NEW YORK ACADEMY OF SCIENCES

SCIENTIFIC SURVEY
OF
Porto Rico and the Virgin Islands

VOLUME IV—Part I

Geology of the Virgin Islands, Culebra and Vieques

Introduction and Review of the Literature—*James F. Kemp*
Physiography—*Howard A. Meyerhoff*

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INTRODUCTION AND REVIEW OF THE LITERATURE ON THE GEOLOGY OF THE VIRGIN ISLANDS

By James F. Kemp

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INTRODUCTION

When the Scientific Survey of Porto Rico and the Virgin Islands was organized under the auspices of the New York Academy of Sciences, in 1913, the committee in charge felt that it was wisest to study first the larger island, Porto Rico, because of the more extensive exhibition of geological phenomena. The opinion was held that when once the geological section should be established for it, the investigation of the smaller islands to the east could be best undertaken. In the ten years which followed, so much was learned of Porto Rico that in 1923 the time was considered ripe to take up the geology of the Virgin Islands. Meantime the study of the plant life had gone vigorously forward, so that Volumes V and VI of the Survey, by Dr. N. L. Britton and Dr. Percy Wilson, cover both Porto Rico and the Virgin Islands, and have been issued in advance of Volume IV, on the geology of the latter group.

In the spring of 1923 the writer spent two weeks, in company with Dr. Britton, in a reconnaissance of St. Thomas and St. Croix, with a view to preparing for more detailed work by a subsequent observer. These completer investigations were entrusted, early in 1924, to Prof. Howard A. Meyerhoff, to whose pages this preliminary review is intended to serve as an introduction. Mr. Meyerhoff has also studied St. John and the British Virgin Islands, as well as Vieques and Culebra, the two larger islands lying east of Porto Rico and under its jurisdiction.

When the Survey was first organized, it was the plan of the committee in charge to have Dr. Edmund Otis Hovey undertake the study and description of the Virgin Islands, for which his notable work in Martinique and his travels in other islands of the Lesser Antilles, including St. Croix, especially qualified him. But Dr. Hovey's trips to the Arctic and to the South Pacific in the ensuing years gave him such a wealth of material for study and description that in 1923 he very kindly relinquished the original plan to those who could immediately take it up and carry it to completion. We wish, however, to make grateful acknowledgment for this courtesy, and the more so because Dr. Hovey's sudden decease on September 26, 1924, has deprived a wide circle of colleagues and friends of an associate who could ill be spared.

In our reconnaissance of 1923 we learned that St. Thomas consisted essentially of igneous rocks of much the same varieties as those which form the older series in Porto Rico. In St. Thomas, as in Porto Rico, they are predominantly andesitic in character, and they consist more largely of volcanic tuffs and breccias than of solid intrusives or lava flows. With these rocks there are relatively small amounts of true sediments, partly shale whose materials appear to be derived from tuffs, and partly a very small amount of limestone containing Cretaceous fossils. Some of this limestone appears as inclusions, brought up from below or, at least, involved in a mass of beautifully porphyritic, olivine-free basalt with large augite phenocrysts, at Coki Point, on the northeast corner of the island. The inclusions are recrystallized by the igneous rock, but the fossils are still recognizable. That some additional metamorphism had been experienced elsewhere by the shales we learned from the discovery of a sericitic slate or phyllite near Löwenlund, in the north-central part of the island. We also noted the predominant east-and-west strike of the stratified beds, as having a northwesterly swerve at Magens Bay and showing in these two features the same characteristics as the Cretaceous volcanics in Porto Rico. The prevailing dip was to the north and northeast. On Outer Brass Island, which maintains the structural features of Magens Bay, the strike was N. 50° W., dip 72° northeast. The structural features are much more fully discussed by Mr. Meyerhoff in subsequent pages.

REVIEW OF THE LITERATURE ON THE GEOLOGY

Several earlier geologists have left recorded observations on the Virgin Islands, both the British group and the present American group, which latter was, until its purchase in 1917, a Danish colony. A "Bibliography of the Virgin Islands of the United States, formerly Danish West Indies," has been prepared and was printed by the Government Printing Office, in St. Thomas, in 1922. It contains classified references, with brief abstracts under the heads: A, General Works on Danish History; B, General Works on the West Indies; C, Virgin Islands of the United States, General Description; D, do., Historical; E, do., Church History; F, do., Slave Trade; G, do., Sale Question; H, do., Economic; I, do., Geological (under I are seven references, viz., three in English, two in Danish, and two in German); J, do., Botanical; K, do., Zoölogical; L, do., Fiction; M, do., Statistical; N, do., Catalogues and Indices. All the seven articles mentioned on the Geology have been abstracted in this Introduction, and to them several more have been added.

The review has been made in rather full detail because, in justice to the earlier workers, a correct bird's-eye view should be given of what had been accomplished when our Natural History Survey entered the field; and still more because many of the earlier papers are in publications not easily accessible and in the Danish and German languages. The writer desires at this point to express his acknowledgments to Prof. Hans Cloos, of the University of Breslau, for help in abstracting the paper of Robert H. Schomburgk, of 1839, which could not be found in an American library, and to Miss Hedwig Eskesen, of New York, for aid in translating the papers in Danish. Acknowledgments are also due to the writer's assistant, Miss Helen R. Fairbanks, for help in following up references and in preparing the manuscript.

1817. WILLIAM MACLURE. "Observations on the Geology of the West India Islands from Barbados to Santa Cruz, inclusive," Journal of the Academy of Sciences of Philadelphia, Vol. I, 1817, pp. 134-149.

The author treats of the Lesser Antilles and divides them into two groups, which are contrasted in their geology. Beginning at the southern end of the Windward Islands, he places in an eastern group Barbados, Mariegalante, Grandterre in Guadaloupe, Deseada, Antigua, St. Bartholomew, St. Martin, Anguilla, and Santa Cruz. They are all marked by "a stratification of transition rocks, partially crowned by secondary." By transition rocks he meant in general the Paleozoic strata of modern usage, but the beds he referred to are those of our older series, which we now know to be Upper Cretaceous. Under secondary he includes our later limestones, now referred to the Oligocene and later Tertiary. The remaining islands, which he calls the western group, consist of volcanic formations with a few partial coverings of his secondary strata. They embrace the Grenadines, St. Vincent, St. Lucia, Martinico, Dominica, Basseterre in Guadaloupe, Montserrat, Nevis, St. Christopher, St. Eustatia, and Saba. The individuals of each group, beginning with Barbados, are then briefly described as to geology and topography.

St. Thomas is mentioned on page 137, along with the first group, as follows:

> The island of St. Thomas may also be classed in this range. It is stratified, though in much confusion, and so deranged as to render it difficult to ascertain the general direction, which appears to be from northwest to southeast, dipping easterly. The rocks consist of a variety of aggregates resembling the

transition, some of which when fresh have the appearance of hornblend rocks, but when beginning to decompose the aggregate appears with a few plates of a black crystalline rock like hornblend. I found a yellowish brown, quartzy aggregate resembling a rock, in the transition, at the Lehigh Falls, in Pennsylvania.

One scarcely knows to what to refer today the hornblend rocks of Maclure, but probably some dark dike or sill in the predominant tuffs and breccias caught his eye.

Of Santa Cruz, he wrote as follows (pp. 137-138):

Santa Cruz.—This island, though included in our first division, agrees rather with the direction of the volcanic islands; it appears, however, that the volcanic formation ceases at Saba, and that Santa Cruz is composed of madrepore rocks on the west; and, on the eastern side, of rocks similar to those of St. Thomas and St. Bartholomew. The west end and the middle of the island are low, and covered with a shell limestone and madrepore rock. The foundation on which this rock reposes is a stratum that retains water, and may be a compact limestone, as the bases of many of the little hills rest on solid limestone. The east end is composed of different kinds of limestone, alternating with amygdaloid, hornblende rock and porphyry, like the rocks of St. Bartholomew; it is likewise hilly and broken, being stratified in a direction nearly north and south.

One recognizes at once in this description the Tertiary, Oligocene, and Miocene flat limestones of the western and central parts of the island. The older Upper Cretaceous tuffs, sills, and associated clastic sediments, with two or three cases of limestone, are the ones described by Maclure from the east end. Our observations have not shown, however, as much limestone as would be implied by Maclure's description of the east end of the island. The large area of these older rocks in the northwestern part is not specifically mentioned. In judging of his stratigraphical names, it is necessary to put oneself back amid the conditions of America in 1817, when the Wernerian divisions of the geological column were the ones in every geologist's mind.

1832. ROBERT HERMANN SCHOMBURGK. "Remarks on Anegada." Read June 25, 1832, Journal of the Royal Geographical Society of London, Vol. II, 1832, pp. 152-170.

By way of introduction to the first of several papers to be cited from this author, it may be stated that Robert H. Schomburgk is one of the most interesting of the early naturalists concerned with the geology of the Virgin Islands. He was born in 1804, at Freiburg, on the Unstrut, in southern Prussian Saxony, a few miles southwest of Leipzig, in which city he entered business, after a common school education. At eighteen years of age (1822) he took a flock of Saxon sheep to North America, where he remained, engaged in commercial life. In 1830 he removed to the West Indies and sought to establish an independent business enterprise, which failed. As a result, he yielded to a consuming fondness for scientific exploration and travel. Although self-taught, he was botanist, geologist, physicist, geographer, and general scientific observer—in short, a naturalist of the old school. He is best known for his researches in Guyana, 1839-1840, where he became British consul. He received the great gold medal of the Geographical Society of London, and was knighted in 1845, so that he is often cited as Sir Robert Schomburgk. He served as British consul in Haiti, and was Consul General in Bangkok, in the Malay Peninsula, 1857-1864. Debilitated by the climate, he returned to Europe, settled at Schöneberg, near Berlin, where he died in March, 1865. He had a younger brother, Otto Schomburgk, who also explored the Guyanas, with whom he is not to be confounded.

The contribution on Anegada takes up the most northerly and the simplest in its geologic structure of all the Virgin Islands. It is recognized by Schomburgk to be of coral origin and to be built up on a base which, he concludes, because of the shallow soundings between it and Virgin Gorda, is probably the same as the volcanic foundation of the more southerly island, lying eleven and three-eighths nautical miles away (p. 154). Anegada is about ten English miles long and, at its broadest, four and a quarter miles across. It rises at its greatest elevation sixty feet above the sea. The paper opens with a brief historical account and contains, scattered through its pages, records of the botany and zoölogy. "On landing, the beach is found everywhere coated with a gray, siliceous and calcareous substance (the prominent ingredients of which are clay, fragments of limestone and vegetable fibers) which seems to be deposited by the waters; and as the tide retires, hardens and assists slowly in increasing the island." The island consists of sand, formed of fragments of coral and shells, at times cemented into solid rock below the surface. Flotsam and jetsam cast ashore by the currents and residual organic matter from seaweed and land vegetation enter into the composition of the rock. There are some curious benches of rock in which conical cavities are filled with fresh water, down to depths of six fathoms and less. Other benches, or "shelves," are a resting place for residual soils largely of organic matter, on which vegetation grows. Similar deposits are on the lee sides of sand hills. Salt ponds form a considerable portion of the total area, and in dry seasons yield salt. The island is surrounded by coral reefs, which extend but a short distance seaward on the north and west, but appear two miles or more out to the south, and are prolonged to the southeast for five to eight miles. They have proved a graveyard to shipping. Schomburgk gives a list of fifty-three recorded wrecks up to 1831, and marks the place where each struck, on the excellent chart of the islands and their reefs, which he prepared to accompany his paper. Schomburgk also ran a line of soundings in a southwest direction to the island of Jost (or José) van Dyke. He found relatively shallow water, with a minimum of seven fathoms, and sandy bottom all the way (p. 155).

The writer learns from Prof. Hans Cloos that the observations on Anegada are also in Berghaus' "Kabinets-Bibliothek der neuesten Reisen," Bd. I, Berlin, 1834; also, that an account of Schomburgk's first visit to Virgin Gorda and of his observations on its rocks is in Berghaus' "Annalen der Erd-, Voelker-, und Staatenkunde" (Fortsetzung der Hertha) dritte Reihe, Bd. I, Berlin, 1836.

1837. ROBERT H. SCHOMBURGK. "Die Jungfrau-Inseln, in geologischer und klimatischer Hinsicht" (The Virgin Islands, geologically and climatologically considered). Berghaus' "Almanach für Erdkunde," 1837, pp. 367-455.

The writer was unable to find a copy of this reference in the American libraries, but by the great kindness of Prof. Hans Cloos, then of the University of Breslau, Germany, he was favored with a summary of thirty-three typewritten pages, made from the copy in the Breslau University library.

The paper on the Virgin Islands contains much matter not strictly geological, which is omitted in this summary. It opens with a bird's-eye view of the West Indies, remarking that some observers have inferred that the archipelago was once connected with the American continent, forming a range of mountains which by the working of subterranean heat had been in part broken and in part elevated until the basins of the Caribbean Sea and of the Gulf of Mexico had resulted, with the continental land on one side and the mountain chains of the row of islands on the other. The row of islands ranges in a general northwesterly direction, and has been divided by geographers from northwest to southeast into (A) The Bahamas, (B) The Greater Antilles, (C) The Lesser Antilles, (D) The Caribbean Islands. The last-named are subdivided into (1) The Virgin, (2) The Leeward and (3) The Windward Islands. This usage is obviously different from the modern, as C and D are now collectively called the Lesser Antilles.

Our author is strengthened in his belief that the islands were once connected with the mainland because soundings from island to island show at the most 150 fathoms and often as little as 10 fathoms. (This statement requires some modification in the light of modern knowledge.) The trend of the insular mountains is the same as the islands themselves and the faunas and floras of the islands are similar to those of the neighboring continents; thus, Trinidad and Tobago[1] favor South America, while Cuba and the Bahamas favor Florida.

The mountain chain of Cuba runs east and west and is prolonged in the Ceiba, or chief range of Haiti. The same holds true of Porto Rico. The Virgin Islands appear to end this mountain system. The Caribbean Islands take a new direction and were probably once a part of the Venezuelan mountains. Were it possible for a mortal man to take such a position and to have such powers of sight that he might view at once all the islands, they would impress him as a bent mountain chain with the Virgin Islands at the northeast corner.

Confining ourselves to the Virgin Islands, we see that their north sides are exposed to the full force of the Atlantic and are cut into steep fronts. The rocks are chiefly hard fragmental varieties, including an amygdaloid conglomerate, of dark red, brown, or green color. The northern sides of Guano Island and of Tobago (*i. e.,* Virgin Islands' Tobago) are well worth more detailed investigation.

Schomburgk next takes up Guano Island in some detail and mentions not only the amygdaloid conglomerate, but other massive rocks of uniform texture, one of which is set with cubes of pyrite, altered to limonite. On the summit of the island is greenstone porphyry in huge blocks, similar to others on Tortola. On the west side of Guano Island a great columnar mass, 150 feet high, has been split off from the rest and is hollowed out in a winding cave with rounded rooms. After a general discussion of the origin of caves, Schomburgk concluded that this one had been worn by the waves when the island stood lower and the waves dashed through the passage.[2]

As an illustration of other great blocks, Schomburgk selects the island of Great Tobago, where a north and south cleft, three feet wide, reaches a height of 200 to 300 feet and extends 200 feet horizontally. Again, on the northeast side of Ginger Island, the granite of Virgin Gorda is broken into huge blocks, which fail toward the picturesque South Bay. As the rock is composed of predominant feldspar, with quartz, hornblende, and variable biotite, Schomburgk, like many another petrog-

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[1] There are two or three Tobagos; that here referred to is the one near Trinidad. The Great and Little Tobagos of the British Virgin Islands lie north of St. John.

[2] One is reminded of the window or hole on the island of Torghat, lat. 65° 30′, off the coast of Norway.

rapher of his day, does not know whether to call it granite or syenite. The microscope has now shown it to be quartz diorite. On the western side of Ginger Island, and especially toward the south, are crystalline limestones and hornblende schists. The marble is cut by an igneous dike, which is itself cut by two quartz veins. A westerly hill on South Bay contains white marble with brownish red garnets and associated with gneiss.

Schomburgk does not fail to recognize in this locality the work of what he calls "indirect igneous," if not volcanic forces. When the dike referred to above widens and spreads as it rises, Schomburgk explains the phenomenon as due to lessening load. The shearing and crushing forcibly bring home to him the uplifting forces which rubbed and crushed the rocks against whatever resisted their progress. Considering the development of geology in 1837 or earlier, and that Schomburgk was self-taught, the reader wonders at his insight. He mentions also on the east side of South Bay, and near the trail over the hill, a small pond of sulphurous water believed to be deadly to animals which drink it.

Coopers Island, which varies from Ginger Island in structure, is next described. On the western bay are blocks of granite rocks, apparently embracing both granite and syenite, recalling conditions on Virgin Gorda. The granite is massive, the syenite in layers or benches, with a 75° dip in a direction S. 30 W., or, as we say today, with a strike N. 60° W. and a dip 75° south. Along the southwest bay are steep rocky walls of porphyry and other rocks with a westerly dip toward Salt Island. They are the same kinds of rocks which are later described on Virgin Gorda with a northerly dip. The strata are compressed and have interbedded quartz masses. Salt Island is an obvious continuation of the formations on Coopers Island. There are brownish yellow compact limestones, with streaks of white marble. In the crevices are druses of calcite. Salt Island gets its name from a salt pond suited to the recovery of salt during dry seasons.

On Peters Island appears again the brownish yellow limestone with a streak of white marble. Gneiss with brown mica and white feldspar may be observed near the little western haven, and on the western point is decomposed, pyritiferous porphyry, in which is a cave.

Along the south side of Tortola is marble, and then, as one goes from east to west, finely crystalline, green diorite, interstratified with siliceous, dense, green limestone. Near Coxheath marble and granite are associated. As an example of the geology in general, Schomburgk selects the locality of St. Bernards, in the western part of Tortola, and devotes eight pages (385-393) to its detailed description. Without following his account step by step, we may say that he was confronted with a stratified series in which limestone played a prominent part and in which it was associated apparently with tuffaceous sediments now metamorphosed to slates and mica schists; granite and porphyry do not fail. The limestone is extensively, although not everywhere, altered to marble. Brownish red garnets, for the most part irregularly crystallized, are, at times, scattered through it, and these may pass into solid garnet rock. It has elsewhere much epidote (pistazite) and quartz. It also has a strong showing locally of brown iron ore, which any one familiar with lime-silicate garnet contact zones as we know them today would refer at once to original pyrite. These varieties of rocks and minerals, however, did not appeal to Schomburgk in 1837 as having been formed in this way. The time was not yet ripe in the development of geology. Yet the acuteness and accuracy of his observations are shown in his comparison of what he saw to one of the most famous contact zones of the world, that at Predazzo, in the Tyrol, where, as well as at Lake Baltym, near Ekaterinenburg, in the Urals, he recalls that uralitized augite is found in augite porphyry. Schomburgk's descriptions carried the writer of this review back to days spent on the slopes of the Mulatto, high above the famous inn of the Nave d'Oro or Goldenes Schiff, at Predazzo, in 1886, just fifty years after his studies were made in Tortola. The writer was, moreover, reminded of the revery of W. C. Brögger, made in the guest room of the Nave d'Oro, in August, 1894, a gem of geological literature which every student of the science should know.[3] An almost necessary step in the career of every petrologist is to write his name in the guest book of the Nave d'Oro.

Schomburgk remarks in another place that the limestone seems to have burst or broken through alum slates, reminding a reader of the peculiar relations of the Grenville, Precambrian limestones of the Adirondacks, which Ebenezer Emmons, in the same years with Schomburgk's work, thought for this reason must be igneous in their nature. Schomburgk also thought that he saw primary gypsum (Urgyps) and much dolomite, but footnotes by some one who examined his collections state that he mistook abnormal limestone for them.

One thing alone remained to make the full series of associates of the lime silicate contact zones complete, and that is magnetic iron ore impregnated with later deposited pyrite and copper pyrites. These Schomburgk found on Sandy Cay (or Island), an islet near the larger island

[3] "Die Eruptionsfolge der triadischen Eruptivgesteine bei Predazzo in Südtyrol," forming Part II of the monograph on "Die Eruptivgesteine des Kristianiagebietes." Videnskabsselskabets Skrifter, I Math.-naturv. Klasse, 1895, No. 7. The revery is to be found on pp. 1-3.

of Jost Van Dyke, about three miles northwest of the nearest point of Tortola. The dense magnetite, mixed with garnet and stained green with malachite, he first thought to be a meteorite. Later he discovered similar things at Long Bay and Dawsons Point.[4] He thought that on Sandy Cay the rough appearance of the magnetite rock was due to strokes of lightning—*i. e.,* that fulgurites were before him. He also noted yellowish green garnet rock, allochroite, in several beds. On the south and west sides of the island he records sandstone.

Schomburgk adds a few notes on Great Thatch Island, which lies a half mile or less off the west end of Tortola, and which has the same, more or less garnetized, limestone as at St. Bernards. The limestone rests on hornblende schist. After a few notes on Carvel and Normans islands, St. John is described. He notes the east and west trend of the structure and the occurrence of a rock similar to that at Red Point, St. Thomas, apparently a fine-grained quartz porphyry. Gneiss is mentioned from the north side and "quartz." At the Bordeaux estate he collected loose blocks of porous limonite with the smooth black coating, or rind, which has suggested fusion to so many observers. At Reef Bay, on the south side, he recorded beneath a waterfall, dense gray-green to reddish brown limestone and porphyry with a hard gray-black groundmass. In these rocks were carved figures apparently made by the prehistoric Caribs. On the east point of Parforce Bay he observed more iron ore and some copper-stained calcareous sandstone; also, for the first time, decomposed porphyry yielding white kaolin. On the northeast portion of St. John the rocks appear to be a continuation of those described at Coxheath on Tortola. There is granite with syenite and quartz veins.

On St. Thomas, the rocks are not especially different from those earlier described. Near Charlotte Amalia augite porphyry is the common one. We would infer today that he must refer to the predominant fragments of the "blue beach." Near the Plantation Content, rude stratification is apparent. At Patrick Point, on the southeast end, there is much quartz and porphyry.

Anegada, the northeastern outlier of the Virgin Islands, is next described as a coral island grown upon a submarine base, undoubtedly of the same formations as the other Virgin Islands. Between them, soundings of only eight to sixteen fathoms are found, while to the north of Anegada the sea bottom drops abruptly. The projecting part of the island consists of hard white "hornstein" (chert?) containing much

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[4] These two names do not appear on the modern chart of Tortola, but there is a Long Bay on Beef Island just east of Tortola.

calcite. Salt ponds cover a good part of the surface. (For additional notes on Anegada, see the review of the paper published in 1832.)

The small island, Prickly Pear, northeast of Virgin Gorda, has a loamy and barren soil in which are great numbers of blocks of greenstone, which lie on the sides and backs of the ridges.

Mountain Bluff, a point jutting to the north of the mountains of Virgin Gorda, consists of a porphyritic rock. The hills to the west, near the John Duda estate, consist of a hard, splintery, grayish white rock with a steep dip to the southwest and appearing again in Coopers and Normans islands. Beyond the white rock on Virgin Gorda are high cliffs of granite containing inclusions of quartz and epidote (pistazite) and a white porphyry. The northern limit of the valley is Colissons Hill, of granite and diorite porphyry, having labradorite crystals and scales of talc. A northeast, three-foot vein of quartz and mica cuts coarsely crystalline diorite. At Little Dix Bay, northeast from Colissons Point, dense yellowish brown garnet rock was found.

Broken Jerusalem (generally called Fallen Jerusalem today), southwest of Virgin Gorda, is a small island covered with blocks of granite so large as to look like ruined houses or castles. At the end toward Virgin Gorda diorite porphyry was collected.

Schomburgk closes his geological account with some generalizations on the geology of the islands as a whole. For his conclusions, he states that his previously recorded observations lay the foundation. He states again that the islands broke loose (from the mainland) during the great flowage ("Strömung") mentioned in his introduction; that the lowest group of stratified, non-fossiliferous rocks predominate and generally supply the foundations of the other rocks, as is shown in the sea cliffs. In his descriptions he has cited evidences of subterranean fire which has produced important alterations (Veraenderungen). One result is seen in the granitic veins (pegmatites) which, though not in themselves remarkable, yet are highly significant in their local connections. They guide our thoughts to the conclusion that "Ignition" has played an important rôle in the formation of the islands. The share of volcanic action is not to be overlooked. It, however, was all submarine; no evidence is found of later volcanic action.

Schomburgk comments on a curious ground swell which breaks, on the north coast, quite without warning during the months from September to May and during calm weather. He also discusses the climate and cites some impressive cases of longevity among the inhabitants.

Schomburgk appears not to have visited St. Croix. So far, at least, as is revealed in the abstract kindly sent the writer by Professor Cloos, he makes no mention of fossils nor of the geological age of any of the sediments. He seems not to have heard of the fossils at Coki Point, St. Thomas, which are first mentioned by Professor Hornbeck in 1840, but whose stratigraphical position is first determined in the work of the Rev. John P. Knox in 1852, and then is placed in the Upper Jurassic instead of the Upper Cretaceous.

1839. S. Hovey. The fourth record on the geology is by "Prof. S. Hovey, late of the Faculty of Yale College, Ct., and Amherst College, Mass.," and is entitled "Geology of St. Croix" (Amer. Jour. Sci., Jan., 1839, Vol. XXXV, pp. 64-74).

This paper is somewhat discursive, and in it the West Indies in general come in for treatment. On page 65 the author states:

> No animals or saurians, to my knowledge, contemporaneous with those imbedded in the Secondary and Tertiary formations of Europe and America have yet been detected.

On page 66 he says:

> The prevailing formations in the West Indies are, in the first place, recent igneous rocks, comprising the products of active volcanoes, and different varieties of trap; in the second, Tertiary groups, consisting of marl, calcareous sandstone, and shell limestone; and, in the third, a stratified deposit, which, without at present intending to intimate its place in the geological series of rocks, I shall call *indurated clay*. As I have already suggested, some of the islands present all of these formations, indications of which are seen upon the first approach to them. St. Croix contains only the two latter, which divide the superficial area of the island about equally.

Comment: The rocks of the third group, described as indurated clay, are the volcanic tuffs and breccias, sometimes water-sorted and re-arranged, and now referable to the later Cretaceous. The descriptive phrase "indurated clay" we find in use by some later writers. The rocks of the second group were correctly assigned to the Tertiary, the first record of its kind, but we now have their stratigraphical places in the subdivisions of the Tertiary much more closely determined.

1840. Hans Balzar Hornbeck. In the Skandinaviske Naturforskeres, 2det Möde, 1840, pp. 364-368, is a short paper of four pages by Prof. Hans Balzar Hornbeck, of Copenhagen, entitled "Nogle Bemaerkninger over St. Thomas' Geognosie" (Some Observations on the Geology of St. Thomas).

The size and relief of St. Thomas are first briefly reviewed. The hills are said to be made up of "greenstone porphyry" with more or less of foreign matters. (This is the "blue beach" of later writers—a more or less water-sorted volcanic breccia.) There are some small dikes and veins. Bedding is not often observable, but does show on the western point, with a strike N. 30° W. Concentric weathering is described. There are also feldspar porphyries, parting in 4- to 5-sided columns on the south and north sides. Slaty rocks are also on the north side (Löwenlund). Lava masses appear along the south side, at Red Point and east to Cuculus Bay. On Little Saba Island are lava masses and alum rock. Its south side is believed to indicate an old crater. Most important of all are the records of loose blocks of so-called hornblende porphyry (it is augite porphyry) at Coki Point, with inclusions of blue-gray limestone carrying many fossils. Dr. Hornbeck found *Conus*, many *Cerithea*, *Nerinaea*, traces of bivalves and corals (*Retepora*). The observations on these fossils are of great interest, going back, as they do, to 1840, but the geological age of them remained for later determination in 1852, as set forth under John P. Knox. Professor Hornbeck closes with a few remarks on changes of level and on the salt-making industry.

A short paper follows on the earthquakes, in which he mentions 33 in five and a half years. He groups them by months, showing that in May they are commonest, with June showing the second largest total. In the other months shocks are less frequent. The writer found the original citation in the New York Public Library.

In the citation as reproduced above, the author is merely mentioned as "Professor Hornbeck," but from search of the older Danish biographical dictionaries it appears that the author's full name was Hans Balzar Hornbeck, and that he was born in 1800. He became a distinguished surgeon and professor in the Medical School of the University in Copenhagen. During the late thirties he must have spent some time in the Danish West Indies, although the brief biographical sketch makes no mention of the visit.

1846. Hans Balzar Hornbeck. At the twenty-fourth Versammlung der Naturforscher und Aerzte in Kiel in September, 1846, Dr. Hornbeck read a short paper, "Ueber die mineralischen Vorkommnisse auf der Insel St. Thomas," pp. 262-264. [Twenty-fourth meeting of the (Society of) Naturalists and Physicians in Kiel, September, 1846. "On the mineral occurrences in the Island of St. Thomas."]

Dr. Hornbeck's remarks were based on a collection of eighteen specimens which he donated to the Museum of the University of Kiel. He begins by briefly outlining the size and relief of St. Thomas, describing it as essentially a mountainous ridge, with many bays. The slopes are broken by cliffs and largely covered by talus and loose blocks. The kinds of rock are illustrated by his Nos. 2-8, as shown in the translated list below. Calcite veins sometimes appear toward the west, and quartz veins along the south side. He notes the finely bedded "Lehmschiefer," or calcareous slates, west of the estate of Löwenlund, in the longitudinal valley of the north-central island, and states that this is its only locality. As one goes east, a hard petrosilex appears (specimen 1), having gray-green garnets not unlike the white granulite (Weissstein) of Saxony. Still farther east, at Cooks Point, grayish white limestone occurs, rich in fossils. Dr. Hornbeck lists *Conus,* several *Cerithia, Nerinea,* corals (*Retepora*), and fragments of bivalves. Large blocks of the limestone are crystallized to marble and have very few, if any, fossils, as illustrated in No. 14. Along this same line, two and a half miles to the east, on St. John, are loose blocks of light-colored granite.

