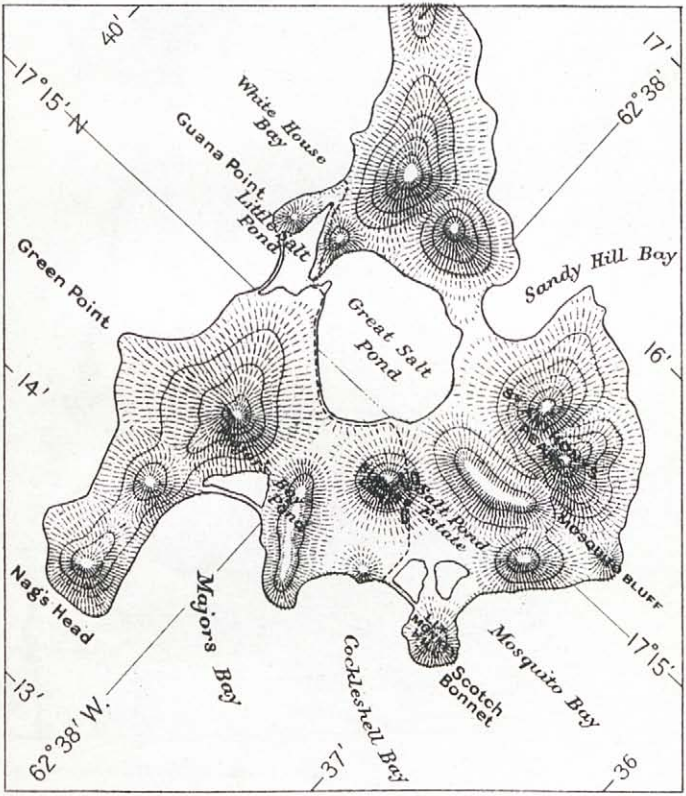
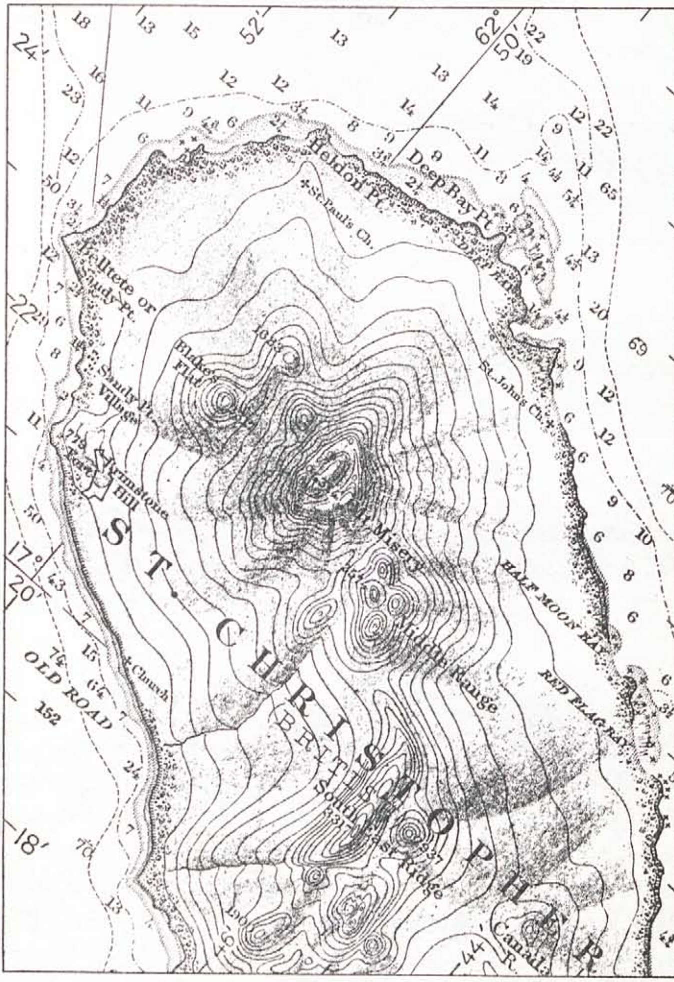
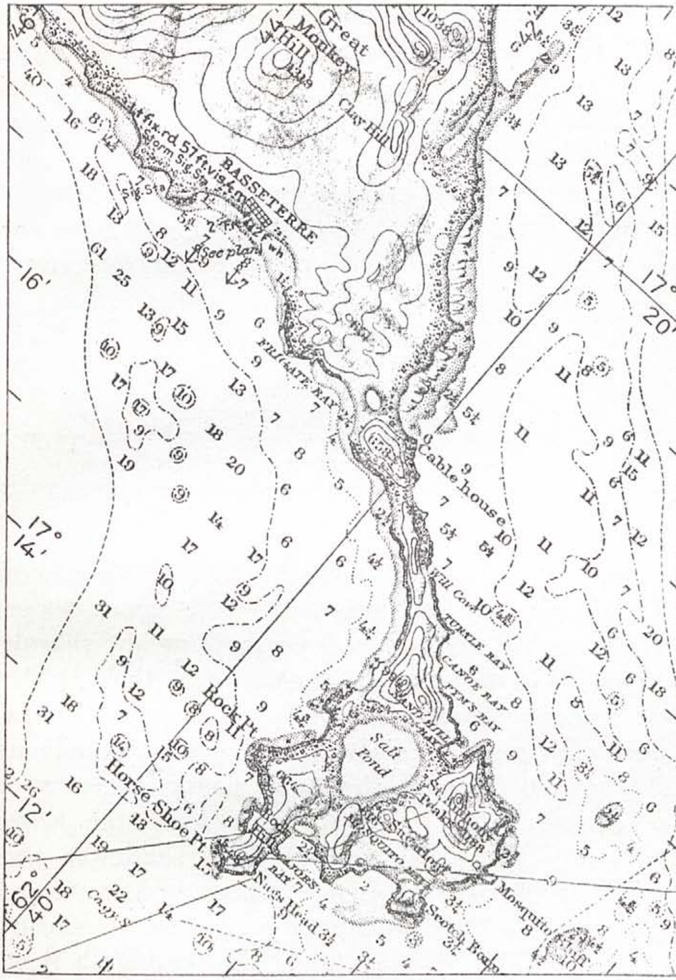


Fig. 11—The southeastern part of St. Kitts (from British Admiralty Chart No. 487).



Figs. 12 and 13—St. Kitts (from U.S.



Hydrogr. Office Chart No. 1011).

small to show embayed valley heads but whose slopes pitch into the sea in a manner betokening advanced erosion while they stood higher than now and abrasion when the ocean was lower than now: they are attached to one another by sea-level beaches and occupy a stretch six miles in length over all: some of them are shown in Figure 11. Adjoining them on the northwest is a group of lofty young volcanoes occupy-

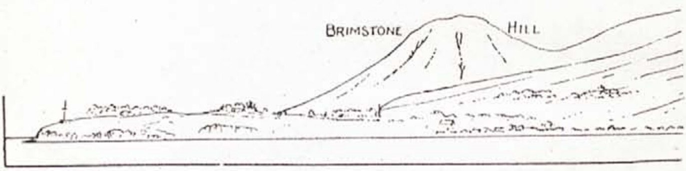


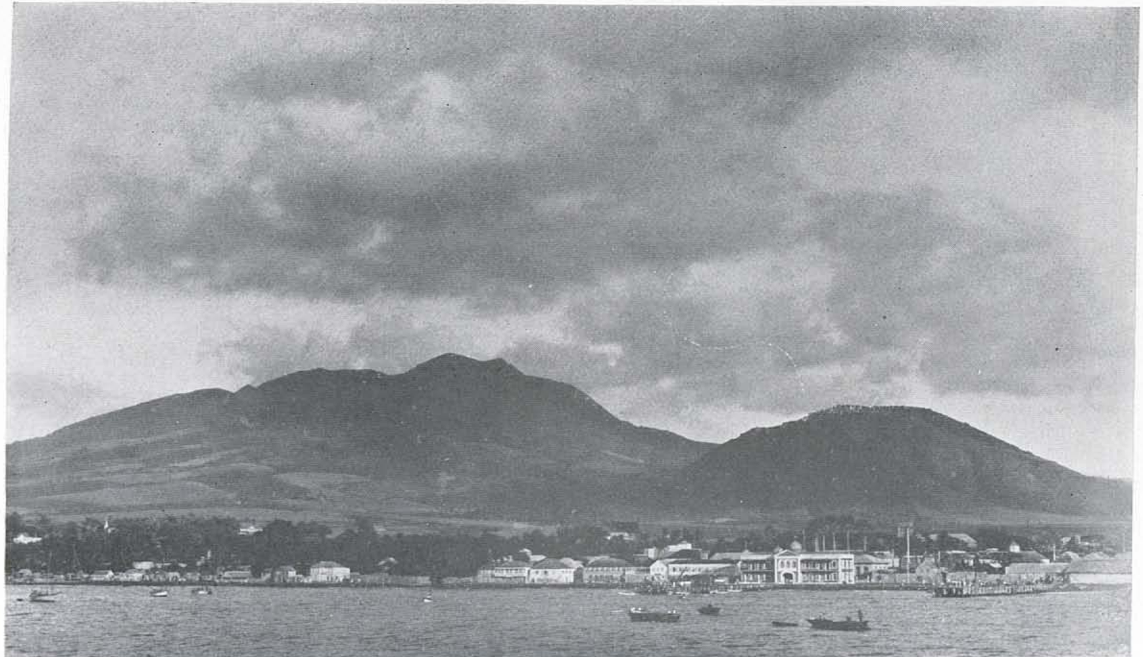
Fig. 14—Basseterre, the chief town of St. Kitts, on the shore

ing an area of 12 by 5 miles, the highest rising to an altitude of 4314 feet. Here the steep upper slopes, verdant with well-watered vegetation, are sharply trenched by close-set valley heads, while their gentler lower slopes, which, like the similar slopes of Statia, suggest the preëxistence of a bank on which the lavas and agglomerates of the lofty young cones were spread out, are moderately incised by the lower courses of the same valleys, there shallower and wider-spaced. The shore is cut back in low, ragged cliffs but is without valley embayments. According to Cleve,[16] large slabs of limestone bearing shallow-water marine fossils cloak the flanks of Mt. Brim-

[16] P. T. Cleve: On the Geology of the Northeastern West India Islands, *Handl. Kongl. Svensk. Vetensk. Akad.*, Vol. 9 (N. S.), 1870, No. 12, pp. 1–48.

Pl. V—The central volcanic range of St. Kitts, looking northeast. Mt. Brimstone on the left.

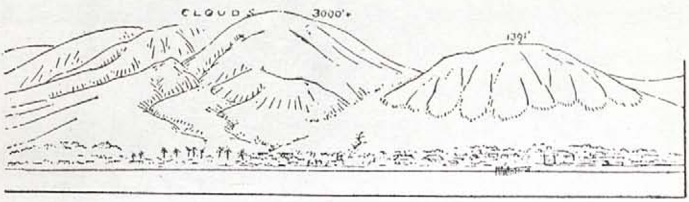
Pl. VI—St. Kitts from Basseterre roadstead. Continuous with Pl. VII.



PL. VII—St. Kitts.

Pl. VIII—Isolated residual hills in the passage between St. Kitts and Nevis, looking east.

stone, a small parasitic cone on the west side of one of the higher cones; hence here again, as in the case of Statia, it may be inferred that a bank had been formed in association with the older volcanic residuals before the younger cones were built. As the bank is continuous over the island-free stretch between the younger parts of Statia and St. Kitts, it is probable that it is there based on several completely sub-



slope of a group of young volcanoes; looking northwest and north.

merged volcanic masses. Basseterre (Fig. 14), the chief town of St. Kitts, lies on the southern slope of the young cones, its open roadstead being protected from the trade-wind swell by the beach-tied volcanic residuals on the east.

Finally, Nevis (Fig. 15), the southeasternmost of the three composite islands here considered, consists of three mature residuals of earlier eruption and erosion, between and above which a younger cone of much later origin has been built up. It is of wonderfully graceful form, the finest island of its kind in the Lesser Antilles. The steep but slightly furrowed slopes of its verdant crater rim, which rises to a height of 3596 feet, descend toward the shore with ever decreasing declivity, little cut by radial con-

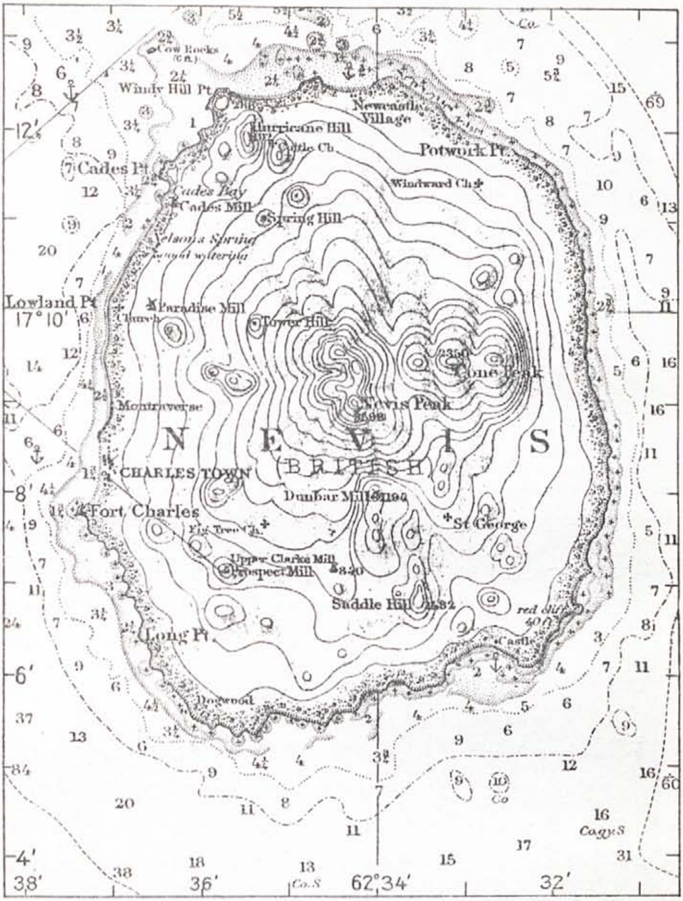


Fig. 15—Nevis (from U. S. Hydrogr. Office Chart No. 1011).

sequent streams in spite of the frequent cloud-cap showers at the stream heads. The shore line is of simple oval contour, five by seven miles in diameter, very slightly cut back here and there in bluffs a few feet in height. The maturely carved residual, Cone Peak, on the east of the crater summit (Fig. 16) is higher than the others; it is completely inwrapped in the flanks of the younger cone; the second, Saddle Hill, on the south, of medium height, is inwrapped on three sides but reaches the sea on the fourth, where it is cut back in cliffs a hundred feet or more in height; the third (Fig. 17), the lowest of the three, forms a salient on the north coast where it advances toward the beach-tied residuals of St. Kitts, the nearest of which is only a few miles distant. Although Nevis has no uplifted bank limestones, the very gentle declivity of its lower slopes suggests, as already intimated, that it was built up from a shallow sea bottom; its contrast in this respect with the steeper slopes of Saba and of the Montserrat Soufrières, which have no bank around them and which therefore must have been built up from deep water, is certainly significant.

The bank from which these three composite islands rise extends two miles northwest of Statia and ten miles south of Nevis, with a total length of 47 miles, a breadth of eight or ten miles, and a marginal depth of 30 or 40 fathoms. Its trend is sympathetic with that of the Lesser Antilles as a whole and with that of the axes of the elongated volcanic islands, like Guadeloupe, Dominica, and several others. Saba stands in line with it, not far to the northwest. Hence, as already suggested, the bank is thought to have been built up as a reef-enclosed lagoon floor in association with a subsiding series of earlier volcanic islands, some of which appear to be wholly submerged in the island-free stretch between Statia and St. Kitts and in the southern end of the bank beyond Nevis; and, as in the case of the Saints, the bank here is believed to have recently lost its enclosing reef by low-level abrasion. The younger volcanoes appear to have been piled up on the bank in Glacial or Post-glacial time. Discontinuous reefs are charted on the bank near some of the islands; one fringes the north-

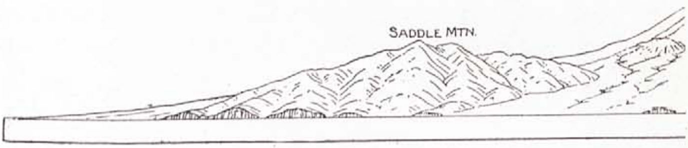
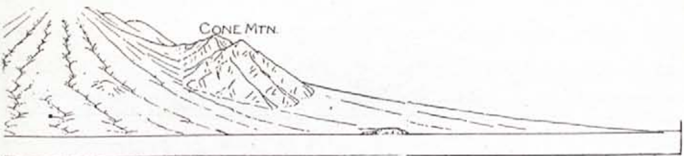


Fig. 16—Nevis, as seen from the southwest. The young cone is built are seen in Saddle and Cone mountains.

east coast of St. Kitts for two miles; another resembles a submerged barrier reef, as it extends with a depth of six or eight fathoms for 15 miles along the northeast border of the bank from St. Kitts to Nevis and encloses depths of 10 or 12 fathoms.

ADJUSTMENT OF BANK DEPTHS TO PRESENT OCEAN LEVEL

An important problem is opened up by the frequent recurrence of submarine banks, associated with marginal belt islands, which slope gradually seaward to depths of about 40 fathoms around their outer border; for that depth indicates that the detritus to be moved and the marine agencies for moving it are in adjustment with respect to present sea level. Daly has found from a study of many charts that the depth at which a marked increase of slope occurs on the outer part of continental shelves is not 100 fathoms, as it is often said to be, but is, as in the case of marginal-island banks, about 40 fathoms. My own studies lead to the same conclusion with respect to the depth at which a change is made from a gentle slope to a steep pitch in the exterior submarine pro-



on the ruins of an older volcanic mass, two surviving summits of which

file of Pacific coral reefs. This appears to mean that the activity of waves and currents is in the long run such that the fine detritus which prevails on the outer part of a bank or shelf will not be allowed to accumulate there at less depths than 40 fathoms but will be gradually shifted to the bank border where it will settle down upon the steeper slope and build it outward up to the standard 40-fathom depth. The longer a land mass remains stable, the broader may the continental shelf or bank in front of it become; but its border depth will remain of about the same measure.

The same relation should have obtained between the level of the lowered ocean in the Glacial epochs and the depth at the outer border of the detrital embankments that were then built of the material abraded in the production of low-level platforms. Hence, if the ocean was lowered 30 fathoms, the border of the embankment then formed should lie at a depth of about 70 fathoms below present sea level. But, as a matter of fact, bank-border depths of 70 fathoms are exceptional. The depth at which a change of declivity takes place between the gentle slope and the steeper pitch on continental shelves, on

Fig. 17—The northern side of Nevis, looking east.

marginal-belt banks, and on the exterior profile of the veteran coral reefs in the tropical Pacific is generally 40 or 50 fathoms, not 70 fathoms. Consequently, if we accept the fact of low-level abrasion during the Glacial epochs, whatever embankments were then formed appear now to have been so well aggraded in Postglacial time that they are no longer recognizable: the built-up banks are now as a rule in good adjustment with normal ocean level. It is perhaps surprising that detritus should have been provided during the relatively short Postglacial epoch in sufficient quantity to obliterate the effects of the low-level abrasion that was accomplished during a longer time; but no other satisfactory interpretation of the facts has been reached. Evidently the smaller the measure of ocean lowering and the less the amount of abrasion then accomplished, the more readily will banks be brought to normal depths in Postglacial time. Two corollaries follow from these considerations. First, the depth of existing banks around marginal belt islands gives no safe indication of the depth of the abraded platforms that are supposed to be beneath them, because the thickness of Postglacial aggrading deposits is unknown. Second, the depth of the larger reef-enclosed lagoon floors in the coral seas of the Pacific should not be regarded as giving a rough measure of an abraded platform beneath them, not only because abrasion appears not to have taken place there but also because, even if it did, the uncertainty as to the thickness of Postglacial deposits prevents a safe inference as to platform depth from lagoon-floor depth.

THE CONTINENTAL SHELF OF BRAZIL

The continental shelf along the coast of Brazil is a specific illustration of the adjustment of offshore profiles to present marine agencies. The region is well shown in H. O. charts 1503, 1504, 1522, 1670, 1671, and 1672. According to Branner,[17] the latest movement of the coast was an early Pliocene depression; the so-called stone reefs which rise to sea level near the shore, as well as the continental shelf outside of the reefs, appear to have gained their present forms since that time. Branner prepared a chart, on which submarine contour lines show that the shelf, sloping

[17] J. C. Branner: The Stone Reefs of Brazil, Their Geological and Geographical Relations, With a Chapter on the Coral Reefs, *Bull. Museum of Comp. Zoöl. at Harvard College*, Vol. 44, 1904.

gently seaward and ten or more miles in width, extends along the coast for more than 13 degrees of latitude, or about 800 miles; its outer border has a depth of 30 or 40 fathoms, beyond which a steep pitch descends to 1000 fathoms or more in a further distance of five or ten miles. South of the area charted by Branner the shelf increases in width to 60 miles in latitude 16° S. and to 80 miles in latitude 19° and 20° S., but its border depth remains about the same. This broader part of the shelf is occupied by several discontinuous bank reefs, to which reference will be made below.

It would therefore seem that, when the shore line was withdrawn toward the border of the Brazilian shelf in the Glacial epochs, a low-level bench should have been cut there, unless the shelf was then defended by growing corals. If it was thus defended at that time, a bank barrier reef should now have been built up on the shelf surface, five miles or more out from the present stone reef as the ocean slowly rose in Post-glacial time. As no such reef is found, it may be inferred that corals were not growing on the shelf border when the ocean was lowered. In the absence of protecting corals, the shelf should have been benched by the lowered ocean; yet no trace of a low-level bench is now to be seen. It would therefore seem that whatever low-level bench was cut along the coast of Brazil in the Glacial epochs has been obliterated during the Postglacial restoration of a normal shelf profile.

A similar obliteration of any low-level platform that was abraded during the Glacial epochs around the border of the bank supporting Statia, St. Kitts, and Nevis appears to have taken place; and the same statement can be made for various other banks yet to be described. Hence the measure of ocean lowering in the Glacial epochs by about 30 fathoms, as calculated by Daly, cannot be independently tested by the submarine profiles of the marginal-belt banks here under examination.

DOMINICA AND ITS SMALL BANK

Dominica is a superb example of an elaborately dissected, composite volcanic island. It is 27 miles in length, north and south, and 12 miles in width—a grand mountain range of impressively bold forms rising from the sea to an altitude of 4747 feet. Receiving an abundant rainfall it is covered with luxuriant vegetation. The western coast was viewed from the passing steamer on my outward voyage; and on the return, opportunity was taken, while the steamer lay at anchor off Roseau, the chief port on the southwest coast, to make a short automobile trip into the interior.

The dissection of the island as a whole is so far advanced that it was not possible to determine how many volcanoes compose its axial range. Certain rather wide-spaced valleys on the west coast, consuming more and more of the initial volcanic slopes as their depth increases inland, have reduced the intervalley sectors, which must have originally headed far up toward the volcanic centers, to short sectors of buttress-like form. These culminate in summits about halfway from the shore to the island axis, where peaks of decidedly greater height still rise. It is probable that the buttress summits are connected with the axial range by sagging intervalley ridges, the degraded representatives of the upper and inner half of the original full-length sectors.

The western half of the island thus seems to include a marginal range with short-sector summits of a considerable height, each of which, rising at the apex of a sloping isosceles triangle, has its base along the shore. It may be noted that the deeply dissected volcanic island of Huaheine, in the Society group of the Pacific, possesses a similar marginal range of triangular buttresses, of larger or smaller size according to the spacing of the valleys, all around its oval circuit; but there each buttressed summit looks down over a lower central area, which probably represents the hilly remains of a caldera floor or of a central mass of less resistance than the overlying lavas of the buttress range. In contrast to this centrally excavated island, the central peaks of Dominica are still so high that they dominate the summits of the marginal range, at any rate on the west side of the island.

The northern and southern ends of the island present instructive features. Morne au Diable, a recent addition at the northern end, is a well individualized volcanic cone, roughly outlined in Figure 18 and mapped in Figure 19, about three miles in diameter and 2917 feet high; it is maturely dissected by radial, consequent ravines and well cut back around its exposed side in model-like sea cliffs, up to 1000 feet in height, at the end of each radial spur. Unlike the low, spur-end cliffs on St. Lucia and certain other islands, yet to be described, which are small affairs compared to the embayed valleys between them, the high, spur-end cliffs of Morne au Diable have such dimensions as to suggest that they, like the more mature cliffs of St. Helena, represent a measure

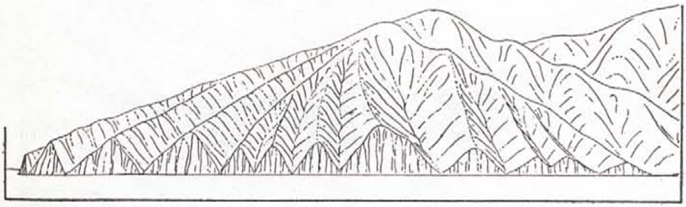


Fig. 18—Morne au Diable, a maturely dissected volcano at the northern end of Dominica.

of abrasion closely comparable with the measure of erosion represented by the valleys. The valleys ought to have hanging mouths, but, as they seemed to mouth at sea level, it is suspected that a slight submergence—perhaps due to Postglacial ocean rise—has taken place since the cliffs and valleys gained essentially their present forms. Although this cone is of more advanced dissection than Saba and has perhaps been slightly submerged, as just suggested, no reefs rise around its shore. Their absence may be plausibly explained by the abundance of its outwashed detritus, for in spite of its inferred slight submergence its valley mouths did not seem to be embayed. Furthermore, as it stands in the marginal

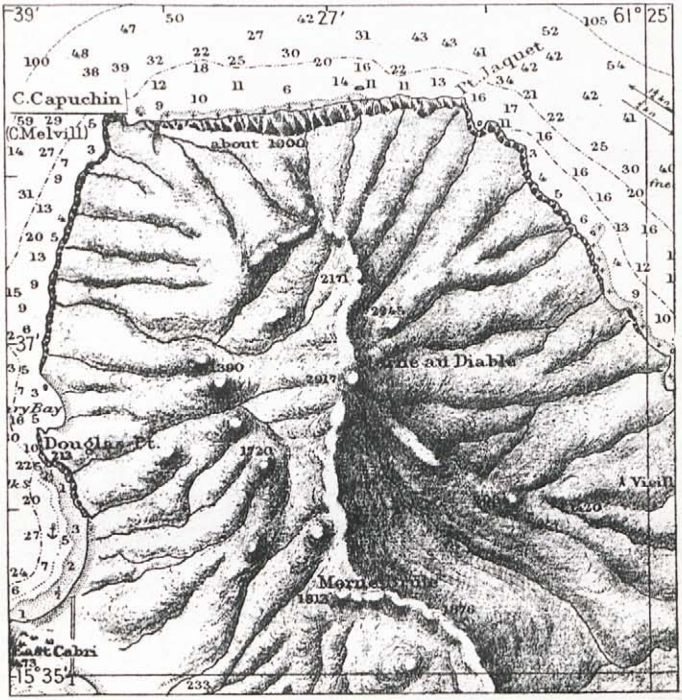


Fig. 19—Morne au Diable (from U. S. Hydrogr. Office Chart No. 1318).

belt of the Atlantic coral seas, a more potent cause of the absence of reefs is probably to be found in the insufficient rise of ocean temperature in Postglacial time.