On the north side of St. Thomas and on the north and south sides of the summit near the estate of Sorgenfri, respectively 1000 feet and 1300 feet above the sea, are interstratified masses of a friable, iron-stained rock, concentrically weathering and illustrated by specimens 10 and 11. On the west side of the neighboring bay is a hard feldspar porphyry with vertical columnar parting, No. 12.

On the east side of the island a trachytic, slaggy rock contains inclusions of limestone. The rock is also found in several other places and especially on the islet, Little Saba, where the alum shales appear, and the south side resembles a half-collapsed crater, presumably an old volcano.

Along the shore, everywhere, the sand, consisting of the fragments of modern shells, is cemented to a moderately coherent sandstone.

List of Minerals of St. Thomas

1. East of Mandal, 200 feet above sea-level, gray petrosilex with disseminated, poorly crystallized garnets in loose blocks. (*Comment:* Doubtless a hornfels, produced by contact metamorphism from a calcareous, tuffaceous shale.)

2. Black Point, near the shore, a green, finely crystalline euphotide passing into serpentine. (*Comment:* Euphotide is an obsolete synonym of gabbro.)

3. Solberg, 1420 feet above sea-level, blackish and bluish euphotide, very hard.

4. North of Madamberg, blackish and bluish euphotide, very hard.

5. Shipley, 100 feet above sea-level, trachyte porphyry, gray-green, cellular, from blocks. (*Comment:* In 1846 trachyte was used for any

light-colored effusive rock, such as we now classify under rhyolite, trachyte, dacite and andesite.)

6. Peninsula of Little St. Thomas. Hard, green serpentine, imperfectly stratified or banded, and with calcite veins. (*Comment:* All these references to serpentine more probably refer to chloritic rocks.)

7. Between Louisenhoi and Canaan, 600 feet above sea-level, a weathered green euphotide. (*Comment:* Probably a chloritized volcanic breccia. The same is true of Nos. 2, 3 and 4.)

8. Mandal Bay, near the shore, weathered green euphotide. (*Comment:* As under No. 7.)

9. Red Point, up to 150 feet above sea-level, reddish and grayish conglomerate of large boulders, with layers of trachytic sand. (*Comment:* Volcanic tuff and breccia.)

10. East of Crown, 1300 feet, decomposed, yellowish red, friable diorite.

11. Northwest of Sorgenfri, 1000 feet, decomposed, yellowish red, friable diorite.

12. West of Shipley, 200 feet and less, grayish yellow, fine-grained, columnar trachyte.

13. Cooks Point, on the shore, greenish black diorite porphyry, with crystals of hornblende; in blocks, as is the limestone. (*Comment:* Cooks Point is the Coki Point of today. The diorite porphyry is the augite porphyry of our reports; the "hornblende" is augite.)

14. Cooks Point, on the shore, compact limestone containing fossils, often cemented together by trachytic lava. (*Comment:* The fossiliferous limestone forms inclusions in augite porphyry and in the associated volcanic tuffs. Dr. Hornbeck's discovery and record of these fossils, as earlier remarked, is of extreme importance.)

15. Little Saba, 80 feet, brownish red trachytic lava.

16. Little Saba, 80 feet, alum rock.

17. Mandal Bay, on the shore, conglomerate of shells and corals.

18. Frenchman Bay, conglomerate of shells and quartz sand.

The above paper adds some details to Dr. Hornbeck's earlier one of 1840, but although he again mentions the genera of the fossils at Coki Point, he gives no determination of geological age.

1852. John P. Knox. The Rev. John P. Knox, an American, who was pastor of the Reformed Dutch Church of St. Thomas, published in 1852, through Charles Scribner, 145 Nassau Street, New York, "A Historical Account of St. Thomas, W. I." The original is now a rare book, but a copy is in the library of the New York Botanical Garden, as it contains a list of the plants. A reprint has been issued by Adolph Sixto, of St. Thomas, 1922, and is easily obtainable in the local book stores.

On pages 207-213 Mr. Knox gives a brief review of the topography and geology. He draws freely on the earlier paper of Professor Hornbeck, which is reviewed above, but adds much that is new. Mr. Knox describes St. Thomas as "the top or ridge of a small chain of submerged mountains." In reviewing the topography, he emphasizes the main continuous ridge from the west end to the east end of the island and the parallel subordinate ridge which constitutes the southeastern portion, with the one pronounced valley and the one flowing brook between the two. The rocks are described as trappean and as containing in the specimens of various textures the minerals augite, hornblende, felspar, iron and olivine. They are not stratified and have numerous veins, often of quartz. They furnish the soils by weathering and leave the hard residuals in pointed shapes. A singular globular structure is also developed, such as we would call today spheroidal weathering. It is likened to cannon balls—a descriptive term still locally current. Actual lava flows are cited, but the nature of the common rock, the blue beach of today, as volcanic tuff and breccia seems not to have been specifically recognized. The most important observations are those which relate to Coki Point, in the northeastern part, where the fragments of fossiliferous limestone are found involved in augite porphyry. They are interpreted as having fallen into the trap when it was molten.

Among the fossils are a conus, numerous cerithea, nerinea, and several bivalves. There is also a multitude of certain fossils which have the appearance of truncated bulbous roots, as they are composed of laminæ encircling each other and forming a varied, half-ball-like mass. They may be coral, but their form and appearance are certainly singular. A specimen of this limestone, containing fossils, was recently forwarded to the British Museum. The following remarks upon it have just been received in a letter written by the Secretary of the Geological Society, London: "It is a block of limestone full of nerina (nerinea?). This genus is confined to the lower chalk and oolite. Your specimens most resemble some from the Portland rock. It is to be expected that if that limestone were well searched for organic remains, the age of it might be put beyond question. At all events, this is, I believe, the first time that the existence of oolite has been suspected in the West Indies."

(*Comment:* The suggestion of their resemblance to fossils of the Portland rock would place them in the middle member of the three which make up the uppermost Jurassic. We now consider them Upper Cretaceous, a determination first made by P. T. Cleve in 1869.)

Where Mr. Knox speaks of "a conus, numerous cerithea, nerinea, and several bivalves," the words are so nearly an exact translation from Professor Hornbeck as to be undoubtedly taken from his paper, but as Mr. Knox continues, he adds much that bears no resemblance to Professor Hornbeck's text. He undoubtedly collected specimens at the Coki Point locality, and had the good judgment to send them to the Geological Society of London. The writer has hunted through its Quarterly Journal for five consecutive years, beginning with 1851, but the only record bearing on the letter sent Mr. Knox by the Secretary is the following from Vol. VIII, p. 7, 1852. Among the acquisitions of specimens during that year are mentioned: "Twelve specimens of Fossiliferous Rock with Nerinaeae, etc., from St. Thomas, West Indies, presented by Thomas Bland, Esq., F. G. S." There were two secretaries of the Geological Society of London in 1852, viz., William John Hamilton, Esq., and John Carrick Moore, Esq., M. A., but we can not now determine which one wrote the letter or who determined the fossils. It may have been Mr. Moore, who had published at this time on the Tertiary fossils of the West Indies, or Thomas Bland, who was a well-known authority in conchology and paleontology. At all events, this first attempted determination of the geological age of the limestones is of more than ordinary interest.

Mr. Meyerhoff has given special attention to this matter and will have some important additional notes to add. Dr. Britton and the writer collected at Coki Point and had no difficulty gathering some of the genera mentioned by Mr. Knox. P. T. Cleve, 1871 and 1881, as later reviewed, was the first to place the fossils in their correct stratigraphical position. Other references to them are made by O. B. Böggild, 1907 and 1908, and by T. Wayland Vaughan, 1919 and 1923.

1871. Per Teodor Cleve. During 1868-69 Per Teodor Cleve, a Swedish naturalist, studied in detail the Virgin Islands, as well as the more northerly members of the Leeward group lying east of them. At the close of his trip he made additional but passing observations on Porto Rico and the larger Antilles to the west. He took his notes and collections to the University of Upsala, Sweden, and there elaborated the following paper, written in English and constituting the most detailed study which has been made of all the Virgin Islands until the present: "On the Geology of the Northeastern West India Islands." Kongl. Svenska Vetenskaps Akademicus, Handlingar, Bandet IX, No. 12, Stockholm, 1871 (Transactions of the Royal Swedish Academy of Sciences, Vol. IX, Paper No. 12, pp. 1-48, two plates). The author selected the area because it is at the crossing of two systems of elevations. He regards the islands as a submerged mountain chain.

The largest part of St. Thomas consists of blue beach, a conglomerate, or breccia, having angular pieces of dark porphyry, or felsite, and rounded, scoriaceous stones, cemented together by a greenish mass, probably derived from decomposed hornblende. The blue beach is regularly stratified, and one record of strike and dip is given as S. S. E.–N. N. W. 30° N. E. Strong metamorphism has elsewhere destroyed the stratification. It contains veins of quartz, calcite, some epidote and pyrites. On the high ridge are varieties resembling syenite and diorite, but the fine-grained rock resembles trap. The blue beach may display spheroidal weathering, with spheroids from 0.5 to 1.0 meter. It may alter to a white clay. It is cut by dikes of diabase and felsite. The scoriaceous fragments in the conglomerate prove its volcanic origin, and its limestone nodules with fossils found in one spot and its stratified character prove it to have been heaped up under the sea. Blue beach makes up the mountains in the western part of the island, and largely in the eastern, but there are large masses of felsite also near Donoe. The total thickness is at least 2000 meters. Near Löwenlund are almost vertical strata of black clay slate, which runs east through Mandal to Coki Point. It resembles Silurian slate, but has no fossils. It is associated with limestone containing bits of blue beach. In the cliffs at Tatro Bay, north of the clay slate, is a regularly stratified rock, consisting of small bits of gray felsite bedded together in a sandstone. It has a strike E.–W., dip 70° N. North of Bucks Bay there is an alternating series of blue beach, metamorphosed clay, slate, and flagstones. Near Coki Point the blue beach contains large calcareous nodules and marble, sometimes silicified. The limestones have fossils, of which the most common are *Nerinea,* fragments of a large *Bulla,* or *Actaeonella,* an ammonite, *Trochus, Pectunculus, Limopsis, Opis, Venus, Astarte* and *Corbula.* Some have a remarkable affinity with Cretaceous species, so that Dr. Cleve concluded that the basal strata of the Virgin Islands were of Cretaceous age. He states that *Favosites dietzii* and *St. Thomae,* of Paleozoic appearance, had been described by Mich. Duchas (Mem. della Acad. dell. Scien. di Torino, II Serie, Tome XIX, p. 84, 1860, and XXIII, 199, 1866)[5] from

[5] With the very kind help of Mr. Herbert F. Schwarz, Editor of the New York Academy of Sciences, these two references have been verified as follows. They involve a matter of apparently mistaken stratigraphy, based on two species of fossil corals, of locality not definitely given. The stratigraphic determination evidently did not greatly impress Professor Cleve.

The original description of *Favosites Dietzi* is in the first reference, and is in French, in a paper by Duchassaing and Michelotti, "Mémoire sur les Coralliaires des Antilles," Vol. XIX, pp. 279-365, plates 10, 1861, and is on p. 360, not p. 84, as given by Cleve.

"Gen. FAVOSITES, Lanik—

FAVOSITES DIETZI, nobis.

Espèce discoïde, supérieurement convexe, à tubes parallèles, égaux, planchers aplatis, Coki Point, but doubts the report. Dr. Cleve mentions a red felsite at several points. Near Coculus Bay appears quartz porphyry, and at Coki Point augite porphyry, which penetrates felsite. The rocks of the small islands are briefly cited. Most important of these records is that relating to the smaller islands stretching from Thatch Cay to St. John, which consist of sedimentary beds such as clay slates and flagstones, E. and W., 70° N. On Congo Cay is hard crystalline limestone or marble. On Hans Lollik is dark green diabase with augite crystals and magnetic pyrites. Inner Brass Island is blue beach, while Outer Brass Island consists of stratified rocks, E. and W., 70° N.

Culebra is next passed in review and is said to consist of dark gray or brown labradorite porphyry. On Culebrita is dark green trap with quartz veins.

St. John is reviewed topographically, and then the green conglomerate, or blue beach, is described as predominant in the south portion with some shore cliffs of red felsite. The northern portion consists of stratified metamorphic rocks. The islands to the east, and so on to Virgin Gorda, are passed in review, with observations on the increasing amount of diorite and deep-seated rocks, with associated pegmatites. On Beef Island the pegmatite is said to contain epidote, nodules of prehnite, rock crystal and magnetic iron.

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rapprochés de trois millimètres. Ces tubes n'ont qu'un millimètre et demi de diamètre. Les tubes sont munis de pores de communication.

Bien que la forme générale de cette espèce se rapproche de celle de la *Favosites Gothlandica,* elle est cependant plus épaisse, et les tubes sont parallèles au lieu d'être couchés les uns sur les autres; sur chaque plan de la muraille de la *Favosites Dietzi* on observe un seul trou au lieu de deux.

Dans la *Favosites Hisingeri* les murailles sont plus épaisses que celles de la *Favosites Dietzi;* les calices sont plus régulièrement polygonaux, et les planchers un peu flexueux. Enfin dans le *Favosites fibrosa* les polypiérites sont irradiants de la base à la surface, et les planchers sont plus serrés que ceux de notre espèce.

Nous la dédions à Mr. Dietz, Conchyliologiste distingué, qui demeure à St. Thomas: elle preuve la présence de bancs paléozoïques dans les îles de St. Thomas et de Ste. Croix, bancs rapportés erronément à l'époque jurassique par Mr. Knox dans son histoire desdites îles."

This citation taken by itself leaves us in some doubt as to whether the corals came from St. Thomas or St. Croix.

In the later volume, XXIII, 1866, p. 199, the record is as follows:

"Genus FAVOSITES.

404, FAVOSITES DIETZI Duch. et Mich. Coral. p. 84 (should be 360).

In stratis siluriis, S. Thomae.

405, FAVOSITES SANCTI-THOMAE nobis.

Parvula, capitata, tubulis perparvis, confertissimis.

Reperitur cum praecedente."

The last reference would seem to place the fossils in supposed Silurian strata on St. Thomas. As we know of fossiliferous limestone only at Coki Pt. and immediately to the west and east of it; apparently the specimens were found there; but as a means of stratigraphic identification, they can hardly contradict the overwhelming testimony of the rather abundant Upper Cretaceous fauna.

On Virgin Gorda are three kinds of rock—diorite on the south, quartzite in the middle and felsite in the northern part. Spheroidal weathering is developed on a large scale and, aided by joints, yields blocks the size of small houses. There are many north and south veins containing quartz, siderite, native copper, gray, red, yellow, or green copper ores and molybdena.

Geological observations follow upon the smaller islands around Virgin Gorda and between it and St. John. Both sediments and intrusive rocks are involved and some interesting minerals are mentioned, which are obviously the results of the contact metamorphism of limestone. On Ginger Island diorite is described as interstratified with amphibolite and as passing into the latter.

Anegada was visited and is depicted as a flat island, of hard, compact limestone of such recent date that the shells involved in it are of species still extant in the neighboring sea. A number of species are cited.

Vieques, or Crab Island, now belonging to Porto Rico, is in turn described as consisting of a dark green rock, succeeded a short distance from the coast by a diorite resembling syenite, which is the chief rock of the island. A few observations follow on Porto Rico, and a very small map with a partial representation of the geology is used in illustration. Dr. Cleve mentions a recent formation of alluvium and shell sand (the San Juan formation of our Survey's recent reports); a Miocene fossiliferous limestone (presumably our Arecibo and Ponce limestones), and unfossiliferous exposures, like the blue beach and felsite of the Virgin Islands, of probable Cretaceous age.

St. Croix, or Santa Cruz, is next taken up. There are three formations; the oldest resembles the old series of the other Virgin Islands and is probably Cretaceous. These early strata are greatly disturbed and are folded so as now to have high dips. Unconformably upon them rest flat beds of coralline limestone. Around the shores is a recent calcareous sand. The oldest rocks are of igneous and igneo-sedimentary origin, and include diabase, sometimes variolitic, diorite, blue-beach conglomerate, felsite, clay, slate and limestone. Much discordance of strikes is found in the stratified members. Northeast of Christiansted, on the shore, and on Queen Cay are coarsely crystalline feldspathic rocks, but almost all the eastern part is clay slate. On Bucks Island are slaty beds with limestones and some obliterated fossils. Dr. Cleve noted also the gray limestones near Judith's Fancy, with badly preserved fossils, but makes no mention of those at Watch Ho (Waiters Point), on the South Side. The Tertiary limestones of the southwest contain casts of fossil shells and corals. He recognized *Conus, Strombus, Natica, Trochus, Venus, Chama,* *Cypraea*, resembling *C. exanthema*, and some impressions of *Cerithium* like the living *C. litteratum* Born. He also found extinct *Cerithia*, one *Bulla*, close to *B. granosa* Sow., of the Santo Domingo Miocene, and one *Turbo* near *T. cookii* Chemn. The Tertiary limestones are 200 meters thick. The recent formations are partly terrestrial, partly marine, and contain some species now extinct on St. Croix, but still living on Vieques and Porto Rico. The extinct species are *Helix santa cruzensis* Pfr., *Bulimus extinctus* Pfr., *B. riiseii* Pfr., *Pupa rudis* Pfr., *Cyclostoma basicarinatum* Pfr. and *C. chordiferum* Pfr. The ones extinct on St. Croix but surviving on Vieques are *Helix caracolla* L. and *H. marginella* Gm. In the alluvial deposits of Salt River at the Glynn and Concordia estates are *Venus flexuosa* L. and *Lucina jamaicensis* Spgl., species still abounding in the Caribbean. In the recent marine solid limestone he noted *Turbo pica* L., *Strombus gigas* L. and other very common West Indian shells with their colors still well preserved.

Notes on the Leeward Islands follow, including in the first group, Saba, St. Eustatius and St. Kitts, but omitting Nevis, Redonda and Montserrat; in the second group, Sombrero, Anguilla, St. Martin and St. Bartholomew, especially the last named, of which a geological map is given on a later plate. As this matter does not immediately bear on the Virgin Islands, it is not reviewed here.

A list of fifty minerals which our author observed is given on pages 27-32, with some original analyses. Of the fifty, twenty-seven were observed on the Virgin Islands, viz., native copper, pyrite, molybdenite, chalcopyrite, tetrahedrite, cuprite, melaconite, specularite, quartz, magnetite, talc, wollastonite, augite, hornblende, chrysocolla, orthoclase, oligoclase (analysis), labradorite, anorthite (analysis), epidote, garnet, mica, desmine, prehnite (analysis), siderite, malachite and titanite.

An annotated list of twenty rocks from the islands studied follows the minerals. Subvarieties are mentioned under some and a number of chemical analyses are given. Dr. Cleve does all that could be expected of a student of rocks who did not use thin-sections and the microscope, but in 1871 this method of study was in its infancy and only a very few had it at command. In the paper by Prof. A. G. Högbom, later reviewed, many of the rocks collected by Dr. Cleve are described in this way. Of the twenty rocks listed, twelve are from the Virgin Islands, viz., limestone, quartzite, granite, with two varieties pegmatite and granular. Of the granular variety, two analyses are given, one from Bucks Island, south of St. Thomas (No. 1 below), and one from Georges Dog, west of Virgin Gorda (No. 2 below). Of the felsites, there are four analyses, respectively from Adlers Villa, St. Croix (No. 3 below), Red Point, St. Thomas (No. 4 below); The Sound, Virgin Gorda (No. 5 below), and Regis Point, St. Thomas (No. 6 below). Of the diorites, three analyses, respectively from Marys Point, St. John (No. 7 below); Beef Island, east of Tortola (No. 8 below), and Ginger Island, southwest of Virgin Gorda (No. 9 below). Some of the diorite was believed to be a fused clay slate. Of the diabases, there are five analyses, respectively from Bucks Island, south of St. Thomas (No. 10 below); Coki Point (No. 11 below) (the augite porphyry of later observers); Whistling Cay, northwest of St. John (No. 12 below); Coral Bay, in eastern St. John (No. 13 below), and Red Point, St. Thomas (No. 14 below). Anorthite diorite from Beef Island, east of Tortola, has one analysis (No. 15 below). The remaining four varieties are mica schist, clay slate, magnetite iron sand and blue beach.

The list of the rocks is followed by notes on the geology of Cuba, Jamaica, San Domingo, Bahamas, Barbuda, Antigua, Nevis, Redonda, Montserrat, Guadeloupe, Dominica, Martinique, St. Lucia, St. Vincent, The Grenadines, Grenada, Tobago, Barbados and Trinidad. The notes are chiefly compiled from authors whose works are cited in the footnotes. A quite valuable bibliography is thus given of papers published before 1870.

A summary of the geology of the West Indies, based on the earlier recorded data of the contribution, concludes the text. Dr. Cleve makes the following generalizations:

The oldest rocks occur in Trinidad and are unfossiliferous.

The oldest fossiliferous rocks are Cretaceous. (NOTE: We know now of richly fossiliferous Jurassic in western Cuba.)

> The fact of the rocks of the West Indian Cretaceous formation being mostly igneous, or igneo-sedimentary, evidently proves them to have been heaped up in a time of powerful volcanic activity, and, as the Miocene formation in several places covers the highly disturbed and metamorphosed Cretaceous rocks, in almost horizontal and undisturbed beds, one may conclude that, before the Miocene time, the Cretaceous rocks were raised to a mountain chain having a common direction from east to west and running parallel with the northern coast-line of South America.

Fossiliferous Eocene beds are cited from Jamaica, Trinidad and St. Bartholomew. They are thought to be probably present in St. Martin, Antigua, Guadeloupe, Barbados, and possibly also in Cuba, San Domingo and Porto Rico. The Eocene is thought to be equivalent to the lower or middle Eocene of Europe (the lower "calcaire grossier" of Paris and "Bracklesham beds" of England). (NOTE: Our recent detailed survey of Porto Rico and the Virgin Islands has revealed no well-established

Chemical Analyses of the Rocks Collected by Per Teodor Cleve

	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	K_2O	Na_2O	H_2O	Total
1. Granite	64.71	15.09	2.56	....	4.51	1.16	1.38	5.29	4.86	99.56
2. "	71.60	13.63	3.03	....	3.37	0.94	1.31	4.54	.63	99.05
3. Felsite	63.89	15.08	4.68	....	9.00	1.06	3.95	1.00	1.45	100.11
4. "	80.79	11.13	0.35	....	0.21	....	1.85	4.22	1.26	99.81
5. "	69.33	12.77	2.19	....	7.23	1.03	0.42	4.75	1.47	99.19
6. "	73.97	12.09	2.90	....	....	1.03	3.55	3.38	1.54	98.46
7. Diorite	59.24	18.16	3.26	3.56	6.31	2.84	1.31	4.00	0.87	99.55
8. "	61.35	15.39	4.41	3.40	6.60	3.32	0.95	3.87	0.58	99.87
9. "	53.85	17.15	4.08	6.95	8.99	5.29	0.24	3.01	0.58	100.14
10. Diabase	48.12	18.60	4.00	6.30	7.36	6.16	1.09	4.11	3.63	99.37
11. "	48.42	17.49	6.79	4.34	9.83	5.35	0.55	3.98	2.68	99.43
12. "	54.07	16.30	5.75	5.84	7.63	3.41	0.90	4.00	1.35	99.25
13. "	49.84	18.32	4.16	5.21	12.31	3.93	....	3.24	2.05	99.06
14. "	52.55	14.20	9.43	6.50	6.68	4.03	0.20	4.51	1.62	99.72
15. Anorthite Diorite	44.60	15.38	8.50	8.03	14.50	6.82	0.01	0.33	0.56	99.65

(In No. 15 TiO_2, 0.92, also is included in the total.)

Eocene, but in Porto Rico richly fossiliferous Oligocene and Miocene.)

Dr. Cleve states that "the Miocene formation consists mostly of limestones, or marls, and is enormously developed in the West Indies. Limestone strata belonging to the Miocene formation cover large spaces in Cuba, San Domingo, Jamaica and Puerto Rico. They are also found in Anguilla, Antigua, Barbados and Trinidad. In St. Croix the white marl also seems to belong to the Miocene time." From the researches of several British paleontologists it appears that the fauna has close affinity with the Miocene of Europe, and with the still living fauna of the Pacific Ocean and the East Indies. Some Miocene species are still living in the Caribbean. An open channel in Miocene time has thus been inferred over Panama to the Pacific Ocean. "The Miocene fauna of the West Indies does not, however, offer any close affinities with the Miocene fauna of North America." The thickness and undisturbed character of the West Indian Miocene indicates a long period of calm, undisturbed by volcanic phenomena.

Pliocene beds are cited from several of the West Indies, but not from the Virgin Islands or Porto Rico.

Dr. Cleve concludes his paper with the structural generalization "that of the two prevailing lines of elevation in the West Indies the one running from west to east originated before the Miocene time, and that from the N. W. to S. E., commencing with the Bahamas and continuing in the same direction down to Trinidad, was formed after Miocene time."

Two plates at the close give first a geological map of the northeastern West India Islands, from Culebra and Vieques to and including Guadeloupe, on a scale 1 : 1,751,000, and a second with a geological map of the Virgin Islands, except Anegada on the north and St. Croix on the south, 13 inches by 4.5 inches; also one of St. Croix, 5.5 inches long, on a scale 1 : 232,000, and one of St. Bartholomew 5.5 inches by 3.3 inches.

The work of Per Teodor Cleve is so important that the writer has obtained from Prof. A. G. Högbom, of the University of Upsala, the following facts of his life: He was born in Stockholm, February 10, 1840, and therefore when he made his observations in the Virgin Islands, in the winter of 1868-69, was in his twenty-ninth year. He had previously prepared himself primarily as a chemist, but was an all-around naturalist, and all his life retained his interest in geology and mineralogy. Returning to Sweden in 1870, he taught chemistry for four years in the Technical High School of Stockholm (really of collegiate or university grade, despite the different meaning of high school in English), and then became professor of chemistry in the University of Upsala, in which position he remained until his death, June 18, 1905. He did notable work upon the rare earths, and received the Davy Medal of the Royal Society of London in 1894. He investigated the organic chromium and platinum compounds, and also the naphthaline derivatives. He studied the sea-plancton, and especially the diatoms, and cast much light on world-wide oceanic circulations. His knowledge of diatoms was of great value in connection with the Quaternary geology of Fennoscandia. He was an enthusiastic collector of minerals and mollusks. His gatherings in the West Indies, which were deposited with the University of Upsala, have been placed at the service of later investigators, among them Dr. T. Wayland Vaughan.

1881. PER TEODOR CLEVE. Ten years after the publication of the paper reviewed above under 1871, Dr. P. T. Cleve, of Upsala, Sweden, corresponding member of the New York Academy of Science, forwarded to the Academy, at the request of Mr. Thomas Bland, a paper entitled "Outline of the Geology of the Northeastern West India Islands." The paper was read November 7, 1881, and published in the Annals, Vol. XXI, pp. 185-192, pl. 17. A brief abstract appears in the Transactions of the Academy, Vol. I, 1881, pp. 21-24, with the discussion which followed.

Dr. Cleve's paper is a summary of his longer contribution, but adds one or two structural features not stated in the earlier contribution. The northeastern islands embrace Cretaceous, Eocene, Miocene, Pliocene and post-Pliocene, of which we now know that in the Virgin Islands all but Eocene and Pliocene are present. Dr. Cleve remarks their axial coincidence with the strike of the Cretaceous volcanics, of whose fragmental nature he had become, if anything, more firmly convinced. The eruptives he treats under four heads: 1. Diorite, with its distribution; 2. Felsite, in the same way; 3. Blue beach; 4. Diabase. The stratified and generally metamorphosed rocks are taken up under three heads: 1. Clay slate; 2. Metamorphic slates, mica schists and hornblende schists; 3. Limestone, hard and crystalline, often with silicates. He remarks the rounded fossiliferous limestone boulders embedded in the blue beach at Coki Point, St. Thomas. Special treatment is given to St. Croix on account of its flat Tertiary limestones and marls, which are regarded as of Miocene age or perhaps more recent. He reverts to the Cretaceous fossils of Coki Point, mentioning abundant fragments of large *Nerinaea, Actaeonella, Pectunculus, Astarte, Corbula, Limopsis, Opis* and one ammonite. All are Cretaceous and correspond to the Gosau formation of the Alps.

The most important new contribution is the following: "On studying in detail the part between Tortola, St. John and St. Thomas, I found that there is a synclinal fault just in the continuation of St. Francis Drake Channel." On Plate 17 he gives a section showing the syncline, without a fault, leading the reviewer to conclude that "synclinal fault" should read "synclinal fold" in the text. The similarity of the German word "Falte," meaning fold, to the English word fault may be responsible for the apparent misnomer. Dr. Cleve shows also in a generalized section a syncline from St. Croix to St. John, each of the islands in his view forming the summit of a lofty Alpine chain of mountains with a valley between, 4000 meters deep. The upheaval came after Turonian strata had been deposited and was believed to have been still in progress in the Eocene. In the Miocene it was finished and ready for the deposition of flat Miocene.

In the concluding pages a few notes are given on Porto Rico, Jamaica, Santo Domingo, Cuba and some of the islands east of the Virgins. He briefly reviews the Pliocene and post-Pliocene, referring Anegada to the latter.