THE SOUTHWESTERN CLIFFS OF DOMINICA

The southern end of the west coast of Dominica, a simplified view of which is given in Figure 20, sketched from the steamer at anchor off Roseau a little farther north, exhibits two great radial spurs—shown in the right half of the sketch—cut off in slanting terminal facets, thus repeating the features of Morne au Diable but on a larger scale as well as in a more advanced stage of sculpture. The more advanced sculpture is shown by the undulation of the spur crests and by the excavation of steep-pitching ravines, widening upward into spatulate forms, on the spur sides and on their faceted ends. A rather strong submergence is clearly indicated here by the separation of the spurs at the shore by valleys filled with sloping mud flows to a width of a quarter or half mile. The submergence thus inferred may well have been as much as 500 or 800 feet, and it must therefore be explained by island subsidence. If the island were restored to the higher stand it held during the production of the inter-spur valleys and spur-end cliffs, the measure of abrasion seen in the cliffs would, as in the case of Morne au Diable, appear to be comparable with the measure of erosion seen in the valleys; but in view of the mature stage of sculpture here attained before submergence, as compared with the immature dissection of Morne au Diable, it is probable that the sculpture of the southern end of the island was well advanced even before the recent cone at the northern end was formed.

At that early time in the history of the island, the temperature of the surrounding sea must have been favorable to reef growth, in spite of the absence of reefs as indicated by the great cliffs of abrasion; for an early stage of this still lofty island must have been contemporaneous with a more advanced and reef-defended stage of a worn-down island like St. Lucia, to be described below. Hence the early absence of reefs around Dominica—or at least around its southern end—may be best explained by the abundance of detritus outwashed from its valleys. It is profitable

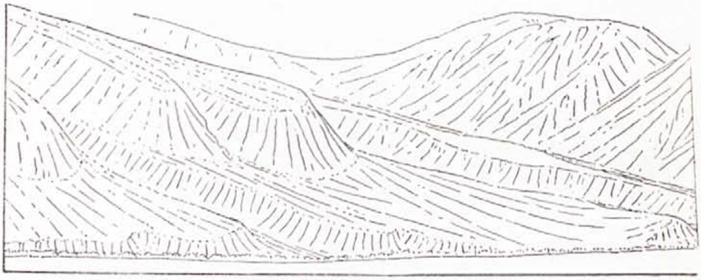
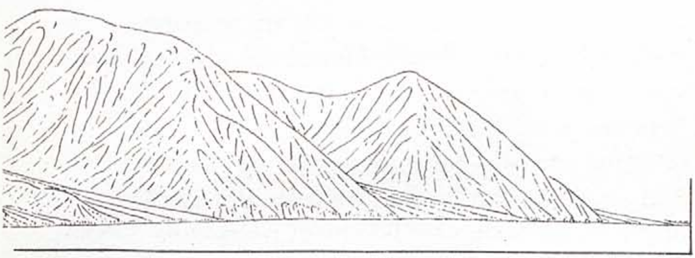


Fig. 20—The southwest-

to recall here that Tahiti, the chief island of the Society group, also exhibits spur-end cliffs of a size commensurate with its inter-spur valleys and that, in spite of its situation in the coral seas of the Pacific, its cliffs were cut at a time when neighboring older islands, like Borabora, were undoubtedly reef-encircled; hence the absence of reefs around Tahiti during the abrasion of its great cliffs is to be explained by the outwash of detritus to its shores. Thus confirmation is found for the same explanation of the cliffs of southwestern Dominica. Furthermore, like Dominica, Tahiti has subsided since its cliffs were cut; but unlike Dominica, Tahiti is now surrounded by an up-built barrier reef. The reason for this contrast may be found partly in the mud flows by which the Dominica valleys have been deluged; for such flows are destructive of any preëxistent reefs, as will be seen on St. Lucia; but partly also in the situation of Dominica in the Atlantic marginal belt, where any Preglacial reefs that may have been formed would have been cut away by low-level abrasion in the



ern coast of Dominica.

Glacial epochs and where, even in Postglacial time, the temperature for reef growth has been reached tardily if at all.

WEST COAST OF DOMINICA

Several valleys of the west coast have benched lateral slopes, apparently the result of alternating epochs of mud-flow eruption and torrent erosion after the coast had been deeply dissected in the production of the buttressed marginal range above described. The benches would appear to represent successive mud flows, each of which occupies a valley cut in an earlier flow and which is in turn cut by a valley occupied by a later flow; except that the first and largest valley would seem to have been cut in the original slopes of the west coast. It would, perhaps, be safer not to imply by the word "successive" that all the flows subsequent to the deep dissection of the coast are now represented by valley-side benches. Many minor flows may have been buried under later and greater flows; and similarly, many little valleys in minor flows may have been entirely consumed in the excavation of greater valleys in greater flows. Hence the above description may be conservatively modified to read: The benches would appear to represent a series of decreasing maxima in an irregular succession of greater and smaller mud flows; and a similar phrasing would apply to the valleys. The most pronounced examples of these forms were seen in the large valley next north of the great faceted spurs; they are roughly outlined in the left half of Figure 20. Other examples of fairly good definition were noted farther north; Roseau occupies the higher part of a torrent delta at the mouth of the benched valley next north of the one sketched. Fine sections of the mud flows were seen in the valley-side cliffs inland from Roseau.

Along the west coast the shore of the inter-valley slopes, as well as that of the benches that slant forward from certain valleys, is generally cliffed to heights of 50 or 100 feet. This small measure of abrasion is by no means comparable with the work of near-by valley erosion. It may therefore be suggested that abrasion of the inter-valley shore hereabouts has been weakened or delayed by the issue of the bench-making mud flows from inland centers of eruption, as well as by the torrential outwash of detritus from the valleys; also that such cliffs as were earlier cut from time to time are now submerged by the subsidence of the island, evidence for which is found

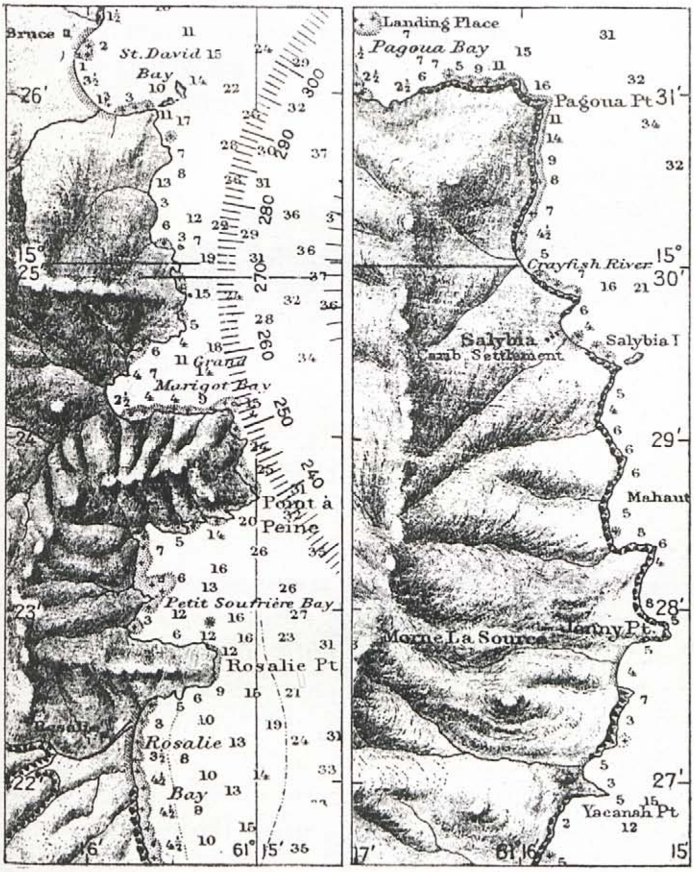


Fig. 21—An embayed and cliffed part of the east coast of Dominica (from U. S. Hydrogr. Office Chart No. 1318).

in the width of the mud flows on the southwest shore between the great faceted spurs, as told above. It may be added that the torrential outwash of detritus is still manifestly effective today in delaying abrasion, as is shown by the slightly convex advance of the Roseau delta farther seaward than the shore to the north and south.[18] According to the chart, the east coast (Fig. 21) is more embayed and more cliffed than the west coast.

THE DOMINICA BANK

The bank adjoining Dominica is chiefly limited to the east coast, where it has a width of three or four miles. As that coast did not come under my observation, it is impossible for me to correlate the bank with the adjoining coastal features; but, from analogy with other islands, it may be inferred that offshore reefs have there had better opportunity of formation in the past than appears to have been the case on the west coast. The absence of a bank along the west coast seems, as above implied, to be due to the fact that eruptions of mud flows have there been intermittently continued to comparatively recent times, thus preventing reef growth. Dominica is therefore not far advanced in the scheme of development here outlined.

The above-described features of Morne au Diable are of some interest as illustrating the results of ero-

[18] A newspaper report dated October 6, 1924, states that torrential rains on Dominica caused the Roseau torrent to flood the town on its delta, with loss of life there and damage to the estates in the valley.

sion and abrasion in a simple and manifest manner. The explanations given for the features of the west coast, including the marginal range of buttressed summits as well as the mud-flow benches in the larger valleys, should be taken as only tentative until confirmed by more detailed observation. The interpretation of the faceted spur ends of the southwest coast is also provisional; for, as already stated, it is based only on inspection from offshore. But if it is supported by further investigation, especially around the end of the island to the southeast coast, it may well be regarded as the most significant lesson of the island. Dominica would then be classed as the only example thus far discovered among the larger islands of the Lesser Antilles still showing high cliffs that were cut during the earlier, reefless stages of its development, before subsidence had set in effectively and while its shore was subjected to severe abrasion because the outwash of detritus from its deepening valleys prevented the establishment of reefs around it.

THE COMPOSITE ISLAND OF MARTINIQUE

My view of this mountainous island was limited to a part of its southwestern coast, as the steamer was running from Fort de France, the chief town, to the southernmost point. The island measures 35 by 13 miles and rises to a height of 4428 feet. It is adjoined by a bank half a mile wide on the west and several miles wide on the east, where the shore line is markedly irregular. The island is evidently of composite origin; the rather large embayment on which Fort de France is situated apparently occupies a reëntrant between two maturely dissected volcanic masses; but the smaller bays which diversify the sides of this embayment are plainly due to the submergence of valleys of erosion. La Montagne Pelée at the north end of the island, famous for its terrific eruption in 1902, is a relatively young cone, not greatly changed from its constructional form by the incision of its numerous but narrow and shallow radial valleys. The geological structure of the island as a whole has been mapped and described by Giraud,[19] and the description includes a chapter on its geological history, in which the sequence of eruptions by which the island mass has been built up, earlier in the south, later in the north, is fully treated; but nothing is said of its erosion and subsidence.

The small part of the island's coast seen by me, being selected for inspection, as it were, by the accidental time of a steamer's passage along it, may perhaps be taken as a fair sample of other parts of the southern coast. Its leading features, outlined in Figures 22, 23, and 24, are simple enough. Maturely dissected mountainous masses, bearing no clear indication of their initial forms, rise in the interior; well opened valleys with smoothly graded side slopes descend to the coast; and the shore line continually varies from the small bays of partly submerged valley mouths to the steep headland cliffs of truncated spur ends. The irregularity of the south-

[19] J. L. Giraud: Esquisse géologique de la Martinique avec carte géologique, Hanoi-Haiphong, 1918.

western and eastern coasts is striking and is well shown in Figures 25 and 26 reproduced from B. A. Chart 371. Although some of the headland cliffs rise

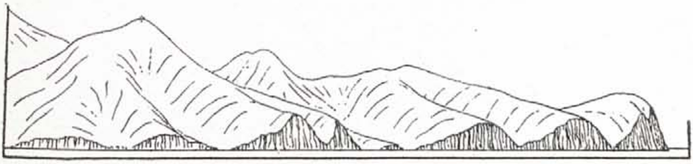


Fig. 22—Cliffed headlands of southwestern Martinique.

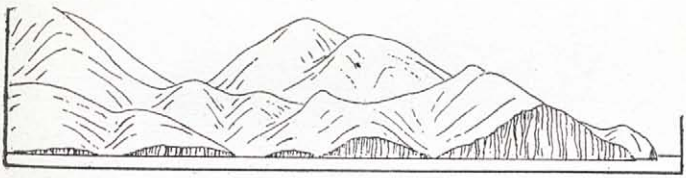


Fig. 23—Cliffed headlands of southern Martinique.

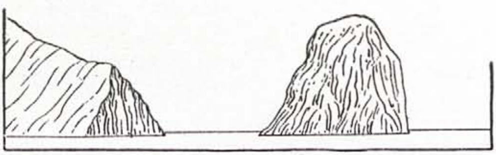


Fig. 24—Cliff and stack of southernmost Martinique.

several hundred feet above the shore line, they seem low in comparison with the summits that rise a thousand feet or more not far inland. The relation of the cliffs to the valley-mouth bays makes it clear that the cliff base lies below present sea level and that the cliffs were cut back either at normal ocean level before the island subsided to its present altitude or while the ocean was lowered beneath its present

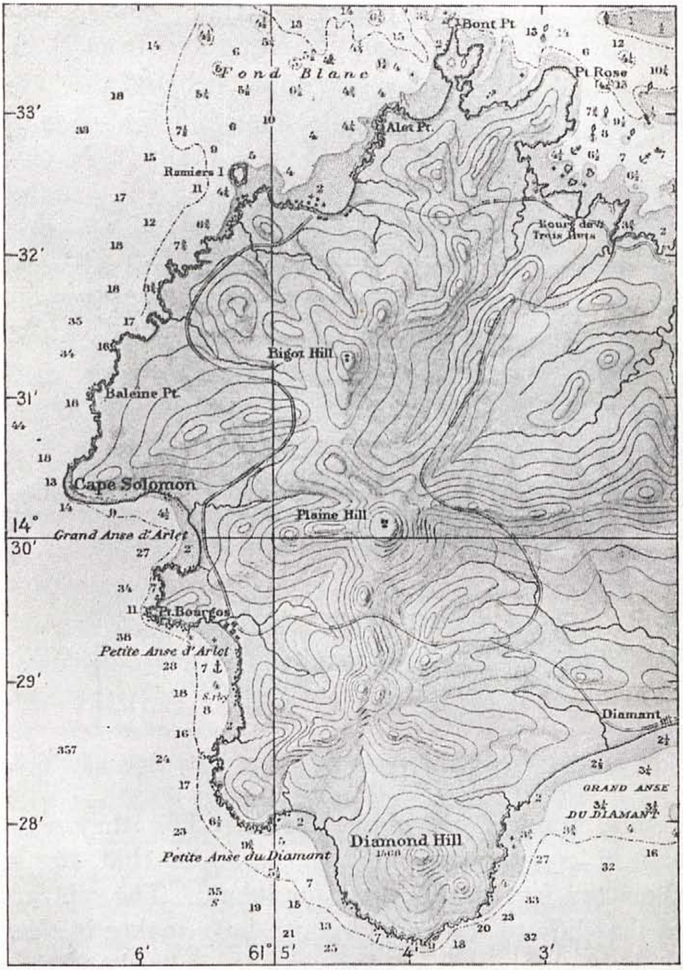


Fig. 25—The embayed and cliffed coast of southwestern Martinique (from British Admiralty Chart No. 371).

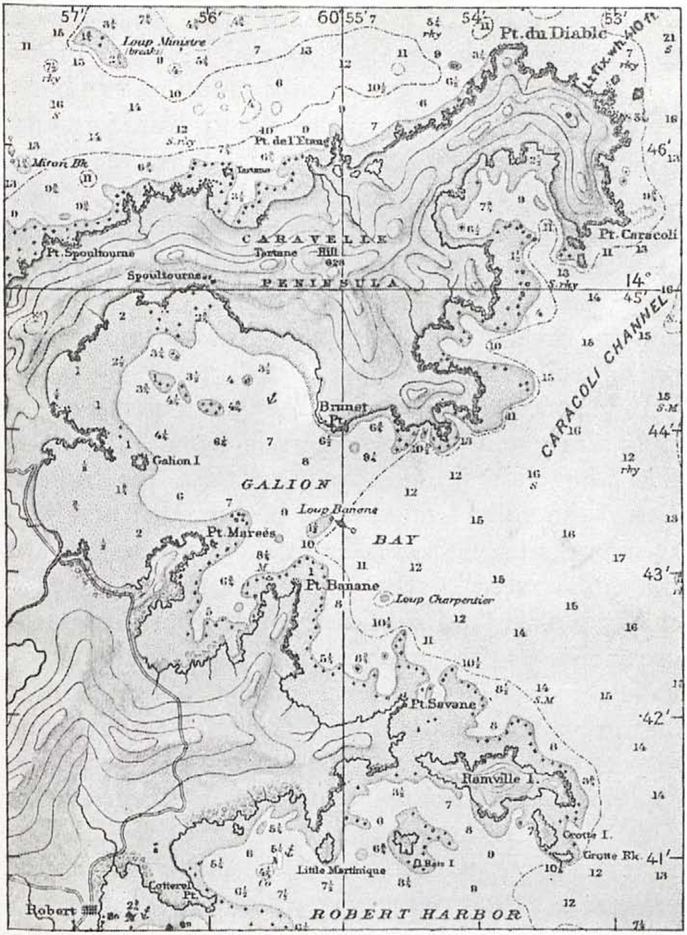
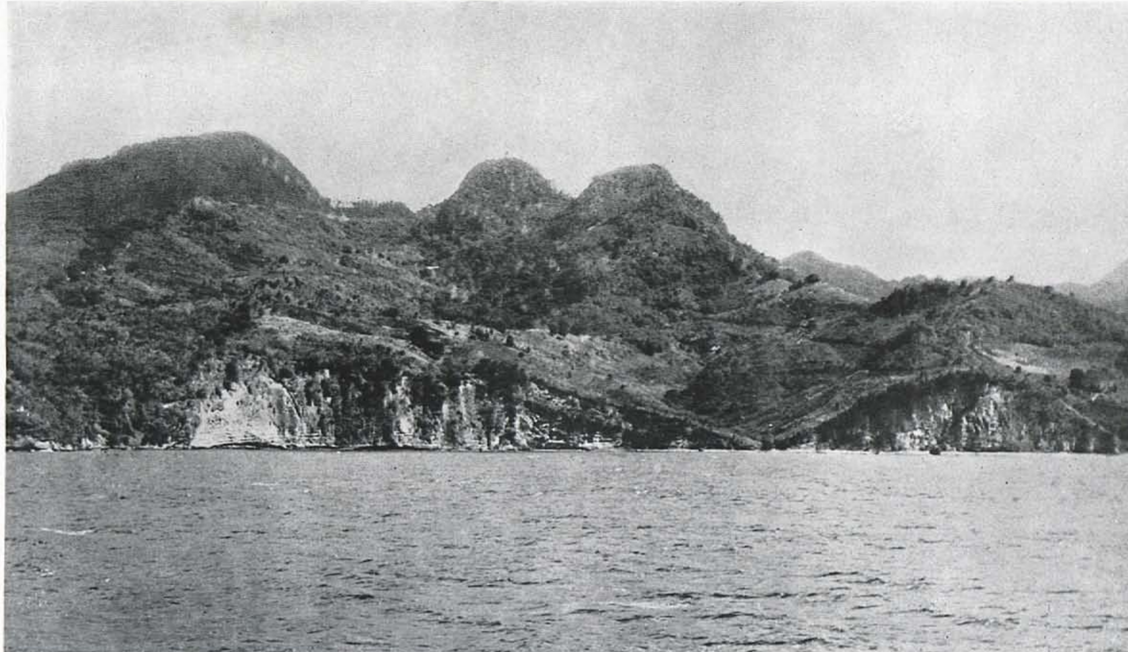


Fig. 26—The embayed coast and coral reefs of eastern Martinique (from British Admiralty Chart No. 371).

level during the Glacial epochs. The occurrence of the shallow banks on the east and west and of discontinuous coral reefs, especially on the eastern bank, makes it probable that the island was formerly, either in Preglacial or Interglacial times of normal ocean level, better reef-encircled than it is now. Under such conditions the headland cliffs could not have been cut, but they might well have been cut while the ocean was lowered in the Glacial epochs and the growth of protecting reefs was temporarily prevented.

Confirmation of the view that the cutting of the cliffs was a temporary process is found in the fact that the cliffs are less mature than the valleys. Hence the valleys must have been eroded nearly to their present openness before the cliffs were cut; and the embayment of the valley mouths must result chiefly from island subsidence, not from Postglacial ocean rise. If the embayments occupied only narrow valleys incised by low-level erosion in the floors of mature valleys that had been previously eroded with respect to normal ocean level, ocean rise alone might explain their occurrence; but such is by no means the case. There is no appearance whatever of valley-in-valley erosion; the erosion of the partly submerged valleys is clearly of one intention; hence the subsidence of the island probably took place either before or during the Glacial period, so that when the ocean was lowered in the Glacial epochs low-level erosion merely continued the work previously well advanced by normal erosion.



Pl. IX—Mont Carbet and the cliff spur ends of Martinique, looking east.

Pl. X—East coast of Martinique, looking north.

Pl. XI—East coast of Martinique, looking southeast.

Thus interpreted, Martinique is farther advanced than Dominica in the scheme of island development here outlined.

THE COMPOSITE ISLAND OF ST. LUCIA AND ITS BANK

This beautiful island, on which I spent nine days, measures 23 by 12 miles across and is 3145 feet high. It gives clear indication of a composite origin, as well as of erosion and subsidence while a protecting reef, now vanished, encircled it and walled in the lagoon deposits which at present underlie the circuminsular bank. The bank extends five miles north and south of the island and two or three miles on the east, but to a less distance on the west, with depths of 30 or 40 fathoms at its border.

The older and larger part of the island, composed of lavas, agglomerates, and ash beds, includes the axial, north-south range with its lateral spurs, as well as a number of almost isolated mounts and hills beyond the ends of the range. All of them are eroded into mature or subdued forms showing no trace of the initial surface of the grouped cones. The valleys are broadly opened, except at their heads. The mid-west coastal slope is occupied by younger volcanic forms, in which the somewhat modified initial slopes are trenched only by narrow, canyon-like valleys. A southwestern sector of the island is aggraded by a gently sloping and slightly dissected mud flow (Fig. 27), which issues from an undetermined source in a central valley of the much older axial range, wraps around certain formerly isolated mounts of subdued form, and just before slanting below sea level at its farthest extremity reaches the southernmost mount of the group, which it transforms from an island into a peninsula. In addition to these easily understood forms, which, by their manifestly unlike stages of erosion, show three different dates of eruption, two huge and precipitous Pitons (Figs 28 and 29), rise

Fig. 27—The mud flow of southwestern St. Lucia, by which several to the main island.

on the west coast just north of the gently sloping mud flow. Their origin is not explained.

The mature valleys of the larger streams on the oldest part of the island are entered by delta-headed bays (Fig. 30), indicative of a submergence measuring several hundred feet at least; these well opened valleys are so mature that it does not seem possible for them to have been excavated by low-level erosion in the Glacial epochs; they must have been eroded chiefly during a higher stand of the island, and therefore their submergence is ascribed to island subsidence. The headlands of the subdued spurs between the bays, as well as the younger slopes of the mid-west coast and the mud flows of the southwest coast, are all cliffed. The continuous cliffs of the mud-flow coast and the narrow consequent trenches of the mud-flow surface appear to represent similar measures of recent time,as if the mud flows had never been bordered with protecting reefs but had been exposed to abrasion as well as to erosion ever since they were poured out. Part of the abrasion of their cliffs must have been accomplished since the Postglacial rise of ocean level, for they are fronted by a beach and relatively shallow water. The same is true of certain older mud flows on the mid-west coast where, as out-

subdued volcanic mounts, formerly independent islets, are now attached

lined in Figure 31, the smaller valleys have hanging mouths over the beach and where the larger ones have embayed and delta-filled mouths. The less mature cliffs of the more resistant headlands seem to have been little affected by abrasion at present sea level, for they have no beaches and plunge into blue water several fathoms deep. They must have been cut either when the island stood higher or the ocean stood lower than now. Furthermore, these hard-rock cliffs, even on the eastern, or windward, coast (Fig. 32), where they are most strongly developed (Fig. 33), seem to be the work of a much shorter period than that needed for the excavation of the maturely opened valleys between them. Hence the shore of this subsiding island must have been protected during most of its erosional history by an up-growing barrier reef, and the headland cliffs must have been cut only during a late and relatively brief period while reef protection was temporarily lost; that is during the Glacial epochs of lowered ocean level.

Fig. 28—The Grand Piton, on the southwest coast of St. Lucia, where it is adjoined by the cliff-margined mud flow; looking northwest. The Petit Piton rises in the background.

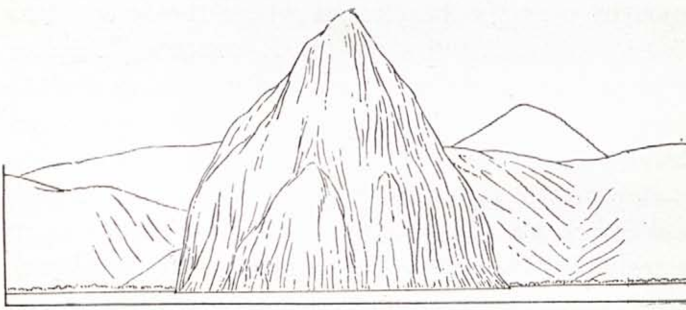


Fig. 29—The Petit Piton, next north of the Grand Piton on the southwest coast of St. Lucia; looking east.