Dr. Cleve's mention of the syncline between Tortola and St. John is the first record of this important structural feature. Its presence has been confirmed by our later, more detailed work.

1898. ROBERT T. HILL. Prof. Robert T. Hill, in his delightful book of travel and science, entitled "Cuba and Porto Rico, with the other Islands of the West Indies," New York, 1898, devotes his Chapter XXVIII, pp. 309-317, to the Virgin Islands and St. Croix. The treatment is chiefly on the sociological and economic sides, but on page 310 reference is made to the geology, as follows:

> The current impression that these islands, as a whole, are either of volcanic or coral-reef origin is a mistake. Traces of marine volcanism are less apparent than in New England, while the coral rocks are only an attenuated fringe, added in recent geologic time. They are all of the same geologic composition as the Great Antilles, consisting of a foundation of rocks of suspected Paleozoic origin, covered by great masses of Cretaceous and Tertiary conglomerates and clay, derived from the now vanished, geologic Atlantis, which in turn are veneered by the mantle of oceanic chalky-white limestones, and these fringed by a border of coral-reef rock. Penetrating the older rocks are dikes of ancient volcanic material.

Our later detailed studies have somewhat modified these conclusions and have tended to show that the oldest rocks are Upper Cretaceous volcanics, mostly fragmental, rearranged as sediments and involving minor limestones.

1905. A. G. HÖGBOM. In 1905, Prof. A. G. Högbom, of the University of Upsala, published the results of an important restudy of the rock collections gathered by Dr. Cleve, and reviewed above, under 1871. Dr. Högbom brought to bear upon them the modern methods of microscopic, petrographic study, and added to the descriptions of Dr. Cleve much of an accurate mineralogical and petrographical character. His paper is written in German and is entitled "Zur Petrographie der Kleinen Antillen" (A Contribution to the Petrography of the Lesser Antilles. Bulletin of the Geological Institute of the University of Upsala, Vol. VI, 1905, pp. 214-232, pls. ix and x). From two hundred specimens, fifty-four were selected and studied in thin-sections with the microscope. They are serially numbered, 1–54. Of the fifty-four, fifty came from the Virgin Islands. Dr. Högbom rightly comments upon the special interest which attached to Professor Cleve's record of granites, diorites and gabbros from strata of at least late Cretaceous age—a relationship scarcely known in 1870. He also remarks their correspondence with the predominant plagioclase-bearing igneous rocks which O. Nordenskjöld had emphasized as characteristic of the extended American zone of folding, stretching from Alaska to Tierra del Fuego. The rocks are sometimes called Andes granites and Andes diorites.

St. Thomas and Neighboring Islets

Fourteen rocks are described from St. Thomas, almost all of which have suffered severe alteration to secondary minerals. From the blue beach were obtained fragments sufficiently large to yield the following determinations (Nos. 4, 7, and 8). No. 4, amygdaloidal porphyrite, Charlotte Amalie, is much altered to secondary minerals. The rock is a basic porphyrite whose feldspar is labradorite and whose dark silicate, augite. It would be called in America today an olivine-free basalt. No. 7 was either a fragment in blue beach or a dike, cutting it, at Löwenlund. It is named kersantite and is a porphyritic rock with phenocrysts of amphibole and zonal plagioclase in a fine-grained groundmass, rich in epidote, magnetite and apatite, and with a few titanites and undetermined decomposition products. No. 8 consists of fragments from a blue-beach breccia at Charlotte Amalie, and is named hornblende kersantite, a porphyritic rock with large phenocrysts of hornblende in well-bounded prisms a centimeter in diameter, set in a thoroughly decomposed groundmass, in which little can be recognized except quartz, epidote, sericite, magnetite and chlorite. There are inclusions (small xenoliths) of quartz with strain shadows. No. 10 is a dike in blue beach from Great St. James, and is a dense plagioclase porphyrite, 80 per cent of it plagioclase near oligoclase. The remaining components are epidote, chlorite, calcite, a little quartz and magnetite.

Two tuffs and breccias are described. No. 1 is a lilac-colored porphyry tuff from Red Point, a badly decomposed rock with sericitized fragments of feldspar, grains of quartz and fragments of felsite. Presumably this rock is a rhyolitic tuff, related to No. 2 mentioned below, and in contrast with the general andesitic and basaltic characters of the prevailing rocks. No. 3 is a greenish gray, tuffaceous lava breccia from Magens Bay. The rock consists of fragments of a dense, feldspathic amygdaloid, showing flow structure in its solid part, and quartz and chlorite in the blowholes. The feldspars are not specifically determined. There is much secondary chlorite, quartz, epidote and carbonates. The rock also contains little xenoliths of felsitic and trachytic rocks. Cleve records it as forming sheets interstratified with slates. The lack of specific determinations of feldspars makes the interpretation of the rock somewhat difficult today, but the presence of epidote and carbonates indicates an andesitic or basaltic original.

No. 2 is a quartz porphyry from Red Point and is a dense white rock, with very small phenocrysts of bipyramidal, somewhat rounded quartzes, of albite crystals and a few orthoclases set in a felsitic groundmass. An interesting feature is a tiny ring of groundmass quartz surrounding the quartz phenocrysts and of similar orientation with them. An analysis by P. T. Cleve is quoted earlier, as No. 4, on page 26 of this review. (*Comment:* The rock is of special interest because of the high silica—80.79 per cent—which is at the upper limits of the rhyolites. Rhyolites themselves are not common among the predominant andesitic outbreaks of the West Indies. The high soda—4.22 per cent—of the Red Point rock as against potash—1.85 per cent—is also worthy of emphasis.) Another obviously high silica rock, although we have no analysis, is No. 12, a reddish white, medium-grained granite, with almost no dark silicates. It appears as a dike, cutting the quartz diorite of Buck Island, four miles off the south coast of St. Thomas. The rock consists essentially of orthoclase and quartz, both with undulatory extinction. The former sometimes gives way to perthitic microcline. Oligoclase is a minor component, and there are small, chloritized micas and grains of magnetite. The rock has a micropegmatitic texture. This rock possesses special interest in that it has orthoclase feldspar in excess—a not common experience in the islands.

No. 6 is a syenite porphyry from Mosquito Bay. It is a dense, greenish gray rock, with feldspar phenocrysts, a millimeter across, set in a groundmass. The automorphic phenocrysts are both orthoclase and soda plagioclase. The groundmass is trachytoid in texture, badly decomposed, and consists of tiny feldspar rods, calcite and small octahedra of magnetite.

No. 14 is a quartz diorite and is the chief rock of Buck Island. It is a light-gray, medium-grained variety. Zonal oligoclase, in short rectangular sections, makes up almost half the rock; quartz and orthoclase, each about 15 to 20 per cent, the former in slight excess, are next in abundance and fill in the spaces between the oligoclases. They are xenomorphic and show pressure effects, such that the orthoclase passes at times into microcline. Green hornblende with subordinate, chloritized biotite are the dark silicates. They are sometimes ophitically intergrown with plagioclase. The accessories are titanite, magnetite and rather rare apatite. An analysis is quoted above in this review on page 26 under No. 1. (*Comment:* The writer may add that the rock is reminiscent of similar ones in Porto Rico and elsewhere in the Greater Antilles. It is a natural intrusive companion of extrusive andesitic rocks.)

No. 11 is augite porphyrite from Great Hans Lollik Island. The rock is porphyritic with augite phenocrysts, up to several millimeters in length, and others, smaller, of labradorite. The augite is sometimes so richly filled with inclusions of feldspar grains and groundmass as to be itself a mere skeleton. In the groundmass are small augites, labradorites, magnetite, more or less altered to leucoxene, and chlorite which may replace the first-named mineral and may penetrate the first two in nets. (*Comment:* The writer may add that this rock is apparently the same as the augite porphyry at Coki Point or is closely related to it. In the Coki Point rock the inclusions of fossiliferous Cretaceous limestone are found. Its time of intrusion must, therefore, have been subsequent to the deposition and hardening to rock of the Upper Cretaceous limestone.)

Professor Högbom describes several varieties of diabase. No. 13, from Buck Island, is a quartz diabase in dikes in the quartz diorite, No. 14. It is a dense, dark-green rock whose dark silicates are completely changed to epidote and chlorite. The lath-shaped plagioclase is clouded by the products of decomposition. Quartz fills interspaces and magnetite is altered to leucoxene. All these secondary products are the usual results in altered diabases. No. 5 is a uralite diabase whose exact locality was not recorded by Dr. Cleve. The uralite ranges up to half a centimeter and is accompanied by a little biotite, ophitic, with little rods of labradorite. The greater part of the labradorite streams in lath-shaped sections around the uralites. The magnetite is often surrounded by a titanite (leucoxene?) rim. No. 9 is an olivine diabase with texture much like gabbro. It was collected in the central part of the island and resembles the well-known Asby diabase of Sweden. The zonal lath-shaped labradorite shows passages to tabular form, and is automorphic as against the augite, olivine and magnetite. It forms about half the rock, leaving half for the dark minerals, viz., olivine, which is next in abundance; violet augite, which follows; then biotite, magnetite and apatite in the order named. Strange to say, the rock was perfectly fresh.

St. John and Neighboring Islets

The rocks from these islands closely resemble those of St. Thomas. Eight slides were studied, numbered from 15 through 22. They are grouped here from acidic to basic and metamorphic. No. 19 is a felsite porphyry from Round Bay and is a platy, porphyritic rock with zonal phenocrysts, chiefly oligoclase, 2 to 4 millimeters across. There are smaller ones of bipyramidal quartz, sometimes in groups with parallel orientation. The groundmass is chiefly rods of plagioclase in trachytoidal texture. Chlorite is abundant in the groundmass and in the feldspar phenocrysts. No. 15, a diorite from Browns Bay, is a dark, finely crystalline rock, resembling diabase. Zonal labradorite appears partly in relatively large rectangular sections whose automorphic character is rendered imperfect by the abutting augite and amphibole. The more abundant small labradorites are irregular in shape and appear in groups or poikilitically included in the dark silicates and even in the magnetite. No. 16 is a contrasted diorite, also from Browns Bay. It is a finely crystalline, greenish black rock, predominantly xenomorphic plagioclase and amphibole in about equal amounts. A few large, somewhat automorphic plagioclases contain inclusions of amphibole. Magnetite and titanite are the accessories. No. 17, an augite diorite, is a medium-grained, dark rock, somewhat porphyritic from plagioclases. The zonal plagioclase, with cores approximating anorthite, and the almost entirely uralitized augite are about equal in amount. The plagioclase affords almost automorphic, tabular sections. Kernels of reddish augite survive in the uralite, and there is dust of magnetite in goodly quantity. The primary rock was possibly a diabase of strong gabbroic affinities. From the blue beach of Mt. Pleasant came No. 18, a labradorite porphyrite, with phenocrysts of predominant labradorite and subordinate uralite in a groundmass of uralite, epidote and plagioclase. No. 20 is a uralite diabase from the Caroline estate. It is a medium-grained, dark-green rock, strongly decomposed. Large uralites, still preserving unchanged augite grains, contain ophitic inclusions of zonal plagioclase. Rosettes of epidote and chlorite are abundant, but quartz is not common. All the above six eruptive rocks are strongly reminiscent of similar ones on St. Thomas.

No. 21 is a fine-grained amphibole gneiss from the east side of Coral Bay. The rock consists essentially of quartz, plagioclase, amphibole, colorless pyroxene, magnetite and granulated titanite. The foliation is due to the subparallel arrangement of amphibole prisms. Sometimes the rock has a structure like the granulites and sometimes it resembles the hornfelses. It may be a blue beach metamorphosed by pressure and contact metamorphism. No. 22 is a garnet rock from Marys Point, and is a contact product from limestone. It consists of grains of garnet in a matrix of wollastonite, or of calcite.

Tortola and Neighboring Islets

The group lies north of the axial line of St. Thomas and St. John, but the rocks are much the same. The sediments, more or less metamorphosed to schists and marbles, appear on the south side of Tortola, but are on the north side of St. Thomas and St. John. Fifteen slides were studied. Four are of closely related quartz diorites from Tortola itself. No. 23, called syenite by Cleve, is a medium-grained quartz diorite, with predominant zonal plagioclase, which shows a tendency toward rodlike cross-sections. Notable quartz and uralite, with about 4 per cent magnetite, fill in the spaces between the plagioclases. No. 23, as well as No. 26, came from the east point of the island. No. 26 consists of about 56 per cent of zonal plagioclase (albite rims) and 40 per cent quartz. The remaining 4 per cent are magnetite and chloritized biotite. The acidic outer zone of the plagioclase is intergrown with the quartz. Orthoclase is very rare. No. 24 is a quartz diorite, which forms a fine to medium-grained dike in the blue beach of Little Cappoon Bay. (*Comment:* Little Cappoon must be a part of the bay called Canegarden on the present-day charts.) The zonal plagioclase ranges from acid oligoclase to anorthite. The large crystals in their outer zone contain magnetite and hornblende. The smaller ones have poikilitic and micropegmatitic hornblende. The hornblende appears in larger prismatic crystals and in the small inclusions already mentioned. There is a little green augite. The quartz is richly developed in the filling between the larger minerals and with it are orthoclase, magnetite and titanite. No. 25, a quartz diorite from Cappoon Bay (or Canegarden), is much like No. 23. It manifests diabasic tendencies and is probably from a dike.

From Great Camanoe Island came No. 27, a plagioclase granite like No. 26; and practically identical with it is No. 28, from the same locality

All three were called felsite by Cleve. A diabasic quartz diorite, No. 29, came from Little Dog Island. The zonal plagioclase is rodlike, and is poikilitic or ophitic with bits of hornblende, diallage and quartz. Quartz is localized at times in little areas and is about 15 per cent of the rock. The hornblende is about 30 per cent; the augite, 15 per cent, and magnetite, 16 per cent. There would thus remain 24 per cent for the plagioclase.

Four slides were prepared of rocks from Beef Island. No. 32 is a quartz diorite, whose analysis is given on page 26 above, as No. 8, under the review of P. T. Cleve's paper. It has zonal plagioclase, hornblende, biotite, quartz, magnetite, zircon and apatite, and is akin to adamellite. No. 33 is a more basic diorite, with labradorite and hornblende in about equal amounts, each over 40 per cent of the rock. Chloritized biotite is 6 per cent and magnetite 8 to 10 per cent. No. 30, the anorthite diorite of Cleve, is an olivine gabbro. The plagioclase, a variety near anorthite or anorthite itself, appears in equidimensional components and has the usual dust and other inclusions. The olivine is smaller and is even sometimes enclosed in the pyroxene. Both orthorhombic pyroxene and diallage are present. Brownish-green hornblende is sometimes by itself and sometimes in parallel growths with augite. Magnetite is abundant. The rock is exceptionally fresh, even the olivine grains showing little serpentine. An analysis is given under No. 15, page 26 above. No. 31 is a very coarsely crystalline phase of No. 30, with pyroxenes and hornblendes several centimeters in length, but otherwise like No. 30. Both numbers 30 and 31 are reported by Cleve to be masses enclosed in the quartz diorite described under No. 32. The olivine gabbros contain also pegmatite dikes or veins, with white plagioclase, red orthoclase, epidote, hornblende, biotite, prehnite and magnetite. The plagioclase, Ab_3An, contains graphic intergrowths of blades of quartz.

An unnumbered slide is a uralite diabase called trap by Cleve, which came from Sandy Cay, a small island near the much larger Jost Van Dyke. No. 34, a felsite porphyry (felsite of Cleve), was collected on Guano Island, north of Tortola. It is felsitic in texture, with phenocrysts of epidote. The microscope reveals others of muscovite (sericite?) and carbonates, all derived from plagioclase, probably oligoclase. The groundmass contains scales of chlorite and grains of magnetite in an otherwise not sharply determined aggregate, which is illustrated by a photomicrograph on figure 3 of Plate IX, by mistake called figure 2 in the original text. No. 35 is a labradorite porphyrite from Scrub Island, east of Great Camanoe. The zonal phenocrysts, 1 to 3 millimeters, have labradorite cores and oligoclase rims, which abut against and partially enclose small hornblendes. There is multiple twinning, according to both albite and pericline laws. The groundmass is micro-dioritic, whose components are green hornblende, plagioclase, sparse quartz and abundant magnetite. No. 36, a tuff, contains chiefly fragments of No. 35, but there are bits of other, related porphyritic rocks.

Virgin Gorda and Neighboring Islets

Seven slides were prepared, of which four are varieties of granite. One is called syenite porphyrite by Professor Högbom, but having no orthoclase would be called diorite porphyry in American usage. One is augite diorite and one is andalusite quartzite. No. 39 is merely recorded as Virgin Gorda and is a granite which consists of badly decomposed, somewhat zonal oligoclase and crushed and strained quartz in about equal amounts. There is a micro-pegmatitic tendency. A few scales of chloritized biotite may also be recognized. Numbers 37, 38 and 41 are all plagioclase granites. No. 37 came from Long Bay, Virgin Gorda, and resembles No. 26, described above, from Tortola. Rather fine-grained in texture, it was estimated at oligoclase, 53 per cent; quartz, 38 per cent; hornblende and subordinate biotite together, 6 per cent; magnetite, 2 per cent; minor accessory minerals, 1 per cent. Its analysis is given above, on page 26, No. 5. A photomicrograph is figure 1 of Plate X. Orthoclase and accessories fail. No. 38 and No. 41 are much the same as the last, and also as Nos. 26, 27 and 28 above. No. 38 is estimated at zonal oligoclase-labradorite, 58 per cent; quartz, 30 per cent; hornblende, 3 per cent; magnetite, 6 per cent; titanite, 2 per cent; zircon and perhaps other accessories, 1 per cent. No. 41 has the following composition: zonal oligoclase, 50 per cent; quartz, 27 per cent; orthoclase, 8 per cent; hornblende, 6 per cent; biotite, 3 per cent; apatite and titanite, 1 per cent; the remaining 5 per cent chiefly secondary epidote. Both 38 and 41 are merely recorded as from Virgin Gorda. No. 43, syenite porphyrite, came from Necker Island. The phenocrysts are short, rectangular, acidic, faintly zonal oligoclase. The groundmass has trachytoid texture and consists of rodlike plagioclase, of quartz and chlorite. Alteration of the phenocrysts has produced epidote and zoisite. The rock is stained with iron oxide. No. 42, augite diorite, is said by Cleve to lie between the plagioclase granite just described and the andalusite quartzite, No. 40, which follows. It would seem to have caused the obvious contact metamorphism of No. 40. No. 42 consists of predominant short, rectangular labradorites, of older crystallization than the augite and hornblende, which exhibit parallel intergrowths and fill in the spaces between the labradorites. There is a little quartz, and there is also notable magnetite in coarse bits and dendritic growths. Apatite is rare. No. 40, andalusite quartzite, often resembles a hornfels, but under the microscope is obviously a sandstone which has suffered contact metamorphism. The andalusite grains exhibit pleochroism, from greenish to rose or weak blood-red colors. Sericite and sericitized feldspar may also be recognized.

The Southern Row of Islands, between Virgin Gorda and St. John

This group of islands extends in a line from the east point of St. John to the south point of Virgin Gorda. Between them and Tortola, on the north, is Sir Francis Drake Channel. They have some of the most interesting rocks of the Virgin Islands. Seven slides were studied by Professor Högbom. No. 47, from Salt Island, is orthoclase granite, which consists essentially of orthoclase and quartz, sometimes in micro-pegmatitic growths. There is a little albite and there are traces of muscovite, chloritized biotite, magnetite and tourmaline. Evidences of pressure do not fail. Another high silica rock is No. 50, a felsite porphyry, from Peters Island. The abundant phenocrysts are well-bounded oligoclase, bipyramidal quartz and chloritized biotite. The groundmass is felsitic. The slide is illustrated by a photomicrograph on Plate X, figure 2. No. 48, from Salt Island, is a very peculiar, apparently schistose plagioclase porphyrite. It has rounded phenocrysts of a basic labradorite approaching anorthite. They are slightly zonal, with zonally distributed microlites of magnetite and probable amphibole. They exhibit no traces of pressure or crushing. With the plagioclase must also be mentioned as phenocrysts large grains of magnetite. The phenocrysts are set in a groundmass, strikingly rich in biotite flakes, in parallel arrangement, so as to give the impression of schistosity, but really in flow-lines. Muscovite and chlorite accompany the biotite and spindle-shaped aggregates of quartz grains. There are with the quartz larger grains, suggesting microcline. In the groundmass are also rods of labradorite. No. 46 is uralite diabase from the south point of Coopers Island. There are broad rods of zonal plagioclase, stained brown and having the uralite in the spaces between them, although both minerals sometimes are individually large enough to suggest phenocrysts. The larger uralites include remnants of unaltered augites and magnetite grains with titanite rims. In the field the rock is cut by a strongly sericitized felsite porphyry.

No. 45, from Round Rock, forms a dike in quartz diorite. It is described as amphibole minette, but it is obviously what would be named camptonite in America, minette being restricted to orthoclase-biotite dikes and sills. The rock consists of phenocrysts of slender amphibole, prisms 2 to 3 millimeters long, in flow structure, and best studied under the microscope. The pleochroism is brownish green to brownish yellow and the extinction angle is 20°. These characters depart from those of the brown, basaltic hornblende of typical camptonite with low extinctions. The amphiboles, in smaller size, constitute the groundmass, along with basic labradorite and some other mineral, called "quartz(?)." Primary quartz would be surprising. One suspects analcite with optical anomalies—a frequent experience in camptonites. Much carbonatization has affected the groundmass. No. 44 is amphibole gneiss, also from Round Rock. It is a whitish, fine-grained rock, consisting of a granular aggregate of quartz, orthoclase and albite, containing poikilitic, amphibole grains in irregular distribution, small octahedrons of magnetite and bits of titanite. It must be either a gneissoid amphibole granite or some metamorphic type. The last rock is No. 49, from Deadmans Chest, and is called granulite. It is strongly foliated, with leaves of biotite along the schistosity. It has a granulitic texture, formed by elongated aggregates of quartz grains in which are lenses of albite, which themselves may be specked with quartz grains. Some small scales of biotite are also visible, and veinlets of quartz cut across the rock. These display undulatory extinction and the same fluid inclusions, with bubbles, which are seen in the quartz of the rock proper.

No microscopic descriptions of the rocks of St. Croix are given, although mention is made on page 215 of a few specimens in the Cleve collection. Four additional slides from the Leeward Islands are described, embracing andesite from Saba, quartz-augite diorite from St. Martin and syenite porphyry and porphyritic quartz diorite from St. Bartholomew. A table of the analyses, made by Professor Cleve, is given on page 230. The analyses are reproduced in the review of Cleve's long paper, above, on page 26.

The paper closes with some general conclusions, in which the relative scarcity of igneous rocks with potash feldspar is emphasized and also the relationship, or parallelism, with the prevailing plagioclase rocks of the Andes. The abundance of tuffs is noted and of the associated volcanic rocks, all of which seem to be Cretaceous except an Eocene case in St. Bartholomew. In the subsequent descriptions of rocks by Dr. Meyerhoff, it should be noted that andesite will be used for the now more or less obsolete word porphyrite; granite will be restricted to rocks with prevailing orthoclase or, at least, alkaline feldspars; diorite to those with plagioclases of the oligoclase-andesine series; and gabbro, or diabase, to those of the labradorite-anorthite series, even though hornblende may be the dark silicate. Although the augite of the last named may be uralitized, these more basic rocks will be considered gabbroic in their affinities. Professor Högbom's contribution is a very valuable one and serves to define much more sharply and accurately the components of the rocks macroscopically named by Dr. Cleve.

1907. John 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," by John T. Quin, F. R. G. S. Printed in New York by Chauncey Holt and published by the author in St. Croix, 4to, pp. 106, figs. 32, plates 7, and a double-page, colored geological map on a scale about two miles to the inch.

Mr. Quin was long inspector of schools under the Danish government of the islands and made his home in Christiansted, St. Croix. His many years of journeying about St. Croix gave him a detailed and exact knowledge of its geology. Upon this experience he drew in preparing what was primarily meant to be an account of the geology, written in so clear and intelligible a style as to be understood by those not especially trained in the science. Mr. Quin carried out this plan very successfully and has recorded alike an accurate description of the geology, the areal distribution of the two principal formations, the topography in hachures and the locations of the principal estates and highways.

There are twelve chapters and additional notes. Chapter I contains the introduction, the facts of size and position, an outline of the submarine foundation and of the surface relief, which is naturally divided into an oblong northwestern mountainous portion, an eastern triangular mountainous or hilly part, and an intervening central valley, varied by minor hills, and continued in a southwestern extension of an altitude slightly above sea-level. The first two correspond to the blue-beach series of rocks and the third to the marls and limestones, as we would describe them today. The two divisions constitute respectively the Upper Cretaceous intrusives and volcanics; with their modified tuffs and breccias, and the Tertiary limestones and marls.

In Chapter II the limestone and marl formation is described in detail. Mr. Quin was well aware of the presence of Foraminifera and illustrated some twenty-four different kinds, but did not determine the species. He also noted the presence of corals and of Gastropoda and Pelecypoda. He recognized that the last two groups were represented by casts, and figured several of them. They are described in popular language, as a means of showing that the limestones and marls had once been the sea bottom.

Their structural relations in a syncline southeast of Christiansted and the methods of determining the structure are described and illustrated.

In Chapter III a description is given of the limestones lying southwest of those of the "central slope," which were described in Chapter II. They are believed to form a gentle anticlinal ridge whose axis pitches downward to the southeast, and in the opposite direction traverses the Mt. Eagle ridge to the northwest. Some small faults are noted and illustrated. The limestones are believed to be over 600 feet thick. The recent fringing limestones along the shore also receive attention. The chapter concludes with a summary of ten inferences regarding the geological history.

In Chapter IV the "blue beach," or "indurated clay," formation is described. Mr. Quin recalls the name "indurated clay" from the paper by S. Hovey in 1839, with which he was familiar, and "blue beach" from P. T. Cleve's observations made in 1868, with which he was also familiar. That some of these rocks are sedimentary and stratified is shown by descriptions and by a picture; that others are igneous is also mentioned; yet the blue beach is believed to be in largest part sedimentary. That they have been tilted to high dips is also appreciated. That limestones are interstratified with them is emphasized. Mr. Quin cites the exposure on the estate called Judith's Fancy, on the north shore, which was seen by P. T. Cleve, and the even more fossiliferous one at Waiters Point (or Watch Ho), on the south shore, of which Cleve makes no record. The strange, columnar fossils of Waiters Point were collected and figured. One which looks like a petrified endogenous tree trunk is figured.

While some unnamed naturalist in New York, to whom it was submitted, pronounced it organic, no more definite determination was made. Mr. Quin describes conglomerates in the blue beach, as well as breccias. He notes the travertine which results from calcareous springs. He was also well aware of the variolite in some of the igneous sheets. The angular joints and the cleavage fragments of the slaty rocks are described.

In Chapter V the geographical distribution of the blue beach is outlined, and then, in the northwestern part of the island, the formation is structurally interpreted as forming a northwest and southeast trending and southeast pitching anticline and syncline, the anticline being on the southwest side. A map, with plotted strikes and dips, is given on page 47. In the eastern blue-beach area a similar series of folds is described, whose axes are plotted on the colored geological map. The contortions, which are sometimes observable in both areas and which are best seen at Hams Bluff, on the northwest, are mentioned. The chapter concludes with an interpretation of the older series under ten heads.

Chapter VI treats of the igneous rocks, or the massive forms in the older series. Dikes are first cited and described. Other intrusive masses are mentioned without giving their forms definite names. In designating the kinds of rocks, Mr. Quin mainly follows Cleve, using felsite, granite, diorite, trap and basalt.

Chapter VII takes up the local minerals, mentioning calcite, possibly aragonite, quartz, flint, felspar, hornblende, mica and magnetic iron sand.

Chapter VIII treats of the sculpturing of the island, and in it the effects of land and marine erosion and deposition are described. It leads up to Chapter IX, on the "Connection of the Foregoing with the Physical Geography of the Island." The more striking of the local physiographic features are explained by the general principles set forth in Chapter VIII.

Chapter X compares the structure of St. Croix to that of the other West Indies. Comparisons are run with the known distribution of the rock formations elsewhere, and especially with the northern Virgin Islands. Mr. Quin relies on both his own observations and on the records of Professor Cleve. He had carefully studied the hydrographic charts and interprets the ups and downs of the islands and sea bottom as indicated in the strata.

Chapter XI is entitled "The Relation of the Geology of St. Croix to Geology in General," and is thus an endeavor to illustrate and expound to residents and to readers at a distance the larger principles of the science as illustrated by the local phenomena. The igneous rocks, plutonic and volcanic, first receive attention, with a general account of volcanic outbreaks as a whole. The sedimentary rocks are then taken up, as lime rocks and clay rocks. Then the subjects of fossils and of the geological column, with its subdivisions, from most ancient to modern, are set forth. At the close, on page 93, Mr. Quin merely cites for local application the statement of Professor Cleve that the marl and limestone formation is Miocene, and the blue-beach formation is Cretaceous. This subject of geological age and the determination of the fossils and their reference to periods and epochs are the parts of the subject which one misses most of all in Mr. Quin's work. Could he have determined and classified the fossils which he observed and collected his book would have been complete. This chapter (XI) closes, first, with a general discussion of recent geological history, in which the elevations and subsidence of the land, both in St. Croix and elsewhere in the world, are reviewed, and, second, with a review of the "Age of the West Indian Volcanic Chain," as brought out by Cleve, J. W. Spencer and Schomburgk.

Chapter XII, entitled "Conclusion," is the geological story of St. Croix in the form of a summary and interpretation of the previous records. Two series of notes form appendices, detailing the methods used in identifying the local anticlinal and synclinal folds and their axes.