NORMAL AND PLUNGING SEA CLIFFS

A paragraph may be here introduced in order to give fuller warrant for the conclusion that the headland cliffs of St. Lucia, as well as of several other islands above described, were cut during a time of greater emergence than now, because the cliff faces plunge beneath present sea level. For certain islands the plunging of cliffs beneath sea level is inferred from the recorded soundings on large-scale charts with

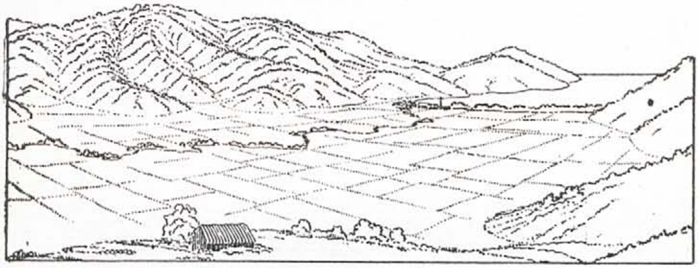


Fig. 30—The delta plain of the Cul de Sac embayment, cultivated as a sugar plantation, on the west coast of St. Lucia; looking southwest. The rectangular subdivision of the plain is drawn to emphasize its levelness. That the enclosing ridges had already gained their maturely dissected forms before submergence reached its present measure is shown by the way in which short arms of the plain enter small side valleys. See also Fig. 35.

depths of five or ten fathoms near the shore; but for several headlands on St. Lucia, as well as on St. Thomas, later to be described, the plunge of the cliffs into blue water was directly observed as I passed them in launches. Such cliffed headlands have no beaches along their shore line, nor are they fronted by a shallow rock platform bearing ragged ledges or pointed stacks such as may often be seen near the base of cliffs that have been cut back at present sea level.

Two normal sea cliffs may be instanced. First, the chalk cliffs of Normandy are manifestly the work of abrasion and are as manifestly retreating actively in consequence of the attack of the waves at their base. This is proved by the not infrequent cracks seen on the upland surface a little distance back from the cliff top and of so recent origin that they cross the lines of plow furrows; it is also shown by the not infrequent occurrence of recently fallen cliff-face slabs, which form rock-fall cones not yet removed by the

Fig. 31—The low cliffs of

waves. The rock platform at the cliff base is ordinarily covered by a sheet of detritus, chiefly composed of chalk flints, which forms a pebble beach along the shore and extends seaward below low-tide level with gradually increasing depth; but the platform is occasionally and locally laid bare near the shore, presumably by storm action, and it may then be seen to lie between low- and high-tide levels.

A second instance may be cited from the southern end of the North Island of New Zealand, near Wellington, where the coast, which I saw in company with Mr. C. A. Cotton in 1914, was suddenly elevated a few feet at the time of an earthquake three-quarters of a century ago. There the cliff-base platform is well revealed (Fig. 34). It rises landward very gradually from the new shore line, bearing a few small unconsumed rock stacks and patches of gravel;

its line of junction with the cliff base is a little lower than the gravel beaches which must have stood a little above high-tide level when the platform and cliff were in process of production.

With these indications of the normal relation between cliffs, platforms, and sea level in mind, it seemed to me clear that the plunging cliffs of St. Lucia recorded a change in the relative attitude of

the mid-west coast, St. Lucia.

land and sea. Their plunge might be explained as a consequence of insular subsidence in an ocean of constant level. In view, however, of the repeated occurrence of plunging-cliff islands in the marginal belt of the coral seas, where they are so constantly associated with rather extensive submarine banks and with imperfect bank reefs, the plunge of the cliffs seems best explained by the Postglacial rise of the ocean from the somewhat lowered level it had in the Glacial epochs, when it is supposed the cliffs were cut because of the temporary lapse of reef protection which the islands had long previously enjoyed.

CONTRAST OF ST. LUCIA AND ST. HELENA

In order to emphasize the inference stated at the end of the second preceding section, a direct comparison may be made between St. Lucia and St.

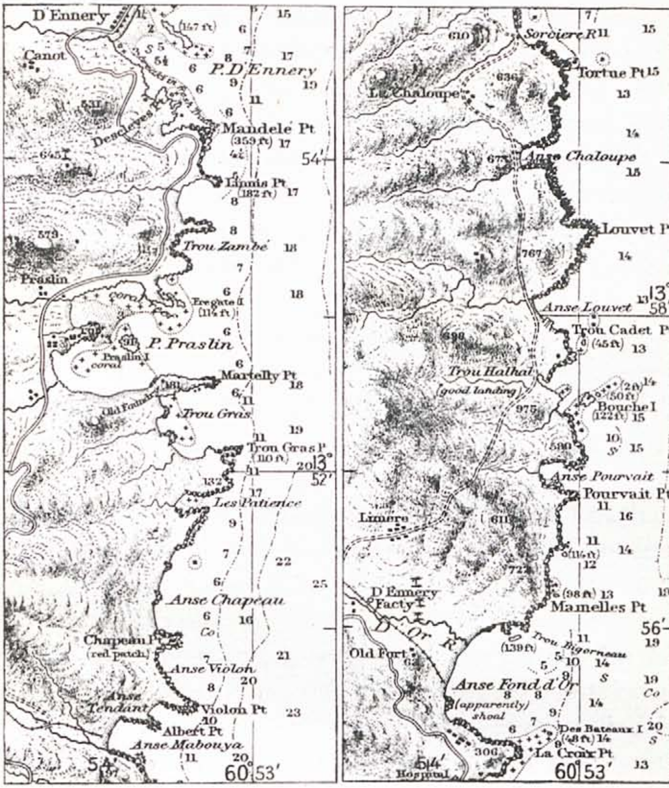


Fig. 32—The east coast of St. Lucia (from U. S. Hydrogr. Office Chart No. 1261).

Helena, to supplement the general comparison already drawn between marginal-belt and cool-seas islands. The comparison shows that these two islands are strongly contrasted as to the relations of stream erosion and wave abrasion exhibited by them. On the one hand, St. Helena is submaturely dissected by relatively narrow, steep-sided valleys of rapid fall and considerable depth in their lower courses; yet all of them but the largest have hanging mouths in the mature sea cliffs girting the island to heights of 1000

Fig. 33—The highest headland cliffs on the east coast of St. Lucia; the village of Dennery occupies a beach in the left foreground. An important sugar plantation lies on a delta plain between the low ridge in the middle distance and the higher ridge in the background.

Fig. 34—An elevated cliff-base platform, near Wellington, New Zealand.

or 1500 feet. St. Lucia on the other hand, is in a late mature stage of dissection but in an early stage of abrasion. Its valleys are broadly opened, and although their upper courses are rather steep, their fall next inland from the delta plains of their embayed lower courses is of moderate declivity. Its cliffs are of small dimensions; even if the ocean were lowered to the level at which it is supposed to have stood during the Glacial epochs, the spur-end cliffs, in spite of the increased height and length thus acquired, would still be relatively subordinate features and would demand a much shorter period for their rapid retrogressive abrasion than that demanded for the very leisurely widening of the valleys. The two features are clearly not commensurate. The combination of late mature valleys and of immature cliffs which St. Lucia presents therefore calls for a special explanation, under which its coast shall have been protected from wave attack during the greater part of its history. Inasmuch as this island is situated near the warm seas, there is no way of providing former protection for its coast so reasonably as by the upgrowth of a great barrier-reef breakwater.

On the other hand, a comparison of St. Lucia with such islands as Matuku in Fiji and Borabora in the Society group—the first in about the same stage of late mature dissection as St. Lucia, the second in a more advanced stage—brings out another contrast; for those islands, like others in the coral seas, have no spur-end cliffs—a fact which implies that they have always, or at least since their early youth, been reef-protected. Let it be noted that identity of rock resistance on all these islands is not essential in the comparisons here instituted, for variations of resistance from island to island will not significantly affect the relation between stream work and wave work on any one island. If the rocks of an island are so weak that the valleys are rapidly excavated, the cliffs will be rapidly cut back; and if the rocks of another island are so resistant that the valleys are slowly excavated, the cliffs will be slowly cut back. Hence these islands of the Pacific coral seas show that if St. Lucia had always been as well reef-protected as they have been, its headlands would not have even the moderate cliffs that they now show: conversely, St. Helena shows that if St. Lucia had always been without reef protection as it has been, the St. Lucia headlands would have been much more strongly cliffed than they now are. In a word, St. Lucia, like the other members of the Lesser Antilles, lies in the marginal belt of the Atlantic coral seas, where it has been much better protected by encircling reefs in Preglacial and Interglacial times than it is now and yet was wholly unprotected during the Glacial epochs.

Another lesson may be drawn from the comparison between St. Lucia and St. Helena. The latter island, which according to Daly is of Preglacial origin, must have experienced low-level erosion during all the Glacial epochs; and yet its valleys, excepting one or two or the largest, were not then deepened enough to be embayed by the Postglacial rise of the ocean to its normal level. Indeed, most of the valleys still have hanging mouths at a considerable altitude above present ocean level. Hence the broad embayments of St. Lucia cannot possibly represent valleys that were excavated only by low-level erosion during the Glacial epochs. Their excavation must have been accomplished chiefly by prolonged erosion with respect to normal ocean level; and their embayment must be due not simply to Postglacial ocean rise but to island subsidence, as has already been announced. This comparison, however, unlike the two preceding comparisons, tacitly implies a similarity in the resistance of the lavas of St. Lucia and St. Helena, which is not proved to be the case. On the other hand, it is altogether improbable that the resistance of their lavas is so unlike as to have permitted the deep excavation of the late mature valleys of St. Lucia during the same period of low-level erosion that left the submature valleys of St. Helena hanging even above normal ocean level. Thus, from various points of view, the conclusions above presented seem satisfactory.

AN ALTERNATIVE EXPLANATION FOR THE ST. LUCIA CLIFFS

An alternative explanation nevertheless deserves consideration. It is probable that when the original volcanic cones of St. Lucia were young they were reefless, because the large quantity of detritus that was washed down by their streams must have then formed a cobble and gravel beach around the island shores, as has been shown above to be the case with the nearly reefless island of Reunion. Hence around St. Lucia at that early stage in its history, as around Reunion today, the unhindered waves would have cut the shore back in cliffs with rock platforms of appropriate breadth at their base—"appropriate" here meaning that the rock platform breadth, somewhat increased by the external addition of a detrital embankment, should be to the cliff height about as the cosine is to the sine of the initial volcanic slope. As long as the island remained stationary and reefless, abrasion would be continued, the platform growing wider, the cliffs growing higher. But as soon as subsidence embayed the valleys the stream detritus would be pocketed there, and the fringing reefs then formed on the submerged part of the cliff faces would grow up and form a barrier reef as the subsidence progressed; or perhaps the reefs might be originally established on offshore parts of the rock platform which were swept free of detritus—or on the larger cobbles of the platform which would have been little shifted by the waves after the platform depth was increased by subsidence. In either case, abrasion of the cliffs would thereafter cease.

With this inferred history of the island in mind, it seems at least theoretically possible that the small spur-end cliffs on St. Lucia today may be, like the much greater spur-end cliffs above described on the southwest coast of Dominica, the tops of ancient cliffs which, after their partial submergence by island subsidence, have only been a little cut back by renewed abrasion in the Glacial epochs and since. But the acceptance of this explanation for St. Lucia and other similarly cliffed islands of the Lesser Antilles carries with it an unacceptable tacit postulate; namely, that, if the visible cliffs of these islands in the marginal belt are really the upper part of early-cut cliffs, then either the early cliffs must have been unusually high or island subsidence must have been unusually slow; while, on the other hand, the early-cut cliffs of islands in the broad coral seas must have been low or island subsidence there must have been rapid, because, apart from a few young islands, they have no spur-end cliffs. No sufficient reason can be found for such a relation between early cliff cutting and later subsidence on the one hand and the climatically limited areas of the narrow marginal belts and the much broader coral seas on the other hand. Hence, while the occasional survival of early-cut cliffs in plunging cliffs may happen here and there, especially on relatively young islands either in the marginal belts or in the coral seas—witness Dominica and Tahiti—the prevalent survival of such cliffs in particular oceanic areas like the marginal belts, defined by climatic rather than by diastrophic controls, is altogether improbable; and still more improbable is it on islands so ancient as St. Lucia and several of its neighbors. The here-proposed alternative explanation for the plunging cliffs of St. Lucia is therefore rejected, and return is made to the previously offered explanation which, as has been said, is satisfactory on various grounds.

THE EXISTENCE OF BARRIER REEFS AND ATOLLS IN PREGLACIAL TIME

We must here turn aside to examine a conclusion of the Glacial-control theory, to which attention has occasionally been explicitly called: namely, that only fringing reefs existed in Preglacial time; for only such reefs could have then been formed on stable islands. The barrier reefs and atolls that characterize the warmer seas today are therefore explained under that theory not as a consequence of upgrowth during the subsidence of their islands, as Darwin postulated, but as a consequence of the low-level abrasion of stable islands in the Glacial epochs, whereby submarine platforms were prepared, on whose outer border barrier or atolls reefs could grow up with the rise of the ocean in Postglacial time and thus enclose the rest of the platforms in lagoons.

It is believed that the facts observed on St. Lucia and the inferences based upon those facts, as presented above, contradict that conclusion as well as the postulate of prevalent insular stability on which the conclusion is based. Reefs appear to have been present, first presumably as onshore fringes and later as an offshore barrier, during nearly all the long period in which the late-mature valleys of St. Lucia were eroded; otherwise it would be impossible to explain the small dimensions of the rapidly abraded cliffs in comparison with the great dimensions of the slowly widened valleys.

In reaching this conclusion I have not been unmindful of the well known inability of ocean waves to cut back the low shores of a gently sloping sea bottom like that of the Gulf of Mexico, where the wave energy is, in the early stages of the evolution of such a shore at least, almost wholly expended on the bottom sediments. The difference between such a case and that of St. Lucia and its neighbors is well marked. The gently sloping sea bottom around the northwestern margin of the Gulf of Mexico consists of unconsolidated sediments which were spread out by submarine agencies of aggradation when the water above them was somewhat deeper than now; and they have gained their present decreased depth by a moderate uplift, whereby a part of their former surface was emerged. As waves roll in toward the shore line, especially at time of storms when most wave work is done, their energy is, as above noted, gradually expended on the bottom; and, instead of actively attacking the mainland shore, they may actually shut themselves off from such attack, for a time at least, by building up an offshore sand reef. But the upbuilding of such a sand reef appears to involve an associated process; namely, the removal of some of the offshore bottom sediments, the coarser sands being swept in to form the reef, and the finer silts being chased about until their particles settle in deeper water, where they will be free from further disturbance. In consequence of the removal of bottom sediments outside of the sand reef, its face will in time come to be attacked and worn back; thus eventually the inner shore line will be reached, and then the mainland will be slowly cut back in a cliff, low at first, but gradually increasing in height. The attainment of this stage of retrogressive abrasion will be delayed or prevented if elevation takes place but will be accelerated if a slow subsidence supervenes.

No such delay in the attack of the waves upon the shore is expectable in the case of a volcanic island around which a bank of unconsolidated sediments, inorganic and organic, is formed; for the submarine slope which the circuminsular waves and currents allow such a bank to assume will not be such as to defeat their attack upon the island, especially upon a slowly subsiding island like St. Lucia. The attack upon the island is attempted even during the period of eruptive construction; it is more successfully carried on after eruptive growth ceases. The cliff-base rock platform then carved in the submarine slopes of the island and extended seaward by a detrital embankment will be very gradually degraded to greater depth at a slowly lessening slope as the cliffs at its inner border are cut farther and farther back; thus the attack upon them will be maintained, even though with decreasing strength because an increasing share of wave energy is expended in degrading the broadening platform. Firmly bound reefs of coral or banks of lithothamnium attached to any part of such a platform will be able to withstand wave attack; but loose sediments, organic or inorganic, will not; such sediments will be comminuted and swept off to the outer edge of the exterior detrital embankment and there employed to build out the embankment slope, but not to build up the embankment surface. The same sequence of events may be expected if an upgrowing coral reef enclosing an aggraded lagoon floor is successfully attacked and cut away by low-level abrasion when the corals are weakened or killed by the reduction of ocean temperature in the Glacial epochs; the reef and lagoon floor will be cut down to a platform of such slope that the attack on the low cliff, first of limestone, later of volcanic rocks at the inner border of the platform, will be continued as long as coral growth is inhibited. This case is complicated by the fluctuating level of the Glacial ocean; the cliff-base line of abrasion may be continually withdrawn seaward while the lowering of the ocean is in progress; but it will as continually advance landward while the rise of the ocean is going on. The innermost advance of the cliff-base line will therefore probably be reached when the ocean is rising after the time of maximum reduction of its level.

In view of these general considerations, and also in view of the independently proved subsidence of St. Lucia and of the relative narrowness of the banks that adjoin it, the immaturity of its spur-end cliffs in comparison with the late mature stage of its valleys still seems to indicate that the cliffs were cut back during a relatively short time in the Glacial period when the island was unprotected from wave attack and, conversely, that it must have been protected from such attack during a much longer and earlier period of Preglacial time. A circuminsular bank alone could not then have provided such protection; but bank-margin coral reefs would have provided an effective protection. St. Lucia is therefore believed to have been encircled by a barrier reef in Preglacial time; and the same argument holds good for the slightly cliffed neighboring islands. This conclusion will be reënforced when the island of Antigua is described. Barrier reefs and atolls should not therefore be regarded as having been formed only in Postglacial time.

MINOR FEATURES OF ST. LUCIA

Several details remain to be mentioned. The later lagoon deposits, which formed the upper strata of the Preglacial lagoon floor around the greater part of the St. Lucia coast, must have encroached more and more upon the flanks of the subsiding island after whatever cliffs were cut around the shore in its youth were submerged; and such strata must therefore rest unconformably on the eroded volcanic slopes; but the deposits now accumulating on the submarine extension of the southwestern mud flows may lie on them conformably, just as those flows presumably lie conformably on the lagoon deposits previously accumulated there. Hence the ash beds and mud flows that were spread out around the island in the earlier stages of its history, as may be inferred from the numerous sections of their successive deposits now exposed in the headland cliffs, may also have extended smoothly off the shore of their time and may therefore bury conformably the earliest lagoon deposits; indeed, alternating volcanic and organic deposits may then have accumulated in the peripheral area to a considerable thickness, so long as intermittent outbursts were continued on the subsiding island. It was only after eruptions ceased and after the erupted lavas and agglomerates were eroded and in part submerged that the encroaching lagoon deposits could have overlapped their slopes in a markedly unconformable manner. This point will be adverted to in a later section when the tilted and degraded atoll of Antigua is discussed.

The St. Lucia bank has already been described as extending seaward five miles on the north and two or three miles on the east of the island but to a less distance on the west. The present island is therefore probably somewhat eccentric with respect to the original island outline. If the original island had consisted of resistant rocks on the southwest and of weaker rocks on the northeast, it would be reasonable to suggest that the bank represents a lowland that was worn down on the weaker rocks and then submerged and somewhat aggraded; but there is not the slightest evidence that the island ever had such a dual structure, and it is therefore unreasonable to account for the bank in this way. Its foundation is much more probably of volcanic origin; and, while the oldest and weakest parts of the foundation may have been worn down to low relief before they were submerged and thus have provided a moderately uneven floor on which the bank strata were afterward deposited, this is only a less improbable supposition than the preceding one. A more probable supposition is that the northeastern part of the bank was built up on relatively smooth mud flows; but this also is without proof: the most probable supposition is that the bank foundation is a volcanic mass of earlier origin and therefore more completely submerged than the younger part of the total island.

The effect of the southwestern mud flow in attaching several isolated mounts to the main body of the island has been briefly noted. A similar effect has been produced in the north by wave-built beaches broadened by progradation; the enclosed lagoons behind the beaches are now converted into low-lying alluvial flats. Thus a number of northern mounts of subdued form, thought to have formerly risen from the Preglacial reef-enclosed lagoon as satellite islets independent of the main island, are now tied to it. The physiographic configuration seen in St. Lucia has therefore been brought about by different processes in the north and south.

The delta plains by which the potential area of the embayments is much reduced, as well as the beaches by which the northern mounts are attached to the main island, appear to be largely of Postglacial origin; for their Preglacial or Interglacial ancestors must have been drowned by subsidence or, if not, must have been largely worn away by low-level erosion in the Glacial epochs. It is interesting to note that the beaches, although swung in curves between mounts of volcanic rock, are composed almost wholly of calcareous sand, which must have been swept in from the offshore bank; some of the beaches have been thus prograded to a considerable width. If the offshore bank were planed down by low-level abrasion during the last Glacial epoch, the aggradation by which its present moderate depth of 30 or 40 fathoms was produced must have been about as great as the down-planing. The discontinuous bank reefs charted here and there around St. Lucia, doubtless were important agencies in supplying detritus for this aggradation as well as for beach building; but, as the reefs are frequently absent, many of the cliffs are still retreating under wave attack at present sea level. It may be suggested that, if the greater part of the headland cliffs had been cut at present sea level, the beaches ought to consist largely of volcanic sand and that, as they consist almost wholly of calcareous sand, the greater part of the cliff cutting must have been performed, as already inferred, while the ocean was lowered in the Glacial epochs; the beaches then formed are now submerged. But the above statement does not hold for the beach that lies for several miles along the cliffed shore of the southwestern mud flow; that beach includes a good share of volcanic detritus, part of which is contributed by outflowing streams, and part supplied from the cliff face.

DEGRADATION IN THE PRESENCE OF FORESTS

Just as the calcareous sands of the St. Lucia beaches afford proof of the Postglacial aggradation of the circuminsular bank, so the alluvial deposits of the St. Lucia delta plains afford proof of the Postglacial degradation of adjoining valley-side slopes, although they had been reduced to maturely graded forms at an earlier date and although they must surely have long been forest-covered. For it is not to be supposed that the reduction of atmospheric temperature in the Glacial epochs sufficed to cause the temporary destruction of forests in the Lesser Antillean islands with any such completeness as the reduction of ocean temperature permitted the destruction of their encircling coral reefs. The fine alluvial material of which the delta plains are largely built up must therefore have been washed down from the side slopes adjoining the deltas and not only from the main valleys upstream from the deltas; that is, the wash must have been carried in part by every little wet-weather side stream; for, as shown in Figure 35, the

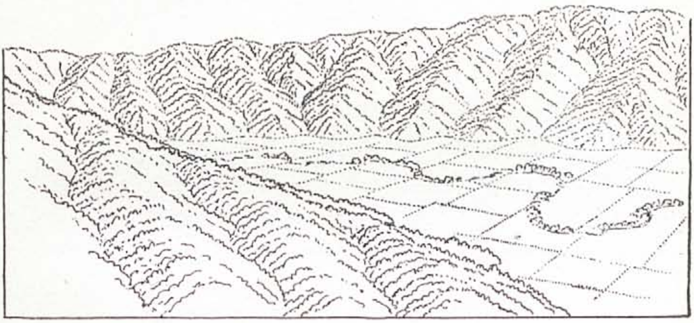


Fig. 35—The inner part of the delta plain of Cul de Sac, St. Lucia, looking northwest. See also Fig. 30.

delta plain has a gradual lateral ascent into every side valley as well as a still more gradual headward ascent to its main-stream valley. The deltas may therefore be cited in support of the belief—in case any one doubts it—that the degradation of maturely graded, valley-side slopes proceeds in the presence of a forest cover, although doubtless at a much slower rate there than on slopes that are free from vegetation.

CULTURAL FEATURES OF ST. LUCIA

St. Lucia would be an excellent subject for a detailed study of island anthropogeography. Its chief towns are all on bay-head delta fronts. The largest is Castries, on the half-mile delta of a bay of the northwest coast. The streets are laid out in small squares; many of the business houses are well built and of two stories, but the greater number of dwelling houses are small and of one story. The delta front has a series of wharves

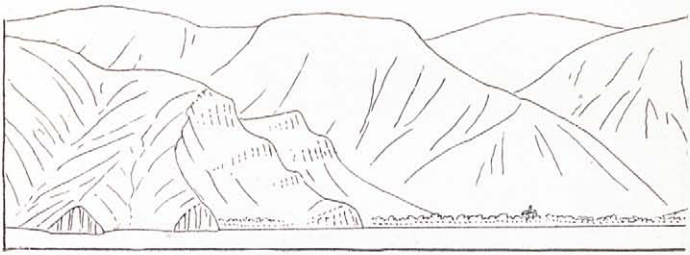
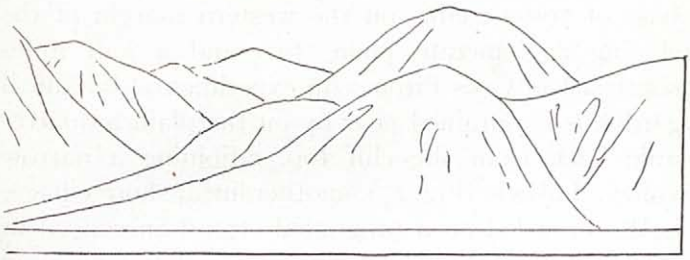


Fig. 36—The village of Soufrière on a delta

available for large steamers; much coal is stored near by. A beautiful botanical garden adjoins the northern side of the delta plain. The northern side of the harbor is formed by two low hills, tied together and to the main island by the first of the mount-tying beaches above described. The outer and higher hill bears a lighthouse and a signal station; the inner hill is crowned by a large hospital. Many villas occupy the hill slopes above the town. Government House stands high above the harbor where Morne Fortuné, the rounded ridge on the south, falls off rapidly to the sea on the west; it enjoys a fine view of the northwestern part of the island, with Martinique clearly outlined in the distance.

Most of the other towns are hardly more than villages of a single water-front street. Such are Anse la Raye and Canaries, on the beached front of deltas which fill narrow valleys incised in the volcanic slopes of later eruption on the mid-west coast. Soufrière (Fig. 36), is of larger size and has a few cross streets; it stands on a reëntrant delta front at



front on the southwest coast of St. Lucia.

the mouth of a wide valley in the maturely dissected volcanic area of earlier eruption, between the little-dissected slopes of later eruption on the north and the Petit Piton on the south; the gentle seaward slope of successive agglomerate beds is well shown by their benched outcrops on the northern side of this valley; a mile or more inland, a small group of hot springs, from which the name of the shore town is taken, has an unwarranted reputation as a volcano. The inland view here includes some of the high mountains of the south-central district. Dennery is a linear delta-front village on the mid-east coast (Fig. 33), but its delta plain is much smaller than that of the Fond d'Or valley, two miles to the north, which has no village. Micoud, the only other village on the east coast, is farther south in an apparently similar situation, but it lay beyond the limit of my island excursions. The open-spaced village of Gros Islet stands on a broad, west-facing, hill-tying strand plain, two miles from the north end of the island. Choiseul is a linear village crowded along a narrow strand at the base of 70-foot cliffs on the western margin of the sloping agglomerate plain, two and a half miles southeast of Gros Piton. An experimental botanical garden is maintained near by on the plain a quarter mile back from the cliff top, adjoining a narrow valley. Laborie (Fig. 27), another linear shore village, is less crowded on a prograded strand ensconced in the open reëntrant of a group of isolated volcanic hills, above mentioned as interrupting the cliffs of the agglomerate plain of the southwest coast near their mid-length. Vieux Fort lies on the low northern slope of the peninsular hills at the southern end of the island and therefore enjoys a view of the long slope of the agglomerate plain as it gradually declines between groups of subdued hills of earlier date to its isthmian end; the exposed southern slope of the peninsular hills is strongly cliffed; a lighthouse stands on their summit. The chief building in all these villages is the Catholic church.