Mr. Quin has left us an excellent piece of work and has prepared the way for the subsequent closer stratigraphical and structural studies of Dr. Vaughan and Mr. Meyerhoff. The book may be obtained from Mr. Quin's daughters, the Misses Quin, of Christiansted.

1907. O. B. Böggild. "Om Dansk-Vestindiens Geologi, Geografisk Tidsskrift, udgivet af Bestyrelsen for det Kongelige Danske Geografiske Selskab, XIX, 6-11, 1907" (On the Geology of the Danish West Indies. Geographical Journal, publishing the Transactions of the Royal Danish Geographical Society, Vol. XIX, 1907, pp. 6-11). After a few words of general introduction, the author emphasizes the local evidence of mighty volcanic outbreaks, and of movements of the earth's crust, by which the islands were elevated above the sea. Little else than volcanic rocks appear on St. Thomas and St. John, but on the southwestern portion of St. Croix are later, flat strata, which afford fertile soil.

Beginning with St. Thomas and St. John, the formations are said to run in belts, east and west. Most abundant is the so-called blue beach, or blue bit, which extends from the west point of St. Thomas to the east point of St. John, and which is a volcanic breccia and tuff of bluish or greenish gray color. It has angular fragments sometimes reaching whole meters in diameter, but generally only a few centimeters. All are set in a fine-grained matrix. The particles are cemented to a firm, hard rock, which is used as a building stone. Some phases consist of fine volcanic ash and lapilli, originally deposited where they now lie. Again they suggest mud streams down the sides of a volcano. All are greatly altered or decomposed. Interstratified with the blue beach, especially toward the north side of the two islands, are layers of pure sandstone and shale (slate) which are devoid of fossils. Farther north, and in best development on Lovango and Congo cays and on the south side of Tortola, fine-grained gray limestones begin to mingle with the fragmental rocks, and contain a few poorly preserved fossils. All these three varieties—blue beach, fragmentals and limestones—are cut by dikes of fine-grained igneous rocks running in all directions. The dikes are diabase and quartz porphyry with small hornblendes. Many dikes and irregular masses of deep-seated granular rocks appear on the south sides of the two islands, suggesting that they are near the source of the outbreaks and indicating a center of powerful volcanic action. Buck Island has diorite.

In places the intrusive rocks have cut the limestones and have produced contact zones, notably at the east end of Thatch Cay, where excellent crystals of green epidote and brown garnet may be collected. There is some chalcopyrite with these zones, which has been explored in a small way for ore. The amount of ore is probably not great. On Mingo Cay is a small vein with galena. Silver and gold are not important. There is some kaolin on the south side of St. Thomas and St. John. It may be mottled with spots of brown rocks in the white ground and is probably in part due to steam escaping through the open-textured portions from volcanic sources.

All the above formations are of Cretaceous age, as proved by the few fossils which show that here, as elsewhere in the West Indies, the Cretaceous was a period of strong vulcanism. Following the deposition of the Cretaceous beds came a time of mountain-making which produced the Antilles and brought the islands above sealevel. The axial strike is east and west and the dips are very steep, approximating the vertical. On Tortola, to the north, the same strike prevails in similar rocks, but the steep dip is south. A strong synclinal is thus indicated, which the author believes, from such evidence as he had, runs through Porto Rico, Haiti and Cuba. The total section of strata involved is believed to be over 3000 meters, so that great erosion is assumed to account for the present outlines. The fragmental and limy sediments probably spread far over the underlying volcanics, and their extended removal corroborates the inference of profound erosion. Although in the tropics seasonal variations of temperature are not great, yet the excessive heat of the sun falling on exposed rocks, aided by the roots of vigorous vegetation, breaks up the solid rocks and accelerates the work of water.

The duration of volcanic activity is difficult to determine precisely, but it and the upheavals must have ceased before the Miocene period, because these strata on St. Croix are flat or very slightly disturbed. Not until the Pliocene did the chain of volcanoes in the small Antilles appear, which is now so powerfully active. In the other West Indies there are now no active vents.

At its eastern end and along its northern side, St. Croix is geologically much like St. Thomas and St. John. Mountains of the old volcanic rock abound, but the proportion of stratified varieties is greater and blue beach is less abundant. The slaty rocks are sometimes very hard and were used for tools by the Caribs. The gray limestone appears with solitary, poorly preserved fossils. At one locality, Waiters Point,[6] it contains many petrified tree trunks, mainly palms. Dikes are found but rarely. On the north shore is one exposure of diorite and another appears on Green Cay Island. The kaolin fails. The strata are everywhere steeply inclined, almost to the vertical. The structure is complicated, the strikes running in every direction. One infers that when the mountain chain was formed, the island was exposed to a multitude of upheavals. It seems impossible now to range the strata in orderly sequence as we can on the other islands.

The southwestern portion of St. Croix is covered with a white, porous chalk consisting of coral fragments. It contains many fossils, almost all Pelecypods and Gastropods. The original shells have been dissolved away, but molds and casts remain which are beautifully preserved. The fossils appear to be Miocene, so far as investigated. The strata lie very flat; the base of the formation is nowhere visible, but the top rises to about 120 meters above sea-level, so that it is thicker than this. It is a pure carbonate of lime and is quarried near Frederiksted for use in sugar refining. It would probably be suitable also for Portland cement, for which, very likely, the necessary clay could also be found. The low-lying, flat portion of the island is covered by Quaternary, or Recent, formations of two kinds. There is a loosely textured chalk consisting of coral sand and containing shells of living species, especially of *Strombus gigas*. It often appears along the beach, and, when consolidated, is worn into strange shapes by the waves. The second formation consists of loose gravel, of perfectly sharp fragments, which are sometimes cemented together by percolating waters. It has been probably washed off the hills by cloudbursts and has moved as do mud-flows.

As a source of water for bored wells, the older formations are unfavorable, being dense rocks with few joints and cracks. The later chalks and gravels are more favorable, but the sealevel is regarded as an horizon below which fresh water may not be expected. In borings in the Miocene chalk, concealed projections of the old volcanics might be intersected at unexpectedly high levels.

Dr. Böggild's paper contains much that is suggestive, especially on the large structural matters and the questions of kind and derivation of rocks. No petrographical details are given, nor are there maps. Close studies of the fossil faunas were left to the future.

[6] Now usually called Watch-Ho, or, as given on the new topographic map, Vagthus Point. It is on the south coast, almost due south of Christiansted. The fossils referred to as petrified palms certainly resemble such an original. The reviewer submitted some specimens to Dr. J. J. Galloway, paleontologist, and received the same verdict.

1908. O. B. Böggild. Dr. O. B. Böggild's second paper appeared in 1908, a year later than the one just reviewed, and formed one of the articles on the Danish West Indies which constitute Part IV in a volume entitled "The Danske Atlanterhavsoer" (The Danish Islands in the Atlantic Ocean). The earlier parts, which began to appear in 1904, cover in order Iceland, the Faroes and Greenland. All are bound in one volume, completed in 1911. The copy consulted by the writer was kindly loaned by the American Geographical Society. Dr. Böggild's contribution is entitled "Jorden, dens Art og Benyttelse" (Geological Formations, Kinds and Uses), pp. 586-597, with nine illustrations, figures 267-275, from photographs.

The paper covers much the same ground as the one from the Geografisk Tidsskrift. After remarking the similarity of the Danish Islands to the other Antilles, and then speaking especially of St. Thomas and St. John, the "blue beach" is cited as the most important formation. It is described as a breccia of larger fragments of fine-grained eruptive rocks set in a bluish or grayish matrix of fine particles. It has transitions to well-sorted sandstones and even shaly or slaty beds. All the components are of much-decomposed eruptive rocks, and quartz is rare or lacking. There are also transitions to calcareous phases and even to limestone and marble. Fossils fail in all but the limestone, from which enough have been obtained to establish the Cretaceous age, making the beds represent the oldest time division known in the West Indies. (Note: Two years later than Dr. Böggild's paper Jurassic strata in western Cuba were reported to the Geological Congress in Stockholm. C. de la Torre, "Comprobation de l'existence d'un horizon jurassique dans la région occidentale de Cuba." Comptes Rendus, XI, Congrès Géologique International, II, 1021, 1910.) The "blue beach" and its associates are cut by dikes of eruptive rock, which themselves contain inclusions of older rocks. The east and west strike and the steep northerly dip of the stratified phases are emphasized.

St. Croix is described as having the blue beach on its eastern and northern portions, but as containing Tertiary fossiliferous limestones on the southwestern part.

The soils of all the islands are explained as due to the weathering of the igneous and sedimentary types. Their ability to cling to steep slopes is remarked. The agricultural advantages of the Tertiary areas of St. Croix are brought out.

The earth movements which have led to the steep dips of the older beds are appreciated by Dr. Böggild, and, by contrast, the gentle folding of the Tertiary limestone is indicated. A brief physiographic résumé of the elevations or relief, of the irregular and indented coastlines and of the bays and steep shores, conclude the paper. A bibliography of the principal earlier papers is recorded. A map of St. Thomas, St. John and the small islands, on a scale 1: 120,000, or slightly over two miles to the inch, is added at the end of the volume, and another, on the same scale, of St. Croix. Elevations are shown by hachures, but actual heights are printed only in the text.

The paper is immediately followed by one from the pen of H. U. Ramsing, captain of engineers, on "Arealet og dets Benyttelse" (The Area and its Several Uses), pp. 597-599. It may be interesting to record here the principal figures of interest, as the original is not always accessible. Total area of all the larger and smaller islands, 358.9 square kilometers, or 6.52 geographical square miles. St. Thomas and all its small islands, 86.17 square kilometers, or 1.56 geographical square miles. St. John and small islands, 54.40 square kilometers, or 0.99 geographical square miles. St. Croix and small islands, 218.33 square kilometers, or 3.97 geographical square miles. Some agricultural details are also given.

1914 and later. In 1914 Dr. T. Wayland Vaughan, then of the United States Geological Survey in Washington, began a series of papers on corals and coral reefs which, in time, embraced contributions on the geology of the West Indies and Central America. A list of the publications is appended to the paper reviewed below under 1923. From the series, four which especially relate to the Virgin Islands are here summarized.

1916. T. Wayland Vaughan. "Some Littoral and Sublittoral Physiographic Features of the Virgin and Northern Leeward Islands, and Their Bearing on the Coral Reef Problem." Journal of the Washington Academy of Sciences, Vol. VI, 1916, pp. 53-66.

By plotting a series of profiles based on soundings taken from hydrographic charts, the author endeavors to demonstrate the existence of a series of two well-marked terraces and of a third not so definitely discernible. With the formation of the terraces is involved the growth of coral reefs and from both lines of evidence the recent depression of the islands in three subsidences beneath the surface of the sea is inferred. Only slight reference is made to the geology of the islands, and therefore only this brief abstract is presented. The subject of the submarine physiography will be discussed at length by Mr. Meyerhoff.

1916. N. L. BRITTON. "The Vegetation of Anegada." Memoirs, New York Botanical Garden, Vol. VI, 1916, pp. 565-580.

The paper is essentially a summary of the plant life, based on a visit in February, 1913, but on pages 565 and 566, after describing Anegada's relations to the surrounding sea bottom, Dr. Britton states: "The eastern and central portions are a nearly level limestone plain, slightly eroded, but the western part is a sand plain with large saline areas and many salt ponds. There are small areas of arable land, originating, in part, from the decay of limestone, more or less mixed with calcareous sand." The contrast presented by the flat limestone and sand area of Anegada with the hilly topography and eruptive rocks of the other Virgin Islands is then noted, as is its similarity with the Bahamas, Bermuda and other æolian islands. "Its soil is, therefore, quite different from that of the other Virgin Islands, and some of its plants are not known to grow upon them."

1919. T. WAYLAND VAUGHAN. "Some Features of the Virgin Islands of the United States." Annals of the Association of American Geographers, Vol. IX, 1919, pp. 78-82.

Dr. Vaughan remarks at the outset that the Virgin Islands rise in two distinct parts from a comparatively shallow eastward prolongation of the bench on which stands Porto Rico, but that now St. Croix is separated from the rest by a deep trough of 2400 fathoms of comparatively recent geologic development. He then reviews the submarine platforms of Cuba, Jamaica, Haiti and Porto Rico, and regards the Virgin Bank, or the submarine platform of the northern Virgin Islands, as only a slightly submerged part of the platform on which stands Porto Rico. "St. Croix is connected by shallower water with the St. Christopher chain than any other islands, and might on this ground be considered as naturally forming a part of the inner prong of the Caribbean Arc, but its geological kinship is with St. Thomas and Porto Rico." The number—about 100—of the Virgin Islands is then mentioned, and their discovery, recent human history and topography are briefly reviewed. The material composing them is stated to be largely andesite and andesitic tuff and agglomerate, but there are some sediments, and some Cretaceous fossils were collected by Cleve. The characters of the harbors of St. Thomas and St. John are described and the industrial conditions of the two are briefly summarized.

St. Croix is taken up in more detail, and its abrupt rise of 13,656 feet, on the north side, from the sea bottom in a horizontal distance of 25,800 feet is referred to a fault-line. The island's two geological formations are outlined. The sharp contrast is brought out between the older of Cretaceous sediments and igneous rocks and the later of gently tilted limestones and marls.

Remarking again that the abyss which separates St. Croix and St. Thomas is due to faulting at a time geologically recent, and that it is continued in Anegada Passage, the author states that "a continually increasing volume of biogeographic data seems to demand land connections from Porto Rico to Anguilla and to St. Croix during either Miocene or Pliocene time, and that St. Croix and the islands of the Virgin Bank then formed part of one land area, which has been broken into separate masses by block faulting."

1922. A. K. Lobeck. "The Physiography of Porto Rico," forming Part 4 of Vol. I of the Scientific Survey of Porto Rico and the Virgin Islands, pp. i-vii, 301-384, figs. 41, physiographic map of Porto Rico, with Culebra and Vieques, on a scale, 16 miles to 5 inches.

The portions on Culebra and Vieques are all that immediately concern this review. The two are briefly described on pp. 343, 373-374. Both are regarded as separated from Porto Rico because of submergence. Vieques consists chiefly of the older volcanic formations which "are flanked on the east end and south side by remnants of the Tertiary coastal plain. A well formed cuesta has been developed and the subsequent drowning of the island has permitted the sea to enter the inner lowland at several places along the south coast." Alluvial deposits clog the valleys. "The low headlands throughout the coast are being cliffed by the waves." Culebra and its islets consist wholly of the older volcanic formations, which are moderately folded. Its topography is controlled by erosion along strong joint systems, one, the major, northwest and southeast; the other almost transverse to it. The bays are drowned valleys, but as streams are small and intermittent, alluvial deposits have accumulated but slowly.

1923. James F. Kemp. "Report to H. H. Hough, Captain, U. S. N., Governor, Virgin Islands." Printed at the Naval Station, St. Thomas, April 6, 1923.

CHRISTIANSTED, ST. CROIX, V. I., March 25, 1923.

H. H. HOUGH,
Captain, U. S. N., Governor, Virgin Islands.

SIR: In accordance with our conference and your request of March 10, I have the honor to submit the conclusions which I have reached regarding the water supply of St. Croix from subterranean sources. The problem of under ground water supply turns upon the local geology. Therefore, by way of introduction, I summarize the formations and structure.

There are two sharply contrasted geological formations, of different character and age—an older series, which I will call the Mount Eagle series, and a later, which I will call the Kingshill series.

The Mount Eagle series consists almost entirely of fragmental volcanic rocks, such as are yielded by explosive outbreaks, and are scattered far and wide from the vent. The particles are generally small in St. Croix, and where they have fallen in the sea and have been deposited in beds by the waters, they present a stratified appearance and resemble ordinary sediments. They are, however, now compacted and hardened to a very dense rock. In a few places, notably in the Salt River Hills and the Mount Eagle range, coarse fragments up to several inches in diameter are mingled with the fine volcanic ash. In a few places solid rock from lava flows or intrusive dikes is also involved.

Obviously there were a few intervals between explosive outbreaks when animal life in the form of corals and small organisms with calcareous shells could live on the sea bottom and furnish from their hard parts the material for a relatively small development of limestone which is interstratified with the other beds.

These older strata of the Mount Eagle series have experienced great disturbances, such as accompany mountain upheavals, and are now tilted from their original horizontal position to prevailingly steep inclinations. The inclinations range most frequently from sixty degrees with the horizontal to the vertical. Rarely they are below forty-five. As a whole, the series consists of dense rocks, not at all porous or open-textured, and the chief cavities in which water might gather are fortuitous cracks and joints, which might indeed be locally more abundant than elsewhere, but which can not be foreseen from the surface.

The later, or Kingshill, series rests upon the upturned edges of the older Mount Eagle series and was deposited upon them after the tilting and disturbances which the Mount Eagle suffered and long after cessation of volcanic activities. The Kingshill series consists of white or cream-colored, soft limestones, chalky beds and marls. I have only once seen a bed which was at all sandy. The strata are not very permeable to water; by no means so much so as beds of sandstone or sandy layers. They are largely formed of minute organisms and have frequent layers rich in corals, and others in which water-worn pebbles of the volcanic rocks of the Mount Eagle series are buried in fine, chalky sediment. The inclination of the Kingshill series is very flat. The largest variation from the horizontal which I have seen is 12°–15°. Usually the readings are 3° to 8° and often the beds are practically flat. The Kingshill series reaches a maximum altitude above the sea at Bülowsminde, near its eastern edge, where the summit is 615 feet and the inclination is flat. The total thickness may therefore reach 500′–600′, perhaps even more, but over the general area covered by these beds a large proportion of this section has been removed by erosion. There is some evidence that these beds, in the central belt of the island and, as noted by the late John T. Quin, Esq., in his interesting book on the geology of St. Croix, called "The Making of an Island," lie in a broad, flat trough or syncline whose axis pitches at a very low angle downward to the southwest. The inclination of the strata is, however, only a few degrees, and while the trough or synclinal structure is the one associated with artesian wells where we have porous, water-bearing beds (usually sandstone) contained between impervious beds, such as clays, and outcropping where they can gather in and conduct downward, to the hollow of the trough, the rain-water which falls on their exposed portions, we lack, so far as my observations go, good porous, permeable beds. I would not therefore look for a copious flow, even if water were struck in the Kingshill series. Pumping wells, suitable for watering stock, seem to me to be the ones which, were water encountered, would be the most probable expectation. I cannot bring myself to believe that any supply abundant enough for irrigation would be encountered.

The best and most practical plans for increasing and conserving the water supply seem to me to be two. In accordance with the first, wells could be dug to depths of approximately fifty feet or less on the flats which are opposite valleys and amphitheaters in the mountains and hills. At times of heavy rains much water falls in these catchment areas, and while a goodly proportion runs off, some seeps into the ground at the mouth of the valleys. The ground may be expected to be open-textured and porous down to the bedrock and to consist of stream gravels and sand washed down from the hills. By selecting relatively low points, as indeed has been already often done, water supply for stock can be had. In selecting sites, regard should be had for the catchment basin higher up and for the probable line of flow of underground water along the general line of surface drainage. There are many such locations not yet utilized on the island, and the expense involved is not great. Drive wells would answer far enough away from the hills to avoid the very coarse rocks which might have been washed down from the hill country at times of torrential floods.

The second plan would be the storage of water by dams. One such plan which seems to me feasible is already being studied by Mr. Folmer Andersen, the Manager of the Bethlehem Sugar Works. Two hills of the Kingshill limestones are sufficiently near each other just north of the South Road to give good reason to study the practicability of an earth-work dam with a tight core wall. Enough water in rainy times could apparently be impounded to furnish a supply for irrigation during drought, so as to carry the sugar crop through the worst stages of dryness.

Study of the local conditions along other watercourses might reveal additional opportunities for similar structures.

In conclusion, I may summarize as follows:

1st. I think it highly improbable that any deep boring will furnish sufficient water for irrigation.

2nd. The most that can be expected is a supply for stock.

3rd. Additional supplies for stock over present sources may be found in wells on the flats opposite catchment valleys in the mountains.

4th. In a few specially favored localities along the larger streams, dams for water storage of sufficient magnitude for irrigation in times of drought are apparently feasible and are worthy of careful study, as regards tight foundation strata, resistant spillways, and the other engineering features of earthwork dams, so as to prevent disastrous floods from the collapse of the dams under unusual rainfall.

5th. While I realize the hardships involved in the recent protracted dry times, I am hopeful that the worst is now past and that the country will experience a gradual increase in the rainfall for several years to come. Dry times and wet times come in recurrent cycles.

In reaching these conclusions, I wish to acknowledge the great assistance I have received from my colleague and companion, Dr. N. L. Britton, Director of the New York Botanical Garden.

Respectfully,

(Signed) JAMES F. KEMP.

1923. T. WAYLAND VAUGHAN. "Stratigraphy of the Virgin Islands of the United States and of Culebra and Vieques Islands, and Notes on Eastern Porto Rico," by T. Wayland Vaughan. Journal of the Washington (D. C.) Academy of Sciences, Vol. XIII, pp. 303-317.

From May 21 to June 24, 1919, Dr. Vaughan spent a little over a month in geological reconnaissance of St. Croix, St. John, St. Thomas, Culebra, Vieques and the eastern end of Porto Rico for the Navy Department. The above paper gives the results, and in its preparation Dr. Vaughan was aided by the following: C. P. Ross, in connection with igneous rocks; T. W. Stanton, Cretaceous mollusks; J. A. Cushman, Tertiary Foraminifera; R. S. Bassler, Bryozoa, and C. W. Cooke, Tertiary mollusks. The corals were identified by Dr. Vaughan.

The paper begins with a list of the principal Virgin Islands, and cites their altitudes above sea-level and their relations to the submarine platform. Three major sets of rocks may be recognized, as follows: "(1) Upper Cretaceous sediments and interbedded volcanic tuffs, breccias and lava flows; (2) post-Cretaceous, probably early Tertiary, intrusive gabbro, dolerite, diorite and quartz diorite, and perhaps also volcanic extrusions; (3) Oligocene and Miocene marls and limestones." Based on this threefold division, Dr. Vaughan briefly outlines the characters of the exposures of each in the six islands or areas visited during his reconnaissance.

ST. CROIX

Upper Cretaceous strata are found on St. Croix in the eastern and northwestern area of older rocks, already reviewed above under P. T. Cleve, O. B. Böggild and J. T. Quin. They comprise sandstone, shale and limestone, with interbedded volcanic tuffs. Dr. Vaughan studied the instructive exposures at Waiters Point (or Watch-Ho), which are first mentioned by J. T. Quin and Dr. Böggild in 1907, and not only collected the fossils on the ground but was given the selection of the collections of Mr. Quin by the Misses Quin. The ones not taken by Dr. Vaughan for the United States National Museum were subsequently presented, in

1923, to the writer by the Misses Quin and will be deposited in the American Museum of Natural History, New York, along with additional ones collected by the writer and others obtained by Mr. Meyerhoff in 1924. Dr. T. W. Stanton identified for Dr. Vaughan *Inoceramus* sp. related to *I. proximus* Tuomey, *Barrettia monilifera* Woodward, *B. sparcilirata* Whitfield?, *Radiolites nicholasi* Whitfield, *Caprinula gigantea* Whitfield?, *Caprinella occidentalis* Whitfield. As Dr. Vaughan remarks, "There is no room for doubt as to the geologic age of the deposits from which these fossils come; it is Upper Cretaceous."

St. Thomas

Dr. Vaughan refers to the recognition of Upper Cretaceous sediments (*i. e.,* the Coki Point exposures) by P. T. Cleve in 1869, who compared the fossils with those of the Gosau beds in Austria. The Cleve collection was loaned to Dr. Vaughan by Professor Högbom, and the following genera were identified: *Glycimeris; Limopsis; Astarte,* several species; *Opis; Cyprina?; Corbula; Cerithium,* two or more species; *Nerinea,* several species; *Actaeonella; Phylloceras?* immature, septa not well shown. Dr. Vaughan collected in person *Astarte, Glauconia, Cerithium* and *Actaeonella.* He remarks that the limestone near Coki Point contained volcanic material and was associated with and was probably interbedded with shaly rocks which have been metamorphosed to schists.

"The principal country rock of St. Thomas comprises andesitic breccia and latite, which in places shows rude bedding." Although not observed in definite relations with the Cretaceous limestone, yet, following the testimony of Cleve, Dr. Vaughan concludes that the older volcanic rocks seem to be of Upper Cretaceous age.

St. John

Although no fossiliferous beds have been found on the island, yet, from his own observations of the similarity which is shown by the igneous and metamorphic rocks to those of St. Thomas, and aided by the records of Cleve, Dr. Vaughan concludes that Cretaceous sediments and volcanics are present, but that there may be rocks of pre-Cretaceous age.

The notes on Culebra, Vïeques and eastern Porto Rico do not come under this review of the Virgin Islands and will be omitted here.

Early Tertiary Events

Dr. Vaughan corroborates the observations of Cleve and Böggild of the mountain-making upheaval which followed the deposition of the

Upper Cretaceous and which has been so fully demonstrated by our Survey in Porto Rico. He finds some of the older igneous rocks so crushed as to be now chlorite or sericite schists, and suggests that they may be older than the Cretaceous. He noted the northwest and east-and-west trends and speaks of them as "intersecting." There were extensive intrusions of diorite, dolerite and quartz diorite and probably the extrusion of lavas and tuffs. The older series of rocks were subjected to subaërial erosion, so that they were practically base-leveled. The younger sediments were then laid down on a nearly plane surface of the older ones, whose strata in the southwestern part of St. Croix dip as steeply as 80°. These observations fall in closely with the earlier ones of our Survey, as recorded for Porto Rico, and bring out the close parallelism between the two areas.

Tertiary Sediments

St. Croix alone of the Virgin Islands visited by Dr. Vaughan contains these strata, but upon the St. Croix exposures his visit has shed much important stratigraphic light. After outlining their distribution and remarking their flat dips of 8° to 15°, he states that three horizons seem to be represented: (1) Middle Oligocene, (2) probably Upper Oligocene, (3) Lower Miocene. The Middle Oligocene was found at his Station 8649, two-tenths of a mile southwest of Wheel of Fortune estate house, which is a short distance east of Frederiksted. The Foraminifera were *Rotalia* sp., abundant; *Amphistegina* sp.; *Lepidocyclina morgani* Lemoine and R. Douville (also reported from Cuba); *Carpenteria americana* Cushman (also in Cuba). The Madreporaria were *Astrocoenia decaturensis* Vaughan (also reported from Antigua and Bainbridge, Georgia); *Gomiastrea reussi* (Duncan), also in Antigua; *Cyathomorpha tenuis* (Duncan), also in Antigua, in the Pepino formation of Porto Rico (now called the Arecibo limestone by our Survey) and in other places; *Goniopora microscopica* (Duncan) (also in Antigua).

The fossils correspond so closely with those of the Antigua formation of the island of Antigua that no doubt is felt by Dr. Vaughan regarding their Middle Oligocene age.

The Upper Oligocene was found at three stations, all near the northern edge of the Tertiary in the central part of the island, west of Christiansted. Station 8647 is 1.4 sea miles west of Christiansted lighthouse, at Evening Hill, where J. T. Quin, on page 17 of his book, recorded large Foraminifera. Dr. Vaughan mentions the following three species: *Amphistigina* sp.; *Heterostegina antillea* Cushman (also known in Antigua and northeastern Mexico); *Heterosteginoides* sp., cf. *H. Antillea* Cushman (also in Anguilla).

Station 8648 is farther west, on the north shore road, at Montpellier East. Three Foraminifera were found: *Amphistegina* sp. (compare above Station 8647); *Peneroplis* sp.; *Gypsina globulis* (Reuss) (also reported from Anguilla, Recent). There seemed no reasonable doubt that the formation was the same as at 8647. The age is either Middle or Upper Oligocene, more probably the latter.

Station 6850, also at Montpellier East, is of interest because Mr. Quin gathered and figured a gastropod, or volute shell, which with its adhering matrix passed to Dr. Vaughan in the gift of specimens from the Misses Quin. The fossil proves to belong to the genus *Orthaulax,* and is regarded by Dr. Vaughan as probably identical with *O. aguadillensis,* originally described by Dr. Carlotta J. Maury from the collections made by Dr. Reeds, of our Survey, in northwestern Porto Rico. [See Natural History Survey of Porto Rico and the Virgin Islands, Vol. III, Paleontology, Part I, page 58, Plate IX, figure 4. As will be seen from the paper of Dr. Bela Hubbard (idem, Vol. II, Part I, pages 72-73, "The Geology of the Lares District"), much hinges in the way of stratigraphic determination on the age of this fossil, whether Upper Oligocene or Lower Miocene.]

In the sections prepared by Dr. Vaughan from the matrix of the specimen of Orthaulax, Dr. Cushman identified the following Foraminifera: *Alveolina* sp. (also reported from St. Martin); *Orbitolites duplex* Carpenter? (also from St. Martin); *Spiroloculina* sp. (also from St. Martin); indeterminable species of the genera *Quinqueloculina, Triloculina, Globigerina* and *Amphistegina.* Dr. Vaughan remarks that the species of *Orthaulax* suggests Upper Oligocene, about the horizon of the Anguilla formation, and that Dr. Cushman considers the Foraminifera to be precisely the same as those collected by Dr. Vaughan in the yellowish limestone of St. Martin. The horizon, therefore, may be very low Miocene instead of topmost Oligocene. The question of the stratigraphy of the lower beds of the Tertiary limestones and marls seems to offer a field for further investigation, and we hope that Mr. Meyerhoff may throw additional light on it. All the four stations cited by Dr. Vaughan appear to be in the lower portion of the series. Along the north shore, Dr. N. L. Britton and the writer have collected a number of fossils, both Mollusca and corals, which have been entrusted to Mr. Meyerhoff and will amplify those gathered in his own more detailed study.

Miocene

From Station 6851, Anna's Hope estate, along the road, Dr. Vaughan records a quite rich fauna in Foraminifera and two corals, viz., *Clavulina* sp., cf. *C. parisiensis* d'Orbigny (also reported from the Culebra formation); *Clavulina* sp., cf. *C. communis* d'Orbigny (also in the Culebra formation); *Nodosaria* sp., cf. *N. insecta* Schwager (also in the Culebra formation); *Uvigerina* sp. (?); *Orbulina* sp.; *Globigerina* sp.; *Truncatulina wuellerstorfi* Schwager (also in Culebra formation, and Recent); *Siphonina* sp., cf. species from Oligocene of U. S.; *Osterigerina* sp., cf. species from Oligocene of U. S.; *Amphistegina* sp.; *Ellipsoidina* sp.

There are thus twelve species of eleven genera, but of the twelve only one is sharply named specifically. Of corals, or Madreporaria, two undetermined species from two genera were collected, viz., *Obicella* sp., cf. a species from the Lower Miocene of Trinidad and Vieques Island; *Psammocora* sp., cf. a species from the Miocene of Trinidad. Other species of this genus are known from the Lower Miocene of Trinidad, Vieques Island and the Dominican Republic.

Dr. Vaughan concludes that the basis for correlating this deposit is not definite, but the horizon seems to be very low Miocene.

The Anna's Hope estate was one of the localities considered important by Mr. Quin; so that, unaware that Dr. Vaughan had collected at it, the writer gathered a series of specimens from each contrasted horizon from the lowest at the highway to the topmost, probably fifty feet higher at the summit of the hill. These have been entrusted to Mr. Meyerhoff.

Dr. Vaughan gives some notes on Vieques, with the record of a quite rich fauna, believed to be certainly Miocene. Some further notes are also given on eastern Porto Rico, where, at Station 8653, five kilometers east of Rio Piedras, on the north side of the Fajardo road, fossils were found which were regarded as uppermost Oligocene or very low Miocene.

In summary of the Tertiary, Dr. Vaughan states that "deposits of middle Oligocene (Rupelian) and probably upper Oligocene (Aquitanian) age occur in St. Croix, and that deposits of lower Miocene (Burdigalian) age occur probably in St. Croix, certainly in Vieques, and probably on the north side of Porto Rico, east of San Juan."

Pleistocene Deposits

No records of deposits on the Virgin Islands were made.

Summary

An important summary of the geologic history under nine heads concludes the paper. Practically the same summary will be found forming the abstract of an oral communication to the Paleontological Society of America, in session as an affiliated society with the Geological Society of

America (Bulletin of the Geological Society of America, Vol. XXXI, 1920, pp. 216-217). The nine points are here reproduced and some comments are added by the writer, based on his experience in Porto Rico, the Virgin Islands, Cuba and the Panama Canal.

1. The presence of shoal water deposits of Upper Cretaceous age in Saint Croix and in the islands on the Virgin Bank from Saint John to Porto Rico and in Porto Rico shows that the major tectonic axis of this part of the West Indies antedates Upper Cretaceous time, because there was an antecedent basement on which these deposits were laid down. I have suggested that these major trends may be even as old as late Paleozoic.

(*Comment:* All we know positively is that volcanoes were active in Upper Cretaceous time, and there seems no good evidence contradicting the assumption that they broke out on the ocean floor in this period and built up the islands and banks. The rocks embrace water-sorted and unstratified fragmental and massive igneous products along with very minor limestones, which in a few cases carry the fossils which furnish the determining evidence of the Upper Cretaceous geological age. Some cones may have been raised above the ocean surface.)

2. During Upper Cretaceous time it is probable that most of, perhaps all of, the areas now occupied by land were under water; and that there was considerable volcanic activity is proved by the water-laid tuffs and lava flows which are interbedded with the shoal-water calcareous sediments.

(*Comment:* These points are covered, in part at least, by the comment under No. 1.)

3. In early Tertiary, probably Eocene, time there was mountain-making by folding which in places was so intense that the stratified rocks were left in an almost vertical position and both the sediments and the older igneous rocks were metamorphosed. There were also intrusions of diorite, dolerite and quartz diorite, and probably the extrusion of some volcanic rocks. West of the Virgin Islands, there was during later Eocene time extensive submergence in the Dominican Republic, Haiti and Cuba, as is attested by the Eocene formations now above sealevel in those areas.

4. The episode of mountain-making was followed in the Virgin Islands by one of prolonged subaërial erosion, and the production of the Virgin Bank apparently may in large part be assigned to this period of the history of the region. It seems that the axial islands on the Virgin Bank and the Central Sierras of Porto Rico, from its east to its west end, have continuously stood above the water since the close of Cretaceous deposition. In Saint Croix by middle Oligocene time erosion had proceeded far enough to reduce almost to baselevel the tightly, steeply folded strata of the mountains.

5. In middle Oligocene time a large part of Saint Croix was submerged and, with slight fluctuations, remained under water until some time during the Miocene. Although both the northern and southern, but not the axial, parts

of western Porto Rico were submerged in middle Oligocene, and probably in lower Oligocene time, the eastern end of Porto Rico and the axial islands of the Virgin Bank west of Anegada Island were not submerged. The age of the limestone on Anegada Island is not known. These facts mean that there was differential movement, the movement being greater toward the west than in the central part of the bank. In lower Miocene time the northern shore of Porto Rico east of San Juan was submerged, as were also the southern shore and eastern end of Vieques Island; both the northern and the southern edges of the bank were submerged probably by marginal down flexing. Although there are corals in the exposed sediments of Oligocene and Miocene age, and corals were therefore constructional agents during those epochs, their work as compared with that of other agents was of minor importance. If the work of these organisms in forming deposits concealed under water can be evaluated by their work in deposits exposed to view, the conclusion would be drawn that they played only a minor rôle in the formation of the Virgin Bank. There is as yet no evidence showing intense deformation during later Oligocene time in the Virgin Islands and Porto Rico, such as is known to have taken place in the Dominican Republic.

6. Subsequent to early Miocene time there has been uplift, greater along the axis of Porto Rico and the Virgin Bank than on the flanks, bringing Miocene and older Tertiary sediments, in places where they are present, above sea-level. The Tertiary sediments are tilted and gently flexed, but they have not been so much deformed as the Upper Cretaceous deposits. It is about this time that the land connections permitting migration of land animals from Anguilla to Porto Rico, Haiti and Cuba seem to have existed. Saint Croix seems to have been connected with Anguilla, Saint Martin and Saint Bartholomew.

7. The period of high stand of land was followed by faulting, such as I have several times described recently; but, as pointed out by Woodring, the faulting was concomitant with folding. By these processes Anegada Passage, between the Virgin Bank and Anguilla, was produced and the islands assumed very nearly the outlines and arrangements of today.

8. Subsequent to the episode of faulting, there was emergence of land, and terracing of the margins of the Virgin Bank, followed by submergence. In places in Porto Rico and along the Cordilleras reef, which extends eastward from the northeast corner of Porto Rico, there has been local emergence due to differential crustal movement.

9. The living coral reefs on the Virgin Banks are growing on an extensive flat in a period of geologically Recent submergence. This flat is geologically an old feature. Its origin, in large part at least, may reasonably be attributed to the long period of erosion following early Tertiary mountain-making.

1924. W. M. Davis. During October and November, 1923, the author made a voyage throughout the Lesser Antilles for the purpose of studying their physiographic development. The islands Culebra and Vieques, off the east coast of Porto Rico, are included. A condensed statement of the results of the investigation was communicated to the

National Academy of Sciences, May 5, 1924, and was published the following June under the title, "The Formation of the Lesser Antilles."[7] The paper was greatly expanded subsequently and published as a separate volume by the American Geographical Society. In the summary of this fuller work, in so far as it affects the Virgin Islands, which is given below under **1926,** the earlier paper of 1924 is included.

1924. K. W. EARLE. "The Geology of the British Virgin Islands." With one plate, a geological map of the islands on a scale of two miles to the inch and one text figure. The Geological Magazine, Vol. LXI, August, 1924, pp. 339-351.

INTRODUCTION

After citing the papers of P. T. Cleve and A. G. Högbom as those of the only two writers who had given more than passing attention to the British Virgin Islands, the writer almost too modestly, considering the excellence of his work, offers his contribution as a preliminary guide to more detailed future study.

TOPOGRAPHICAL

The geographical position in latitude and longitude is defined. The British Virgin Islands are then divided into three groups, with the remote Anegada really making a fourth. The first group consists of Tortola, the largest of the islands, and of its satellites, at the east end, Great and Little Camenoe, Scrub, Guano and Beef Islands; at the west end, Frenchmans Key and Great and Little Thatch Islands. The second group, lying farther northwest, comprises Jost Van Dyke, Little Jost Van Dyke, Tobago and Little Tobago. The third group curves around in an arc to the south and east of the first group, and comprises the islands of Virgin Gorda, with the adjoining islets, Necker, Prickly Pear and Mosquito, and the islands, Fallen Jerusalem, Round Rock, Ginger, Cooper, Salt, Norman, Dead Chest, or Dead Man's Chest (the one immortalized by R. L. Stevenson in "Treasure Island"), and Peter. The Three Dogs form a connecting link between the first and third group, and Anegada, thirty miles north of Virgin Gorda, is a unit by itself.

All the islands but Anegada are hilly or even mountainous. Tortola, the largest, culminates in Sage Mountain, 1780 feet above sea-level. The lowest cross pass is 1200 feet. Anegada, the second in size, is a flat coral island of thirteen square miles, and is said to be nowhere more than ten

[7] Proceedings of the National Academy of Sciences, Vol. X, pp. 205-211, June, 1924.

to fifteen feet above tide. We may note that Schomburgk, a careful observer, in 1832 recorded an elevation of sixty feet; so that erosion must have been severe in the interval of ninety-two years. Virgin Gorda culminates at 1370 feet and is third in size. Jost Van Dyke, the fourth in size, resembles Tortola, on a smaller scale. All the remaining islands are relatively small, precipitous, rugged and covered with brush, which features make exploration difficult. Coral reefs add an element of danger to landings. On the islands, trails are the best means of communication. Only seven islands are inhabited.

Geological

The British Virgin Islands, with the exception of Anegada (and Sombrero), form, with the Greater Antilles, the eastern end of a geological unit and are essentially a continuation of the American islands of St. John and St. Thomas, from which they are separated by a channel less than a mile wide and not less than fifteen to twenty fathoms deep. They trend with the geological structure generally east and west. They are entirely igneous and metamorphic and include accumulations of pyroclastic rocks, volcanic breccias and agglomerates. There are no signs anywhere of unaltered sedimentary rocks,[8] and only by analogy with the neighboring American islands and Jamaica can a reliable estimate of their age be obtained. The igneous rocks are of all three types—plutonic, hypabyssal and volcanic. The plutonic are diorites, granodiorites and gabbros; the dike rocks, pegmatites, felsites, hornblende porphyrites and dolerites; the lavas, augite andesites and basalts.

The metamorphic rocks are of various types, and for the most part are metamorphosed sediments. They embrace hornblende-, quartz- and mica-schists, phyllites and spotted schists, together with marbles, garnet-wollastonite rocks, granulites and other types resulting from the alteration of impure limestones or lime-bearing sediments. These rocks are often interbedded with volcanic breccias and agglomerates, and it appears that the sediments were originally largely of the nature of stratified tuffs. Where intrusives fail, the mineralogy of the rocks is but little changed; hence the metamorphism is believed to be largely dynamic, perhaps accompanied by a rise in temperature, rather than to be due to contact effects from intrusives. The dynamic forces have served to tilt the beds to high angles without destroying stratification, and there is little evidence of crushing, faulting and deformation.

[8] This statement seems rather sweeping, in view of the subsequent description of Necker Island.

The stratified metamorphics cover the larger part of the islands and strike invariably east and west. They dip from 45° to 90°, averaging 70°. A steeply dipping bed may form an abrupt sea wall nearly 200 feet high, as at Dead Chest and Ginger islands. If not duplicated by faulting, the section from Peters Island to the north coast of Tortola is at least six miles in thickness.

Only on Necker Island, at the extreme northeast, do the strata escape metamorphism. They are blue-gray or yellow clays, tuffs and gritty conglomerates, with opposing dips from the north side to the south side of only 10° to 15°. Epidote nodules, however, appear in the tuffs and may be bombs. The only evidence of the age of the beds rests, it is said, on Cleve's record of the fossils at Coki Point, St. Thomas, as earlier mentioned in this review of the literature. Mr. Earle quotes the list of fossils and this sentence from Cleve: "Some of them have a remarkable affinity to Cretaceous species, and I have no doubt that the rocks of St. Thomas and the other Virgin Islands are of Cretaceous age." The writer may call attention at this point to the earlier mention of the fossils by Professor Hornbeck, to the record of the Rev. John P. Knox, and to the present determination of Upper Cretaceous age as recorded by T. Wayland Vaughan; also to the determinations of Upper Cretaceous strata by Dr. Vaughan on St. Croix.

Mr. Earle's appreciation of the pyroclastic nature of most of the apparent sediments marks a decided advance on earlier observers, and his corroboration of his field observations by his own microscopic studies adds certainty and clearness to his determinations. The pyroclastics are cut by later dikes, but the locations of actual vents he finds impossible to establish.

The plutonic rocks form bosses of comparatively small extent in the metamorphic series, and our author concludes that they entered after the dynamic metamorphism. Their banding, when developed, is attributed to flowage. The diorites are said to send "veins" into the metamorphics and to have caught up many xenoliths, sometimes in such quantity as to make a "diorite breccia," which is not to be "confused with a sort of 'patchwork' diorite due to abnormal concentration of the basic or 'heathen' parts of the magma." The reviewer may remark, however, that thoroughly digested xenoliths and basic segregations are hard problems to differentiate. Mr. Earle mentions the beautiful orbicular diorite near Colison Point, Virgin Gorda, and the radially crystallized nests of epidote; also the garnet-epidote veins in the diorite of Salt Island and the spheroidal weathering which has impressed nearly all the observers who have visited the Virgin group. The remarkable blocks of Fallen Jerusalem are mentioned, as well as similar phenomena on parts of Beef Island and Virgin Gorda. To contact metamorphism of the diorite our author is inclined to attribute the black amphibolites which pass insensibly into slaty rocks and hornblende schists; also the garnet-epidote-wollastonite rocks and the garnet-bearing hornfelses close to the intrusions at Cooper Island and Frenchmans Key. The large bosses of diorite at both ends of Tortola and on ten of the other islands are listed. They all show clearly in the geological map which constitutes the plate facing page 344.

The dike rocks are of numerous kinds and are the last product of igneous activity. Quartz veins and pegmatites radiate from the diorite and follow along stratification planes. One series of quartz veins with copper pyrites, malachite, native copper, hematite, pyrites and molybdenite has been mined quite extensively in former years at Copper Mine Point, Virgin Gorda. A rather perplexing group are the felsites, which appear alike as dikes, sills and bosses. More basic dikes are also recorded.

The volcanic rocks embrace both pyroclastics and definite flows, but the latter are not always easy to distinguish with the eye from metamorphosed or hardened tuffs.

Mr. Earle next takes up for brief microscopic description the several rock types—plutonic, metamorphic, dikes, lavas and tuffs—which have just been reviewed in their physical forms in the field. Under plutonic, he remarks with Högbom the lack of potash rocks and the rarity of biotite. The diorites are found to be exceedingly variable. The normal variety is holocrystalline, with white or pink feldspar, quartz and ferromagnesian minerals, but without porphyritic feldspars. Under the microscope the rock may be predominantly quartz and orthoclase, or oligoclase, with few dark silicates, approaching thus a hornblende granite, as at Josias Bay, Tortola; again, quartz and orthoclase are subordinate to plagioclase, as at Cappoons Bay, Tortola. Biotite is inconspicuous except on Virgin Gorda. Muscovite is rare. Sphene and apatite are constant accessories; iron ores are common, but augite is rare or wanting. On Salt Island, large, elongated crystals of hornblende give a porphyritic appearance to the diorite. Included in the hornblende is epidote, which is also a primary constituent elsewhere. Biotite and apatite are abundant in this locality. The so-called "heathen" patches are local enrichments with ferromagnesian minerals.

Gabbros were collected from Beef Island and the neighboring end of Tortola, and from North Sound and Savannah Bay, Virgin Gorda. They appear to be local variations of the diorite. They are the most coarsely crystalline rocks of the island and have augites up to three-quarters of an inch in length. They consist of anorthite, olivine, augite hornblende and iron ores. On Beef Island hypersthene is sparingly present. At Savannah Bay the olivine and augite fail.

Under the metamorphic rocks, true mica schists are mentioned from Dead Chest, Great Harbor Point, Peter Island, and from Norman Island. Under the microscope, they reveal a granular quartz and pale-brown biotite mosaic, with sparing larger crystals of quartz and feldspar. Hornblende schists, quartzites, etc., are the commonest members of the metamorphic series. They vary from a mosaic of quartz and hornblende of granulitic texture, with accessory iron ores and biotite and sometimes (as at Grassy Point, Tortola) with large crystals of plagioclase, to amphibolites produced by the increase of hornblende to the exclusion of the other components and with the loss of foliation. At the other extreme, decrease of hornblende gives rise to quartz schists and quartzites. The grain may be so fine that the rock resembles the halleflintas. Granulites are even more common than the hornblende schists and quartzites. They are quartz-diopside rocks in one variety, with subsidiary feldspar, and are referred to calcareous tuffs as an original. One variety from Salt Island has large so-called phenocrysts of composite crystals of broadly twinned labradorite often containing abundant zonally-arranged grains of magnetite, so that in the hand specimen they look like leucites. The history of this rock is, as yet, obscure. Another variety of granulite consists of quartz and epidote and is referred to argillaceous tuffs. The rocks are pale green and very hard. There is no constant micro-structure and granular feldspar crystals are accessory only. Epidote is said to be a very widespread mineral in the Virgin Islands, and to be a primary constituent of the diorites as well as a component of the metamorphics. Under the "Altered Limestones," etc., true marbles are briefly mentioned. They often crumble badly on weathering. The metamorphism of less pure varieties has given rise to new minerals, such as garnet, wollastonite and epidote, of which Cooper Island furnishes a beautiful example. Another interesting rock is found at West End, Tortola, and has fine, sheaf-like crystals of wollastonite, with garnet and colorless idocrase.

Under "Carbonaceous Rocks, etc.," a graphite schist is cited from a locality beyond the West End office, Tortola. It contains about 5 per cent carbon and varies from a soft, powdery rock to a hard, gritty variety. Slates and phyllites are also in the sedimentary series, and spotted slates occur, but no andalusite, sillimanite, or kyanite were found in the slides. Reference is, however, made to Högbom's note on andalusite quartzite from Virgin Gorda.

Under the "Dike Rocks," pure quartz veins furnish the siliceous extreme. Micropegmatites are described as common, with traces of biotite, hornblende, iron ores, sphene, and, in one pegmatite from Cooper Island, minute pink garnets. Under the microscope the felsites of Cleve prove to be highly decomposed aggregates of quartz, kaolin and calcite, with relics of plagioclase, hornblende and biotite phenocrysts. The plagioclase favors albite or andesine. Apatite and magnetite are accessories and the groundmass is felsitic. The felsites appear both as dikes in the diorite and schists, and as large bosses on Norman and Peter Islands.

Dikes cut the diorite on Fallen Jerusalem and Peter Island and consist of long, lath-shaped crystals of hornblende in a groundmass of felted oligoclase. At Savannah Bay, on Virgin Gorda, is one more holocrystalline, which has macroscopic phenocrysts of hornblende and feldspar irregularly distributed in a trachytic groundmass. These dikes are referred to hornblende porphyrites. Again, at Pond Bay, Virgin Gorda, is a dike with some large phenocrysts at least as basic as labradorite or bytowňite, and others of granular hornblende set in a fairly coarse groundmass of plagioclase. The rock is called diorite porphyrite. Another dike, from Crook Bay, Virgin Gorda, consists of sparing feldspar phenocrysts, decomposed to calcite and kaolin, in a groundmass of feldspars with distinctly parallel arrangement. The rock is somewhat questionably compared with bostonites, but as bostonites are high soda-potash, low lime rocks, their feldspar phenocrysts could hardly yield so much calcite on alteration. Mr. Earle did not chance to collect the amphibole minette described by Högbom from Round Rock, nor did any of his slides reveal dolerites (diabases) among the dikes.

Under "Lavas and Tuffs" the slides were mostly cut from bombs and reveal andesites rather than basalts. The phenocrysts are andesine or labradorite and hornblende in a trachytic groundmass. Augite is sometimes present as phenocryst or in the groundmass and, it is stated, occurs with quartz as a secondary mineral lining cavities. The last is a very unusual occurrence for augite. A rock near Road Town, Tortola, revealed large twinned labradorite phenocrysts in a groundmass of small labradorites without dark silicates. The tuffs were andesitic in character. Some were pyritous and, even under the microscope, spheroidal. The andesitic character of the bombs and tuffs coincides with the reviewer's microscopic determinations of the similar rocks from St. Thomas and St. Croix.

Under "Summary and Conclusions," Mr. Earle emphasizes the close geological and structural connection of the British Virgin Islands with the Greater Antilles rather than with the Lesser. He briefly summarizes the observations of previous workers in the Greater Antilles as throwing light on the geological times of the upheavals and the igneous outbreaks. Of nine of their papers he gives a bibliography at the close. His last sentence may be quoted entire: "There appears, however, to the writer to be nothing either in the geological or faunal evidence necessarily indicating previous land connection at any time between the Virgin Islands and the Lesser Antilles, and on this matter it is hoped to furnish further evidence at a later date."

1926. WILLIAM MORRIS DAVIS. "The Lesser Antilles," Publication No. 2, in the series entitled "Map of Hispanic America," of the American Geographical Society of New York, small 8vo., pp. 207; figs. 66; plates 16. This very interesting discussion embraces and greatly amplifies the condensed summary cited above under **1924.** Professor Davis observes and writes from the standpoint of a very discerning and experienced physiographer. The stage of physiographic development which has been reached in the still unsubmerged land areas has, therefore, great significance for him; and the extent and character of the submarine banks, from which the actual, mountainous islands rise, call for interpretation in no less degree. He does not overlook the light which may be thrown upon the existing outlines of the banks by the inferred presence of former barrier and fringing coral reefs which may go back into the Tertiary period. The carving of projecting headlands in cliffs, implying thereby subsidence and wave-cutting, often where now the waves do not break with the necessary violence, is a form of evidence repeatedly used. Reference is often made to the author's earlier expressed views on the character of coral growth according to the situation of the reefs in marginal areas where the sufficiently warm seas are near waters or currents prohibitively cool; or, by contrast, in areas which are so far within warm waters as to be reasonably assured of stable temperatures. Finally the very important and suggestive hypothesis of R. A. Daly regarding the influence of the Pleistocene glacial ice-sheets, and the interglacial, warmer climatic conditions upon the lowering or raising of the ocean waters in tropical and temperate latitudes, is always before Dr. Davis when he traces the probable physiographic conditions of the Lesser Antilles during these times. He tests the hypothesis itself by the observed outlines of the islands and their associated submerged banks.

Professor Davis classifies the islands into "First Cycle" and "Second Cycle" groups. The former group embraces those built up by volcanic ejections on a subsiding foundation, so that we have today islands consisting of one or more volcanic mountains of geologically recent date, of youthful topographic outline, and of position upon submerged banks of relatively limited size. The Second Cycle group is older in time of volcanic upbuilding. The islands of this group exhibit deformation of their original, constituent lavas and pyroclastics; and now present topographic forms of physiographic maturity. Undoubtedly they have passed through a much more varied history than have the members of the first group.

Following one or two of the older writers on the geology of the Virgin Islands, Professor Davis believes that the volcanic rocks, whether massive or clastic, rest upon older strata which are of sedimentary character and more or less metamorphosed into slates and related varieties.

Culebra, Vieques and all the Virgin Islands, except St. Croix, are placed in the First Cycle group, although described as involving a more complicated sequence than that of some of the Lesser Antilles to the east and southeast. St. Croix is placed with the Second Cycle composite islands. The Virgin Islands, except St. Croix, are described on pp. 109-127. On p. 109 the following quotation will be found: "The islands of 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, chiefly slates, which appear to underlie the volcanic rocks." On p. 110 this statement appears: "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 enlargement, the original extent of a subsided landmass. The reduction of the composite landmass from its original mountainous continuity to its present submountainous discontinuity must be ascribed in part to erosion, whereby much of even the most resistant features 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 embayments; 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."

The bays of St. Thomas, with their delta flats, are next discussed in some detail, with outline sketches of the island, showing the mature nature of the topography. That the flats indicate submergence and drowning of erosional valleys is urged with sound and correct reasoning. The same inference for Culebra is set forth likewise in detail. The interpretations of both Culebra and St. Thomas are founded on personal observations while visiting them. On the basis of the marine charts, Norman Island, with its skeletal outline, and several others are treated with illustrative figures. The cliffs of St. Thomas and those of some of its smaller satellites are next described and illustrated. Their cutting is explained by emergence during the relatively short-lived Glacial epochs.

In discussing the Great Bank around the Virgin Islands, Professor Davis concludes that a considerable part of the area represents worn-down lowlands of relatively weak continental rocks; and that the subsidence is less than that in the more eastern Lesser Antilles. He infers that the old relief, however, has been softened and masked by aggradation and by low-level abrasion during the Glacial epochs.

The limestone island of Anegada is believed to consist of strata of older age than the Glacial period, and to be a remnant left by low-level abrasion during the Glacial epochs. Its surrounding submarine bank is, therefore, a bank of second generation.

The Post-glacial coral reefs are briefly reviewed and none, not even the Horseshoe, which runs south from the east end of Anegada, exhibit all the characters of true barrier reefs. The smaller ones well back from the edge of the bank are discontinuous fringing or bank reefs.

In his concluding page upon the Virgin Islands, Professor Davis admits the hypothetical nature of his views of the physiographic development, but he believes, nevertheless, that they give an acceptable interpretation of the observed facts.

On pp. 138-146, under the head of "Second-Cycle Composite Islands," Professor Davis takes up St. Croix, on the basis of observations made during a day and a half, with the aid of automobiles. Undoubtedly a very good idea of the general relief of all but the eastern end of the island could be obtained in this way. Belief in the presence of old, fundamental slates, as distinct from the later volcanics, colors somewhat the interpretations. The extensive area of slightly tilted Tertiary limestones constitutes for the Virgin Islands proper a new and virtually unique feature requiring explanation. The only similar occurrence is the relatively small area of them on Vieques Island, which is not usually considered a member of the Virgin group. The Tertiary limestones are interpreted as lagoon deposits, presumably laid down inside of an encircling coral reef, "which might have been almost or truly an atoll." Subsequent uplift with faulting, as suggested by other observers in order to account for the great, precipitous cliff along the northwestern front, receives rather casual approval, although this great cliff might justly be considered the outstanding topographic feature of the island. The greater former extent of the Tertiary limestones; the rather weak cuesta now shown along their northern edge; the slight embayments along the coast; and, except for the great precipitous cliff just mentioned, the inconspicuous cliffing, are all observed and recorded. The difficulties which they present to some of the conclusions, based on succeeding emergences and subsidences during Glacial and Interglacial epochs, are mentioned.

Comments: The reviewer may record the great interest which attaches to Professor Davis' studies. The studies are all too briefly recorded here and should be read in full, with the aid of the accompanying illustrations. They are of especial interest when taken in connection with the studies of Mr. Meyerhoff which follow, and which were received for publication before the issue of Professor Davis' book. The large points of view are in some respects sympathetic, as might be expected from two observers familiar with present-day physiographic principles and methods.

Professor Davis several times in his book emphasizes the physiographic nature of his studies, and the fact that he had given but passing attention to the geological work which had been done on the islands specially under investigation. Much less did he feel the necessity of considering the work done on Porto Rico, the nearest of the Greater Antilles. And yet the Virgin Islands cannot be properly studied either geologically or physiographically, except in connection with Porto Rico. Past conditions could not be very different in two areas so closely related, and now only separated because of a relatively slight submergence. Professor Davis does not refer to the essay of Professor A. K. Lobeck on the "Physiography of Porto Rico," 1922, which forms Part 4 of Vol. I of this Survey's Reports; and in which some treatment, though brief, of Culebra and Vieques is given. This study by a well-prepared physiographer contains much of interest and of immediate bearing on the Virgin Islands, because, as K. W. Earle correctly states, the Virgin Islands are geologically much more closely connected with Porto Rico than with the other Lesser Antilles lying to the eastward.[9]

[9] Geological Magazine, Vol. LI, pp. 341 and 350, August, 1924.

The geological results in Porto Rico, accumulated to date, especially by our Survey, corroborate the early inference of Dr. Charles P. Berkey, that the series of strata, called by him the "Older Series," is of volcanic origin, and that its shales and other clastics are water-sorted volcanic tuffs and related fragmentals. There are a few interbedded limestones. All the later stratigraphic and paleontologic determinations corroborate his early inference that they were deposited during the Cretaceous period.[10]

Going to the Virgin Islands in March, 1923, after an extended tour of Porto Rico, the writer was impressed with the recurrence of the same formations on St. Thomas and St. Croix, and that the oldest strata, with the exeception of the very subordinate limestones, were all of volcanic or intrusive origin, although at times water-sorted and well-stratified. Of the minor interstratified limestones of St. Thomas, St. John and several of the British Virgin Islands, we now know that some are greatly affected by contact metamorphism. On St. Thomas there is the often-mentioned exposure of fossiliferous limestone at Coki Point, now recognized as Upper Cretaceous. On St. Croix are the two other localities of the older limestones with Upper Cretaceous fossils, respectively, at the estate of Judith's Fancy on the north coast and at Waiters or Watch Ho or Vagthus Point on the south, these three names all referring to the same locality. All these strata were violently folded in the mountain-making upheaval, following the deposition of the volcanics and their interstratified limestones.