The larger delta plains are occupied by plantations of sugar cane, five of which have steam sugar mills near the shore. Three of these are on the above-mentioned valleys of Cul de Sac (Figs. 30 and 35) and of Roseau (Fig. 37) on the west coast and of

Fond d'Or on the east coast; the fourth is on a lagoon plain behind a beach about a mile from the northern end of the island; and the fifth is on the southern isthmian plain near Vieux Fort. Coconut palms are productive on some of the delta fronts; groves of lime and of cacao trees occupy some of the

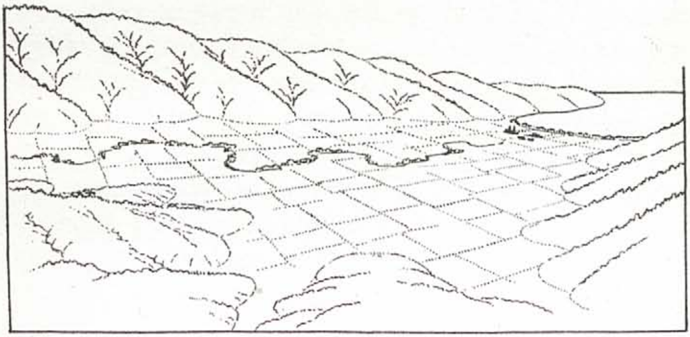


Fig. 37—The delta plain of the Roseau valley on the west coast of St. Lucia looking southwest. See also Figs. 30 and 35.

more open valleys and the gentler slopes adjoining or inland from the delta plains. By far the greater part of the mountainous island is forested.

Besides many rough wagon roads and bridle paths, automobile roads of fair or good quality run north from Castries on low ground near the coast to Gros Islet and south over the rounded ridges and across the delta plains to the sugar factories of Cul de Sac and Roseau. A good cross-island road turns up the aggraded portion of the Cul de Sac valley into its upper north-south part; then crosses over the forested axial ridge in a well laid but very winding course, near the highest points on which fine views are disclosed down the Roseau plain on the west and the Fond d'Or plain on the east. The road next follows down the last-named valley nearly to the shore, where it turns southward over many ridges and valleys a short distance inland from the cliffed headlands of the ridge ends, passing Dennery and Micoud on the way to Vieux Fort on the southernmost peninsular hill slope. Thence it runs northwest near the cliffed margin of the sloping agglomerate plain, thus reaching Laborie and Choiseul, where a turn inland is made to cross over a rather high col back of the Pitons before descending to Soufrière. No wagon road has yet been made along the mid-west coast between Soufrière and Roseau, over the sharply dissected lava slopes of later eruption. Telephone wires are stretched all over the island. At the time of my visit a launch was running along the west coast three days a week between Castries and Soufrière and two days a week between Castries and Vieux Fort, touching at various intermediate points. The absence of similar means of transportation along the east or windward coast, as well as the smaller number of villages established on east-coast delta plains, appears to be due to the rougher water there prevailing.

THE MOUNTAINOUS ISLAND OF ST. VINCENT

St. Vincent, 15 by 9 miles across and 4048 feet high, wholly of volcanic origin, is much more dissected in its older southern half than in the younger northern half, where eruptions of an active volcano, the Soufrière, took place in 1812 and in 1902. The latter outburst is described by Hovey [20] as having devastated the northern part of the island with a cover of ashes; but the cover was, in the same year, so rapidly washed away that vegetation was beginning to grow, and within another year crops might be again cultivated. This observer records that "extensive landslides have taken place on the western side . . . removing a strip of coast, in places one hundred yards wide . . . These landslides have left precipitous walls along the shore line, and deep water is found where villages stood and prosperous plantations existed before the eruption . . . The eastern or windward side of the island is not nearly as steep as the leeward, and landslides have not occurred there as features of this eruption. On the contrary, the windward shore line has been pushed out by the vast quantities of fresh lapilli which have been brought down from the slopes by the rivers and the heavy rains." It is noteworthy that, as in the case of Martinique above stated, the eruptions of the Soufrière, violent as they appear to have been, produced no significant change in the general form of the island. From this one may infer that a great number of prehistoric eruptions must have followed one another in order to build up the original island before its general dissection began. The charts show the shore line to be fairly well embayed and the headlands to be mod-

[20] E. O. Hovey: Martinique and St. Vincent: A Preliminary Report upon the Eruptions of 1902, *Bull. Amer. Museum of Nat. Hist.*, Vol. 16, 1902, pp. 333–372.

erately cliffed; the embayments as charted are presumably diminished from their original size by deltas.

According to Anderson's handbook of the island (1914), the eastern slope, which as in Grenada is longer than the western and probably for the same reason, shows "flat-terraced coastal plains," cut by

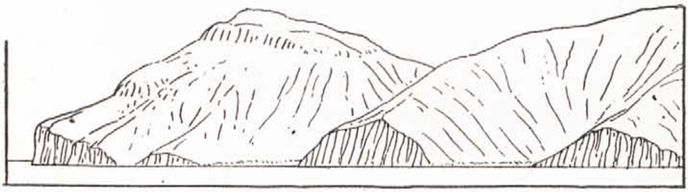


Fig. 38—Cliffed headlands west of Kingstown harbor, southern end of St. Vincent.

valleys, and "a narrow rim of comparatively level country skirting the coast," both the terraces and the level coastal rim being explained as "benches of marine erosion." If the failure to mention similar features on the western coast means that they do not occur there, the island would appear to have suffered a slight and intermittent tilting of recent date. The southern end of the island (Fig. 38), which alone came under my observation from a passing steamer, showed such a relation of valleys and spurs, ending in bays and cliffs, as to warrant the same inferences concerning subsidence and abrasion as those stated for St. Lucia and other islands. There is no submarine bank around the younger northern end of the island; elsewhere a bank is charted with a width of from one to three miles. In spite of the uplifts indicated by the east-coast terraces, the bank falls off on the east at the normal depth of 30 or 40 fathoms. Few coral reefs are charted.

THE VIRGIN ISLANDS AND THEIR GREAT BANK

The Virgin Islands, excepting the outlying member, St. Croix, which surmounts a small bank of its own farther south, rise from the largest bank of the Lesser Antilles. It extends 80 miles eastward from Porto Rico with a breadth of 25 or 30 miles. The islands in this group are largely or wholly of volcanic origin and are now in a late mature stage of dissection; but some of them include also larger or smaller areas of deformed and greatly eroded stratified rocks,[21] chiefly slates, which appear to underlie the volcanic rocks. The group includes, besides a number of small islands and islets, four good-sized mountainous members. Two of these on the east are British: Tortola, ten by three miles, 1780 feet high, and Virgin Gorda, nine by from one to three miles, 1370 feet high, which apparently consists of several smaller islands united by sand reefs. Two others farther west are American: St. John, eight by four miles, 1277 feet high, and St. Thomas, eleven by three miles, 1550 feet high. Ten days of my journey were spent on or near the last-named island, and during that interval I was enabled to visit two near-by islands on the mine-sweeper *Grebe*, through the courtesy of Captain Henry H. Hough, U. S. Navy, Governor of the American group.

[21] The general distribution of these rocks is shown on a map by P. T. Cleve, in the article cited in footnote 16, on page 54.

All the islands, including Culebra on the west but not Vieques still farther west—these two being of Spanish settlement and associated with Porto Rico—nor Anegada, a low limestone island far to the east, are rather compactly grouped in an area much smaller than that of the great bank, which must nevertheless be taken as indicating, perhaps with moderate en-

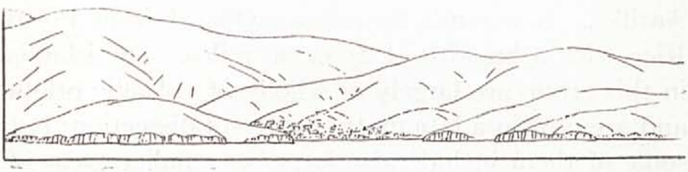
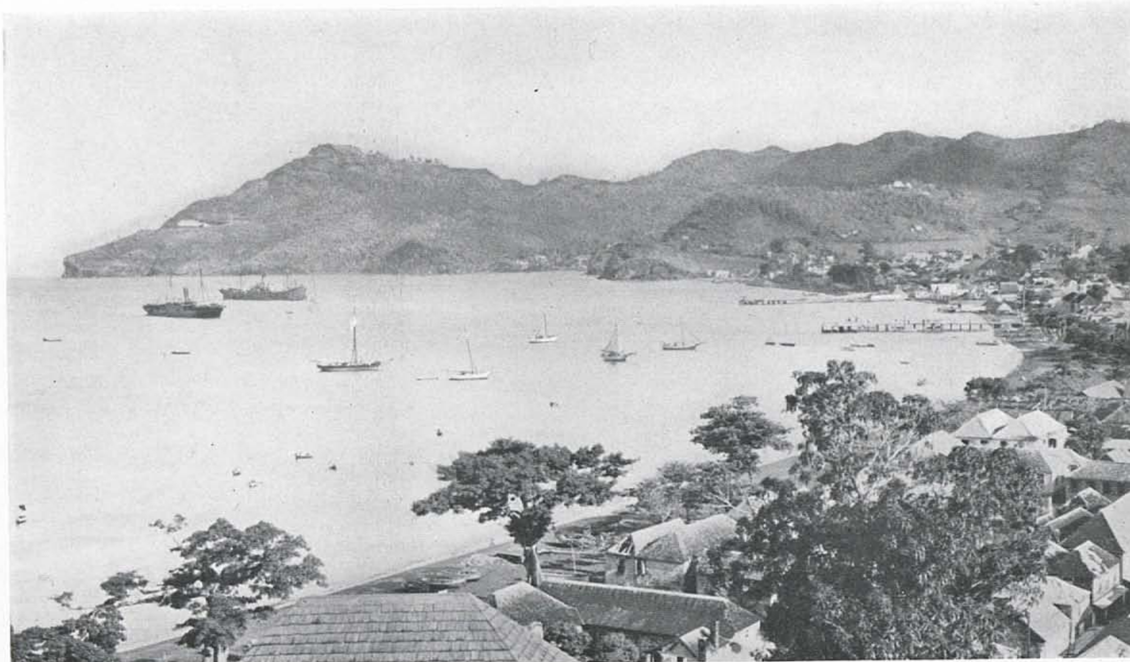


Fig. 39—Part of St. Thomas, as seen from the south. The immaturity spurs and valleys is strikingly shown. Part of the town of St. Thomas

largement, the original extent of a subsided land mass. The reduction of the composite land mass from its original mountainous continuity to its present submountainous discontinuity must be ascribed in part to erosion, whereby much of even the most resistant structures were degraded to subdued forms (Fig. 39), and whereby the less resistant structures must have been reduced to lowlands of small relief; but the reduction of the original area of the composite mass from almost as great an extent as that of the present bank to the small fraction of that extent seen in the existing islands must be due chiefly to submergence, whereby all the worn-down lowlands have been drowned and only the subdued eminences now survive. The larger islands give abundant evidence of this submergence in their em-

Pl. XII—Castries harbor, St. Lucia, looking north.

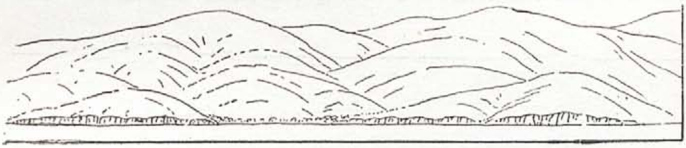


Pl. XIII—Kingstown harbor, St. Vincent, looking west.

Pl. XIV—General view of harbor, St. Thomas, Virgin Islands.

PL. XV—Island of St. Thomas: north coast from the crest, looking northeast.

bayments; and the submergence must here, as in the case of other islands already described, be due to subsidence, because the valleys now entered by embayments are so manifestly more maturely broadened—and also because they are in some cases of greater rock-bottom depth—than can be accounted for by low-level erosion during the Glacial epochs.



of the low headland cliffs in contrast with the advanced maturity of the is seen at the bay head on the left.

THE BAYS OF ST. THOMAS

No island enforces this conclusion better than St. Thomas. The submergence of valleys on its south-western coast, sketched looking landward in Figure 39 and looking seaward in Figure 40, has produced open bays which still have a considerable inland reach, although their heads are now occupied by delta flats; and it has isolated several hilly spur ends. Botany Bay at the west end of the island is a beautiful reëntrant between advancing points; Magens or Great North Side, Bay near the middle of the northern coast is a highly picturesque feature when viewed either from the mountain crest above it or from the sea offshore. The irregular coast lines at the eastern end of St. Thomas and the west end of St. John are shown in Figure 41.

In estimating the depth of submergence demanded by these bays, it should be borne in mind that the shore line to which they were originally drained did not lie close to the perimeter of the island as defined by its present headlands but lay 10 or 15 miles farther away in the neighborhood of the present bank margin; and that a down-slope of the draining streams must have been maintained along all that distance. The

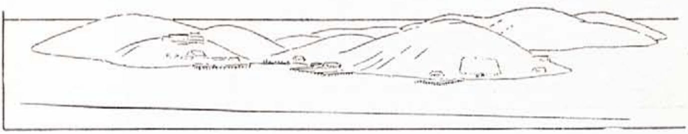
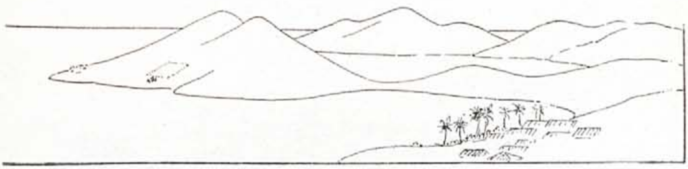


Fig. 40—Spurs and islands on the southwest coast of St. Thomas, as and southwest.

inferred rock-bottom depth of 200 or 300 feet at the bay mouths should therefore be increased by an additional 100 or 200 feet in estimating the change of level by which the present embayment of the island was caused. The absence of all indications of valley-in-valley erosion appeared to me to demonstrate that on St. Thomas, as on other islands, the embayment of the shore line was produced by a considerable measure of subsidence in Preglacial and Glacial time, so that, when the ocean was lowered in the Glacial epochs, the streams were simply extended along their former courses. Had the subsidence taken place at a much later date, the lowering of the ocean in the Glacial epochs should have been accompanied, as above intimated, by valley-in-valley erosion; that is by the incision of narrow young valleys in the floors of the previously excavated, broadly mature valleys; but no signs of such compound valleys were seen.

THE SUBDUED ISLAND OF CULEBRA

The small island of Culebra, not far west of St. Thomas but formerly a dependence of Porto Rico and hence still occupied by a Spanish-speaking population, reënforced the conclusions reached on St.



seen from "Blackbeard Castle" on a hill back of the town; looking south

Thomas. It is reduced to subdued forms, among which hardly a trace of its original form remains, except that its highest summits are presumably situated beneath the original island center. Its shore line is liberally embayed (Fig. 42) and slightly cliffed; a small fringing reef was seen at a bay mouth on the southern side; elsewhere the shore is exposed to wave attack. This island has extensive pasturages of Guinea grass, which support a large number of cattle in excellent condition.

THE SKELETON OUTLINE OF NORMAN ISLAND

It was impossible for me to visit the other members of the Virgin group, as transportation among the islands is very defective; but the large-scale charts show that all the islands have embayed shore lines

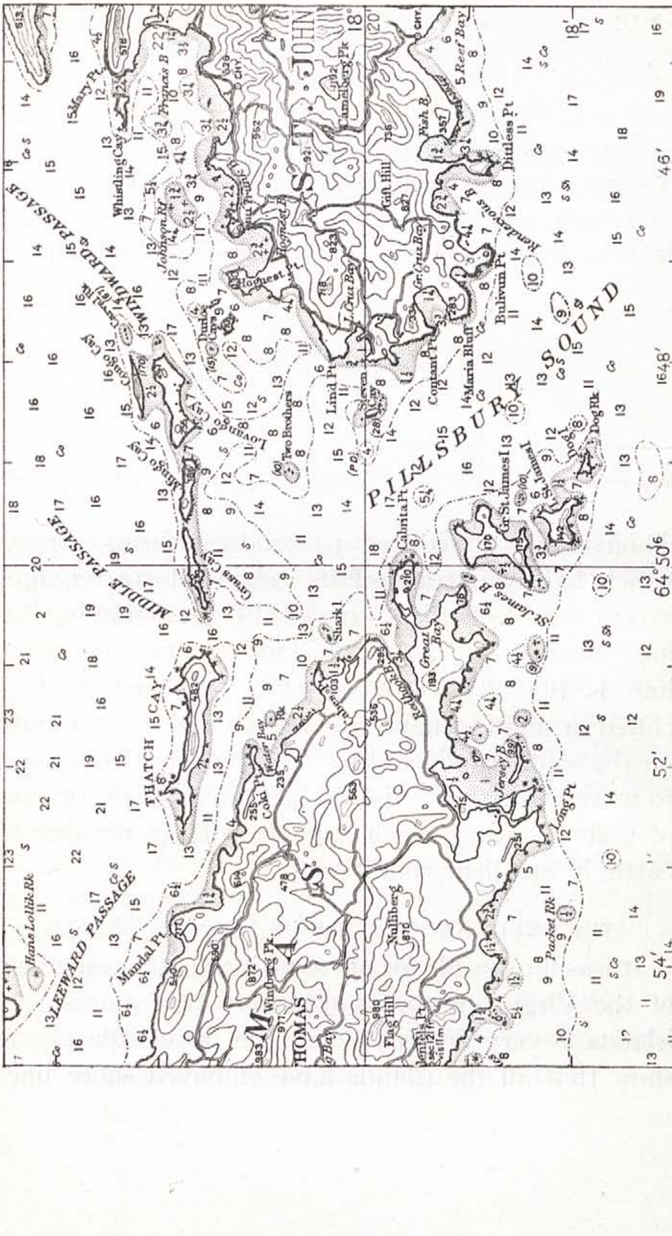


Fig. 41—The eastern end of St. Thomas and the western end of St. John (from U. S. Coast and Geodetic Survey Chart No. 905).

similar to that of St. Thomas. One of the most significant members is Norman Island, which stands five miles south of St. John and two miles back from the southeastern border of the great submarine bank; it measures three by two miles across and 440 feet in height. It is of skeleton outline, like the neighboring Peter Island, as shown in Figure 43; that is, its narrow axial ridge may be compared to a back-

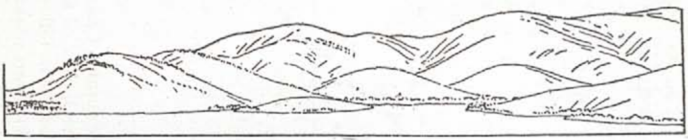


Fig. 42—Great Harbor, Culebra, looking northwest.

bone, from which rib-like spurs stand out between well opened embayments; and this indicates rather strong subsidence after prolonged erosion. For had a small island like this one, on which the streams are short and weak, long been stationary, so that its embayments would occupy only such valleys as were eroded with respect to the lowered ocean level of the Glacial epochs, the bays could not possibly be so wide with respect to the inter-bay spurs as they are here. Moreover, during the greater part of the prolonged period of valley erosion that this island has manifestly suffered, it must have been protected from abrasion, presumably by a true bank-margin barrier reef; otherwise its relatively slender spurs could not possibly extend so far beyond its bay heads, as I have shown elsewhere with respect to certain skeleton islands south of Japan.[22]

[22] See page 21, footnote 3.

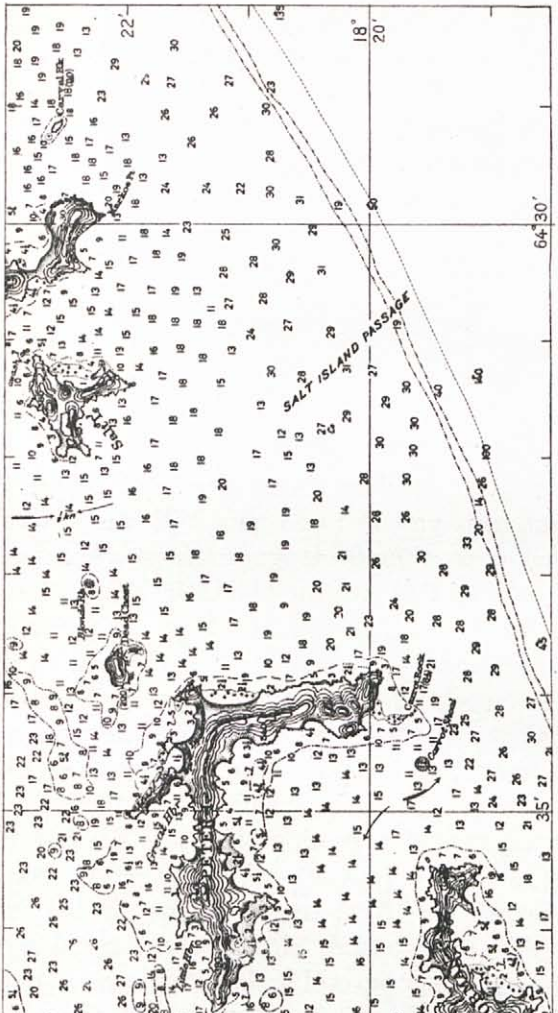


Fig. 43—Norman and Peter islands (reproduced from British Admiralty Chart No. 2019). These skeleton islands lie southeast of St. Thomas, two miles back from the outer border of the great Virgin Island bank. The form of the islands suggests a long period of erosion without abrasion followed by a brief period of relatively strong submergence in association with which the headland cliffs were abraded.

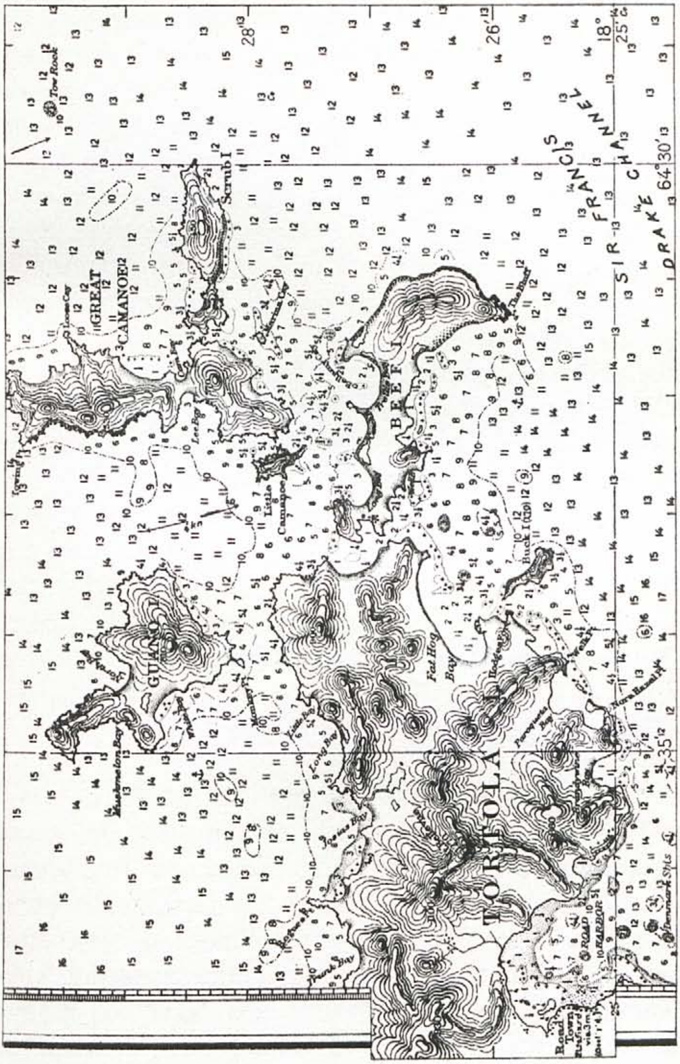


Fig. 44—The embayed island of Tortola and the near-by islands (from U. S. Hydrogr. Office Chart No. 3904).

Indeed, all the islands of the Virgin group—except the low eastern island of Anegada, which is composed of limestone—appear to have been exposed to erosion for a much longer time than St. Helena has been. While its valleys are narrow and steep-sided, theirs are broadly opened (Figs. 44 and 45); and yet, in spite of their exposure to erosion for so long a time, their spur ends are but little cliffed. It is not permissible to explain the small development of cliffed headlands by the breadth of the adjoining bank, across which the ocean waves must have had to advance; for the cliffs show by their abruptness that, when abrasion was permitted, it acted vigorously, even though the ocean was then shallower than now. Moreover, Norman Island near the bank border does not appear to be much more cliffed than the islands near the bank center. It must be concluded, then, that the Virgin Islands, like the other members of the Lesser Antillean chain, were protected from abrasion during most of the period of their prolonged erosion; otherwise they should out-cliff St. Helena.

THE CLIFFS OF THE VIRGIN ISLANDS

It is true that the cliffs of some of the small satellite islands, two of which are shown in Figures 46, 47, and 48, appear somewhat formidable when seen from a small boat near their base; and it is true also that in the abrasion of such cliffs a considerable fraction of the small islands has been consumed; hence, if the small islands alone were considered, abrasion might be assigned a considerable value in

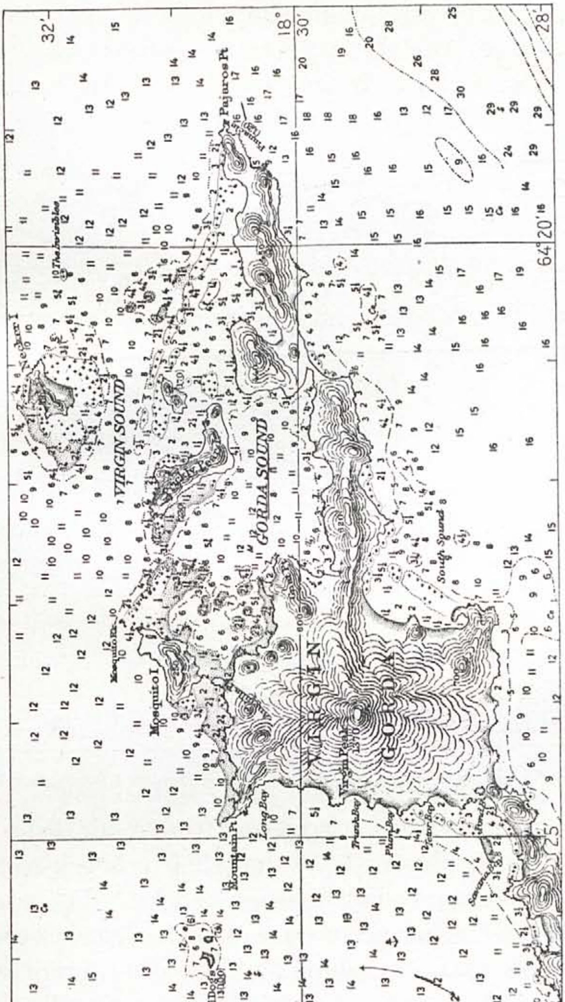


Fig. 45—The embayed island of Virgin Gorda (from U. S. Hydrogr. Office Chart No. 3904).

the production of the existing forms. Its relative insignificance will be better understood when the cliffs on one of the larger islands, like St. Thomas, where the cliffs are practically of the same height as

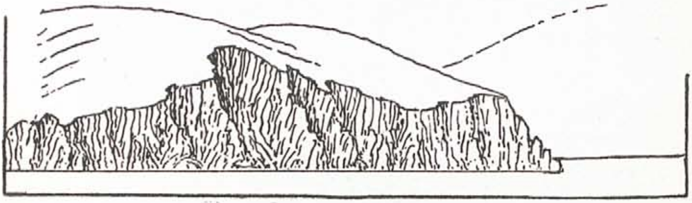


Fig. 46—A cliffed island at the entrance to St. Thomas harbor, looking north.