It is evident that along the lines of our best geological knowledge the northern American Virgin Islands and the British Islands would, therefore, come under Professor Davis' Second Cycle group, and not in the First Cycle group, where he places them: and also that we have no good reason to believe that any fundamental strata are exposed in these islands, which are older than the volcanics with which their upbuilding began.

From personal knowledge of the hills and mountains on St. Thomas and St. Croix, consisting of the older or Upper Cretaceous strata, as contrasted with the later, almost flat Oligocene-Miocene limestones, the writer feels that the smooth and sweeping outlines of sketches made from a distance give a somewhat incorrect impression of their actual roughness, and their local steep and precipitous slopes. To a geologist on the ground they constantly suggest faulting, which has been a potent factor in the topography, perhaps once smoother or more mature than it

[10] "Geological Reconnaissance of Porto Rico." Annals of the New York Academy of Sciences, Vol. XXVI, pp. 58-61. 1915.

seems to be today. Mt. Eagle, on St. Croix, has a very steep slope, especially on the west and north, and the ascent of the main ridge of St. Thomas involves a decided scramble.

Possibly because of the rather recent retreat of the last continental ice-sheet and the comparatively few thousand years which, as Baron De Geer and his pupils have shown, have elapsed since it shrank away from its terminal moraine, almost all geologists still habitually think of the lapse of time represented by the Glacial period as quite short when compared with periods represented by the stratified rocks. But the recent studies of Professor George F. Kay, of Iowa, upon the relatively great depth of weathering of the older drift, as compared with the very slight depth of weathering of the last drift, of whose time of exposure we have some knowledge, lead us to the conclusion that the Glacial period as a whole was many times longer than we have hitherto supposed. Perhaps, therefore, a much longer time interval was available for physiographic changes in the West Indies than we have generally realized.

In concluding the above review, the writer can only express again the hope mentioned at the outset, that it will afford the reader a fairly complete and just statement of what had been done by earlier observers and writers. There are several additional papers on the West Indies as a whole, notably those of the late J. W. Spencer and one by Persifor Frazer, which have not been reviewed, as the areas under discussion are but a minor feature of these papers. The citations, however, follow:

1894. J. W. SPENCER. "Reconstruction of the Antillean Continent." Bulletin of the Geological Society of America, Vol. VI, pp. 103–140.

1898. J. W. SPENCER. "The West Indian Bridge." Popular Science Monthly, Vol. LIII, pp. 577–593.

1903. PERSIFOR FRAZER. "History of the Caribbean Islands from a Petrographic Point of View (Abstract)." Proceedings of the Academy of Natural Sciences of Philadelphia, Vol. LV, pp. 396–400.

1903. J. W. SPENCER. "On the Geological Relationships of the Volcanics of the West Indies." Transactions of the Victoria Institute, Vol. XXXV, pp. 189–207.

THE PHYSIOGRAPHY OF THE VIRGIN ISLANDS, CULEBRA AND VIEQUES

By Howard A. Meyerhoff

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FOREWORD

In 1913 the Council of the New York Academy of Sciences approved a proposal to undertake a scientific survey of Porto Rico. At the end of 1913 Dr. H. E. Crampton inaugurated the work with a zoölogical reconnaissance; in 1914 this beginning was followed by botanical investigations under the leadership of Dr. N. L. Britton, and by a geological reconnaissance under Dr. C. P. Berkey and Dr. C. N. Fenner; and in 1915 Dr. Franz Boas began a series of anthropological and archæological studies. Field studies in these four lines have been prosecuted almost continuously; and at the present time the geological investigations are almost complete, and the results of the work have been printed as parts of the first, second and third volumes of the Academy's series on the Scientific Survey of Porto Rico and the Virgin Islands.

In 1917 the Danish West Indies became attached, by purchase, to the Caribbean insular possessions of the United States, and it was deemed desirable to extend the scope of the survey to include these islands, which geologically constitute an eastern extension of Porto Rico.[1] In consequence, volume four of the series was set aside for the geology of the Virgin Islands. Early in 1923 Prof. James F. Kemp, accompanied by Dr. N. L. Britton and Mrs. Britton, began the study of the geology of the American Virgin Islands with a reconnaissance of Saint Thomas and Saint Croix.

In November of 1923 the writer was given the opportunity to continue the survey in greater detail. As the geology of the British Virgin Islands is so intimately related to that of the American islands, political boundaries could not wisely be observed, and it was suggested that a brief study also be made of the British islands in the group. From February to June, 1924, the writer, in company with Mrs. Meyerhoff and Mr. James Lee, made as detailed a study of the American islands as time permitted, and in addition visited about twenty-five of the British islands, spending several days on Tortola and Virgin Gorda and making shorter visits to the others. The survey was concluded with a ten-day study of Vieques and a five-day study of Culebra, and with shorter visits to Icacos Cay and the other island members of the Cordilleras Reefs northeast of Playa de Fajardo (Fig. 1). Finally, three days were employed in an examination of the rock types of Porto Rico, in order that all phases of the Virgin Islands work might be correlated more intelligently with the geology of Porto Rico. The work of 1924 was supplemented during June, July and August, 1925, when a study of the geology of the Fajardo district of Porto Rico was made by the writer and Mrs. Meyerhoff. A second visit was paid to the island of Vieques, and on the mainland considerable attention was given to the correlation of the physiographic forms with those of the islands to the east. The results of these field investigations will be published according to the original plan, the present section on the physiography of the Virgin Islands, Culebra and Vieques, constituting Parts I and II of Volume IV. The succeeding parts of Volume IV will be devoted to the geology and paleontology of the group, and the geology of the Fajardo district of Porto Rico will form a part of Volume II.

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[1] Britton, N. L., "History of the Survey." Scientific Survey of Porto Rico and the Virgin Islands, Volume I, Part I, 1919, pp. 9-10.

The thoroughness with which geological field investigations were conducted varied directly with the degree of culture, especially the road and trail development, afforded on each island. Permanent headquarters were established at Saint Thomas; but Christiansted, Saint Croix; Cruz Bay, Saint John; Road Town and Belmont, Tortola; Esperanza, Vieques; Great Harbor, Culebra; and Fajardo, Porto Rico, were used as temporary bases during progressive stages of the work. It was thus possible to examine in fair detail all of the larger and better populated islands, but even on these some rugged, unsettled areas proved quite inaccessible. Most of the smaller islands were reached by sloop, and upon them considerable variety in working conditions was found. A majority of them are so overgrown with cactus that examination had to be restricted to portions of the shoreline. Others possessed such rugged coasts that landing was either impossible or hazardous. A few, including Sail Rock, Dutchman Cap, Cockroach Island, Cricket Rock and Little Hans Lollik, were so unfavorably situated that they could have been visited only at an expenditure of time and money, which their geological possibilities and the scope of the survey did not justify. Because most of the unvisited islands were seen at close range, or because they are in structural alignment with known rocks, their geology may be inferred with reasonable safety. Comparatively few localities, whose geology is entirely unknown, were by force of circumstances left unexamined.

Maps and Charts

Field and laboratory work and navigation among the cays were greatly facilitated by excellent maps and charts, many of which were supplied by the United States Coast and Geodetic Survey. Because the accuracy of the field-work hinged in a measure upon the correctness and scale of the charts, those employed merit mention and annotation.

Chart No. 2318, Hydrographic Office, United States Navy, shows in small scale the West India Islands from Haiti to Saint Lucia.

Chart No. 3904, Hydrographic Office, United States Navy, scale one mile to an inch, includes most of the British Virgin Islands from Tortola to Anegada and shows the depths of the underlying platform. Sketch contours have been drawn in from hachures on the British maps; but neither the hachures nor the contours are correct, and they give an inadequate and, in some localities, an erroneous impression of the topography of the islands.

Chart No. 920, United States Coast and Geodetic Survey, 1923, scale approximately 4½ miles to an inch, embraces Porto Rico and the American Virgin Islands, extending from Mona Island west of Porto Rico to

Virgin Gorda on the east. It does not extend to the eastern extremity of the Virgin Islands bank, for it omits Anegada and most of Virgin Gorda. The islands are shown in outline, with locations of coastal towns and a few inland elevations.

Chart No. 904, United States Coast and Geodetic Survey, 1924, scale one mile to .7 inch, embraces the western coast of Porto Rico and the islands eastward to Saint Thomas. The topography is shown by hachures.

Chart No. 905, United States Coast and Geodetic Survey, 1921, scale one mile to .7 inch, includes the islands from Saint Thomas to Virgin Gorda, and the island of Saint Croix. Surface relief is indicated by contours spaced at intervals of 200 feet. The contouring is accurate for the American islands, but in the British islands sketch contours from hachures are again employed and are not correct, although they show considerable improvement over other maps.

Maps of varying grade and kind are available for most of the individual islands. Charts Nos. 3240 (1922), 3241 (1922) and 3242 (1923), published by the United States Coast and Geodetic Survey, show respectively Saint Thomas, Saint John and Saint Croix—scale, 1:40,000; contour interval, 50 feet. These excellent and accurate maps proved invaluable in the detailed survey of the American Virgin Islands. The United States Coast and Geodetic Survey very kindly furnished bromide copies of the original topographic sheets of these three islands—scale, 1:10,000; contour interval, 20 feet. These sheets are justly regarded as one of the most accurate and detailed pieces of cartography ever done.

A large-scale hachure map of Tortola was purchased at the government building at Road Town. The island was surveyed and the map issued in 1826. Although the outlines of the island are essentially accurate, most of the culture shown is no longer in existence. The main roads still exist, but many trails and estates have disappeared. The elevations given do not correspond to those on later maps, and the hachures appear to be the originals upon which later inaccuracies are based.

A chart (No. 2019), reprinted in 1917 by the Hydrographic Office of the British Government, from a survey of 1848, shows the eastern three-quarters of Tortola, Virgin Gorda and the islands south of Sir Francis Drake Channel. Relief is shown by inaccurate hachuring. Chart No. 2008, also issued by the Hydrographic Office of the British Government, reëdited in 1914, gives the island of Anegada, the outlying reefs and the depth soundings southward to Virgin Gorda.

No separate map of Vieques has been printed, but the United States Coast and Geodetic Survey kindly supplied photographic copies of the original topographic sheets of the island, based on a survey made in 1901; scale, 1:20,000; contour interval, 10 meters.

Chart No. 914 (from surveys of 1900 to 1904), printed by the United States Coast and Geodetic Survey, offers a partial topographic survey of Culebra. The shoreline, peninsulas and outlying islands are shown with a ten-meter contour interval; the interior is unsurveyed. The scale is 1:20,000.

ACKNOWLEDGMENTS

The prosecution of the field-work was materially and generously aided by many hands, and the success of the expedition was in no small part due to the hearty coöperation given by the inhabitants of the islands. The writer feels especial indebtedness to his two companions in the field, Mrs. Meyerhoff and Mr. James Lee; to Dr. N. L. Britton and Prof. James F. Kemp, whose invaluable advice and help were extended in every phase of the work; to Commissioner O. L. Hancock, whose hospitality and aid made work in the British Virgin Islands possible; to Mr. Walter A. Lowrie, whose home was opened to us during our stay on Vieques; to Mr. A. Holst, whose cottage at Botany Bay, Saint Thomas, was placed at our disposal; to Lieutenant John C. Gebhard, public works officer in Saint Croix during 1924, and Mr. Frank Smith of Saint John, who volunteered their services in portions of the field-work; to Captain Mattison, of the United States Coast and Geodetic Survey boat, the *Ranger,* and to the other officers of the *Ranger,* who made some of the shoreline work on Saint Croix possible; to Miss Lucy W. Gillette, director of the local Red Cross work, for facilitating our movements on Saint Thomas and Saint Croix; to Mr. Alfredo Duurloo and Mr. Joseph Reynolds, who kindly attended to many of the expedition's interests in Saint Thomas; to the officials of the Virgin Islands Government, who solved many local problems, especially those of transportation; to Señor Jorge Bird, whose launch was twice placed at our disposal for work in the islands adjacent to Porto Rico; to the crew of the sloop *Niger,* whose skill and loyalty made the reconnaissance in the small and remote British islands a success.

Preparation of Parts I and II of Volume IV of the Survey has been greatly facilitated by criticism and advice given by Dr. N. L. Britton and Prof. James F. Kemp, whose unfailing interest the writer gratefully acknowledges. The writer is indebted also to Prof. D. W. Johnson for invaluable suggestions of method and criteria in solving the problems of the submarine platform; to Mrs. E. M. Brown for brief notes from an independent study of the submarine platform, performed under the direction of Prof. D. W. Johnson; and to Miss Dorothy Merchant for the reading of part of the manuscript. The entire section has benefited immeasurably by the careful review and criticism given its form and expression by Prof. Isabel F. Smith. Finally, the writer feels that the completion of the report has been effected no less by the assistance given by Mrs. Meyerhoff in the preparation of manuscript, diagrams, maps and plates than by his own efforts.

CHAPTER I

INTRODUCTION

Location

The Virgin Islands are situated due east of the mainland of Porto Rico, beginning with Savana Island, thirty-three miles[2] east of Cape San Juan (Fig. 1). They extend to Anegada, in the British group, eighty-five miles slightly north of east of Cape San Juan. Their west to east extent is, therefore, approximately fifty miles. They are separated from Culebra (which is attached politically to Porto Rico) by Virgin Passage, a channel of seventeen fathoms depth. To the east they are separated from the Lesser Antilles by Anegada Passage, over one thousand fathoms deep immediately off the Virgin Bank. North and south their extent is greater; it is sixty-seven miles from Anegada on the north to Saint Croix on the south. On the north they are bounded by the Atlantic Ocean; on the south by the Caribbean Sea. Saint Croix and its three dependent islands, however, constitute a separate group, detached from the northern islands by thirty-two miles of open water and by a deep of 1000 to 2400 fathoms.

The northern group of islands rests upon a bank less than 35 fathoms deep, extending westward to Porto Rico. It represents, therefore, the eastern extremity of the Greater Antilles, with which it has a continuous submarine connection, and is separated sharply from the Lesser Antilles by the great depth of Anegada Passage. Saint Croix, in spite of its present isolation, indicates from its geologic relations a former attachment to the northern group and to Porto Rico, but an equally sharp detachment from the Lesser Antilles.

The islands of Vieques and Culebra and the members of the Cordilleras Reefs lie between the Virgin Islands and Porto Rico, upon the submarine bank connecting Porto Rico and the northern Virgin group (Fig. 1). Culebra, the most easterly, is separated by Virgin Passage from

[2] Throughout the ensuing report measurements of distance will be given in nautical miles, equivalent to 1.15 English statute miles.

Savana Island, seven miles distant. It is situated seventeen miles due east of Playa de Fajardo, Porto Rico. Cordilleras Reefs constitute a chain of small cays[3] and rocks extending in an east-southeasterly direction from a point one mile off Cape San Juan to the islands off Culebra, a distance of seventeen miles. They form the northern boundary of Vieques Sound, south of which lies Vieques, separated from the nearest point on the east coast of Porto Rico by Vieques Passage, six miles wide. Its eastern extremity lies seven and one-half miles south of Culebra, and it is thus the most southerly island on the submarine platform.

Political History

The Virgin Islands were discovered and named by Columbus during his second voyage, in November, 1493; and while some of his men in

Fig. 2.—*Salt River valley and estuary, Saint Croix*

smaller boats explored the northern islands, Columbus landed at the Carib village situated at the mouth of Salt River, on Saint Croix (Fig. 2). Several attempts were made by the Spaniards, French, Dutch,

[3] The name "cay," derived from the Spanish "cayo," is used somewhat indiscriminately for rocky islands of small size. In conversation it is frequently pronounced like the word "key," to which, however, it is not equivalent in meaning.

Danes and British to colonize the islands, but until 1666 they were little more than a rendezvous for buccaneers. In 1666 Tortola, Virgin Gorda, Anegada and the adjacent islands passed permanently into British hands. In 1672 the Danes settled Saint Thomas and Saint John, and, except for two short periods of British occupation, held them until 1917. The Dutch settled Saint Croix in 1643; but until 1733 the island went through a stormy and uncertain career, and was occupied successively by British, Spaniards and French. In 1733 the French sold it to the Danes, and it remained under Danish rule until 1917. In that year, after some fifty years of indecision, the United States purchased the islands from Denmark, probably as a precautionary pre-war measure. The government of the islands is administered by the Navy Department, whose representative has the title of governor. By the terms of the treaty the local form of government established by the Danes has been retained, and many of the old customs and regulations remain in force, even to the use of Danish West Indian currency as legal tender. Culebra and Vieques were early settled by Spaniards, and since their settlement have remained under the political jurisdiction of Porto Rico.

Climate and Rainfall

The Virgin Islands (American and British) lie between latitude 17° 40′ and 18° 51′ north and longitude 64° 7′ and 65° 6′ west. They lie within the belt of the trade winds, which afford them a mild, uniform climate and a moderate well-distributed rainfall.

The temperature is exceedingly equable, with an annual range of less than thirty degrees and with a mean range of less than eight degrees (76.3° F. in February to 84° F. in October). During the year the range is from 67° F., as a minimum in winter months, to 97° F., as a maximum in the hottest months. Daily temperatures normally fluctuate less than ten degrees between these limits. The climate is, therefore, subtropical. Except in sheltered valleys, the highest temperature is always tempered by the trade winds.

The average annual rainfall for the entire group of islands is forty-five to forty-eight inches, but the variation from year to year is considerable, ranging from thirty-two inches in dry years to more than sixty inches in wet years. The smaller islands of the group are poorly watered and are commonly characterized by extreme aridity. The larger islands, which rise to higher altitudes, receive a regular supply of rain, which varies locally in amount with topography, elevation and situation with respect to the trade winds. Detailed measurements of rainfall have not been made areally, but the vegetation indicates heavier precipitation on the northern slopes. Saint Croix and Vieques exhibit the anomaly of being extremely arid on their attenuated eastern or windward ends.

During the year the rainfall shows a somewhat erratic monthly distribution, varying from a fraction of an inch in a dry month to as much as eighteen inches. There is no rainy season, and a monthly average for twenty years shows moderate differences from month to month. From May to December, particularly during September and October, precipitation is slightly heavier; and the heaviest single showers of the year are expected during the latter two months. Precipitation during the first four months of the year is characteristically low (one to three inches per month). Four of the past five years have been exceptionally dry; and although all of the islands have suffered somewhat, the partial drought has been felt most acutely on Saint Croix and Vieques, where the principal industries, sugar- and cattle-raising, are dependent upon rainfall. The islands lie within the hurricane belt and are visited spasmodically by destructive hurricanes. For years at a time they escape these devastating storms, but during the months of August, September and October hurricanes may be expected.

Physical Geography

The Virgin group includes about one hundred islands, cays and rocks. The American islands, about forty in number (not including rocks), lie southwest of an irregular line of demarcation drawn from the north between Little Hans Lollik and Little Tobago; thence through the Narrows between Saint John and Great Thatch islands; thence around the eastern end of Saint John, between Flanagan Island and Pelican Island (Fig. 1). To the north and east of this tortuous boundary lie the British islands, also about forty in number. The total area of the American group is 132.42 square miles;[4] of the British group, approximately 60 square miles.

The American islands contain three major members, on which more than 99 per cent. of the population lives. Saint Croix, the largest, situated in the southern group,[4] is nineteen miles long and has a uniform width of five miles from its western end to Salt River Point; eastward it narrows. Its area is 84 square miles. Its northern side is an upland, rising to a maximum elevation of 1165 feet in Mount Eagle. The northern coast of the western half of the island is rugged and rises sharply from the water's edge (Fig. 3). The southern side of the island is a broad, rolling coastal plain, the center of Saint Croix's sugar industry

[4] Lightbourn, A. G.: "Lightbourn's annual and commercial directory of the Virgin Islands of the United States." St. Thomas, 1923, p. 15.

FIG. 3.—*Northern coast of Saint Croix*

FIG. 4.—*The coastal plain of southwestern Saint Croix*

(Fig. 4). The east end beyond Christiansted is a rough, hilly tract, which becomes progressively more arid toward East Point.

Saint Thomas is thirteen miles long from east to west, and is one to three miles wide, with an approximate area of 25 square miles. It rises abruptly from sea-level into a high ridge attaining an elevation of 1550 feet in Crown Mountain and 1504 feet in Saint Peter (Signal Hill). Both these points lie west of the city of Saint Thomas. To the east the island widens and the ridge fans out into a broad dissected upland, less than a thousand feet high, which becomes progressively lower toward the

FIG. 5.—*Embayed mountain shoreline, Perseverance Bay, Saint Thomas*

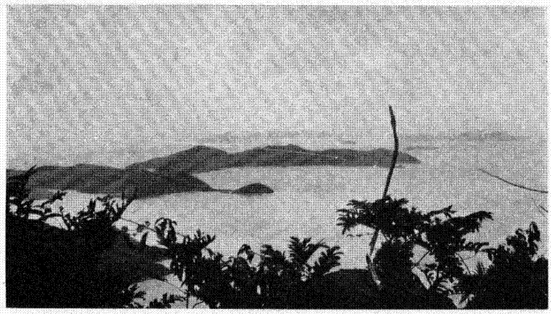

FIG. 6.—*Coral Bay and East End peninsula, Saint John*

eastern end of the island. The shoreline is rugged and is deeply embayed (Fig. 5).

Saint John is eight miles long, and eastward to Coral Bay is five miles wide, terminating on the east in a narrow, curving neck, which encloses a group of small bays (Fig. 6). It rises abruptly to an upland about 1000 feet high, the highest elevation, Bordeaux Mountains, standing 1277 feet above Coral Bay.

Three other islands, Water and Hans Lollik islands and Thatch Cay, are over a mile long and Hans Lollik reaches an elevation of 713 feet.

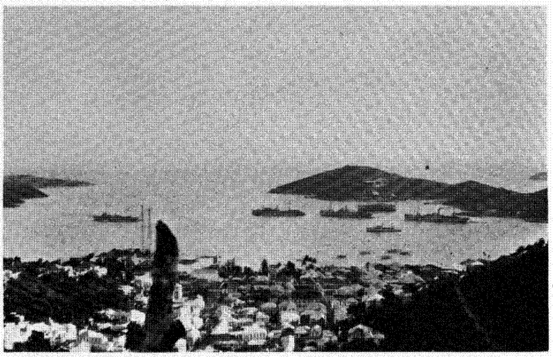

FIG. 7.—*Saint Thomas town and harbor*

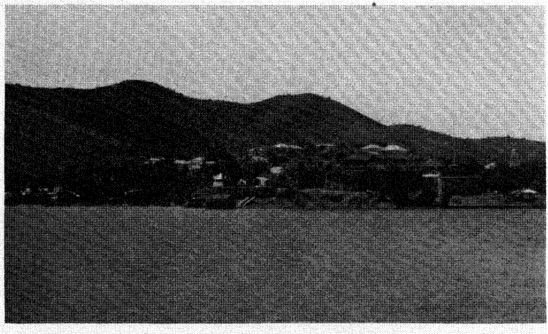

FIG. 8.—*Christiansted, Saint Croix*

The balance of the cays are small and are less than three hundred feet high.

The population of the American islands in 1917 was 26,051. It is confined to the three largest islands of the group, but a small, shifting population of Cha-cha (or French) fishermen lives on Thatch Cay; a small permanent settlement wrests a living from Lovango Cay; and a

FIG. 9.—*Road Town, Tortola*

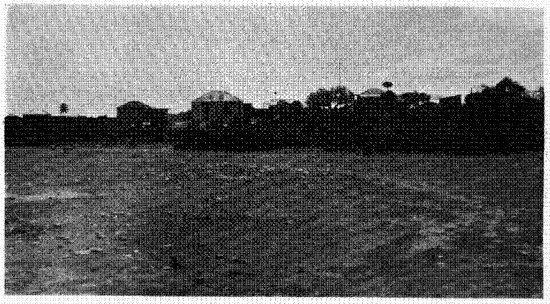

FIG. 10.—*Settlement, Anegada*

few people live on Hassel Island in Saint Thomas Harbor. The island of Saint Thomas has 10,191 inhabitants, of whom 7747 live in the city of Saint Thomas, formerly called Charlotte Amalie (Fig. 7). Of the 14,901 inhabitants of Saint Croix, 4574 reside in Christiansted (Fig. 8) and 3144 in Frederiksted. The balance of the population lives in scattered villages, clustered around the sugar estates of the southern and western half of the island. Saint John has a dwindling population of 900 to 950 people, concentrated around the embayments at the eastern end of the island and at Cruz Bay. A few small settlements are found along the southern and northern shores, but the interior is at present unsettled.

The British Virgin Islands include four large and thirty odd smaller members. Tortola, the largest, is ten miles in length east and west and has a maximum breadth of three and one-half miles. Its outline is irregular, and it possesses the most rugged form of all the Virgin Islands, rising to an elevation of 1780 feet in Sage Mountain. Much of the interior is more than one thousand feet high. Jost Van Dyke, three miles northwest of Tortola, is three and one-third miles long by one and one-quarter broad. It is rugged and attains a height of 1070 feet. Virgin Gorda consists of a central block two miles square, rising 1370 feet in the rounded summit of Virgin Peak, from which a low, rolling, irregular peninsula extends to the southwest and a rugged neck stretches to the east. Anegada, the most northerly of the Virgin Islands, is a low limestone island, nowhere more than thirty feet high in its nine miles of length and one to two miles of breadth.

The lesser islands of the group are notable for their diversity in size, elevation, ruggedness and irregularity. The most important of them extend in a chain from the southern extremity of Virgin Gorda, south of Sir Francis Drake Channel, to a point near the east end of Saint John (Fig. 6).

In 1911 the population of the British islands was 5562, but at present it is believed to be even less. The bulk of it is located on Tortola, where it is congregated into settlements at West End, Seacow Bay, Road Town (Fig. 9), Fat Hog Bay and Cane Garden Bay. Nearly every part of the island is inhabited, however, except the northeastern corner. A scattered population lives on Virgin Gorda and a small settlement finds a precarious existence on Anegada (Fig. 10). Jost Van Dyke also supports a small population, well distributed along the southern and eastern shores. Families live on many of the smaller islands, even though they are dependent upon Tortola for a water supply. Great Camanoe, Cooper, Salt and Peter islands are inhabited, and abandoned dwellings were found on several others.

Vieques and Culebra, situated west of the northern Virgin Islands and east of Porto Rico, have the same subtropical climate and about the same amount and distribution of rainfall as the Virgin group. Vieques is situated between latitude 18° 5′ and 18° 10′ north and between longitude

65° 16′ and 65° 35′ west. It is eighteen miles long and has a greatest breadth of three and one-half miles near the middle. Low hills, attaining a maximum of 981 feet in Mount Pirata, extend through its entire length, some contrast being afforded by the rounded topography of the western half of the island and the more rugged barren hills of the eastern half. The population, as given by the 1920 census, is 11,651, of which 3424 are concentrated in Isabel Segunda (Fig. 11), the principal town. Practically all of the inhabitants are Spanish-speaking.

Culebra, with its small outlying islands, lies between latitude 18° 17′ and 18° 21′ north and longitude 65° 13′ and 65° 21′ west. It is six miles long and three miles wide, but is made very irregular in shape by the deep embayment facing southeast, called Great Harbor, and by the

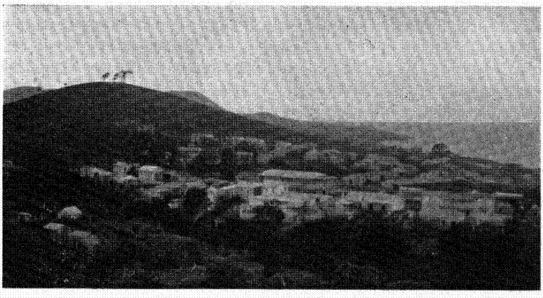

FIG. 11.—*Isabel Segunda, Vieques*

long northwest-southeast ridge terminating in peninsulas forming its southwestern margin. In 1920 it supported a Spanish-speaking population of 704. There is but one small village, named Dewey, which is located between Seine Bay and Great Harbor, and a scattered settlement, called Roosevelt (formerly San Ildefonso), on Great Harbor.

The cays of Cordilleras Reefs are low, barren, rocky and arid. Only one of them, Icacos, is peopled by a small colony of men, who are employed in the limestone quarry of the Fajardo Sugar Company.

Physiographic Divisions

The physiographic history of the Virgin Islands presents several problems in addition to those of unraveling the chronological development of land-forms and the forces which produced them. The added problems are those of correlation of the land-forms, first, among the islands within the group; second, with those of Vieques and Culebra between the Virgin group and Porto Rico; and, third, with those of Porto Rico. The physiography of Porto Rico, with brief notes on Vieques and Culebra, has been well presented by Lobeck,[5] and an attempt will be made to compare the physiographic development of the parent island as he has outlined it with its smaller eastern outliers.

Three methods of approach are possible. Each major island of the Virgin group may be treated separately and its history worked out and compared with the history of Porto Rico. Such a course would obviously cause unnecessary repetition. Or the land-forms of the entire Virgin group may be discussed as a whole. But in such a method divergence from the norm in any of the parts would cause confusion in presentation. Or the islands may be divided into groups whose members have apparently undergone a similar history, and each group may be considered independently. As only three such divisions are necessary, the last-mentioned method seems preferable.