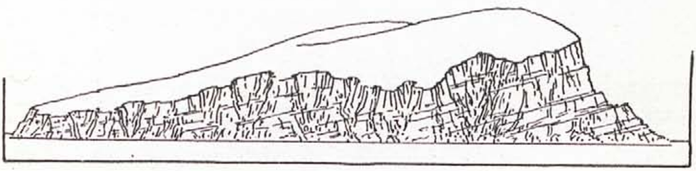


Fig. 47—Cockroach Island, northwest of St. Thomas, looking east.

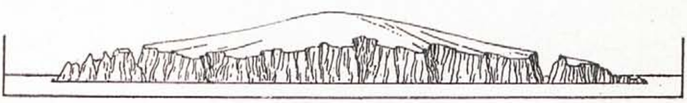


Fig. 48—Cockroach Island, northwest of St. Thomas, looking north.

on the small satellites, are viewed from a fair distance offshore, as in Figure 39, so that their relation to the whole island mass may be apprehended. The small time value and the recent date of their abrasion compared to the early beginning and long duration of valley erosion thus becomes manifest; hence St. Thomas reënforces the conclusion reached on other islands already described, that the headland cliffs were produced during relatively recent and short-lived efforts of abrasion, such as the Glacial epochs would have afforded. It also supports a conclusion which has already been implied in the accounts of other islands and which may be here more explicitly expressed: namely, that the fluctuations of ocean level during the Glacial period were much more rapid than the subsidence by which the maturely dissected island has been given its embayed shore line and during which the former protecting reefs were built up; for it was upon the headlands of the already dissected and partly submerged, reef-encircled island that the cliffs were cut when the time for abrasion arrived.

Good opportunity for inspecting a number of the headland cliffs on St. Thomas by passing close along their shore in a small launch was given me by the courtesy of Captain Siems of the U. S. Coast and Geodetic Survey. Their height above sea level is of moderate measure, such as 20, 40, or 60 feet; hence they have not involved much spur-end shortening. They are not fronted by shallow rock platforms, as they should be if they had been abraded at present sea level. Instead, they plunge directly into blue water, and depths of 4, 5, and 6 fathoms were sounded within a boat's length of the face; yet even this depth is presumably less than that of the true cliff-base rock platform, which must now be more or less aggraded with waste fallen from the exposed part of the cliff face. I hesitate, however, to infer that the true platform depth is as much as 20 or 30 fathoms, as it should be according to the estimated depth of ocean lowering and platform abrasion adopted in Daly's exposition of the Glacial-control theory of coral reefs. If the platform really has any such depth around the islands, it must have been 40 or 50 fathoms deeper at its outer margin; and the much less depth of the existing bank would therefore demand a larger measure of Postglacial aggradation than seems reasonable.

THE GREAT BANK AROUND THE VIRGIN ISLANDS

The bank around the Virgin Islands is unlike any other bank thus far described, in that a considerable part of its area may be underlain by lowlands worn down on relatively weak continental rocks, remnants of which are seen in some slender islands north of the passage between St. Thomas and St. John (Fig. 41), as well as farther east on some of the larger islands. The subsidence by which these worn-down lowlands were submerged is for two reasons inferred to be of smaller measure than the subsidence which the other members of the Lesser Antillean chain have suffered: first, because the Virgin group, the northernmost member of the chain in which subsidence has long been a dominant movement, lies nearest to Porto Rico, the first member of the Greater Antilles where upheaval appears long to have been equally dominating; second, because on the one hand none of the other members of the chain exhibit any continental rocks although all the members are supposed to have their volcanic cones based on a former land belt of such rocks, while on the other hand the Virgin group exhibits a considerable area of such rocks on which its volcanic rocks are visibly based.

There is, however, little probability that the worn-down lowlands, which since their submergence form the foundation for much of the bank, had been worn down before their submergence to nearly so smooth a surface as that which the bank presents today. The submerged part of the lowlands probably had a hilly surface, though of less altitude and relief than those other parts of it still standing above sea level; its hilly surface was probably smoothed by aggradation while it was submerged in a reef-enclosed lagoon; after the lagoon floor had been smoothed in this way, it was probably somewhat planed down by low-level abrasion in the Glacial epochs; and since its abrasion it has presumably been more or less aggraded. This interpretation is manifestly very speculative; but it appears to be in accord with all relevant facts of observation. The bank now has a depth about 40 fathoms along the northern border and of 20 or 30 fathoms along the southern. This would seem to imply that it has suffered some change of depth, either by tilting or by unequal aggradation, since it was planed off by the lowered Glacial ocean. The aggradation of so large an area as that of this great bank by marine organic detritus without significant aid from inorganic detritus outwashed from an extensive land area may seem at first thought improbable, and, if the organic detritus were wholly derived from an encircling barrier reef, it might indeed be difficult to account for a sufficient supply; but Vaughan's studies have shown that in wide lagoons a vastly greater supply of detritus comes from organisms living in the lagoon waters than from the enclosing reef. When it is thus understood that the chief supply of organic detritus for lagoon aggradation is proportionate to the area of the lagoon, the smooth upbuilding of the vast lagoon floor now represented by the bank does not seem unreasonable.

THE LIMESTONE ISLAND OF ANEGADA

That the shallower parts of the lagoon floor were somewhat planed down by low-level abrasion in the production of the present bank seems to be especially true in the eastern part of the bank, where the limestone island of Anegada now stands. This island, nine by two miles, 30 feet high, was described long ago by Schomburgk as consisting of coral limestone; his map shows 53 wrecks on its shore.[23] It cannot be of Postglacial origin; the accumulation of its strata must antedate at least the later Glacial epochs, and its uplift—presumably in much larger area than that of the present island—probably antedated the last Glacial epoch, because the low-level abrasion that was operative during that epoch furnishes the best means of cutting away part of the uplifted limestone area and reducing it to the present island. The surrounding submarine bank is therefore to be regarded thereabouts as a bank of second generation. It has a width of two or three miles east of the island.

[23] R. H. Schomburgk: Remarks on Anegada, *Journ. Royal Geogr. Soc.*, Vol. 2, 1832, pp. 152–170.

POSTGLACIAL CORAL REEFS ON THE VIRGIN BANK

The bay-head deltas and the cove-filling beaches of the Virgin Islands appear to be of Postglacial date, as are also the discontinuous coral reefs which now rise from certain parts of the bank towards or to sea level. One of the largest sea-level reefs is the Horseshoe, which extends several miles southward from Anegada, two or three miles back from the eastern border of the bank; but whether this is a true coral reef or simply a trail of detritus swept away from Anegada has not been determined. Two other reefs are of greater length; one is a submarine reef, which is charted with a width of an eighth of a mile and a length of 40 miles, near the southeastern border of the bank, thus resembling a true barrier barrier reef in its position, although failing to rise, as such a reef should, to the ocean surface. It is shown on H. O. charts 1002 and 3903 by a pair of continuous and parallel, 20-fathom contour lines, enclosing soundings of from 14 to 20 fathoms; but its continuity seems open to question. Part of this reef is here included in Figure 43. The other long reef is partly emerged in a string of low calcareous islets stretching 15 miles eastward from the northeastern cape of Porto Rico toward the subdued volcanic island of Culebra, the physiographic dependence of St. Thomas briefly described above; this reef stands 10 or 15 miles back from the northern border of the bank. Discontinuous fringing or bank reefs are charted at several points, but they are of small dimensions. Vaughan has shown that the Virgin bank as a whole is broadly benched at slightly different levels, apparently the result of abrasion by the changing ocean of Postglacial time.[24]

THE UNAVOIDABLY HYPOTHETICAL NATURE OF THIS ACCOUNT

The scheme here adopted, under which the Virgin Islands are given a certain place in association with their neighbors in a systematic sequence, is very hypothetical. There can be no question of that. But this hypothetical scheme seems more reasonable in its postulates, more coherent in its processes, more comprehensive in its reach, and more competent in bringing order out of confusion than any other scheme of Lesser Antillean evolution that has been announced. As with all hypothetical schemes which seek to recover the unobservable past—such, for example, as those that explain fossil-bearing strata in lofty mountains as former sea-floor deposits, uplifted and eroded; or that explain the observed repetition of similar series of strata by faulting and erosion—it is irrelevant to object to them because they are hypothetical; for they are unavoidably hypothetical. It is more relevant to consider how far they are consistent with other hypothetical schemes which are regarded as established and how far they are therefore able to give acceptable explanation for

[24] T. W. Vaughan: Some Littoral and Sublittoral Physiographic Features of the Virgin and Northern Leeward Islands and Their Bearing on the Coral Reef Problem, *Journ. Washington Acad. of Sci.*, Vol. 6, 1916, pp. 53–66; also abstracted in *Bull. Geol. Soc. of America*, Vol. 27, 1916, pp. 41–45.

the observed facts with which they deal. When the scheme here set forth is thus examined, the Virgin Islands with their great bank may be regarded as a well-advanced member of the sequence in which the other islands of the Lesser Antilles, already described and yet to be described, take their place.

GRENADA, THE GRENADINES, AND THEIR LONG BANK

Grenada and the Grenadines, far southern members of the chain, surmount the second largest bank of the Lesser Antilles; it measures nearly 100 miles in length, north-northeast and south-southwest, and from 10 to 17 miles in breadth. Grenada is a high and relatively young volcanic island and will therefore be described after the smaller and apparently older Grenadines, which are well subdued volcanic residuals scattered over the northern 60 miles of the bank. I saw them only from a passing steamer. The larger ones are 15 in number, varying from one to eight miles in diameter and rising from moderate measures up to 1000 feet in height; many islets and rocks are also charted. The members of this group that were seen by me repeated on a somewhat larger scale the features of the Saints, south of Guadeloupe, already described as the second member of a simple sequence. Carriacou, one of the more northern islands, is briefly described by Clark, who visited the group in 1903 to study its birds, as "in the main composed of beds of fine-grained volcanic sands and tuffs. On the eastern slopes of the island, and at

Belair (in the center), at an altitude of 600 feet, the tuffs of which the hills are composed are covered with layers of a shallow-water foraminiferal limestone, from ten to twenty inches in thickness. It therefore appears to consist of layers of volcanic ash which were deposited in the sea, and afterwards covered

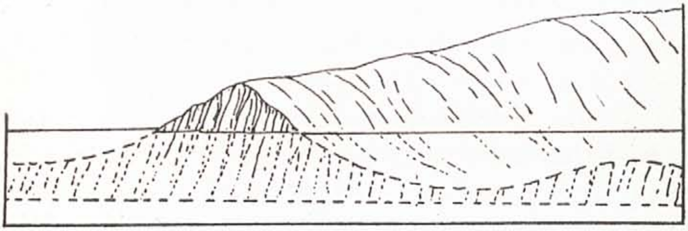


Fig. 49—Diagram of a partly submerged cliff.

with the shallow-water deposit. Later this was subjected to upheaval, with the result that part of the limestone was raised to at least 600 feet above sea level. The rest of the Grenadines are geologically much like Carriacou, but appear to lack the limestone capping of that island.''[25]

None of the islands now have the forms of young volcanic cones; all appear to be residual forms of subdued outlines, except for occasional sharp, neck-like peaks, and abrupt, spur-end sea cliffs. The larger members have irregular shore lines, with open valley-head embayments separated by cliffed headlands. Soundings on a large-scale chart suggest that the cliffs plunge below sea level. The abrupt change not infrequently seen from a steep cliff at the end of

[25] A. H. Clark: Birds of the Southern Lesser Antilles, *Proc. Boston Soc. of Nat. Hist.*, Vol. 32, 1905, pp. 203–312; reference on pp. 213–214.

a headland to a non-cliffed shore along the side of the headland, notwithstanding the open exposure of the side to present wave attack, suggests that the cliff was cut on a shore line of different pattern from that of today, as in Figure 49, and thus confirms the inference from the chart that the cliffs plunge below sea

Fig. 50—Part of Union Island, one of the Grenadines; looking southeast. The subdued forms of the island, taken in connection with its pronounced embayments and immature headland cliffs, suggest that it was first subjected to erosion for a long period, then moderately submerged and embayed and immaturely cliffed.

level. At the same time, the dimensions of the embayments are such that the period required for the erosion of the valley heads they occupy must have been long compared to the period required for the abrasion of the cliffs. Hence these small islands support the interpretation demanded by the larger islands above described, to the effect that, while erosion has been a long-lasting process, abrasion has been of short duration and, therefore, that during much of the long erosional period the Grenadines, like the larger island of St. Lucia, must have been protected, presumably by an encircling coral reef, from wave attack.

Union Island, sketched in Figure 50, stands near the middle of the group; Cannouan Island, not far away, mapped in Figure 51, may be taken as typical of the others. In the smaller islands embay-

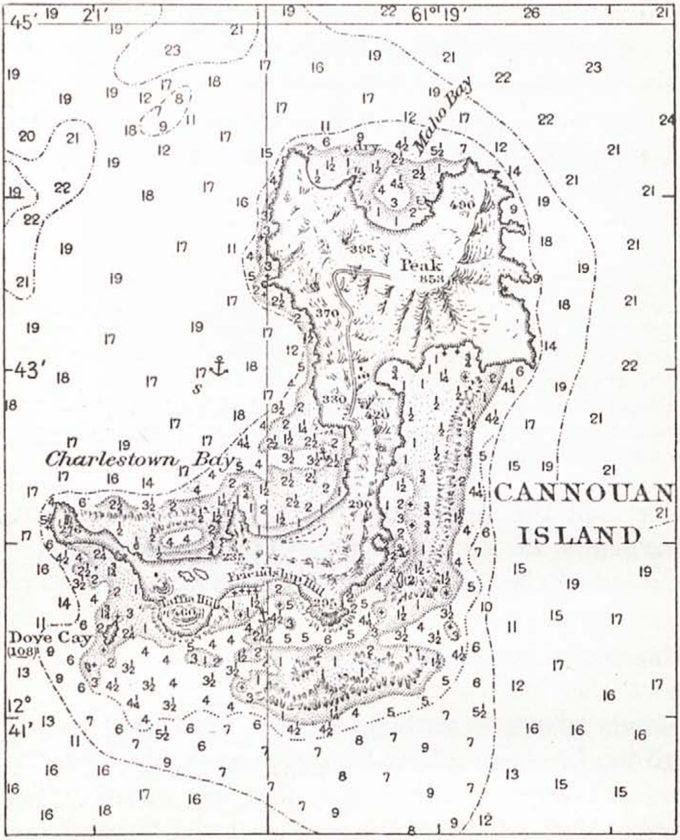


Fig. 51—Cannouan Island, one of the Grenadines (from U. S. Hydrogr. Office Chart No. 1640).

ments are wanting, as they are in the small knobs of southeastern St. Kitts, and for the sufficient reason that such islands are mere hill-top residuals, too small for the retention of embayable valley heads. Some of the smallest islands are, indeed, almost or quite reduced to cliff-faced stacks, as shown in Diamond Island (Fig. 52), because a moderate measure of cliff recession, which consumes only a small fraction of a larger island, consumes nearly all or all the upland surface of a very small island.

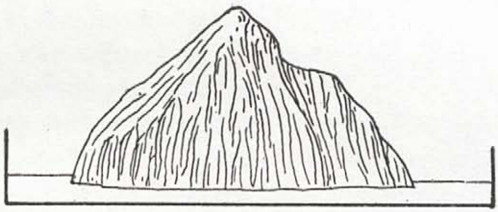


Fig. 52—Diamond Island, a cliffed stack in the southern Grenadines.

The amount of submergence that has taken place here is not easily determined. If each of the islands represents an independent center of eruption, the post-erosional submergence may have been of moderate amount; but if the present discontinuity of the islands means that an originally continuous ancestral island, some 30 miles in length, has been maturely eroded and then separated by submergence into the present number of its small descendents, the measure of submergence must have been great.

THE YOUNGER ISLAND OF GRENADA

Grenada (pronounced Grenayda by its inhabitants) 17 by 8 miles across and 2749 feet high, stands on the northwestern side of the bank at a quarter of the bank length from its southwestern end and falls off on that side into deep water. The bank is from

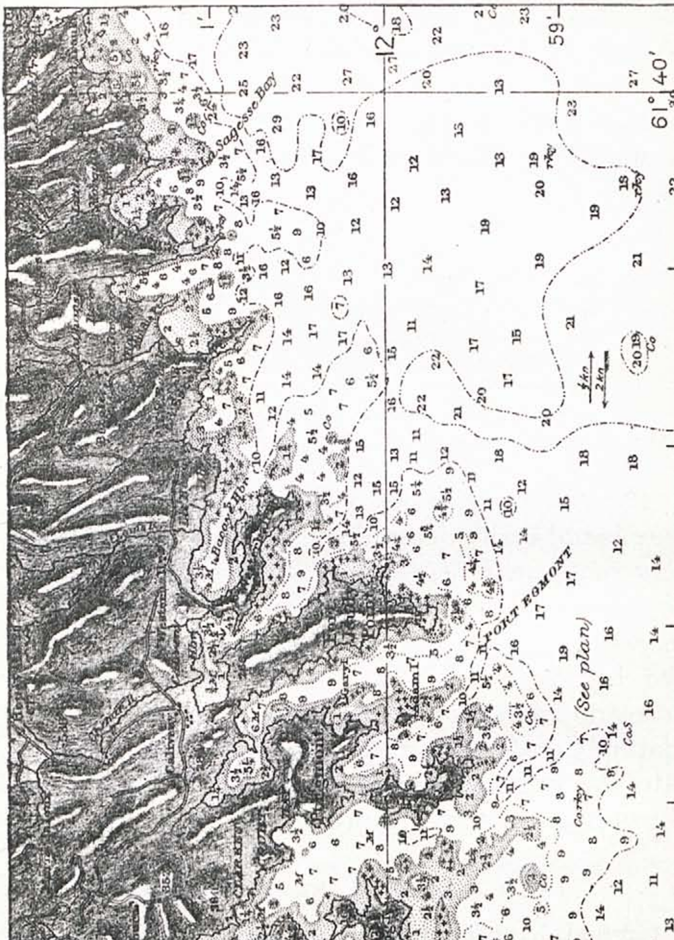
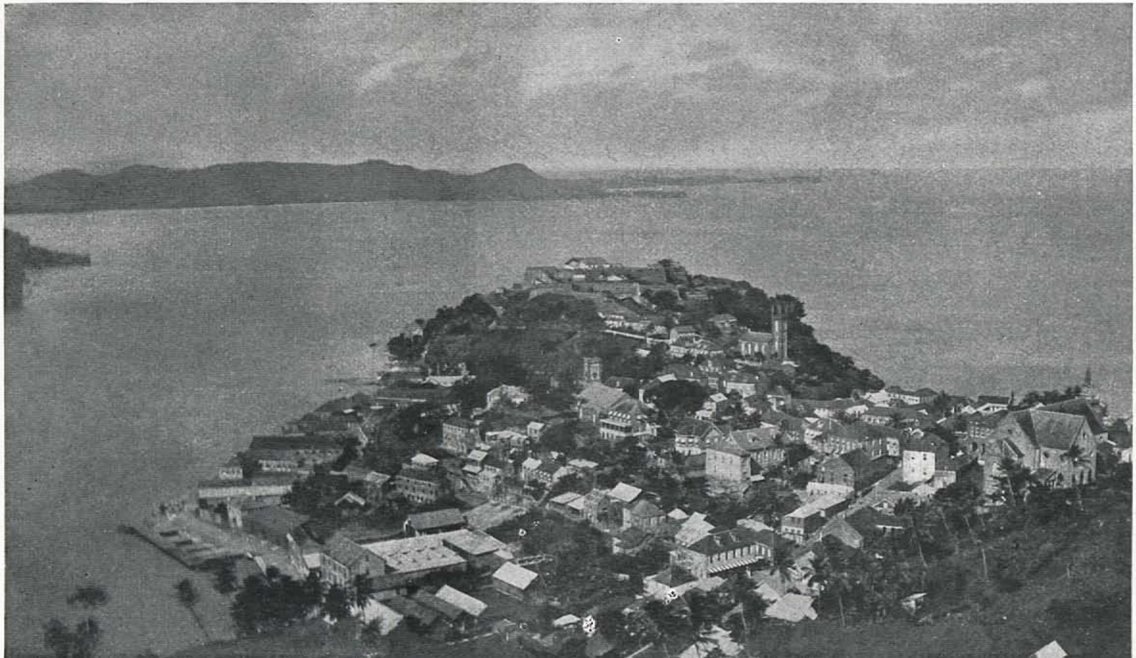


Fig. 53—The embayed southeast coast of Grenada (from U. S. Hydrogr. Office Chart No. 1316)

three to six miles wide on the other side of the island. The axial range of the island, trending with the bank, is elaborately and, for the most part, maturely dissected and is therefore of Preglacial origin. Its southern end is extended westward by a trailing series of subdued volcanic hills, several miles in length. The range is of unsymmetrical cross section: the coastal slopes are of moderate declivity on the southeast and of more rapid descent on the northwest; moreover, the gentler southeastern slopes are strongly embayed and moderately cliffed, as shown in Figure 53; the more rapid slopes on the northwest are less embayed and much more cliffed. As on the other islands, the embayed valleys are here ascribed to prolonged erosion with respect to normal ocean level and not simply to relatively brief low-level erosion; and their embayment is ascribed to regional subsidence and not only to Postglacial ocean rise, because here as elsewhere the embayed valleys are too widely opened to be explained as the work of low-level erosion during the Glacial epochs. None of the many bays that I saw during an automobile excursion around the island appeared to be volcanic craters, although some of them are popularly so explained.

The unsymmetrical form of Grenada seems to be due to its unsymmetrical position on the bank, which, as above noted, is believed to have gained very much of its present extent before this island was built up on it. The southeast side of the island, where its lavas and mud flows found a bank with shoal water on which to spread, appears to have gained moderate slopes like those of Nevis, though perhaps not so very gentle as the basal part of that island. The valleys eroded in these slopes must have had a gentle fall near the shore; and hence, when submergence took place, long embayments were produced there; the cliffs here, still later cut back, are not high because the spurs in which they are cut are relatively low and of gradual declivity. On the northwest side of the island the lavas and mud flows may have perhaps at first been spread out with moderate slopes on the bank; but, as the island grew in height and area, they must have run over the bank border into deep water, and thereafter their slopes must have been steep, like those of the Soufrières of Montserrat. The valleys here eroded have steep fall; the bays are therefore relatively short and are now largely filled with deltas; the inter-bay spurs have high cliffs because the spurs have steep-pitching crests. The cliffs appear to plunge below sea level but only to a moderate depth; the cliff-base platform is probably buried by a considerable amount of detritus from the high and steep cliff faces. Most of these cliffed spur ends descend to a fairly even shore line; but one of the spurs, known as Bois Morice, about three miles north of the trail of hills at the southwest end of the island, is cliffed but moderately and stands forth from the rest of the shore line in a long-sloping salient. This appears to result from the former presence here of a peninsular extension of the spur—perhaps formed by a lava flow of late date or of unusually large volume—farther seaward than the



Pl. XVI—Part of St. George's and the southwestern end of Grenada.

rest of the western slope, so that the low-level abrasion of the peninsula occupied so much time that little time was left for cutting back the main body of the spur. The extension of a bank nearly two miles beyond the end of the salient gives some confirmation to this suggestion.

CULTURAL FEATURES OF GRENADA

The lower slopes of Grenada on the east and south, as well as many of the delta plains on both sides of the island, are cultivated. Many hillsides are occupied with groves of cacao trees; bananas and coconut palms are also common. A good road encircles the island; it lies at a moderate distance inland along much of the southern and eastern coast, in order to pass back of the heads of the bays; it cuts off the northwestern corner of the island by crossing over a col between a northern and a western valley. In descending the latter one finds the only steep grades of the whole circuit. Along the west coast the road sometimes follows a cliff base, where niches are cut for it in occasional rocky salients; it sometimes crosses a cliff face at half height; and sometimes it passes over a ridge crest a little back of its terminal cliff.

The chief town, St. George's, well south on the west coast, is built on a peninsula which, advancing to the southwest, is crowned with an old fort. The town on one side faces a small bay enclosed by the peninsula, and on the other the open sea. The view over the bay and town from Government House, which stands well up on the hills to the east, is exceptionally beautiful. Granville is a delta-front town in an open valley on the mid-east coast; coral reefs obstruct its harbor. Sauteurs crowns a cliffed spur end at the northeast turn of the coast and enjoys a fine view of the nearer Grenadines; a delta plain occupies an open valley close to the west. Victoria and Goyère occupy delta fronts on the west coast between high ridges with cliffed ends.

THE LONG GRENADA BANK

The southern 20 miles of this long bank, which turns somewhat to the southwest, is island-free; whatever volcanic islands have served as it foundation are now wholly submerged. Four small shoals, from 4 to 10 fathoms in depth, rising on the northwestern side of this part of the bank, may mark former island summits. The northern 60 miles of the bank are occupied by the little Grenadines, as above noted. The intermediate portion is crowned by the mountainous island of Grenada. The bank is peculiar in having a less depth than that of its neighbors. Most of the southwestern, island-free stretch is only from 12 to 20 fathoms deep; the northeastern part, occupied by the Grenadines, is from 12 to 25 fathoms deep. The border depth is everywhere about 30 or 40 fathoms. This suggests that the bank as a whole has, along with its many islands, suffered a slight uplift about contemporaneous with the Postglacial rise of ocean level. Discontinuous bank reefs are charted, often a little below sea level, along the southeastern coast of Grenada and among or around the Grenadines. The longest reef is a well defined but submerged bank barrier near the mid-eastern bank border; it has depths of from 12 to 20 fathoms; the bank next inside has depths of from 24 to 27 fathoms.

If all this long bank were either island-free, like its southwestern part, or were occupied by little islands like the Grenadines, it would constitute a systematic sequel to the Virgin bank, where most of the surmounting islands are still of a considerable size. But the addition of the large and lofty island of Grenada, which appears to be of relatively recent eruptive growth after the formation of the bank was well advanced, is an added element of complication and as such far outranks the low-lying mud flows of St. Lucia.