Vieques and Culebra were visited by Lobeck in the winter of 1916-1917, and they receive brief treatment in his description of the physiography of Porto Rico.[6] They constitute a connecting link in physiographic and geologic history between Porto Rico and the Virgin Islands, and it will be profitable to consider these two islands in more detail than was possible in Lobeck's report. They will form one of the three divisions whose physiography will be discussed.

Virgin Passage, a channel less than eight miles wide and thirty fathoms deep, separates Culebra and the Virgin Islands. Beginning with the most westerly of the Virgin group, Saint Thomas, Saint John, Jost Van Dyke, Tortola, Virgin Gorda and all of the lesser islands are clustered, no one of them being separated from another by so much as three miles of open water (Fig. 1). From this assemblage only Anegada on the north and Saint Croix on the south are absent. Anegada, a flat limestone island of the British group, lies thirteen to fourteen miles north of Virgin Gorda, from which it is separated by shallow water, uniformly less than twelve fathoms deep. Situated at the brink of the submarine bank from which the nearest islands rise, with depths of several hundred fathoms immediately to the north and east, it is geographically a member of the northern group. With Saint Croix, on the other hand, the case is different. It is located nearly thirty-five miles south of Saint

[5] Lobeck, A. K.: "The Physiography of Porto Rico." New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, Vol. I, Pt. 4, 1922, pp. 301-381.

[6] Lobeck, A. K.: Op. cit., pp. 314, 320, 324, 356, 373-374.

Thomas and Saint John. Not only is it separated from the northern islands by the greatest inter-island distance in the Virgin group, but it is isolated from them by minimum depths of 1600 fathoms and a maximum of more than 2400; from Vieques on the northwest by minimum soundings of 1900 fathoms and a maximum of 2500. Eastward the depths between Saint Croix and Saba Bank are less, but here 750 fathoms is the minimum sounding. Geographically, then, Saint Croix is isolated from all of the surrounding islands, in spite of its close geologic relationship, particularly with Vieques. And as its isolation, accomplished after the major features of its geology had taken shape, must have been wrought by profound block-faulting, it is to be expected that its physiographic development was not entirely similar to the more closely knit islands of the northern group. Although the differences in physiographic history are not as striking as might be expected, and many parallel stages are common to both groups, there have been a few events in Saint Croix's history which are not recorded elsewhere. The island is entitled, therefore, to independent consideration.

The physiography of the Virgin Islands and the islands east of Porto Rico will be treated, in consequence, under three areal divisions:

I. Northern Virgin Islands.
II. Saint Croix.
III. Vieques and Culebra.

Under these heads the land-forms will be studied in the chronologic order of their development.

CHAPTER II

PHYSIOGRAPHIC HISTORY OF THE NORTHERN VIRGIN ISLANDS

Geographic Factors

The northern Virgin Islands include six major islands: Saint Thomas and Saint John, under American jurisdiction; Tortola, Jost Van Dyke, Virgin Gorda and Anegada, under British jurisdiction. In addition to the larger members, there are about seventy smaller islands and cays, varying in length from a few rods to a mile and a half, besides countless rocks.

All of the islands except Anegada are closely spaced and are aligned crudely into two parallel groups trending east-west, whose combined length is more than two and one-half times their north-south breadth. The southern group includes all of the American islands south of a line drawn through Leeward Passage between Saint Thomas and Hans Lollik, through The Narrows and Sir Francis Drake Channel, and south of Spanish Town peninsula, Virgin Gorda (see Plate I). It thus includes all the American islands except Hans Lollik; embraces Pelican, Norman, Peter, Dead Man's Chest (Dead Chest on the charts), Salt, Cooper and Ginger among the lesser British islands. The northern division includes Hans Lollik, Tobago, Jost Van Dyke, Great Thatch, Tortola, Virgin Gorda and all the lesser associated islands. The parallel alignment of islands and channels is the expression of the structure of the underlying stratified rocks. Anegada, outside the two divisions, is *sui generis* geologically and geographically.

The submarine platform upon which the northern Virgin Islands rest is uniformly less than thirty-five fathoms deep and only locally does it exceed thirty. Its surface is relatively smooth, but is broken by a few widely separated banks, the principal of which are Barracouta Bank, ten miles north of Saint Thomas; Kingfish and Whale banks, respectively five and thirteen miles north of Jost Van Dyke and Tortola. Northeastward the platform shallows, and between Virgin Gorda and Anegada the maximum depth is twelve fathoms. Anegada is protected to the south by a broad margin, to the north by a narrow margin, of reefs and coral heads that continue southeastward for eight miles in Horseshoe Reef. The latter lies under so little water that it breaks heavily in all weather except the most perfect calms; in fact, at "The White Horse" a small pile of dead coral has been heaped up some three feet above the water level. The reefs surrounding Anegada and extending into Horseshoe Reef are living and in active growth. There are also marginal ridges along both the northern and southern edges of the platform at depths of ten to twenty fathoms. The ridges on the southern side are very nearly continuous and have the characteristics of drowned and partly dissected coral reefs. The broader ridges on the north are more widely spaced and appear to be of different origin; but they, too, rise distinctly above the level of the platform and serve with the living and submerged reefs to give it an upturned rim whose origin offers one of the problems of the present study. Beyond the rim depths increase abruptly from the average of thirty fathoms within it, and in relatively short distances soundings of several hundred to a thousand or more fathoms are the rule on every side. The outer edge of the Virgin Islands bank is thus a steep escarpment, in most localities more than 6000 feet high.

All of the islands except Anegada are situated considerably south of a median line drawn through the submarine platform from Porto Rico to its eastern termination. If the history of the submarine platform were that of simple marine erosion, the location of the islands might be explained as a normal one, brought about by more active erosion of the Atlantic Ocean from the north and northeast. Such an explanation would readily account for the fact that the platform north of the islands ranges from twelve to twenty-three miles in width, while on the south the platform ranges from one mile to a maximum of eight. If, on the other hand, the platform level was developed chiefly by the subaërial processes of weathering, rain-wash and stream erosion, the heavier precipitation upon the northern slopes of the islands would cause more rapid erosion upon the northern side of the bank, and so develop a broader and more perfect lowland or peneplane. On Porto Rico, for example, a broad lowland developed along the northern coast prior to deposition of the coastal plain, while the contemporaneous erosion level on the southern coast is rugged and narrow. It is not to be supposed that the development of the platform was as simple as either of these cases postulates, and it will be part of the purpose of this paper to determine the factors involved in its genesis and their relative importance. It has been a failing of many physiographic studies of submarine platforms in tropical seas to treat them as simple results of marine planation in Pleistocene time, and to ignore plain evidences of the activity of subaërial forces. Study of the Virgin Islands bank affords convincing proof of the dominance of fluvial forces in its formation, and it is one of the aims of the present report to establish this view.

Summary of Physiographic Development

The physiographic history of the northern Virgin Islands begins with an oldland composed of a complex mass of folded stratified surface volcanics, thin sediments and hypabyssal volcanic intrusions, cut by massive dioritic intrusives, which are especially prominent in the eastern islands. These rocks record a period of extensive vulcanism, many of whose explosive products were redistributed and stratified in a shallow sea. During lulls in volcanic activity thin, fossiliferous limestones were deposited. Accumulation was terminated by uplift and folding, with intrusion of stocks of molten material, and the result was a range of complex mountains.

Subsequently fluvial erosion reduced the mountainous oldland to an imperfect peneplane, best seen on the relatively level summits of the upland of Saint John, 1000 feet above sea-level. On the steep single-ridged islands of Saint Thomas, Tortola, Jost Van Dyke and Virgin Gorda suggestions of the upper peneplane can be sometimes caught, but for the most part must be divined. The central ridge of Saint Thomas

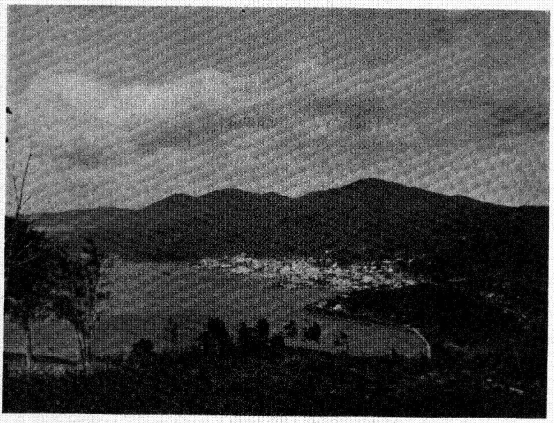

FIG. 12.—*Central ridge of Saint Thomas*

between Perseverance Bay and a point due north of Saint Thomas town constitutes a monadnock group of hills rising to 1550 feet in Crown Mountain (Fig. 12). On Tortola the central ridge northwest of Seacow Bay and Road Harbor to Brewers and Canegarden bays constitutes another monadnock group, which includes Sage Mountain, 1780 feet high, the highest point in the Virgin Islands (Fig. 13). Virgin Peak, on Virgin Gorda, 1370 feet high, rises slightly above the imperfect upland.

The first cycle of erosion was interrupted by 700 or 750 feet of uplift, and a second cycle reduced all but the central cores of the present larger islands to a surface in a late mature or old stage of dissection. Only a few remnants of this surface have been preserved, and they are topographically unconformable with the fluvial erosion surfaces of the preceding and succeeding cycles of denudation.

Again, uplift approximating 500 feet rejuvenated the streams, which worked headward from the new sea-level, cutting into the second erosion level, with the result that in many of the larger valleys there is a marked discordance of gradient at elevations ranging from 300 to 450 feet. The chief drainage system comprised two subsequent rivers, one flowing eastward from The Narrows, the other southwestward through Sir Francis Drake Channel, tributary to a mainstream which appears to have flowed south through Flanagan Passage. The valleys of these streams were prominent in successive uplifts, and with later submergence made deep east-west channels, which divide the islands into the two groups described.

No direct field evidence can be offered for the ensuing stage of physiographic history, because the areas involved are now part of the submerged platform. Yet ample data from Vieques, Porto Rico and Saint Croix, combined with the character of the surface of the submarine platform, indicate that the third cycle of erosion just described was followed by slow submergence and the deposition of a coastal plain. The latter was deposited on the lowland areas that were formed during the preceding erosion cycle. Coastal plain accumulation ended with emergence and fluvial erosion, which proceeded so far that only a few ridges and cuestas remained as testimony of the coastal deposits.

A second submergence brought the water-line within five or six fathoms of its present position, drowning the dissected coastal plain and leaving only a few Tertiary ridges and cuestas above sea-level. These were rapidly planed by wave-action. Connected with the rise of the strandline was the growth of barrier reefs around portions of the platform's margin, development of local fringing reefs, and irregular accumulation

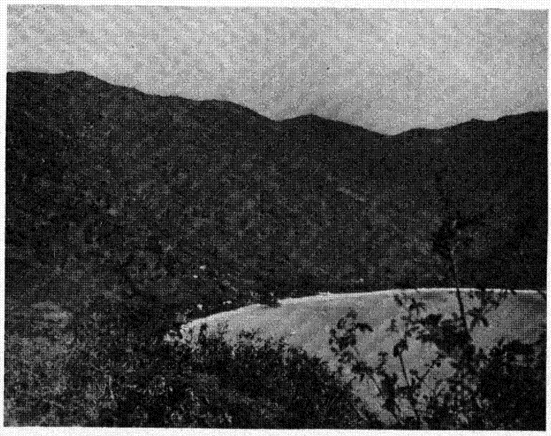

FIG. 13.—*Sage Mountain monadnock group, Tortola*

of clastic material on other parts of the bank. These deposits have partly modified and obscured the forms produced by fluvial erosion in the previous stage of emergence. There has been further submergence to an extent of five or six fathoms, bringing the water-level approximately to its present position. The features of drowning now exhibited in the shorelines of the islands are primarily the direct outcome of the latest upward movement of the strandline. Concomitant with the rise of the water were vigorous reef growth along the northeastern edge of the bank and accumulation of detritus elsewhere, particularly in the embayments. Finally, in very recent time, there has been slight emergence of not more than two or three feet.

The land-forms produced in the sequence of events outlined above will be considered in detail in the order of their development, which may be summarized as follows:

1. The oldland.
2. Erosional history of the oldland.
   a. First cycle.
   b. Second cycle.
   c. Third cycle—the submarine platform.
3. Submergence of the submarine platform.
   a. Initial submergence.
   b. Maximum submergence.
   c. Recent slight emergence.

The Oldland

Presumably the oldland was once not only as extensive as the submarine platform upon which the northern islands rest, but extended without break southward to Saint Croix and westward to Porto Rico. In rock types it is complex; in structure it is composed of closely folded rocks, complicated in places by normal faulting. Much of the topography has developed with singular disregard both of rock types and of rock structures; but in some areas the lithology and geologic structures have played such important rôles in governing dissection that each requires brief consideration.

Rock Types

The rocks composing the oldland comprise a series of reworked pyroclastics, extrusive flows, shallow intrusives and deeper-seated granitoid intrusives on the one hand; and thin limestones, shales and tuffaceous shales on the other. All are Upper Cretaceous in age, as are the related rocks of Porto Rico. Clastic material other than that derived from volcanic eruption is absent, and true sediments are found in much smaller quantity than materials of igneous or explosive volcanic origin. Topographically, however, the sediments have produced important results. In a consideration of the physiography, description of rock types may be appropriately restricted to groups which produce similar topographic forms. Three such groups may be distinguished:

1. Massive eruptives and shallow intrusives.
2. Deep-seated intrusives.
3. Thinly stratified volcanics and sedimentary rocks.

1. *Massive eruptives and shallow intrusives.*—This division includes unstratified, or crudely stratified, coarse agglomerates, which are prominently developed in parts of southern Saint Thomas and Saint John and which make up considerable portions of Hans Lollik, Tobago, Jost Van Dyke and northern Tortola and smaller areas elsewhere. Within this division, also, are included a few volcanic flows, several shallow intrusive porphyries of different thicknesses, and considerable amounts of indurated tuff, all of andesitic composition. These types are characteristically massive and have weathered alike, irrespective of their various structures and attitudes. Like the similar kinds of materials on Porto Rico, they are free from quartz and weather rapidly by chemical decomposition rather than by disintegration. Soils are everywhere existent, on the steepest of valley walls and on the mountain tops; but only locally are they developed to depths greater than five or six feet. The soil-covering in the Virgin Islands, on the whole, is thin, and rock ledges commonly come to view even on gentle hillsides. The tenacity with which soils cling to the steepest slopes is described by Berkey[7] as a feature of the valleys of Porto Rico. The same characteristic is observable in the Virgin Islands. Yet thick soils do not exist except on the island of Saint John, where the vegetation has not been destroyed, and where it still holds the underlying soils in place. On the other islands the thinness of the soil mantle is plainly the outcome of wanton destruction of vegetation, principally for charcoal burning.

The topographic forms produced by erosion in all of the rocks in this division are alike. They bevel the structure indiscriminately. The young valleys cut into the upland are deep and V-shaped, and in the more mature valleys, of which there are few, the forms are normally well rounded.

2. *Deep-seated intrusives.*—Rocks of the second group are also massive in character and include a structureless aggregate of plutonic types, with wide range in composition and in texture. They occur widely as sporadic

[7] Berkey, C. P.: "Geological Reconnaissance of Porto Rico." Annals N. Y. Acad. Sciences, Vol. XXVI, 1915, pp. 34-35.

injections on Buck Island south of Saint Thomas, on northern Saint John, on southwestern Tortola and on the lesser islands near by. The most extensive areas outcrop at the east end of Tortola, on Beef Island, immediately adjacent, and on Virgin Gorda, which is composed almost wholly of a granitoid intrusive extending southward through Fallen Jerusalem to Round Rock.

The erosional forms assumed by this type of rock are strikingly distinctive wherever the type is found in bodies large enough to exert an influence on the topography. Virgin Gorda is the best example. The

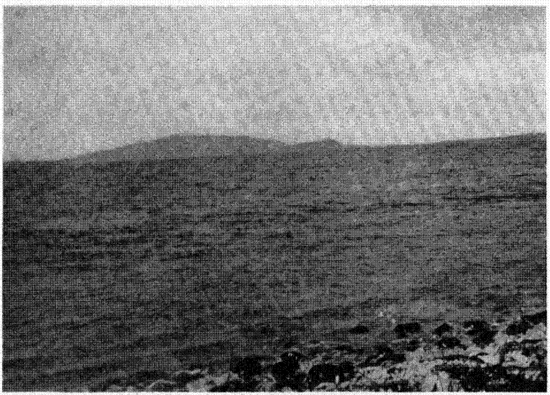

FIG. 14.—*The dome-shaped profile of Virgin Gorda*

British hachure map represents the central block of the island, which rises into Virgin Peak with the upward concave profile typical of a volcanic cone. The American chart, following the British original, attributes by sketch contours a similar form to the island. Nothing could be further from the fact. The form of the island is convex upward (Fig. 14). Virgin Peak is a smooth, rounded dome, strongly contrasted in shape with any of the other islands of the group. The charts correctly suggest radial drainage, but it is not the radial drainage of the volcanic cone, but rather of the laccolith, with fringing peninsulas and islands of flanking stratified rocks. A more special kind of topographic form produced by the coarser-grained intrusives occurs on the Spanish Town peninsula of Virgin Gorda and attains the acme of its development in Fallen Jerusalem. The diorite has decomposed by spheroidal weathering along joints, and a tumbled mass of gigantic boulders, some of them 60 to 70 feet square, has produced natural baths along the shore. The entire surface of the peninsula and of Fallen Jerusalem is strewn with blocks, and from the fancied resemblance to a ruined city Fallen Jerusalem takes its name. The feature is found again in milder form on Beef Island, five miles west, across Sir Francis Drake Channel, where the same type of rock is at the surface. In general the igneous rocks usually offer weak resistance to weathering and in some instances underlie lowland areas.

3. *Thinly stratified volcanics and sedimentary rocks.*—Beginning at Outer Brass Island and extending eastward in a narrow belt through The Narrows and across Sir Francis Drake Channel as far as Ginger Island, there is a zone of rocks composed in large part of stratified sediments and water-deposited pyroclastic rocks which have a distinctive topographic expression. The sediments include thinly stratified tuffs and shales which are probably tuffaceous in origin. These two kinds of rock make up the bulk of the bedded materials; but interstratified with them are at least three limestone members of two different varieties: one a thinly bedded, dense lime mud not unlike the shales; the other a massive crystalline limestone. The topographic forms produced by these sediments conform with their structure, and discussion of their surface expression will be reserved for the next section, in which the structures important to the physiography will be considered. They constitute the weakest division of the rock groups, and upon one of the shaly members Lövenlund Valley of northeastern Saint Thomas has been excavated. The crystalline limestones sometimes form ridges rising above the surrounding levels, as on Congo Cay, which is composed wholly of marble (Fig. 15), and on West End Peninsula, Tortola, where one of the chief members of the central ridge is crystalline limestone.

GEOLOGICAL STRUCTURE

The rocks making up the northern Virgin Islands are complex in structure. The bedded formations are folded, with dips ranging from 20° to 90°. The strike varies, being west-northwest in central Saint Thomas, about 10° south of west in western Saint Thomas, and due east-west throughout all of the eastern islands. On Virgin Gorda, composed mostly of a massive granitoid intrusive, no structure could be determined. The natural division of the islands into two parallel groups separated by a series of east-west channels is a direct expression of the underlying structure. From north to south across the platform the rocks outcropping on the islands possess a belted character. On the north there is a broad strip of strong, massive pyroclastics and shallow intrusives in which structural control of surface forms is lacking; in the center, thin-bedded sediments and tuffs, indifferently resistant to erosion, predominate, while on the south occurs another broad band of massive rocks similar to those on the north. There is thus a strip of weak stratified rocks centrally located between two broader belts of strong, massive rocks. The latter constitute the two island groups; the former, the series of channels separating them. Most of the formations, massive and bedded alike, dip north, about 60° in central Saint Thomas,

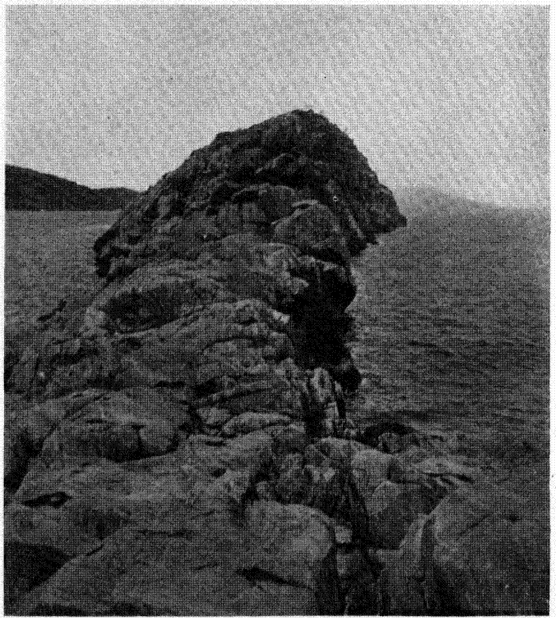

FIG. 15.—*Congo Cay, a partly submerged marble ridge*

increasing to 80° and 90° northward to Little Tobago Island. The structure is open to two interpretations: either it is monoclinal and the sediments constitute a middle member in the Upper Cretaceous series, deposited between stages of active volcanic eruption, or the structure is an overturned closed fold in which the structurally weak strata have served as the axis of folding. The intermediate position of the thinly bedded rocks renders either interpretation permissible, but several lines of evidence favor the conclusion that the sediments lie upon the axis of a fold. The evidence is not physiographic and must be reserved for a later section of the volume, in which the structural geology will be dealt with. Physiographically, the weakness of the sediments is most significant. An easy prey to fluvial erosion, they have been readily excavated into aligned subsequent valleys, which by submergence have formed the line of channels separating the northern and southern island groups.

Within and bordering the channel area the surface forms, shorelines and arrangements of the islands are completely dominated by the geologic structure. They are composed of steeply dipping sediments, and many of their shorelines present steep dip-slopes, in some cases vertical, in others dipping 60° to 80° north toward the Atlantic. Cays and peninsulas are elongated from east to west in the direction of the strike, and structural alignment of small islands is a common feature. Thatch, Grass, Mingo and Lovango cays form the most striking series, a chain five miles in length, three of the members of which are separated from each other only by narrow wave-beaten gaps less than one hundred yards in width. Other less striking cases of structural alignment are found in Great Thatch Island and West End Peninsula (Tortola), Little Thatch Island and Frenchman Cay, and Whistling Cay and Mary Point (Saint John). The Narrows, a deep, east-west channel not three-quarters of a mile in width, is eroded out along the strike. In contrast, most of the topography on the islands north and south of the central channel system displays no dependence whatever upon structural control, whose only effect is seen in their grouping.

That faulting plays some part in the geologic structure is to be expected from the block-fault boundaries of the submarine platform to the north, south and east. Yet nowhere east of Saint Thomas is there decisive evidence of faulting expressed, either in the topography or in the rocks; but westward from Magens Bay and Saint Thomas Harbor several striking structural and topographic features indicate the importance of faulting. Among them the following are most suggestive:

(1) At the base of Picara Point, bounding Magens Bay, measurements of the strike show that the peninsula is not determined by the

structure, but truncates the structure (Fig. 16). The strike is approximately N. 70° W., but Picara Point trends N. 50° W. On the strength of the discordance of structure and topography, the valley extending inland from Magens Bay and the bay itself are considered to owe their origin to erosion along a fault zone.

(2) The rocks from Tutu Bay westward to Santa Maria Bay, on the northern shore of Saint Thomas, have a constant strike of N. 65°–70° W., but from Santa Maria Bay westward the strike is uniformly S. 10°–15° W. Between Santa Maria Bay on the north and Perseverance Bay on the south, there is a low pass which strongly suggests a fault valley, and the abrupt change in strike at this point strengthens the conclusion.

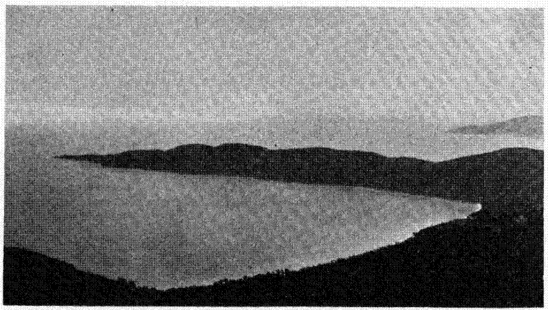

FIG. 16.—*Picara Point and Magens Bay*

(3) The shoreline at the west end of Saint Thomas is rectilinear, truncating the structure at an angle of 55°. Again, the trend of the coast is N. 50° W., as in the case of Magens Bay, whereas the strike of the rocks is S. 10° W.

(4) If observations are extended outside the limits of the northern Virgin Islands, it is found that the long double peninsula of Northwest Point-Point Soldado on Culebra has a trend N. 45° W., and it is paralleled by the Great Harbor-Flamingo Bay depression. The low, undulating dips of the strata on the northeast side of Flamingo Point indicate that the topographic features are independent of the structural trend of the rocks.

Lobeck considers that the depression has been formed by drowning of valleys developed along a major joint.[8] The interpretation seems justified by the fact that the kind of rock on both sides of Great Harbor is the same, but minor faulting seems a preferable hypothesis. The parallelism of the several topographic features between Magens Bay and western Culebra, their development in different types of rocks with otherwise unrelated structures, and their wide and irregular spacing favor a belief that they owe their origin to something more than jointing. The explanation may lie in minor diagonal torsional faulting across the Virgin Island-Porto Rico platform, perhaps in response to differential movement during block-faulting. The trend of the diagonal faulting and fracturing suggests eastward lateral movement of the northern block in the Atlantic, or westward lateral movement of the southern block in the Caribbean. Other proof of the existence of a strong northwest-southeast fracture sytsem is found in the drainage pattern in the central block of Saint Thomas, where most of the ravines dissecting the upland have a trend parallel to the more prominent features described above. The *en échelon* arrangement of fractures appears closely analogous to the *en échelon* faulting in northeastern Oklahoma described by several authors and summarized by Fath.[9] The Oklahoma case affects a larger area, the belts of *en échelon* faulting extending 65 miles north and south, 20 miles east and west. Minor normal faulting is clearly shown by displacements in the Pennsylvania strata, but none of the faults has a throw greater than 130 feet. Cause for the faulting is believed to exist in differential lateral movement, which caused torsional strain and fracturing. The Oklahoma case fits so exactly the features found in the Saint Thomas-Culebra area that minor faulting from a like cause seems the logical conclusion. Further discussion of the subject must be deferred to the section on structural geology.

One other important fault requires mention, for it strongly affects the physiography of southern Saint Thomas. A persistent series of lowlands and low passes reaches from Brewer Bay on the west through the northern expansion of Saint Thomas Harbor, eastward beyond Charlotte Amalie village. Their independence of structure and rock types and the discordance of the structures on opposite sides of the aligned lowlands offer strong evidence of faulting.

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[8] Lobeck, A. K.: "The Physiography of Porto Rico." New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, Vol. I, Pt. 4, 1922, p. 374.

[9] Fath, A. E.: "Origin of the faults, anticlines and buried granite ridge of the northern part of the Mid-Continent oil and gas field." U. S. G. S., Professional Paper 128, 1921, pp. 75-84.

EARLY DEVELOPMENT OF THE OLDLAND

The rocks composing the oldland were formed in Upper Cretaceous time, like the corresponding formations on Porto Rico. Fossils found in the limestone at Coki Point, Saint Thomas, leave no doubt of the age of the formations in which they are embedded. The intimate association of limestones, fragmental volcanics, flows and shallow intrusives indicates that slow accumulation of limestone and thin tuffaceous shales under shallow marine conditions alternated with rapid accumulation of coarse agglomerates during explosive volcanic activity, which was also accompanied by extrusion of flows and intrusion of sills and dikes. Most of the agglomerates were reworked and crudely stratified by wave action; but the absence of clastic materials of non-volcanic origin suggests that the deposits were assembled from a region of volcanics which could not have supplied clastic material of any other type. Accumulation of material was ultimately terminated at the close of Cretaceous time by plutonic intrusion, folding and uplift. Apparently most of the rocks were not greatly indurated, for in early Tertiary time they suffered rapid denudation during three partial erosion cycles. On Porto Rico most of the erosional history of the oldland was accomplished before Middle Oligocene time, when coastal plain deposits were formed upon the lower erosion level.[10] There is every reason to believe that the early Tertiary history of Porto Rico and the Virgin Islands was alike. The early development may, therefore, be summarized as follows:

(1) Accumulation of eruptives, shallow intrusives and sediments (Upper Cretaceous).
(2) Intrusion and orogeny (close of Upper Cretaceous).
(3) Subaërial erosion, with the development of an imperfect peneplane (first cycle—Paleocene–Eocene?).
(4) Uplift, partial peneplanation (second cycle—Eocene).
(5) Uplift, partial peneplanation (third cycle—Lower Oligocene).