FINAL STAGE OF A FIRST-CYCLE SEQUENCE: SABA BANK

The ultimate stage of the first-cycle sequence of good-sized composite islands is represented by Saba bank, next southwest of Saba island but separated from it by a three-mile water passage, 300 fathoms or more in depth. The bank measures 33 by 20 miles and has a depth of 30 or 40 fathoms around most of its border; a submerged barrier reef, from 7 to 10 fathoms below sea level, extends around the southeastern border of the bank for 20 miles and constitutes one of the best approaches to a true barrier reef in this region. According to the scheme of development here adopted this bank is explained as an atoll-lagoon floor, deprived of its original reef and probably somewhat planed down by low-level abrasion in the last Glacial epoch. But, as in the case of many other banks, the depths now found probably do not represent the low-level platform to which the former atoll reef and its lagoon floor were abraded. They are much more suggestive of adjustment by Postglacial aggradation with respect to present sea level; for, if abrasion took place 30 fathoms below normal ocean level as Daly calculates and if no significant change had taken place since such abrasion, the bank border, where the products of abrasion must have been deposited in a detrital embankment, ought now to be from 60 to 80 fathoms deep at least; that is 40 or 50 fathoms deeper than the surface of the lowered Glacial ocean. As a matter of fact, the bank is of much more moderate depth and is in part reef-rimmed, as above noted. The main reason for assuming that a composite volcanic island is buried under this bank is that its size is much greater than it should be if it were based only on a single cone like that of Saba island.

Second-Cycle Composite Islands

THE COMPOSITE ISLAND OF ST. CROIX

Little attention has been thus far paid to the work of earlier observers, because they have as a rule given only secondary consideration to the structural and physiographic features of the Lesser Antilles, upon which the discussion presented in the foregoing pages has been largely based. But if we now turn to examples of second-cycle composite islands, geological structure becomes of large importance, as it was in the case of the second-cycle simple island of Sombrero, already described, and the reports of geologists who have examined such islands must therefore be taken into account.

St. Croix, the southernmost of the Virgin Islands but separated from them and their great bank by a broad passage of deep water, is five miles wide at its western end, whence it narrows in its 17 miles of length to a slender point at the eastern end. It surmounts a bank, two or three miles wide off the southern shore, and extending ten miles east of the island with a breadth of four or five miles. I saw a good part of the island during an active visit of a day and a half, when Mr. Lindborg, director of education, and Mr. Gebhardt, government engineer, were so good as to drive me about in their cars. The structure of the island has been well described by Quin, a local observer, from whose very serviceable book [26] many of the following details are taken.

The fundamental rocks are slates and shales, many thousand feet in total thickness, strongly deformed, cut by dikes, and deeply eroded by insequent streams. These rocks form a maturely dissected

[26] J. T. Quin: The Building of an Island, Being a Sketch of the Geological Structure of the Danish West Indian Island of St. Croix, or Santa Cruz, Printed in New York by Chauncey Holt, and Published by the Author in Christiansted, St. Croix, 1907.

mountain mass occupying a small quarter of the island along the western third of the northern coast—a part of their descent near the northwestern corner of the island being very precipitous—and a range of subdued hills occupying the narrowing eastern half-length of the island. A body of calcareous strata, mostly thin-bedded limestones, over 600 feet thick and dipping gently southward, occupy the southwestern half of the island and rest unconformably on the fundamental rocks; but the general form of the surface of contact has not been described. The calcareous beds are described by Vaughan as of mid-Tertiary date.[27] The uppermost members have been largely worn away, so that the present surface includes a low and discontinuous cuesta on the south and a beveled lowland, largely occupied by sugar plantations, farther inland; the lowland rises gradually toward the mountains on the northwest and the hills on the east. According to Quin it extends between the mountains and the hills nearly to the northern coast, there rising to a considerable altitude a short distance next west of the middle point and then falling rapidly to the shore. In their initial form these calcareous beds probably covered a good part of the eastern hills and lapped much higher than now on the northwestern mountains, possibly covering their tops.

Before the uplift of St. Croix, whereby its lime-

[27] T. W. Vaughan: Fossil Corals from Central America, Cuba, and Porto Rico, with an Account of the American Tertiary, Pleistocene, and Recent Coral Reefs, *U. S. Natl. Museum Bull. 103*, 1919, pp. 189–524.

stones were exposed to erosion, it is believed that they had been accumulated on a reef-enclosed lagoon floor, from which a part of the northwestern mountains and perhaps some of the eastern hills rose as islands. That this condition was the result of slow sinking is clearly shown by the manner in which the limestones unconformably overlap the eroded surface of the older rocks. Hence, although those rocks are not volcanic, the first-cycle history that they and the limestones record is again that of aggradation during subsidence. That a barrier reef rose around the outer border of the area on which the limestones were accumulated is made probable by the absence of all signs of wave-cut cliffs on the southern slopes of the northwestern mountains where the limestones approach them. Before the first cycle in the history of St. Croix was interrupted by uplift, the old-rock islands appear to have been reduced by submergence to so small an area that the encircling reef might have been almost or truly an atoll. If the precipitous part of the northern slope of the northwestern mountains was then as steep as it is now, the reef must have been attached to it as a fringe; just as the great barrier reef of Tagula, east of New Guinea, is attached to a part of the northern coast of that island as a fringe, although it is elsewhere a barrier enclosing a great lagoon over 100 miles in longer diameter.[28] It has been suggested, however, that the precipitous part of the northern coast is a fault scarp produced when the second cycle of island history was

[28] See page 30, footnote 10.

introduced by uplift; but with that possibility we are not here particularly concerned.

In consequence of the uplift of the St. Croix almost-atoll, probably accompanied by a slight tilting to the south as the limestones are gently inclined in that direction, the reduced old-rock islands have re-

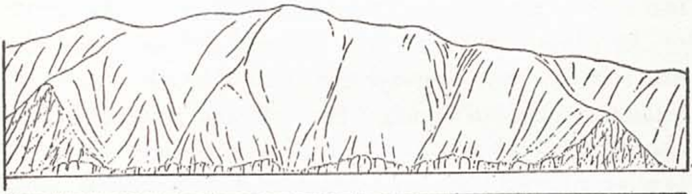


Fig. 54—Ham bluff, the precipitous northwest coast of St. Croix.

gained some of their previously lost height and, in consequence of the erosion of their limestone cover since uplift, some of their previously buried extension. The limestone area has at the same time been degraded to a beveled inner lowland enclosed by a weak and discontinuous cuesta, as above stated; and the inferred almost-atoll reef has been, in so far as it was elevated, destroyed either by normal erosion or by low-level abrasion or by both. Singularly enough, the shores of the present island are little embayed and are not cliffed, with the exception of the precipitous part (Fig. 54) of the northern slope of the northwestern mountains and of little nips (Fig. 55) cut at present sea level in sloping headlands east of that part. This makes St. Croix unlike the islands thus far described. The absence of shore cliffs along the western end of the island (Fig. 56) where Frederiksted stands on an open coast near the junction of the limestone cover with its founation rocks was very striking. Cliffs are again wanting along the northern side of the eastern hills where Christiansted, the chief town of the island, has a reef-enclosed but shallow harbor (Fig. 57) and farther east (Fig. 58), and also along the low exterior slope of the weak

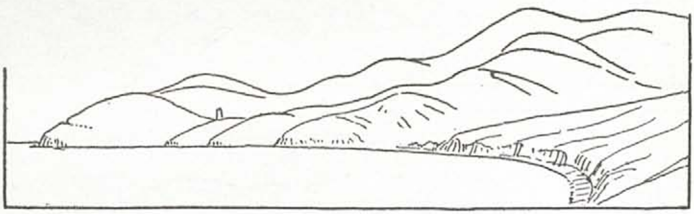


Fig. 55—A lightly cliffed headland on the north coast of St. Croix.

cuesta of the southwestern limestone area. The absence of cliffs on this island constitutes an unexplained failure of the Glacial abrasional element in the scheme of Lesser Antillean development; perhaps it may be ascribed to a better persistence of reef protection in the Glacial epochs here than elsewhere. Unexplained also is the unusually small depth of the present bank; it is generally less than 17 fathoms over the greater part of its surface, and seldom more than 20 fathoms at its outer border: like the absence of embayments, this suggests recent uplift. Discontinuous fringing reefs rise at various points near the island shores, and some submerged bank-barrier reefs, with depths of 6 or 8 fathoms, are charted on the southeastern part of the bank.

ANTIGUA AND BARBUDA AND THEIR BANK

Let it be imagined[29] that a composite volcanic island of good size passes through all the stages of a first-cycle sequence, so that after complete submergence it is crowned by an oval atoll reef (Fig. 59) 50 miles in longer diameter; that the atoll is then

Fig. 56—The western end of St. Croix at Fred-

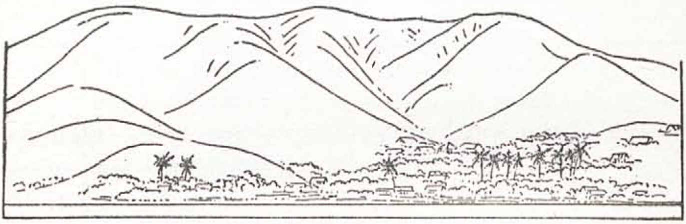
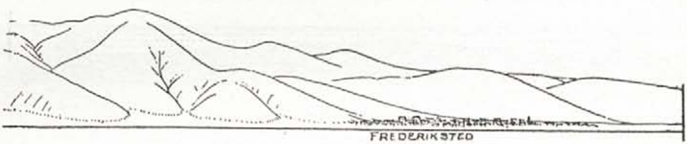


Fig. 57—The non-cliffed north coast of St. Croix at Christiansted.

tilted in such a manner that it is elevated at the southern and depressed at the northern end; that the tilted atoll is, during and after its tilting, almost re-leveled by the degrading of its raised southern area to low relief, as in Figure 60, and by the aggrading of its depressed northern area to a shallow bank; that the uptilted part is, during these changes, again characterized by slow subsidence, reef upgrowth, and lagoon aggradation; and that, thus re-

[29] See W. M. Davis: A Tilted-up, Bevelled-off Atoll, *Science*, Vol. 60, 1924, pp. 51–56.

modeled, it recently suffered the effects of low-level abrasion. The new island thus developed in the uptilted, degraded, and partly resubmerged area of the former atoll would exhibit a beveled section of the atoll under-structure; and if the uptilting and degrading were of sufficient measure, part of the



eriksted, showing the absence of shore cliffs.

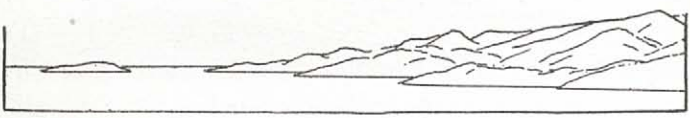


Fig. 58—The north coast of eastern St. Croix.

volcanic foundation of the atoll would be laid bare beneath its limestone cover.

It is believed that Antigua (pronounced Antíga by its inhabitants), 16 by 13 miles, 1330 feet high, is an island of such origin, and that it therefore exemplifies a well advanced stage in a second cycle of development following the final or atoll stage of a first cycle; for its beveled strata, dipping with considerable regularity 10° or 15° to the northeast, are volcanic below and calcareous above. The present bank is very narrow on the south; it extends five miles to the southeast, ten miles to the northwest, and 50 miles to the northeast and bears near its farther end the low limestone island of Barbuda, twelve by seven miles in extent and 112 feet high; it thus exemplifies an advanced stage in the production of a bank of second generation by the aggradation of the down-tilted part of the first-cycle atoll, just as Antigua exemplifies the development of an island of second generation by the degradation of the up-

Fig. 59—Ideal section of an atoll.

Fig. 60—Ideal section of the uptilted and down-worn half of the same atoll, drawn on twice the scale of Figure 59.

tilted part. Whether the uptilted Antigua area is bounded on the southwest by a submarine fault or by a sharp flexure cannot be determined by the soundings now charted.

OTHER TILTED ISLANDS

The tilting of an island ought not to be regarded as in any sense a peculiar, still less an abnormal phenomenon. It is simply the manifestation at the ocean surface of a tilting of the underlying sea floor, similar to the tilting of parts of continental areas as attested by the occurrence of faults or flexures in which formerly horizontal strata are inclined. The young volcanic island of Tristan da Cunha in the South Atlantic appears to have been gently tilted, so that a part of its cliff-base platform is emerged in a lowland of crescentic pattern, locally called "the plateau," around the northwest part of the shore. St. Croix, above described, seems to have been given a gentle southward slant in the passage from its first cycle of subsidence and aggradation to its second cycle of degradation. Uvea, the northwesternmost of the three Loyalty Islands, northeast of New Caledonia, is manifestly the up-tilted half of a former atoll slanting to the west, just as its companions, Lifu and Mare, are evenly uplifted atolls. The Pelew group, east of the Philippines, appears to have been as a whole gently inclined to the north, for its southern members consist of emerged reef limestones and an elevated atoll stands a little farther south, while its northern part bears no limestones and is followed by some little sea-level atolls. The tilting of this group was implied by Darwin 50 years ago in explanation of the above facts which had been described by Semper; the implication seems to hold good, in spite of Semper's incredulity about it. The tilting of Antigua is stronger than that of any of the other tilted islands here mentioned; but that does not make the tilting improbable.

GEOLOGY OF ANTIGUA'S FIRST CYCLE

Antigua has fortunately been visited by a number of geologists, most recently by Earle, whose report,[30] to which a bibliography is appended, furnishes the following details regarding the beveled strata and

[30] K. W. Earle: The Geology of Antigua, Antigua, 1923.

the probable conditions of their deposition. The physiographic notes here introduced are largely based on my own observations during a ten-day visit, when I received many helpful courtesies from His Excellency the Governor and other officials as well as from Mr. William Forrest, a resident well versed in the geology of the island. The southwestern

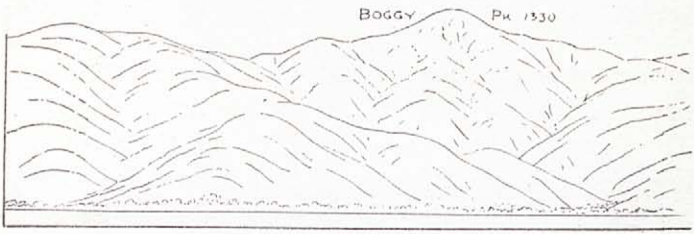
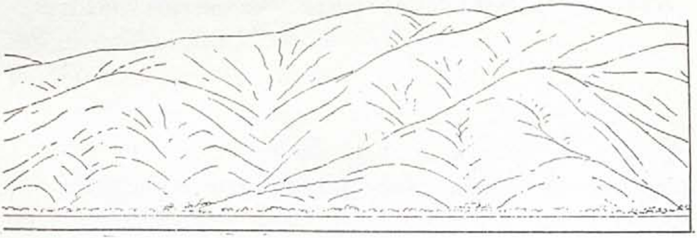


Fig. 61—The subdued mountains of volcanic rocks in the south-

fourth of the island area exhibits the lowest members of the inclined series, in part lavas but more largely agglomerates, with a total thickness of several thousand feet. A subaerial origin is inferred for the agglomerates because of their irregular bedding. The rocks here seem to be of relatively uniform resistance, for they are dissected chiefly by insequent streams, under the lead of which the volcanic mass has been reduced to subdued mountainous forms (Fig. 61) with bare outcrops only of small extent. Next follows an additional series of volcanic beds, described by Earle as "water-deposited and stratified tuffs, volcanic grits and sands, with intercalations of marine and fresh-water chert and limestone" of "local development. . . .

There appears to be no very definite junction between the true bedded tuffs and the pseudo-bedded agglomerates and ash beds of the [underlying] volcanic area. . . . At intervals during the deposition of these beds, there must have been long periods unbroken by any volcanic eruptions. This is proved by the existence of beds of marine limestone and



western quarter of Antigua. No shore cliffs are seen here.

chert enclosing the remains of corals which cannot flourish except in waters free from external detritus.'' These beds include also a number of shallow-water mollusca, ''such as Pecten, Lima, Cardium, Turbo, Turritella, Lithodomus, etc.'' Higher in this series and associated with the volcanic grits is a flint breccia, ''made up of silicified fossils—corals, lamellibranchs, algae, etc.,'' which appear to be almost identical with the fossils of the great series of limestones in the northeastern third of the island, to be described below. Indications of renewed volcanic activity are found in an agglomerate spread out upon the grits. The occurrence of stronger and weaker beds in this part of the series is betrayed by the development of several overlapping cuestas, with their steeper scarps to the southwest and their gentler slopes to the northeast, best seen in the central and southeastern part of this quarter of the island. Inasmuch as the cuestas strengthen to fairly strong relief and weaken to disappearance along their strike, it is inferred that the determining beds are of lens-like form.

Above the grits is a series of "lacustrine and fresh-water cherts," associated with "impure limestones and marls. The cherts contain a large amount of petrified wood, both monocotyledons and dicotyledons, sometimes a foot in diameter, and abundant fresh-water gasteropods which are sometimes so plentiful as to form a very large proportion of the rock." Some of the chert beds form a rather strong cuesta a few miles in length which rises to good height near the center of the island, where, as it is separated from the submountainous volcanic area by a well defined subsequent valley presumably excavated along a series of weak tuffs, its long-arched crest serves as a delightful belvedere from which a fine prospect is opened in all directions. Weak tuffs of a considerable thickness overlie the cherts and determine the excavation of a medial subsequent lowland, one or two miles in breadth, which crosses the island from coast to coast. Thus several thousand feet of bedded deposits overlie the basal volcanic rocks.

THE ANTIGUA LIMESTONES

A deposit of gravels, including pebbles of lava and petrified wood, is placed by Earle between the tuffs of the medial lowland and the heavy series of overlying marls and limestone. "The heterogeneity of the deposit would point to its being a beach deposit laid down under the influence of strong currents and tides in an epoch of subsidence." Then come the heavy calcareous beds, the so-called Antigua formation, at least 1500 feet thick. It is said to be separated from the gravels by a slight unconformity. "These beds contain a fossil fauna as noted for its variety as for its abundance. . . . This fauna is essentially a marine one and consists of compound corals, lamellibranchs, foraminifera, calcareous algae, gasteropods, and echinoderms. . . . The commonest and most characteristic fossil is *Orbitoides mantelli*, which with other species often forms the larger part of the deposit. The commonest lamellibranchs are species of Ostrea and Pecten, the former often reaching a very large size. The algae are chiefly represented by species of Lithothamnion . . . while the compound corals are represented by genera too numerous to mention here."

According to Vaughan, a coral reef at the base of these limestones "grew upon a basement that had been subaerially eroded and was later depressed below sea level;" and the limestones were "deposited in shoal water on a flattish floor." The corals here must have formed a lagoon reef, for they do not stand at the margin of their area of limestone accumulation. As now eroded the calcareous beds exhibit a number of discontinuous cuestas and intermediate subsequent valleys which occupy the northeastern third of the island. All the valleys of the limestone area as well as the medial subsequent lowland are cultivated, mostly in sugar-cane plantations.

The manifest lesson of this instructive rock series is that it was accumulated during a time of long-continued subsidence; and, if the lower agglomerates are rightly interpreted as of subaerial origin, the total measure of the subsidence must be 6000 or 8000 feet at least. It must be inferred from the nearly conformable sequence of the volcanic series, as well as from their position with respect to the entire area of the Antigua-Barbuda bank, that the lavas and tuffs are peripheral beds, like those associated with the southwestern mud flows of St. Lucia; hence, if there was a higher central area of the original volcanic island, it is very likely buried nearer the center of the bank. But, on the other hand, in view of the late date of eruption and the eccentric position of Grenada with respect to the long bank on which it is believed to have been built up, it is possible that the volcanic rocks of southwestern Antigua represent an eccentric addition made to a bank of earlier beginning and later completion. In any case, the occurrence of the pure limestones, with abundant reef-making corals and other fossils, in the upper part of the series suggests that those strata were deposited in a reef-encircled lagoon and that the encircling reef was at first a barrier and later an atoll.

The barrier-reef stage of Antigua was clearly recognized by Purves[31] 40 years ago, although he did

[31] J. C. Purves: Esquisse géologique de l'île d'Antigoa, *Bull. Mus. Hist. Nat. Belge*, Vol. 3, 1884, pp. 273–318.

not explicitly suggest that the barrier reef later became an atoll. He wrote:

''La puissance de cette vaste formation calcaire indique qu'elle s'est déposée pendant une longue période d'affaissement du sol qui a suivi l'extinction de l'activité volcanique et pendant laquelle des récifs de coraux très-étendus se sont librement établis autours des bancs formés par les matériaux volcaniques éjectés lors des dernières éruptions. Ces roches, actuallement visibles, ne représentent pas la substance même du récif, car, pendant la formation du dépôt, ce récif devait être situé à une distance considérable de la côte. Ces amas de marnes et de calcaires avec leur masse de débris de coraux détachés mais très-bien conservés, de bois flotté et échoué, de coquilles et d'orbitoïdes, représentent évidemment le dépôt particulier que l'on voit encore de nos jours se former par l'accumulation entre la barrière de récifs et les côtes d'une île affectée d'un mouvement d'affaissement lent et continu.'' This interpretation of the early or first-cycle history of Antigua seems to be essentially correct; for in view of the abundance of reef-making corals preserved in the limestones of that cycle and in view of the evidence given by the later or second-cycle history of Antigua, as stated below, as well as that given by other islands already described for the former occurrence of protecting barrier reefs, the growth at first of a barrier and later of an atoll reef around the margin of the first-cycle limestone area of Antigua seems wholly reasonable.

THE SECOND CYCLE OF ANTIGUA'S DEVELOPMENT

The continued upbuilding of the atoll was interrupted by the uptilting of its southwestern part, and the uptilting was accompanied and followed by prolonged erosion. So extensive, indeed, has the erosion been that the inferred atoll reef is not discoverable today; it must have been, after tilting, completely removed by erosion over the uplifted southwestern part of Antigua, as Purves implies, and it must be submerged in the bank on the east and west. It may well be that the disappearance of the reef by erosion will be taken by some readers as a reason for doubting that it ever existed; but that it did exist is made extremely probable by the abundance of reef-building corals in the limestone strata; for if corals grew so well on the bank they must have grown still better around its edge. And as to the disappearance of the reef, it would be, in view of the great amount of erosion that has taken place since the uptilting of the island, and more particularly in view of the situation of the atoll reef with respect to the part of the uplifted island that has been worn away, and still more particularly in view of the submergence the island has suffered since it was well worn down in its second-cycle erosion, as unreasonable to expect to find the reef visible today as to expect still to see the crater rim preserved in a deeply dissected volcano. A visit to the island would doubtless make this clear, even if reading a description of it does not.

Thus interpreted, the deep-lying, central volcanic foundation of Antigua may be of late Eocene date, and its lagoon limestones and marls were deposited in Oligocene time, these being the events of the first cycle: the deformation and degradation of the second cycle have taken place in later Tertiary time and thereafter. Certain of the second-cycle physiographic features next to be considered repeat those of the first-cycle volcanic islands above described so closely as to indicate that the second-cycle sequence is much like the first.

The subdued forms of insequent dissection in the southwestern volcanic district as well as the alternating cuestas and lowlands carved on the strong and weak belts of sedimentary strata prove that a long period of subaerial erosion has elapsed since the first-cycle atoll was uptilted. The coast is now well embayed, and the distance to which the embayments, now more or less filled with delta plains, originally entered the valleys indicates that a considerable subsidence took place in the latter part of the long second-cycle period of subaerial erosion, if not in the earlier part also. Bendel River, the longest stream of the island, flows sluggishly westward for five or six miles on a smooth flood plain, which occupies a subsequent valley next north of the hilly volcanic district, and mouths in Five Island Harbor (Fig. 63) on the west coast. When the valley was in process of erosion the island must have stood higher than now, and the mouth of the river must then have been two or three miles west of where it is now. The depth of that mouth of the valley below present sea level must be several hundred feet.

The subsidence by which the coastal embayments were produced must have caused a significant diminution of the island's extent where the weak sedimentary strata had been previously reduced to lowlands, as appears to have been the case in the area of the bank on the northwest, northeast, and southeast of the present island. Hence, the foundation of this bank of second generation adjoining an island of strong and weak structures may very possibly be a worn-down and slightly submerged area of weak rocks, chiefly limestones, of an earlier generation, although such a possibility was rejected for the bank of first generation around St. Lucia.

The distinction here made between banks of first generation formed around islands of simple structure, and banks of second generation formed around islands of compound structure, is of significance in estimating the measure of upgrowth accomplished by the reefs within which the strata of the banks are supposed to have been accumulated, or the equivalent measure of island subsidence during reef upgrowth. In the case of an island of compound structure, it may be imagined that after its weaker rocks are worn down to low relief, the resulting lowland is slightly submerged so that a barrier reef grows up from small depth around its outer margin and encloses a lagoon, above which the resistant rocks will stand in submountainous relief. Evidently such a reef may be of small thickness. On the other hand, in the case of an island of simple structure, like a volcanic cone, no part of it can be worn down to a lowland until all the rest of it is reduced to small relief; hence, if a well-offset barrier reef is found around a volcanic island that is dissected only to the stage of maturity, such a reef cannot be reasonably explained as based upon a slightly submerged lowland and as therefore having but small thickness; it should be explained as based on the submarine slopes of the island, which are probably not unlike the supermarine slopes; and hence the best estimate of the thickness of such a reef, and of the measure of the subsidence which has permitted its upgrowth, is to be made by prolonging the visible slopes of the island downward beneath the reef. In many Pacific islands the thickness of their barrier reefs thus estimated may be 1000 or 2000 feet at least.

THE BAYS AND CLIFFS OF ANTIGUA

The work of abrasion, seen in the immature cliffs by which the headlands of Antigua are a little cut back, is very small as compared with the great work of erosion by which the island has been so well degraded. This is conspicuously the case at several parts of the coast; for example, the well degraded or subdued tuff ridges (Fig. 62) of cuesta-like form advancing eastward on the south of the broad and shallow embayment, Willoughby Bay, that enters the southeastern end of the medial subsequent lowland, are so little cut back that their headland cliffs are inconspicuous features. Similarly the subdued agglomerate hills (Fig. 63) advancing westward on the south of the broad and shallow embayment that serves the chief town, St. John, as a harbor at the other end of the medial lowland, are little cliffed. The

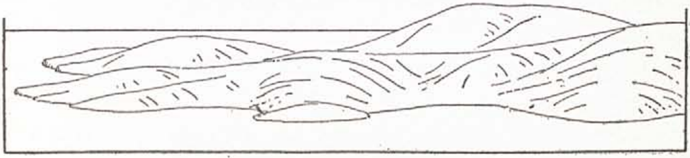


Fig. 62—The subdued spurs on the south side of Willoughby Bay, southeast coast of Antigua, seen from a ridge on the north side of the bay. The slight amount of cliff cutting on the spur ends is notable.

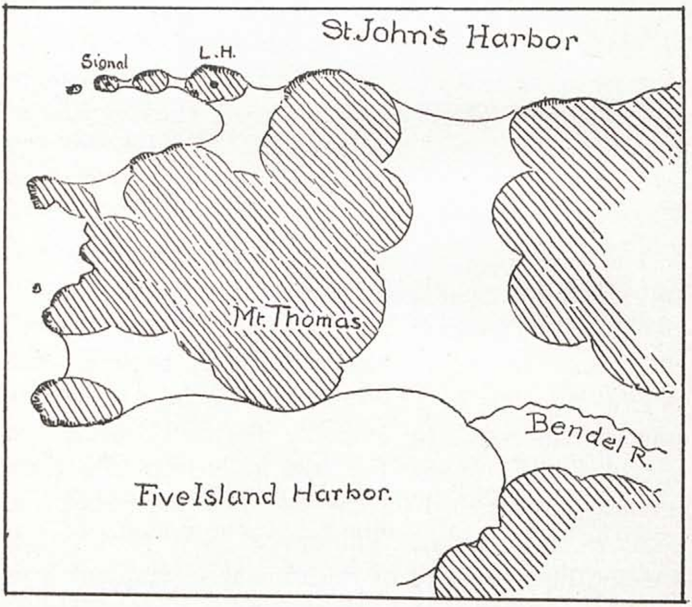


Fig. 63—Rough plan of part of the west coast of Antigua, showing slightly cliffed headlands and beach-filled bays.

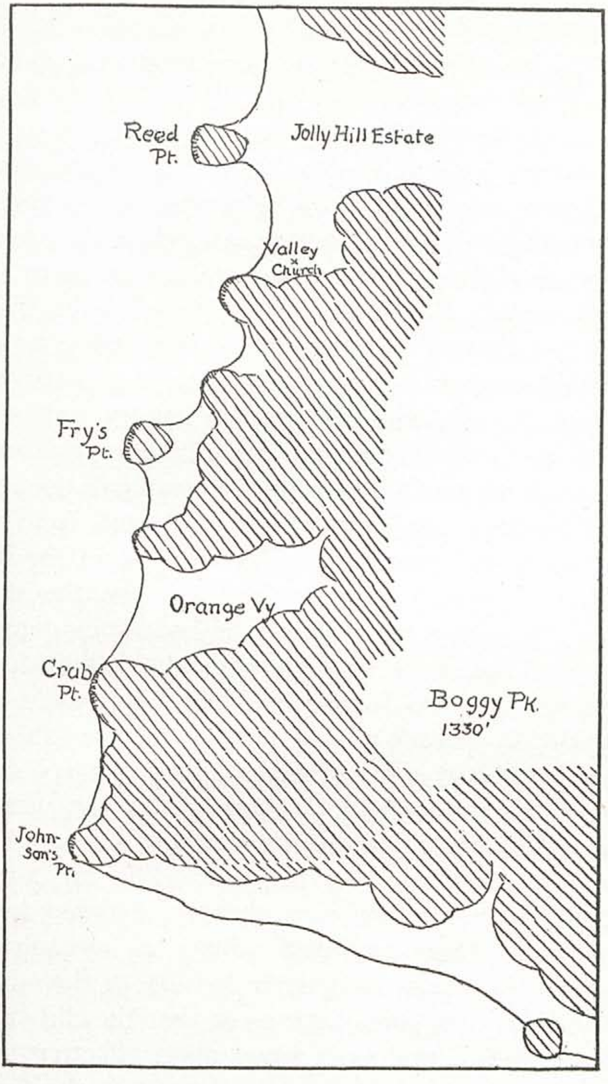


Fig. 64—Rough plan of the southwest coast of Antigua, showing slightly cliffed headlands and beach-filled bays.

same is true of the headlands farther south (Fig. 64). The higher hills of agglomerates enclosing Falmouth and English harbors on the mid-south coast are but moderately cliffed, in spite of the fact that the submarine bank there has, according to the chart, a width of only about a mile before deep water begins; and farther west on the south coast, where the highest summits of the island are maintained on lavas and agglomerates, the slopes descend to sea level, where they are fronted by a narrow alluvial flat (Fig. 61) without any sign of wave work at their present base. Whatever cliffs were cut here by low-level abrasion are now wholly submerged. It is therefore clear that the small work of abrasion on the headlands demands that Antigua shall have been protected from the attack of the ocean waves during most of the long period of second-cycle erosion; but, on the other hand, the immature cliffs of the headlands demand that that protection shall have been lately withdrawn for a brief period. If the island were everywhere surrounded by as wide a bank as that on the north, that would afford it some protection from wave attack; but, as a matter of fact, it has only a very narrow bank along the middle of its southern side; and yet there as elsewhere the headland cliffs are almost insignificant as measures of abrasion, compared with the intermediate embayed valleys as measures of erosion. It cannot possibly be because of the narrow bank along this part of the coast that the cliffs there are so little developed; some more effective coast protection must have long been present there; and by far the most effective protection for such a coast is a neighboring barrier reef, as has already been inferred in the case of St. Lucia. But, if such a reef existed there, it probably encircled the whole of the second-cycle Antigua-Barbuda bank, except for certain lapses of development on the leeward border, such as are usually seen in present-day barrier and atoll reefs in the Pacific, presumably because the drift of fine sediments from the lagoon floor is unfavorable to coral growth there.

Not only is a barrier reef thus seen to have afforded the most effective protection against abrasion, but that protection is easily removed, during the brief period of abrasion that is attested by the headland cliffs, by the chilling of the ocean waters and the resultant killing of the reef-building corals in the Glacial epochs. That the abrasion took place during a time of lowered ocean level is also suggested by the plunge of the south-coast cliffs below present sea surface. Certain cliffs, however, in the weak limestones on the northwest coast of the island give less evidence of plunging; hence they have probably been more cut back from their original position by abrasion at present sea level than have the cliffs in volcanic rocks on the south.

The protecting barrier reef here inferred is a wholly second-cycle product, a reef of second generation, begun during the late Tertiary subsidence of the island and cut away by low-level abrasion in the Glacial epochs; it is therefore not to be confused with the inferred first-cycle barrier and atoll reef, which is believed to have grown up during the Oligocene or first-cycle subsidence of the original island and to have been destroyed by second-cycle erosion after the atoll had been tilted up, probably in Miocene time. If the late-Tertiary barrier reef encircled almost the entire bank area, as just suggested, its northern loop must have been built up as the northern part of the Oligocene atoll was tilted down; and that northern part of the late Tertiary reef may therefore have grown up from the top of the Oligocene reef: there the first-cycle reef would have merged into the second-cycle reef. The imagined north-looping reef thus constituted would have resembled, although constructed on a larger scale, the actual reef loop around the Fiji island of Lakemba. That reef today runs close around an island at one end of its oval circuit and loops around a lagoon at the other end; and, according to Foye,[32] the unsymmetrical form of the Lakemba reef with respect to its island is the result of down-tilting and upgrowth at the looped end, just as is here inferred to be the case with the imagined late Tertiary reef loop of Antigua.

POSTGLACIAL FEATURES OF ANTIGUA AND ITS BANK

The delta plains by which many of the Antigua embayments have been much shortened, the beaches swinging in concave curves between the headlands—and composed of calcareous sands even where the

[32] W. G. Foye: Geological Observations in Fiji, *Proc. Amer. Acad. of Arts and Sci.*, Vol. 54, 1918–19, pp. 1–145.

headlands are made of volcanic rocks—and the discontinuous fringing and bank reefs charted around the island, all seem to have been largely formed in Postglacial time during and since the rise of the ocean to its present level. This must be wholly true for the bank reefs, and must be also true in the main for the beaches and deltas; part of their volume may be of Preglacial or Interglacial formation, but Postglacial additions sufficient to make good the effects of low-level erosion in the Glacial epochs must have been of a considerable volume.

The limestones of Barbuda are, according to an unpublished report by Earle, of Pliocene or Pleistocene age and probably correspond to certain horizontal limestones of small thickness and late date which unconformably overlie the worn-down Oligocene limestones near the northeastern shore of Antigua. Both these late-date limestones indicate that the subsidence which accompanied or followed the advanced erosion of the tilted atoll has been recently reversed by a slight uplift; and since this recent uplift erosion has not only continued the work previously well advanced on the uptilted part of the atoll but has also attacked the horizontal limestones deposited at the time of the greatest subsidence. How far this attack was aided by low-level erosion and abrasion is not determined.

If the headland cliffs of Antigua are the work of low-level abrasion in the Glacial epochs, as seems highly probable, then it is also probable that a large part of the present bank was more or less planed down in its shallower areas at that time and that a detrital embankment was added around it with a marginal depth about 40 fathoms below the level of the lowered ocean. But if so, the bank has since then, like the Saba bank, been significantly aggraded; for much of its surface has such depths as 15 or 20 fathoms, while its margin is only about 40 fathoms below present ocean level. This bank, with an island at each end of it, would be an excellent place for studying the nature of the deposits by which a rimless bank is built up.

Antigua was the most instructive island I visited in the Lesser Antilles: it not only exhibits in its physiographic features an interesting stage in a second-cycle sequence of island development but presents in its geological structure a most encouraging confirmation of the scheme of a first-cycle sequence. Indeed, it reveals the deep under-structure of coral-reef lagoon deposits better than any of the 35 reef-encircled islands seen by me in the Pacific in 1914, for most of those islands had not been elevated, and those which had been elevated gave no such exhibition of their under-structure as Antigua affords. Its well displayed series of volcanic and calcareous strata is far more demonstrative of the conditions under which atolls are formed than is the famous Royal Society boring in the reef of Funafuti, an atoll in the Ellice group of the Pacific; for while that boring, which was but little more than 1000 feet deep and did not reach a volcanic foundation, yielded only a slender rock core whose interpretation has given rise rather to dispute than to agreement, the beveled section of the Antigua monocline is broadly open to deliberate observation in many outcrops, road cuts, and quarries in its surface of scores of square miles, as well as in many headland cliffs around its shores; and the evidence that its tuffs and limestones give for long continued and great subsidence during this deposition is not to be questioned. To be sure, an island that is supposed to be a tilted and degraded atoll, the encircling reef of which is lost, may be regarded as an uncertain witness as to the origin of atolls by those who have not seen it; but even they may still find some value in the evidence given by the island as to the origin of a former pelagic bank; for, while such a bank may in some cases be built up to small depth by the accumulation of organic detritus on a deep, non-subsiding foundation, as Rein and Murray supposed, it is clear that this bank had no such origin. Its upper 1500 feet of strata show conclusively, by their fossils as well as by their structure, that they were built up as persistently shallow-water deposits on a bank or lagoon floor by the slow accumulation of organic detritus on a slowly subsiding foundation; and the presence of a reef around the bank while it was building is made so highly probable by various converging lines of evidence that I am persuaded the bank will, in time, come to be accepted as representing the deposits of a former barrier-reef lagoon and later of an atoll lagoon, and indeed as the most instructive section of an atoll thus far known in the oceans.

ST. BARTHOLOMEW, ST. MARTIN, AND ANGUILLA

These three islands, each including both volcanic and calcareous rocks, surmount the western part of an

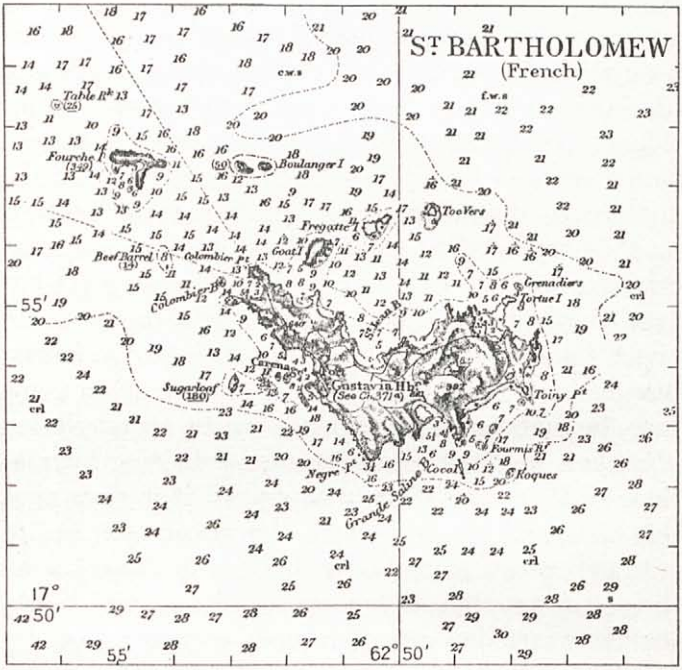


Fig. 65—The Island of St. Bartholomew (from British Admiralty Chart No. 2038).

extensive bank measuring 55 by 24 miles and having a smooth surface of moderate depth and a well defined border at 30 or 40 fathoms. The islands lay outside my route and are only briefly described by earlier observers. St. Barts (Fig. 65), as the first-named island is often called for short, is the southernmost of the three; it is five by two miles across and 992 feet high, of irregular outline, with some of its headlands moderately cliffed; a few islets stand near by. Ten

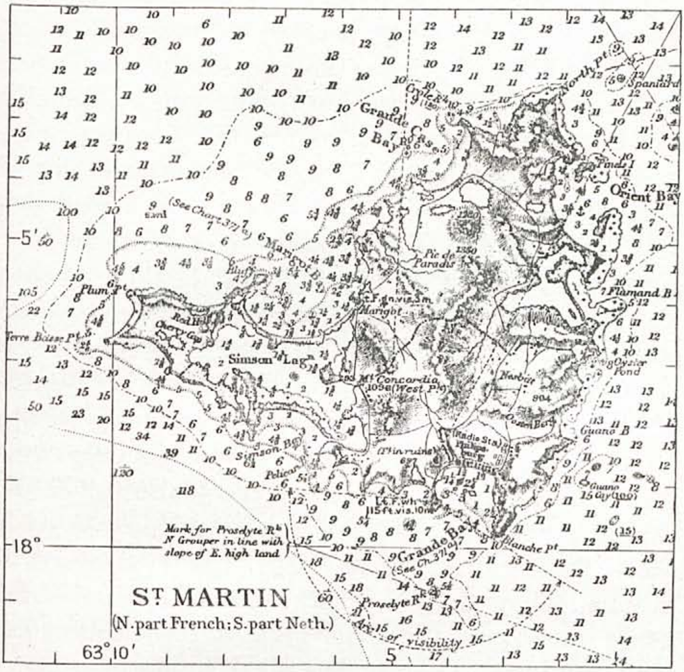


Fig. 66—The Island of St. Martin (from British Admiralty Chart No. 2038).

miles to the north is St. Martin (Fig. 66), seven by four miles, 1360 feet high; its shore line is embayed and beached; a satellite on the west is tied to the larger island by two beaches, enclosing a small lagoon. Discontinuous fringing reefs are charted near the shore. Four miles farther north is Anguilla, twelve by three miles, 213 feet high, with a comparatively simple shore line: some smaller islands stand not far away. According to Cleve, as already cited, and Spencer,[33] the volcanic rocks of the group are followed by a considerable body of tuffs and limestones; but the descriptions by these observers do not suffice to determine whether the upper limestones originally extended over the highest part of the volcanic rocks, as is clearly the case on Antigua. An old account of Anguilla by Sawkins,[34] describes a rock series 950 feet thick, and as that measure is more than four times the height of the island, it may be inferred that the strata are gently inclined; furthermore, as the underlying volcanic rocks are said to occur on the west coast, the inclination of the strata is presumably eastward, and this suggests an uptilting on the west. According to this older record, the basal volcanics are 420 feet thick; then come 360 feet of clays, shales, sandstones, and volcanic conglomerate with some lignite; over these come 160 feet of coral breccia, followed by a small measure of marls and white limestones, the latter lying unconformably on the other beds. Duncan described St. Barts as composed of volcanic beds and intercalated limestones, the latter being indicative of deposition in deep water.[35] According to Vaughan, as cited above, a

[33] J. W. W. Spencer: On the Geological and Physical Development of Anguilla, St. Martin, St. Bartholomew, and Sombrero, *Quart. Journ. Geol. Soc.*, Vol. 57, 1901, pp. 520–533.

[34] J. G. Sawkins: Reports on the Geology of Jamaica, London, 1869; an appendix, pp. 257–261, gives an account of Anguilla.

[35] P. M. Duncan: On the Older Tertiary Formations of the West-Indian Islands, *Quart. Journ. Geol. Soc.*, Vol. 29, 1873, pp. 548–565.

coral limestone on St. Barts rests unconformably on a volcanic base; it is inferred to be "a shoal water deposit . . . laid down on a submerged flat;" and on Anguilla a fossil coral reef was "formed during submergence after the subaerial erosion of its [volcanic?] basement;" the overlying limestone is said to represent "a submarine flat." The evidence for the former connection of these islands with South America, as furnished by mammalian fossils in the upraised limestones, will be cited later.

It may therefore be provisionally concluded that these islands and their bank, like the Antigua-Barbuda islands and bank, represent a former atoll which has been gently tilted eastward, so that its western part was uplifted and its larger eastern part was depressed; that the uplifted western part has been much reduced by erosion, while the depressed eastern part has been built up in continuation of its former aggradation, as a bank of second generation. An isolated bank, twelve by seven miles in extent and about 35 fathoms deep, lies three miles southeast of the larger one: this was presumably depressed and built up again like the eastern part of the larger bank. As around other islands, the absence of reefs around these bank borders today is ascribed, first, to the destruction of former reefs by low-level abrasion in the Glacial epochs, and second, to the failure of renewed reef growth in Postglacial time.

THE GUADELOUPE GROUP

The Saints and Marie Galante, independent southern members of this group, have already been described as first- and second-cycle members of a simple sequence. The other members of the group are much larger and appear to belong together in a more complicated sequence. Guadeloupe, 24 by 14 miles in extent and 4868 feet high, rises in a youthful, strongly dissected volcanic range; along the southeast coast, where alone I had a passing sight of it, it is flanked by a sloping detrital plain, now more or less trenched by its streams. The west coast is said to have a more abrupt descent to the sea, as if no detrital slope existed there; and this may be, as in the case of Grenada, because the submarine bank on that side of the island is very narrow, probably composed only of volcanic detritus from the island valleys and not representing a previously formed calcareous bank. Grande Terre, closely adjoining on the east, 18 by 15 miles, 354 feet high, is described by Duchassaing[36] as consisting chiefly of volcanic tuffs and marine limestones, raised above sea level and eroded into rolling hills of small relief. A section by Spencer[37] shows the strata of the island dipping gently eastward, with low cliffs on the northeastern shore line where an emerged reef stands six or eight feet above the sea level. The limestone island of Désirade, one

[36] Pierre Duchassaing: Essai sur la constitution géologique de la partie basse de la Guadeloupe, dite la Grande-Terre, *Bull. Soc. Géol. de France*, Ser. 2, Vol. 4, 1846–47, pp. 1093–1100.

[37] J. W. W. Spencer: On the Geological and Physical Development of Guadeloupe, *Quart. Journ. Geol. Soc.*, Vol. 57, 1901, pp. 506–519.

by six miles, 912 feet high, with steep sides and discontinuous fringing reefs, stands five miles farther east. A bank of late generation which occupies the northern bight between Guadeloupe and Grande Terre, where many discontinuous bank reefs are found, also extends eastward from the last-named island so as to surround Désirade; its border has the small depth of 20 or 30 fathoms.

No safe conclusions can be reached at present regarding the physiographic evolution of these islands, but it may be briefly suggested that they are now in a third cycle of development. The first cycle probably witnessed the deposition of their calcareous strata, presumably on an early formed and subsiding volcanic foundation wholly submerged before the cycle closed. The second cycle was introduced by a slanting uplift which gave the strata of Grande Terre a slightly more pronounced dip to the east than they now possess, thus initiating the erosion of the uplifted areas; the eruptive growth of Guadeloupe may be associated with this uplift. The third cycle was introduced by another uplift with a very gentle slant to the west, as testified by the present greater height of Désirade over Grande Terre. This west-slanting uplift is confirmed by the uplift of Marie Galante a little farther south, while the Saints, to the west of that island, appear to have suffered continuous subsidence. Although the uplift of Marie Galante is like the uplift of Désirade in being greater than that of the islands to the west, the date of the Marie Galante uplift would seem to be much the more recent of the two; for no significant submarine bank has been formed around it, while the bank that connects Désirade with Grande Terre is so large as to indicate the lapse of a considerable period in its production, either by abrasion or by aggradation. It is possible that Grande Terre and Désirade are the eroded and abraded remnants of a single atoll-like bank of the first cycle and that the present bank represents the rest of the earlier bank, converted into a bank of second or third generation by low-level abrasion in the Glacial epochs and more or less aggraded in Postglacial time. The mountainous volcanic range of Guadeloupe appears to be, as above suggested, a late and irrelevant addition to the western part of the bank.

THE ABERRANT ISLAND OF BARBADOS

It has been noted above that St. Croix departed from the scheme of development here proposed for the Lesser Antilles in not having had its shores cliffed by low-level abrasion; and it was suggested that this departure may be explained as the result of a slightly more persistent growth of corals there than elsewhere in the island chain. Barbados, 19 by 10 miles across, and 1104 feet high, of which I had a good sight during a brief visit, will now be shown to exhibit even more peculiar features; indeed, in several respects it falls entirely outside of the scheme, just as its eastward position places it somewhat outside of the Lesser Antillean chain; it belongs in a class by itself. According to Harrison and Jukes-Browne[38] the island contains no volcanic rocks but is composed for the most part of strongly deformed and much eroded strata, mostly sandstones and mudstones, apparently an upheaved part of a continental shelf that was formed when northeastern South America extended farther into the Atlantic. As thus constituted, the island must have once been decidedly higher and larger than now, for its deformed strata show no signs of giving out as they approach the coast. Its decrease of altitude was in part due to erosion, but decrease of area as well as of altitude was also caused by subsidence, even to the point of disappearance; for the older rocks are unconformably covered by a thin cloak of calcareous beds containing pelagic fossils, thus indicating that the island was completely submerged for a time. This subsidence was followed by upheaval; and, during successive pauses in the resulting emergence, the expanding shores of the resurgent island were benched by a series of late Tertiary and Pleistocene fringing reefs, now seen in a series of terraces rising in low and broad steps to a height of 1040 feet and covering six-sevenths of the island surface. A fringing reef is formed along the present shore, and a bank surrounds the island with a breadth of one

[38] J. B. Harrison and A. J. Jukes-Browne: The Geology of Barbados, *Geol. Mag.*, Decade 4, Vol. 9, 1902, pp. 550–554.

A. J. Jukes-Browne and J. B. Harrison: The Coral-Rocks of Barbados and Other West-Indian Islands, *Quart. Journ. Geol. Soc.*, Vol. 47, 1891, pp. 197–248.

G. F. Franks and J. B. Harrison: The Globigerina-Marls [and Basal Reef-Rocks] of Barbados, *ibid.*, Vol. 54, 1898, pp. 540–555.

or two miles and with a marginal depth of about 50 fathoms; it bears a slightly submerged bank-barrier reef which extends for ten miles parallel to the southeast coast about halfway from the shore to the bank margin, with a depth of from 7 to 10 fathoms; the lagoon thus imperfectly enclosed has depths of from 20 to 27 fathoms.

The absence of shore cliffs, even along the northeast coast where no reef terraces are present, is more difficult to understand here than in the case of St. Croix; for Barbados, lying to the east of the Lesser Antilles, should have had, as will later appear more clearly, less protection from coral growth during the Glacial epochs of lowered ocean level than the islands already described; and, as it is a rising island, the cliffs then cut should today be more exposed to view than on the members of the Lesser Antillean chain that are supposed to be subsiding islands. It does not seem possible that Barbados escaped being cliffed by being completely submerged in the Glacial period; for the terracing reefs by which it is now covered are of too great a total thickness to have been formed wholly in Postglacial time. It is perhaps possible that the cliffs that were cut by the lowered ocean around the rising island have been partly masked by the addition of later fringing reefs in front of them, the unconcealed top of the cliffs being mistaken for normal fringing-reef fronts. The failure to find these cliffs in the older rocks on the northeastern slope of the island, where the terracing reefs are absent over a stretch of several miles, may be due to their having been destroyed by later erosion, just as the cliffs that must have been cut on that unprotected side of the island while fringing reefs were forming around the other sides have been destroyed. But these suggestions have rather the nature of plausible excuses than of valid explanations; it must be recognized that Barbados does not fit into the scheme that accounts so well for the other islands.

Detailed Analysis of Island Forms

DISTRIBUTION OF FIRST-CYCLE AND SECOND-CYCLE ISLANDS

If the foregoing descriptions are now reviewed with the object of discovering whatever system there may be in the distribution of the islands in consequence of the manner of their development, two generalizations may be stated. First, the one-cycle islands, St. Thomas and other members of the Virgin group, Saba, Statia, St. Kitts, Nevis, Redonda, Montserrat, Guadeloupe (which may be here listed although it is closely associated with two second-cycle limestone islands on the east), the Saints, Dominica, Martinique, St. Lucia, St. Vincent, Grenada and the Grenadines, and probably Tobago, are all of volcanic origin and are all, with the exception of the last one named, on the inner, or western and more continuous, side of the Lesser Antillean chain. The many variations exhibited by these islands are chiefly dependent on differences in the date of their original eruption and on the duration of their later eruptions, as well as on differences in the measure of their subsidence, although these differences are not systematically arranged along the island chain. Second, the two-cycle islands, partly or largely composed of limestone, namely, the three members of the St. Martin group, Sombrero, Antigua and Barbuda, Grande Terre and Désirade, Marie Galante, and Barbados, are, as has often been noted, mostly on the outer, or eastern and less continuous, side of the chain; but St. Croix, which is also partly composed of limestone and is well advanced in its second cycle, lies on the inner side of the curve. Manifestly the first-cycle islands of the inner curve are younger than the second-cycle islands of the outer curve. Indeed, Guadeloupe, Martinique, and St. Vincent have experienced volcanic eruptions in recent historic times; and Statia, Nevis, and St. Lucia have had eruptions in recent geological times. This suggests that the line of volcanic activity has migrated westward from an earlier position on the outer curve to a later position on the inner curve.

FOUNDATION OF THE VOLCANIC ISLANDS

Confirmation of the possibility that at least some of the volcanic islands were built up from a former land surface is provided by the occurrence among the Virgin Islands of patches of deformed and eroded continental rocks, apparently parts of an eastward extension of the Greater Antillean mountain system. As the Greater Antillean fragments of that system show various signs of relatively modern upheaval, increasing westward and of much greater measure in Cuba than in Porto Rico, it is not improbable that a southward-curved extension of the same system has suffered a depression increasing southward and eastward; for the patches of the system seen among the Virgin Islands are of strongly deformed structure, as if the end of the mountain chain of which they once made part lay far beyond its point of disappearance.

Such a submarine extension of mountain systems is by no means uncommon. The Appalachian system undoubtedly extends northeast of Newfoundland, under the Atlantic, just as it extends southwest of northern Alabama, under the Gulf coastal plain. Similarly, the mountain structures of southern Ireland and western France extend westward into the Atlantic in undiminished force of deformation. The mountains of Burma are continued southward under the Indian ocean to and beyond the Andaman and Nicobar Islands. The mountains of eastern New Guinea, which bear marks of recent upheaval, are continued eastward to and beyond the Louisiade Islands, most of which bear marks of recent subsidence. But whether the curved Lesser Antillean mountain system ever formed a continuous land connection from the Greater Antilles to South America can probably be better determined by biological than by geological evidence, as will be shown below.

Confirmation of the idea, briefly stated in an early page of this essay, that the volcanic islands of the Lesser Antilles have been built up from a subsiding foundation—perhaps originally a land surface, as just suggested—is found in the occurrence of new eruptions while the subsidence of the islands formed by earlier eruptions was in progress: Martinique and St. Vincent are good examples of this relation, which goes far toward upsetting the old idea that volcanic eruptions are necessarily associated with upheavals. Here, as well as in the Hawaiian Islands, eruption is closely associated with subsidence.

THE UNCERTAIN DEPTH OF LOW-LEVEL ABRASION

The lowering of the ocean surface in the Glacial epochs, by reason of the withdrawal of ocean water to form several continental ice sheets and to enlarge many mountain glaciers, has been estimated by Daly to have been about 30 fathoms; and that measure has been frequently cited in the foregoing pages. It has nevertheless been impossible to secure any satisfactory visible proof of this estimate either in the Lesser Antilles or in the Pacific, because the platforms that are supposed to have been abraded around islands in the marginal belts during the Glacial epochs, especially during the last Glacial epoch, now seem to have been very generally aggraded enough to adjust them to the bank-building processes of normal ocean level. The banks of the Lesser Antilles that are exceptions to this statement depart from it by being even shallower than those which support it.

A corollary of this rule is that the depths of atoll and barrier-reef lagoons in the Pacific cannot be accepted as giving any close indication of the depth of low-level abrasion, not only because they lie in the coral seas where no low-level abrasion has taken place, but also because, even if they had been abraded at a low level, the platform then produced would have been shoaled so much by Postglacial aggradation as to be unidentifiable. It may be added that certain submerged atolls, like the Macclesfield Bank in the China Sea, have so great a depth in spite of some Postglacial aggradation that they cannot possibly be explained by the low-level abrasion of a stationary atoll.

OTHER INTERPRETATIONS OF THE LESSER ANTILLES

Various writers on the Lesser Antilles, among whom Spencer, Hill, and Vaughan may be named, have expressed diverse opinions as to their origin. Vaughan alone has given special attention to the coral reefs, and therefore his views concerning their development, summarized from a number of special articles in a full and detailed report,[39] may be briefly outlined as follows. The reefs are based on submarine platforms—circuminsular, terrace-like masses —which were formed by other than coral-reef agencies, and in the production of which reef-building corals therefore took no essential part. Whether the platforms were produced "by marine planation, by alluviation and the building of a coastal flat, by base-leveling through subaerial erosion, by the formation of a submarine plain of deposition, or by any other special process, is unimportant, provided the flat [platform] be formed." Both reef upgrowth and the infilling of reef-enclosed lagoons remain unmentioned among various specified methods of platform production, although five different origins are enumerated, for each of which an actual example is adduced, and a sixth—platforms of "complex and not definitely known origin"—is added, for which the examples given are the Antigua-Barbuda and the Virgin banks. The failure to men-

[39] See page 140, footnote 27.

tion reef upgrowth and lagoon infilling among the various methods of platform production can therefore be regarded only as meaning their exclusion; indeed, lagoon infilling is elsewhere explicitly excluded from consideration; it is directly asserted that "none of the . . . platforms were formed by infilling behind a barrier reef," and it is even thought that no one would try to explain them "as the result of infilling behind barrier reefs: they are submarine plateaus, leveled by planation agencies, which almost certainly were both subaerial and submarine, and they have been submerged in Recent geological time." And, as if in further evidence of the inefficacy of lagoon infilling, it is urged that "no evidence has yet been presented to show that any barrier reef began to form as a fringing reef on a sloping shore and was converted into a barrier reef by [upgrowth during] subsidence."

EVIDENCE FOR THE CONCLUSION HERE PRESENTED

It has not been without serious consideration of Vaughan's view that my very different view of the circuminsular banks of the Lesser Antilles, above set forth, has been adopted. The two views agree in only one respect; namely, that the present reefs are based on platforms in the production of which they, the existing reefs, took no part; but they differ widely as to the manner of platform production; reef upgrowth and lagoon infilling being rejected in one view and being accepted as leading and essential processes in the other. The following lines of evidence have guided me in assigning to those processes so important a rank.

First, it is believed that coral reefs, now submerged and buried, were formed in mid-Tertiary time during the earlier stages of the building of the platform masses around those Lesser Antillean islands which have not been uplifted into a second cycle of development, because fossil reefs of mid-Tertiary date occur in homologous masses on neighboring islands that have been uplifted; and it is believed that reefs were also present in late Tertiary time because the absence of strong spur-end cliffs on various islands shows them to have then been protected from wave attack. Second, it is believed that the Lesser Antillean chain of islands has subsided, because the presence of a fossil mammal in the stratified rocks of Anguilla and St. Martin demands such subsidence, as will be told below; because the considerable thickness of marine strata on the calcareous, second-cycle islands, the basal members resting unconformably on their foundation, confirms such subsidence; and because the well embayed shore lines of the maturely dissected volcanic islands attest this confirmation. Subsidence is, indeed, believed to be a dominant movement in the region, because it has been renewed in several of the uplifted islands. Furthermore, it is thought that subsidence has been relatively slow, because it has been compensated by the formation of the heavy circuminsular, terrace-like masses around the first-cycle islands and because continuous shallow-water deposition took place in the strata of certain second-cyle islands. Third, it is held to be entirely reasonable to regard barrier reefs as having been formed by upgrowth from fringing reefs that were first established on the slopes of subsiding islands, because the physiographic features of various islands which barrier reefs encircle in the Pacific coral seas demand such a method of reef formation; and because such an origin for the uplifted barrier reef of Mangaia in the Cook group has been demonstrated by Marshall in the clearest manner. Fourth, it is thought that lagoon infilling during Tertiary reef upgrowth was an effective process, whatever the source of the material, because a similar process is needed to explain the abundance of calcareous detritus that has been accumulated in Postglacial time on various Lesser Antillean banks since the sub-bank platforms were prepared by the action of low-level abrasion on the preëxistent circuminsular, terrace-like masses; the evidence of this abundant accumulation being found not only in the moderate depths of most of the banks but also in the beaches of calcareous sands that now stretch in concave curves between the cliffed volcanic headlands. At present, while the banks are very imperfectly rimmed with reefs or not rimmed at all, a considerable share of the detritus must be "wasted" by being swept off into deep water; while upgrowing reefs were present in Preglacial time, less detritus would have been swept away and a larger proportion of it would have therefore been available for lagoon infilling. Fifth, it is believed that low-level abrasion has recently acted to transform great, barrier-reef, terrace-like masses into circuminsular platforms because the reefs that must have long protected the islands from abrasion while they were undergoing far-advanced erosion are now absent, and also because the plunging cliffs on the island headlands bear witness to the recent action of low-level abrasion.

It is felt that these several lines of evidence converge upon the conclusion above announced and that they are well enough argued to show that the conclusion has not been adopted hastily or without good warrant. It may, indeed, be declared that this conclusion has the merit of a successful theory in that it brings order out of confusion by providing for many apparently independent items of observation a systematic arrangement in a well coördinated whole. When such a theory has been framed, the facts that pertain to it are no longer regarded only as so many isolated, individual occurrences; they fall into their proper relative positions so naturally, become the essential elements of a reasonable entity so spontaneously and so unconstrainedly, and in those positions supplement and support one another so helpfully that one wonders why they ever seemed unrelated. Yet in my own experience an incubation period of five months elapsed after observational exposure to the facts above detailed before their coördinated meaning "broke out" upon me. Since then the islands, banks, and reefs of the Lesser Antillean chain have seemed almost transparent, so great has been the aid given by the adopted explanation of their origin in penetrating their structures and in recognizing the past conditions and processes through which they were brought into being. Yet the large share of the adopted explanation, which, apart from the facts of direct observation, consists of mental inferences, is after all only a figment of the imagination. Perhaps it is incorrect. Time will show.

Biological Relations

EVIDENCE FOR A LAND BRIDGE

The distribution of plants and animals, fossil and living, in connection with the study of the physiographic evolution of their habitat may be profitably studied in the Lesser Antilles. Certain conditioning views as to the origin of the islands must be considered. According to one view, the eruptive construction of the larger islands was begun while their subsiding foundation still constituted a continuous land bridge between the Greater Antilles and South America, whereby a free distribution of species was made possible from those great organic reservoirs. Then, as the bridge was submerged and the volcanic mountains became islands, the plants and animals, driven from one part of an island to another by intermittent eruptions, mounted the slopes of the volcanoes as the bases were submerged, so as to escape drowning or to find a suitable climate. Thus isolated, specific variations might go on without restriction, except the chance arrival of waifs from the continents; but the waifs being in a small minority would, according to Robinson's principle,[40] probably be unable to check any variation that had begun before their arrival. As long as an island remained of fair size, its mounting fauna and flora might continue to thrive; but as the island area and altitude became reduced by erosion and subsidence, the struggle for existence must have become more and more severe, and one species after another would have become extinct; and when an island was completely submerged, and only an atoll reef left to mark its site, all its species would have disappeared except those capable of survival on small reef-sand islets.

On the other hand, certain volcanic islands may have been built up after their part of the assumed land bridge had been submerged; Saba is certainly one such island, and it is probable that Statia, St. Kitts, Nevis, and Montserrat are others. Here the fauna and flora must consist of waifs only. However, again according to Robinson's principle, a waif species, once well established, may develop variations about as well as a species that survives from a larger area after isolation of its habitat by subsidence, provided that new waifs of the same species do not arrive too frequently. Hence the fact that an island species is different from its relatives on a near-by continent cannot be taken to prove—as it sometimes has been—that the species did not arrive as a waif but reached the island by a land connection that has since disappeared.

[40] B. L. Robinson: Flora of the Galapagos Islands, *Proc. Amer. Acad. of Arts and Sci.*, Vol. 38, 1902, pp. 75–269.

Finally, second-cycle islands which passed through the final or atoll stage of the first cycle must also be populated only by waifs, except in so far as certain first-cycle occupants survived on reef-sand islets.

In applying the above conditioning factors several essays on Antillean fauna and flora may be here briefly noticed.

THE BIRDS OF THE LESSER ANTILLES

Consultation with Messrs. Bangs and Peters, ornithologists of the Museum of Comparative Zoölogy at Harvard University, has given me several interesting items about the birds of certain islands. In the first place, the birds of the four relatively young volcanic islands above named are of wide-spread distribution, and they may therefore be regarded as having arrived there after the islands had been built up by eruption; they are not species of ancient relationships, peculiar to the islands, as if they had long been resident there from the time of a long-submerged land bridge. The same is true of the second-cycle islands of the St. Martin's group; for, after the earlier avifauna was largely extinguished when the group had reached the atoll stage, the islands must have been repopulated by wanderers after elevation gave them a new lease of life. The birds of Antigua are said to be similar to those of low, limestone islands, as if the forms that were appropriate to it during the atoll stage had not been largely added to since renewed uplift produced its present submountainous relief.

The avifauna of the Grenadines presents some striking peculiarities. It will be remembered that these islands are the present reduced representatives of relatively ancient and originally much larger volcanic masses. The northernmost of them, Bequia, is separated from the larger island of St. Vincent by so narrow a water passage that it is administered politically under its larger northern neighbor instead of in association with its smaller physiographic comrades to the south; but the narrow water passage is relatively deep, and apparently for that reason a number of birds that are common to Bequia and several of the little Grenadines as well as to the larger Grenada, all of which rise from the same shallow bank, are unknown on St. Vincent, which surmounts another bank. There could hardly be a better illustration of the desirability of studying island faunas in view of the physiographic history that the islands have passed through.

THE MAMMALS OF THE LESSER ANTILLES

The mammals of these islands have been studied by Allen and Anthony.[41] Anthony classes the mammals of the West Indies as a whole in two distinct groups, one of ancient, the other of recent introduction. As the representatives of the latter group, chiefly agoutis, opossums, rice rats, armadillos, and raccoons are found for the most part on the Lesser

[41] G. M. Allen: Mammals of the West Indies, *Bull. Museum of Comp. Zoöl.*, Vol. 54, 1911, pp. 175–263.

H. E. Anthony: The Indigenous Land Mammals of Porto Rico, Living and Extinct, *Memoirs Amer. Museum of Nat. Hist.*, Vol. 2 (N. S.), 1918, pp. 333–435.

Antilles; and "it is very probable that man has played the major part in their distribution . . . for they are in every instance clearly derived from adjacent mainland ancestors existing today." On the other hand, "the ancient terrestrial mammals belong to three orders, Edentata, Rodentia, and Insectivora." One of the most remarkable of these is an extinct rodent, Amblyrhiza, of South American affinities, "as large as a good-sized pig." Its fossil remains were first found by Cope in 1868, when a vessel from Anguilla discharged its ballast on a Philadelphia wharf; a later find was made by Spencer on St. Martin in 1910: both probably came from the mid-Tertiary deposits that were laid down late in the first cycle of those islands' evolution. As this heavy land animal could have reached the St. Martin's group only by a land bridge at the opening of its first-cycle history its presence there gives confirmation to the first view above stated, that the older islands existed as volcanic mountains before their dry-land foundation, connecting them with South America, was submerged; and it appears also to exemplify the view that the extinction of a land mammal would occur when the late stage of the first cycle of island development was reached; for the islands that the Amblyrhiza occupied are best explained as having passed through the atoll stage of their first cycle before entering upon the second cycle in which they are now well advanced.

Singularly enough, bats are believed by both Allen and Anthony not to fly from island to island.

Anthony says: "Although possessed of strong powers of flight, the bats are found to be affected by nearly the same distributional factors as are terrestrial mammals. Islands quite near to the mainland have in numerous instances developed species of bats peculiar to themselves. . . . The greater part of the bat fauna of the Antilles is peculiar to the islands, and here again we encounter two types of fauna, the ancient and the recent or waif fauna. . . . The ancient forms are quite distinct from the mainland forms, usually as well marked genera, and are doubtless a remnant of an earlier bat fauna on the mainland now unknown there. These genera have several species on the different islands, and this gives an index to the rate of specialization since the time that the bats became cut off from the mainland and from each other." According to this singular interpretation, additional evidence is gained for an ancient land bridge on which the volcanic mountains were built up before they became islands.

THE AGAVES OF THE LESSER ANTILLES

As an illustration of the distribution of Lesser Antillean plants, citation may be made of Trelease's monograph of the Agaves,[42] in which a too favorable consideration seems to be given to Spencer's idea—an idea that seems to have no sufficient foundation—that the depressions between the adjacent islands represent river valleys eroded during a time of much

[42] William Trelease: Agave in the West Indies, *Memoirs Natl. Acad. of Sci.*, Vol. 11, 1913, pp. 1–55.

greater elevation than now.[43] Trelease writes: "The mental image that may be formed of the Antillean region in early Quaternary time is that of a rather low table land stretching from what is now Yucatan and Central America to South America; bordered by a volcanic range, the peaks of which now project thousands of feet above water, though the present difference of level between their summits and the intervening deeps may perhaps be due to crumpling as well as general elevation and attendant erosion. . . . The Caribbean volcanic peaks were connected by land at one time during the insular history of the genus [Agave], though they are now divided by deep-sea channels. . . . Even narrow channels here constitute all but insuperable natural barriers to their distribution. . . . The significance of a channel barrier lies rather in depth of submergence, corresponding to lapse of time, than in width. The Agaves are conceived as having spread eastward from Central America along the curved land belt, and to have undergone specific differentiation as they were progressively isolated by subsidence."

Spencer's idea that the inter-island channels are submerged valleys of erosion has not gained acceptance among geologists; the channels appear to be merely the deep-water spaces that have not been filled up by the growth of the adjacent volcanoes. Trelease's assumption that the antecedent land area survived here until Quaternary time is altogether im-

[43] See several articles by J. W. W. Spencer in *Quart. Journ. Geol. Soc.*, Vol. 57, 1901.

probable, in view of the Tertiary date of the limestones in Antigua and the St. Martin group; and his implication that all the volcanic mountains now seen existed on the border of that land area before its submergence cannot hold good for the younger islands, such as Montserrat, and still less can it hold good for the even younger islands farther northwest. Indeed, it is improbable that such vigorous volcanic mountains as are seen on Guadeloupe, Dominica, and Martinique gained their present volume before their foundation was submerged. They seem to represent later eruptions after submergence was well advanced. As such, they have probably been built up on earlier-formed volcanic masses, or on banks surmounting submerged volcanic masses. On the other hand, it is perhaps reasonable to regard the little Grenadines as the surviving summits, much worn down by erosion, of volcanoes that may have been based on the assumed land area before it was submerged. The same origin is even more reasonable for the Virgin Islands, because patches of preëxistent land areas are still seen there, not wholly submerged even today. In view of this interpretation, it seems questionable whether some of the Antillean Agaves are not waifs; for Tealease's rejection of that possibility appears to be based chiefly on the fact of specific differentiation, rather than on any direct proof that the Agave could not be transported occasionally from island to island by natural processes; and perhaps also on the view that a few members of a species arriving on an island as waifs would not give rise to a new species peculiar to that island because they would be held to their original form by crossing with waifs of later arrival. But Robinson's principle, already cited, seems to make the local differentiation of waif-supplied species quite possible, provided, as above noted, the arrival of later waifs is not too frequent.

In any case, the occurrence of *Agave barbadensis* on Barbados should not be regarded as a local variation from an ancestor which reached that island by a land bridge, because the geological history of the island shows that it has been completely submerged since its first insular existence and that even when first formed it was very likely not connected with the continent. Similarly, the occurrence of *Agave obducta* on Antigua can hardly be explained as the successor of an Agave that reached the island by a land connection from elsewhere, because Antigua is believed to have past through the ultimate or atoll stage of its first-cycle history before it was introduced into its present, or second cycle by upheaval. Whether *Agave Van-Grolae* of Statia and *Agave nevidis* of Nevis can have survived by mounting those volcanic cones as their bases were more and more submerged, seems doubtful, not so much because a great measure of mounting was required, as because after the original islands were decreased in size by submergence, the Agaves of that time might have been destroyed by the showers of ashes thrown out by the eruptions that built up the young cones of today. Furthermore, as the specific difference between the Agaves of different islands are so small that Trelease regarded the genus as of rather slow plasticity, even though only Quaternary time was in his view available for their variations, its plasticity must have been much slower if the separation of the islands by submergence dates from middle Tertiary time. The Agaves thus seem to give much less valuable evidence as to the evolution of the islands than that presented by the mammals.

Pacific and Atlantic Reefs

NOVICE AND VETERAN CORAL REEFS

Attention must now be called again to the contrast, already briefly noted in an early paragraph of this essay, between the novice reefs on circuminsular banks in the marginal belts of the coral seas and the veteran reefs in the true coral seas; for without a clear understanding of that contrast, the new light thrown by the Lesser Antillean reefs upon the old coral-reef problem cannot be appreciated. The contrast will be first stated for the Pacific ocean where it is best developed. There the novice reefs of the marginal-belt islands and banks—namely, the smaller northwestern members of the long Hawaiian chain and certain southern members of the Bonin and Riu-kiu groups in the North Pacific; Norfolk and Lord Howe Islands, and probably Raoul Island in the South Pacific—are discontinuous, one might almost say timid structures, which stand well back from their bank border; and the islands with which these reefs are associated have cliffed shores, sometimes embayed, sometimes not. But the veteran reefs that abound in the vast area of the Pacific coral seas are strongly developed, stalwart structures, which rise bravely, not to say boldly, from the outer border of their lagoon floors next to deep water; and, if the lagoons include islands, their shores are not cliffed unless the islands are young. These veteran reefs appear to have been growing continuously since middle or late Tertiary time and are therefore the direct successors of ancient ancestors, without more interruption in the succession than has been involved in a small downward migration of reef-building corals on the outer reef slope and a solutional erosion of the emerged reef crest with each lowering of the ocean, and a similar upward migration and rebuilding of the reef crest with each rise of the ocean in successive epochs of the Glacial period. On the other hand, the novice reefs are not the direct successors of ancient ancestors; their predecessors appear to have been cut away to platforms of low-level abrasion in the Glacial epochs, and the present reefs are therefore only of Postglacial date. They thus exemplify, within the narrow limits of their belts, certain processes of the Glacial-control theory of coral reefs, as set forth by Daly, although their islands do not exemplify the stability of reef foundations postulated in that theory, and their banks do not show the accordance of depth that is supposed in that theory to have been produced by low-level abrasion, little modified by Postglacial aggradation.

The same contrast is found in the Atlantic, but it is less marked, because the true coral seas of that ocean, as indicated by the occurrence of stalwart reefs bordering deep water, are imperfectly developed; they are limited to the Caribbean sea and to parts of the Gulf of Mexico. Yet in the Atlantic the contrast is of precisely the same kind as in the Pacific; the novice reefs of the Lesser Antilles appear to be of Postglacial date and are associated with cliffed islands; they are discontinuous and weak as compared with the bank-border reefs of Cuba. The Cuban reefs have probably grown up from a considerable depth, as there is no indication that their predecessors were cut away by low-level abrasion; the Lesser Antillean novices seem to be based on preëxistent platforms produced by low-level abrasion and afterwards shoaled by aggradation; and, as Vaughan has pointed out, in the production of these platforms the present-day reefs have not been concerned.

In neither ocean has the contrast between the veteran and novice reefs received sufficient attention. Indeed, the Lesser Antillean novices have been taken as so nearly the equivalent of the veterans of the Pacific coral seas that the latter have been interpreted as based on platforms, like the former. This seems to me an error. The novice reefs of the two oceans are closely alike; and the novices of one ocean may be well believed to have the same kind of abraded platforms beneath them and the same Postglacial origin as those of the other; but the novices should not be accepted as exemplifying the origin of the veterans. In both oceans the novices of the marginal belt are strikingly unlike the veterans of the coral seas. It is therefore important that these two classes of reefs should be distinguished.

THE MARGINAL BELT OF THE CORAL SEAS IN THE ATLANTIC

The difference in the dimensions of the Atlantic and Pacific oceans leads to an unequal development of their climatic subdivisions with respect to which oceanic islands have been classified in an earlier section. In the Pacific, the cool seas of the north and south temperate zones unite across the eastern part of the torrid zone in a broad space some 3000 miles wide, west of South America, by reason of the equatorward flow of cool currents; and coral reefs are there excluded. But the total equatorial breadth of the Pacific is so great that the surface water, warming as it flows westward through the torrid zone, first acquires and then maintains a temperature high enough for reef growth through an equatorial distance of 5000 miles in the central and western part of the ocean; and there are the great coral seas of the world. Similarly in the Atlantic the northern and southern cool seas unite across the torrid zone as they do in the Pacific and for the same reason; but here they occupy almost the entire equatorial breadth of the ocean. It is only in the northwestern extension of the equatorial waters in the American mediterraneans that they are warm enough for vigorous reef growth;

for there only are stalwart reefs found bordering on deep water and therefore comparable with the veterans of the Pacific coral seas. Between the cool seas which occupy so great a part of the temperate and torrid Atlantic, and the warm mediterraneans which occupy the relatively small reëntrant space bordered by North and South America, we should expect to find islands and reefs of a marginal-belt habit: and, truly enough, the reefs of the Lesser Antilles are discontinuous bank reefs and the island shores are cliffed. Hence, while the Atlantic is as complete an ocean as the Pacific with regard to its currents and tides and deep temperatures, it is a much less complete ocean than the Pacific with regard to coral reefs. The open Atlantic is, in that respect, only a reefless East Pacific.

The marginal belt of the Atlantic seems to extend along the east coast of torrid South America; a number of bank reefs are charted well back from the outer border of the continental shelf on the Brazilian coast south of Cape San Roque, the southernmost being the Parcel das Paredes and the Abrolhos Islands in latitude 18° S. The belt passes near that cape, for the nearest approach to an atoll contained in the open Atlantic is a small reef known as the Rocas, which stands 125 miles off the coast in latitude 3°51′S. and is best described in a little-known report of Lieutenant Lee of the U. S. Navy, who examined it in 1852.[44] It is about a mile and a half in diameter,

[44] S. P. Lee: Report and Charts of the Cruise of the U. S. Brig Dolphin, *Senate Doc. 59, 33rd Congr., 1st Sess.*, Washington, 1854. See also H. O. Chart 537.

enclosing a small lagoon; but it is a bank atoll, not a true atoll, for it surmounts a shoal with depths of 15 fathoms six miles to the north and of 15 to 18 fathoms two miles to the northwest; the bank border is not charted. To the east of this bank atoll is the rocky island of Fernando Noronha, measuring four and a half by two and a half miles across and 1000 feet high; it has irregular shores with headland cliffs of moderate height; a shoal extends a mile to the north and northwest, with 35 fathoms of water. Branner states that no coral reefs occur here, although a few growing corals are seen on the rocky shore and water-worn coral fragments are found on the beaches.[45] There are, unfortunately for our present needs, no islands between the Rocas and the Lesser Antilles; the shallow coastal waters of northeastern South America lie upon a continental shelf of muddy deposits, where no coral reefs are found; nevertheless, if islands occurred there, they would probably have cliffed shores and bank reefs like most of the Lesser Antilles, for the marginal-belt conditions are reasonably sure to prevail in this part of the Atlantic in spite of apparent absence of cliffs on Barbados. From the Lesser Antilles the marginal belt probably extends farther northward and after making a long northeast loop to Bermuda, where a submarine bank of much greater extent than the island is found, crosses the Gulf of Mexico. It may be again noted that the reëstablishment of reef-building corals on the Lesser Antillean platforms in

[45] See page 61, footnote 17.

Postglacial time was probably delayed in part by the absence or extreme rarity of floating coral larvae in the equatorial current that bathes their shores, as well as by an insufficient rise in its temperature.

Each of the Lesser Antilles is worth study; but the study of each island gains an increased interest when an examination of all shows them to be systematically related as members of a relatively simple scheme of development. Similarly, the study of the island chain as a whole is well worth while; but that study in turn gains a larger value when it is extended so as to show that these islands and certain others belong in what is here called a marginal belt of the coral seas, characterized by coral-reef growth in warmer climatic epochs, but by the inhibition of such growth in cooler epochs, and lying between the cool Atlantic, where no coral reefs have been formed even in warm epochs, and the American mediterraneans, where reefs have long flourished even in the less warm epochs. An even greater interest is found in the study of the Lesser Antilles when it is discovered that the Atlantic marginal belt to which they belong has its counterpart in a Pacific marginal belt and that the small American mediterraneans, enclosed from the cool Atlantic by its marginal belt, therefore correspond to the vastly larger coral seas of the Pacific, similarly enclosed by a marginal belt from the cooler parts of the Pacific. The Lesser Antilles thus take their proper place in a world-wide problem.

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