EROSIONAL HISTORY OF THE OLDLAND

FIRST CYCLE

It is doubtful whether the word "peneplane" would suggest itself as being applicable to the northern Virgin Islands, from a casual inspection of their form. Certainly, the irregular, angular ridges of Saint Thomas (Fig. 12) and Tortola, and the gently convex mass of Virgin Gorda, offer

[10] Hubbard, Bela: "The Geology of the Lares District, Porto Rico." Scientific Survey of Porto Rico and the Virgin Islands. N. Y. Acad. Sciences. Vol. II, Pt. I, 1923, Table 8.

surficially little hope of interpreting their uneven skylines as a simple erosional surface that might be termed a peneplane. Viewed from the island of Saint Croix, the irregular crests are greatly smoothed out; and it was not until the northern islands were seen from this distance that the possibility of identifying an elevated peneplane, developed by subaërial erosion, was seriously considered. Only the island of Saint John offers immediate conviction that the oldland was early reduced to an imperfect peneplane (see Plate IIa). From Centerline Road, north of Camelberg Peak, and again from the road a half mile west of Bordeaux, one sees a gently undulating skyline with scarcely more than one hundred

FIG. 17.—*West End peninsula, Tortola*
The Saint John peneplane in the background

feet of relief. The dissection is deep, it is true; for it is impossible to find a single point from which a deep V-shaped valley does not open up a glimpse of a small embayment in the shoreline a thousand feet below. Yet the even-topped skyline is widespread, though it is breached by a few low passes between streams eroding headward from north and south. From the higher elevations of western Tortola the level-crested upland of central Saint John is more impressive, for there the entire island is in sight (Fig. 17). Not an eminence rises above the common level; it is a gently undulating surface, very typically a peneplane, 1000 to 1247 feet high. West of Camelberg Peak it is represented by isolated knobs which are only 820 to 975 feet high and which decrease in height and number toward Cruz Bay.

With the upland of Saint John as a datum-plane, study of the other islands of the group reveals numerous but less perfect levels and knobs developed approximately at the same elevation. On Tortola the spurs of Sage Mountain have long, gently sloping crests 900 to 1200 feet high, and the central ridge of the island maintains a minimum elevation of 900 feet, on which such eminences as Sage Mountain, 1780 feet high, rise as a monadnock cluster (Fig. 13). Few of the other peaks attain a height greater than 1400 feet. The near-by islands aspire to the common level: the ridge of Jost Van Dyke reaches a comparatively even top over 1000 feet high in the eastern two-thirds of its length; Guano Island rises 810 feet above sea-level. On Virgin Gorda the central area is domed into a rounded crest slightly above the requisite level (Fig. 14), but there are no planed upland areas and the spurs on its southeastern and northeastern flanks and the peninsulas to the east and south fall 300 feet short of the mark. Saint Thomas presents a more complex case. The ridges north, east and southeast of Saint Thomas town ascend abruptly to altitudes ranging from 875 to 983 feet. These elevations are maintained in two parallel east-west ridges, separated by a valley which broadens into a basin at the small settlement of Charlotte Amalie. The basin is drained to the southeast through a valley which terminates the southern ridge, while the northern ridge is terminated by a low pass. Eastward the island rises less than 600 feet above sea-level. The main ridge of Saint Thomas west of the town (Fig. 12) has an uneven crest, undulating between 1100 and 1550 feet. There are no flats, and there is no suggestion of planation at the thousand-foot contour, for all of the ridge ascends steeply above it. It appears to be one of the two principal low monadnock groups in the northern Virgin Islands. The small block west of Perseverance Bay attains a height of 910 feet in Fortuna Hill, but there is little convincing evidence of an upland. North of Saint Thomas, Hans Lollik protrudes its 713 feet prominently above the water, but falls short of attaining the upland level.

Although fragmentary, the evidence favoring the existence of an upland erosion surface is widespread and is most conclusive at the following places:

(1) On Saint John, whose even skyline serves as a datum-plane for the first cycle peneplane.

(2) On Tortola, where the main ridge and the spurs of monadnocks maintain elevations between 900 and 1200 feet.

(3) On Jost Van Dyke, whose backbone is 1000 feet high.

(4) On eastern Saint Thomas, where the two ridges of a forked upland have subequal heights above 875 feet.

(5) In the isolated residuals of islands, which rise to elevations but little below the peneplane.

SECOND CYCLE

Early in the course of field-work there came to notice a series of gently sloping spurs along the southern coast of Saint Thomas (Fig. 18). Northward they terminate abruptly against the sharply rising central ridge; southward they are inclined toward the Caribbean at an angle of 2° to 4°, where most perfectly developed, terminating in cliffs. If the profile of the Constant Mill-Haypiece Hill slope is projected across West Gregorie Channel, it continues less perfectly in the hill summits of Water Island (see Plate IIa). The profile of Hassel Island shows a similar relationship to the mainland. The recurrence of flats at elevations of 225 to 375 feet throughout this portion of the southern coast of Saint Thomas demanded explanation as a separate cycle in physiographic development.

Because of the gentle southward inclination and the abrupt termination of these rock benches against the main ridge of the island, it was at first postulated that they were elevated wave-cut benches. Examination was made for evidence of wave-cutting, but none was found. There is no trace of a wave-cut cliff at the base of the main ridge slope, and marine deposits are absent. Further study was immediately begun to find a corresponding level of marine or subaërial erosion at the same elevation elsewhere, particularly on the islands facing the Atlantic, where, if the feature were of marine origin, more extensive development was to be expected. Field and map studies have been rewarded by the following examples:

West of Saint Thomas, Dutchman Cap, Salt Cay and Savana Island reach the approximate elevation of the Saint Thomas benches, ranging between 242 and 278 feet. The crest of Savana Island is noticeably level. Along the north coast, Inner Brass, Little Hans Lollik and the southern end of Big Hans Lollik islands, Tropaco and Mandal points, and the hills northwest and south of Water Bay, all maintain persistent levels slightly above and below the 250-foot contour; but the most extensive development of the level is found in the central and southern part of eastern Saint Thomas. Beginning at the low pass (400 feet high) on the road extending east from Saint Thomas town to the New Herrnhut Mission, it expands and fills the broad basin from Charlotte

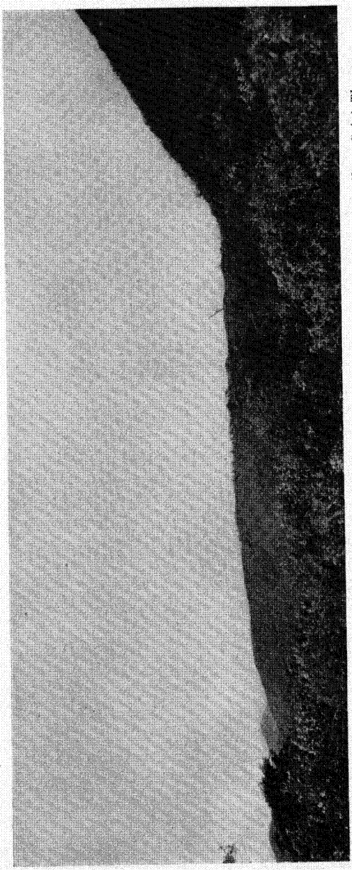

FIG. 18.—*Constant Mill rock bench, part of the second cycle erosion surface, as represented in southern Saint Thomas*

Amalie to Tutu, stretches southeast throughout Langmath, Mariendal and Nadir, and is represented in the broken ridges and hills from Coculus Point on the south to Redhook Point on the east. The chain of islands east from Thatch Cay also maintains an elevation of 230 to 255 feet. On Saint John the level has a less perfect representation, but along the southwest shore from Cruz Bay to Reef Bay most of the peninsulas and spurs have altitudes of 269 to 357 feet. Immediately east of Bethany there are two valleys which are well graded above the 400-foot contour, but in their lower courses drop abruptly into short, young, ungraded valleys. A striking case of a hanging tributary valley, imperfectly graded above the 400-foot contour, but dropping to the main stream in a cliff (a waterfall in rainy months), occurs in the valley between the road north from Reef Bay and Camelberg Peak. No indication of its development appears on the topographic map, although the rock walls of the basin at the foot of the fall are famed for their Carib inscriptions and could scarcely have been unknown to the topographers. Other portions of the island on which the given level is preserved include the points surrounding Lameshur Bay, Ram Head, the rise south of Lagoon Point and most of East End Peninsula. Along the north shore numerous spurs, peninsulas and hills rise to subequal heights, 250 to 300 feet above sea-level. Seen from a distance, they appear as a dissected but persistent terrace, in sharp contrast to the upper peneplane on the one hand and later dissection on the other.

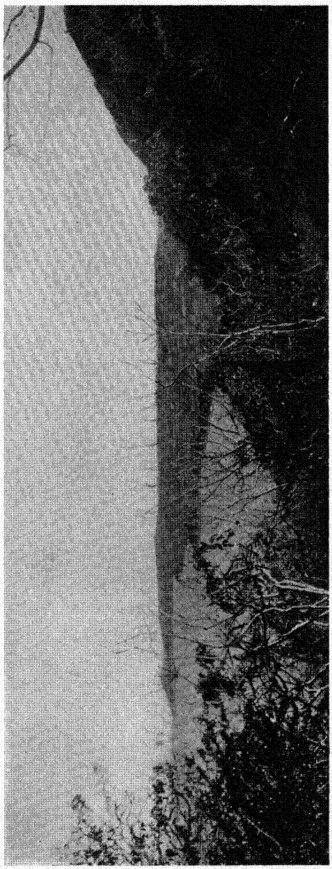

FIG. 19.—*Spanish Town peninsula, Virgin Gorda*

The second cycle erosion surface is represented by the hill-crests in the background

An erosion level between 250 and 400 feet can not be identified as specifically on the British islands, because of the unreliable contouring and hachuring on the maps and charts. The charts suggest a few conspicuous areas, however, and several striking ones were observed in the field. The eastern half of Norman Island and most of Peter Island have even-crested tops averaging about 300 feet above sea-level. Salt Island reaches 380 feet at one point, Ginger Island rises about 400 feet in its center, but flattens out above 300 feet toward the ends. The northern shore of Ginger Island presents a striking truncated spur with flanking hanging valleys whose gradients indicate mature development at the higher level. Most of the Spanish Town Peninsula on southern Virgin Gorda has a gently rolling surface above

FIG. 20.—*Second cycle erosion surface in northeastern Saint Thomas*

250 feet (Fig. 19). The Dog Islands and the islands bordering Gorda Sound, on Virgin Gorda; West End, Tortola; Little Jost Van Dyke, Little Thatch and the east end of Great Thatch islands also show levels at the required elevation; and a rock bench on the southern side of Great Thatch Island is as striking as the benches on the southern side of Saint Thomas. With accurately contoured maps, many more examples which were not checked by field observation could be discovered.

The examples noted are adequate for the conclusion that a widespread erosion level is preserved above 225 and below 450 feet. Its development on peninsulas sheltered from wave erosion; the gently rolling nature of its surface where most extensively developed; the presence of a large flat in the interior of Saint Thomas (Fig. 20); and the well-established gradients of several valleys above the 400-foot contour in Saint John, sharply discordant with the valleys of recent development, all point to the former existence of a baselevel, with the sea 225 or 250 feet above its present position. Sufficient erosion occurred at this level to form a dissected surface as extensive, at least, as the inter-island areas of today and presumably reaching northward and southward to the margins of the platform. The remnants which still exist represent only its innermost edge. From the protected positions of many of them, their origin must be considered fluvial, but marine planation of the marginal areas, since removed, may be assumed. The first cycle of peneplanation seems, therefore, to have been terminated by uplift of 700 feet or more. Dissection of the upper peneplane proceeded until but a few remnants of it remained, while a country of late mature topography was developed toward the new baselevel.

THIRD CYCLE—THE SUBMARINE PLATFORM

The submarine platform surrounding the northern Virgin Islands, Culebra and Vieques has been studied briefly by Vaughan, whose article on its physiographic features[11] gives the impression that its origin was entirely a phase of marine planation during the Pleistocene. The outer portion of the platform, particularly on its northern side, has an average depth of 30 fathoms, which, according to Daly,[12] corresponds to the level of wave-cutting during the time of maximum glaciation. Vaughan assumes that a graded wave-cut terrace can be rapidly formed to depths of 10 fathoms in soft materials, and concludes from the present depth of the outer margins of the Virgin Islands' platform, that sea-level was lowered some 20 fathoms, presumably from a position approximating its present level, and that the areas now below 20 fathoms were wave-cut during the maximum glaciation of Pleistocene time. The profiles which he has selected for interpretation show not only the lower bench at 26 to 34 fathoms, but an intermediate one at 14 to 20 fathoms and an upper one at 6 to 10 fathoms. Each of these he considers to have been cut independently during temporary stands of the shifting water-line of Pleistocene time. The depth of the lower bench corresponds closely to the depths of the platforms surrounding oceanic islands the world over, whose origin is ascribed by Daly to marine planation when the ice-caps

[11] Vaughan, T. W.: "Some littoral and sublittoral physiographic features of the Virgin and northern Leeward Islands and their bearing on the coral-reef problem." Jour. Wash. Acad. Sci., Vol. VI, 1916, pp. 53-66.

[12] Daly, R. A.: "The glacial control theory of coral reefs." Proc. Amer. Acad. Arts and Sciences, Vol. LI, 1915.

of Europe and America had withdrawn a maximum of water from the ocean. Lobeck passed over the subject by citing Vaughan and Daly,[13] but not without addition of a vital idea, which carries back the initial origin of the submarine platform to the Tertiary, and which affects any explanation offered to account for the redevelopment of the platform in more recent time. He concludes that Tertiary limestones underlie the Cordilleras Reefs, although there are no Tertiary outcrops above the reef, on Culebra or on the mainland near by. His considerations were restricted to that portion of the platform immediately east of Porto Rico and will, therefore, be given further consideration in Chapter IV. Vaughan's interpretations, it is true, do not preclude this probability, and perhaps he had it in mind in describing the banks or ridges north of Saint Thomas.[14] But the probable existence of Tertiary ridges upon the platform necessitates a consideration of the initial origin of a platform on which a Tertiary coastal plain was deposited, and of the means by which the coastal plain sediments were partly stripped to form the surface of the present platform.

Solution of the Tertiary coastal-plain problem thus raised made a careful study of the platform necessary. In the field, efforts were made to locate Tertiary limestone outcrops; in the laboratory the platform was contoured at five- and ultimately at two-fathom intervals, and a series of north-south profiles were plotted at intervals of five miles from Porto Rico to Anegada (Plate II). The study has shown that remnants of horizontal coastal-plain deposits, presumably Tertiary, are common; that their dissection can not be interpreted as the result of marine planation, but must be considered fluvial; that the re-excavation of the platform antedated the Pleistocene and was thus in no way related to Pleistocene wave-cutting. The latter was effectual, if at all, only in modifying the pre-Pleistocene surface. The evidence on which these conclusions are based will be set forth at length.

Lobeck has described a lower peneplane on Porto Rico over 1000 feet below the upper peneplane, whose irregular surface can be explained only as the result of fluvial erosion.[15] It is marked by a gradual descent in elevation from west to east, and its meager representations in eastern Porto Rico are in many places submerged. Lobeck identifies it again on southern and eastern Vieques and in the larger valleys of Culebra. In Porto Rico much of the lower peneplane is overlapped by a Tertiary coastal plain which completely buries it west of Morovis on the northern

[13] Lobeck, A. K.: Op. cit., pp. 346-348.
[14] Vaughan, T. W.: Op. cit., p. 59.
[15] Lobeck, A. K.: Op. cit., pp. 315-320.

side of the island, and which exists only in fragments between Morovis and Loiza, disappearing completely a short distance west of Rio Grande. On eastern Porto Rico the coastal plain is absent, and the lower peneplane is poorly represented, chiefly in alluvium-covered valleys. Along the south side of the island the lower peneplane is a rough, mature erosion surface, and the coastal plain is restricted and fragmentary. Both reappear in Vieques.[16]

To assume that either the lower peneplane of Porto Rico or the Tertiary coastal plain comes to an abrupt termination at the present coastline would be, to say the least, illogical. The failure of both in eastern Porto Rico is an outcome of the limited dissection of the Luquillo and Sierra de Cayey monadnock groups, in which denudation has been so slow that comparatively high hills approach the coast and locally constitute sections of the shoreline; but in the Culebra-Vieques-Virgin Islands area there are no comparable resistant monadnock groups, and dissection during the formation of the lower peneplane of Porto Rico attained its maximum development by formation of the extensive lowlands which now constitute the submarine platform. The islands are the small unreduced remnants still standing above the third-cycle level, or "lower peneplane." The nature of its surface is conjectural, because only its innermost edges are now unsubmerged and because the surface of the platform has been considerably modified by deposition. On the islands themselves its inner edges constitute a fluvial surface, meagerly represented in the larger stream valleys and in their drowned mouths. The fact that it is submerged from Porto Rico to the eastern end of the Virgin Islands bank is by no means an indication that its surface was formed by marine planation. Its submergence is the result of differential depression, later in origin than deposition of the coastal plain and without bearing upon its genesis. Thus, the surface on which the Tertiary beds rest is 500 feet higher at Lares than at Corozal and at least 250 feet higher at Corozal than at Loiza, where it is below sea-level. Eastward tilting has brought the lower peneplane nearly 1000 feet lower in the Virgin Islands region than it is at Lares. The steep, rocky shorelines of the Virgin Islands from Saint Thomas to Tortola, in strong contrast to the low or subdued shorelines of Vieques and Porto Rico, are attributable to the greater amount of depression, which has brought the level of the sea to the steep erosion slopes between the lower peneplane and the second cycle erosion level. It is not unlikely that the gradual decrease in depths toward the northeastern corner of the platform is due to upwarping in

[16] Lobeck, A. K.: Op. cit., pp. 320 and 324.

this direction, but less dissection prior to submergence is an alternate and equally admissible hypothesis.

Although the marginal portions of the platform north and south of the two island groups offer little means of interpreting the nature of the lower peneplane surface, the inter-island areas present features which have direct bearing on the problem. The Sir Francis Drake Channel area is the most striking and will be considered in detail. Other localities, although equally typical, will be used for supplementary illustration. Sir Francis Drake Channel (Fig. 21) extends from The Narrows, between Saint John and Great Thatch Island, to the Dog Islands, which partly enclose its northeastern exit between Tortola and Virgin Gorda. It is shut in on the north by Tortola; on the south its enclosure is only partly effected by Saint John, Norman, Peter, Salt, Cooper and Ginger islands; on the east it is bounded by Virgin Gorda. It is 20 miles long; in width it varies from three-fourths of a mile at The Narrows to slightly less than five miles. Although it has numerous openings between islands into the Caribbean, it opens toward the Atlantic only at its northeastern extremity and in two very narrow gaps at its western end. None of the openings is more than a mile in width, but their depths are usually considerable (60 to 120 feet). The broken island barrier on the south and the bulk of Tortola on the north completely protect the channel from any important amount of wave erosion and have similarly protected it throughout its history. Its excavation can not, therefore, be interpreted as a phase of marine planation, but is clearly the outcome of fluvial erosion. The complexities of its surface require further analysis.

Study of the submarine contours serves to throw the relief of the channel into two distinct levels whose areal extents are subequal. The upper consists of a group of mesa-like ridges and flat-topped terraces which even in small isolated occurrences attain a strikingly persistent level of six to eight fathoms. The deeper is less regular in elevation and varies between 14 and 28 fathoms. The latter is not a unified area, but is considerably broken into irregular, semi-basinal depressions bounded by steep walls. One of the simplest of these depressions extends westward from Frenchman Cay through Thatch Island Cut. It is 13 to 16 fathoms in depth, and its trend, together with the trend of its ramifications, such as Sopers Hole, parallels the geological structure. The elongate outline of the depression, its relation to the structure, its protection from the sea, and the character of its outlets, now partly choked by deposits, permit but a single interpretation of its initial origin; it is a subsequent valley, formed by normal fluvial processes, modified by later deposits.

The western depression just described is separated by a slender ridge from a similar narrow trough extending from a point a half mile east of Frenchman Cay to Seacow Bay, a distance of four miles (Fig. 21). It parallels the coast of Tortola, lying within a mile of the shoreline, and ranges in depth from 14 to 19 fathoms. It is separated from a deeper depression three-fourths of a mile to the south by a ridge which lies 6½ to 8 fathoms beneath sea-level, but it joins the deeper trough through a narrow channel 1½ miles south of Seacow Bay. It also is flanked by steeply sloping walls, but the southern wall against the submerged ridge is uniformly steeper than the northern against Tortola. Both escarpments are somewhat irregular, and the southern is varied by two deep re-entrants, one of which is over one mile long and one-fifth of a mile wide, with a depth of 19 fathoms. The flat floor of the depression is broken by two isolated ridges and several "noses," or terraces, over 60 feet high, protruding from the northern escarpment. The flatness of the surface is only in small part the result of later deposition, because where deposits can be definitely identified upon its surface, they appear to increase rather than diminish the relief. The deepest areas are found in the re-entrants and in the outlet channel, farthest removed from the Tortolan coast. It may be concluded from their location that the material accumulating in the trough is derived entirely from Tortola, and that none of it has come from the submerged ridge south of the trough. The depression is narrow and follows closely the shoreline, which passes from thin-bedded volcanics into massive agglomerates a short distance east of Fort Recovery, where structural control ceases to play any part in the coastal outline. The trend and shape of the trough and of the submerged ridge paralleling it show that the structure of the Cretaceous rocks is an unimportant factor in determining their outlines. Southeast of Road Harbor another smaller depression, forked by Denmark Banks, grades southward from 12 to 20 fathoms, and also maintains a deep, slender channel connection with the southerly basin. It is separated from the trough to the east by a drowned, flat-topped spur which broadens into an irregular, mesa-like eminence four to seven fathoms beneath the surface.

The largest depression is the southerly one, with which the two just described are connected. Although irregular in outline, it has an east-west elongation of seven miles and a width which varies up to one mile. Its depth begins where the inner ones leave off, ranging from 20 to 28 fathoms. A very narrow, tortuous, partly filled channel leads from it toward the south through Flanagan Passage, between Flanagan and Pelican islands, where the channel is lost in shallower water of 18 to 20 fathoms. Except for the two channels leading into it and the one leading out, the depression is rimmed by an escarpment whose slopes rise from 100 to 130 feet at an angle usually greater than 5°. In places they may be nearly vertical, but chart soundings do not give adequate information for an unqualified assertion. All the levels surrounding it are five to seven fathoms deep and consist of terraces from the adjacent islands, ridges and isolated knobs, which locally rise abruptly above its otherwise flat floor.

In the entire eastern half of Sir Francis Drake Channel the character of the bottom is in strong contrast to the features in the western half. It is at a higher elevation—13 to 15 fathoms, with one depression of 18 fathoms between Beef Island and Virgin Gorda. Escarpments, ridges and channels are conspicuously absent.

The fundamental elements involved in the submarine features in Sir Francis Drake Channel appear to be the following: (1) its location (in the western half, at least) upon the highly folded, thinly stratified Cretaceous rocks, which, from the amount of excavation they have suffered wherever they are found, must be comparatively non-resistant to erosion; (2) its protected position between islands which have made extensive marine planation impossible within it; (3) the occurrence within its central portion of a series of flat-topped ridges, spurs and knobs which rise above the deeper areas to an almost constant level at five to seven fathoms; (4) the existence of four types of basinal depressions at two different levels below the upper submerged terraces (one at the west, conforming strictly with Cretaceous structure, 13 to 16 fathoms deep; one at similar depths immediately off the Tortolan coast, flat-floored, within the 60-foot escarpment of a submerged ridge; a deeper one, like the last, but 20 to 28 fathoms deep, outside the ridge which encloses the inner trough; the last, a reliefless surface, largely veneered by deposits, underlying the western half of the channel 13 to 15 fathoms below sea-level); (5) the presence of traceable outlets from all of the submerged troughs. Any theory of origin proposed to explain the features of Sir Francis Drake Channel must be built upon these five points. The Pleistocene marine planation theory of Vaughan is plainly inapplicable. The 14-to 19-fathom basins recall the 14-to 20-fathom terrace he describes, but, enclosed as they are, they can not be of marine origin. The deeper basin suggests his 28-to 34-fathom marginal terrace, but it, too, is completely circumscribed by higher ridges and possesses but a narrow outlet, through which waves could not work. Marine planation can not, therefore, explain the two lower levels, although it does explain in part the six-to eight-fathom bench. Another explanation must be sought for the basins.

The formation of the depressions may be interpreted as the result of fluvial erosion and yet conform with the Vaughan hypothesis, if they are thought of as interior lowlands carved on soft rocks while marine planation was in process on the coastal borders of the oldland. Even this supposition fails, however, if the baselevels necessitated by Vaughan's hypothesis be accepted. He infers that the 14-to 20-fathom bench was cut first;[17] that uplift occurred to the 20-fathom level (or slightly more), and then wave-cutting formed that portion of the bench now below 26 fathoms; that submergence to the six-fathom level was followed by planation of the upper series of terraces. The depressions of intermediate depth in the Sir Francis Drake Channel area could not have been formed with sea-level at 14 fathoms, because their depths are regularly lower than 14 fathoms. That their depth resulted from fluvial dissection while the sea was working at a 20- or 25-fathom baselevel is admissible, but the interpretation is unnecessary. Depths greater than 20 fathoms occur only in one of the basins, where they are sufficiently close to the 30-fathom depth, four miles southwest of Flanagan Passage, to justify the assumption that both areas were initially eroded to the same baselevel and were continuous. The inner troughs are connected with the deeper depression by channels whose slope is gentle and almost graded. Where discordance of slope exists, it appears to be due to recent deposition of material in the submerged channels. There is, in brief, no conclusive and indisputable evidence which makes it necessary to consider the two trough levels the results of two erosion cycles. It is a fundamental principle in fluvial erosion that a lowland formed on soft rocks wears downward only as fast as its outlet cuts downward. The inner depressions are soft rock lowlands; their narrow outlets have cut through a ridge which presumably is resistant; hence their higher elevation is the result of retarded erosion.

The flatness of the floor of the inner trough and the independence of Cretaceous rock structures exhibited by its outline strongly impel one to conclude that it is an inner lowland in a southward-sloping coastal plain. If the coastal plain and inner lowland of Vieques were completely drowned, an inner trough with narrow channels to the deeper platform beyond would be produced, much as we find them south of Tortola. Perhaps a more striking resemblance would be produced by complete submergence of the coastal plain in the vicinity of Guanica, in southern

[17] Vaughan, T. W.: Op. cit., p. 60.

Porto Rico, where two partly drowned lowlands, separated by flat-topped Tertiary strata, would produce a submarine surface analogous to the inner and outer troughs in Sir Francis Drake Channel. There would, however, be little difference in the depths of the two lowlands in the case of the Guanica region. A dissected coastal plain cut to different but contemporaneous levels by differential fluvial erosion is adequate to explain the troughs, channels, ridges and spurs in the west-central area of Sir Francis Drake Channel.

The narrow depression at the western end of the channel is constantly scoured by strong currents, and little deposition is in process within it at the present time. It may be, therefore, that coastal-plain material was never deposited there; or, if deposited, that it has been removed by later fluvial dissection. That the depth of this trough is the same as that of the inner troughs immediately east appears to be the result of fluvial grading which accidentally attained similar elevations in adjacent but independent lowlands. The eastern half of Sir Francis Drake Channel affords no evidence for belief or disbelief in the presence of a coastal plain. The strong contrast which it affords to the western section seems due to the termination of the weak folded Cretaceous sediments against the dioritic intrusion which outcrops in large areas of eastern Tortola, Beef Island, Virgin Gorda and Fallen Jerusalem and in smaller areas in Ginger and Cooper islands. The diorite weathers rather evenly into smooth, rounded forms of low relief and would not offer the same opportunities for deep differential dissection as in the folded sediments westward. The surface has been smoothed by recent deposition, but whether or not the area is underlain by the coastal plain is not indicated by its form.

Sir Francis Drake Channel, as a local inter-island section of the submarine platform, reveals, therefore, a complex history. Originally dissected during the third erosion cycle by subsequent rivers, which formed an elongate lowland upon the soft layers of folded, thinly bedded Cretaceous tuffs and limestones, it was filled during the period of Tertiary submergence by coastal-plain material. Dissection of the latter during uplift and ultimate resubmergence are responsible for the characteristics of its present surface.

With Sir Francis Drake Channel as a type area, the development of the balance of the northern Virgin Islands platform is more easily understood. The second cycle of erosion was ended by uplift which initiated a third cycle corresponding to that during which the lower peneplane of Lobeck was formed in Porto Rico. The amount of uplift can not be determined with precision, but was not less than 350 feet and appears to have been between 400 and 450 feet. As in Porto Rico, the denudation which followed was fluvial, as may be seen wherever its results have not been buried beneath later deposits. The channels and sounds between the larger cays and islands were excavated during this stage of development. Some of them follow structural lines of weakness; others, geological contacts and boundaries; others, areas of easily excavated rock. For many no geological *raison d'être* can be proposed. Thus, Sir Francis Drake Channel is a subsequent valley, eroded on thin-bedded limestones and tuffs in its western half; its eastern half appears to have been formed on an area of easily denuded diorite, which outcrops on the adjacent islands. The unnamed sound between Jost Van Dyke and Saint John accords with the structural trend of the tuffs and limestones on the south and the massive agglomerates on the north. It is thus a subsequent lowland. Leeward, Salt Cay and Dutchcap passages and Southwest Road are similarly explained. The Magens Bay-Outer Brass drowned valley, Savana Passage and possibly Pillsbury Sound are excavated on fracture lines.

The inter-island channels, however, represent only the inner fringes of dissection; more thorough peneplanation was accomplished along the seaward margins. Thus the broad shelf to the north of the islands and the narrower one on the south were reduced to a peneplane of very low relief. Whether or not wave-cutting played a prominent part around the margins of the platform during this third erosion cycle, there seems no direct means of telling. The importance of the sea as an agent of destruction in the tropics has been considerably exaggerated by many authors. It notches the coastline and constructs a narrow wave-cut and wave-built platform; but before it carries its work of wave-cutting very far—in fact, as soon as a shallow platform is constructed upon which marine organisms can thrive—the waves expend their force against vigorously growing coral reefs, and wave-cutting of the shoreline stops. Except in those localities where a terrace is not yet formed, the coasts of the islands today are largely protected by fringing and barrier reefs. Subaërial weathering, on the other hand, has no checks. Climatic factors enable it to work quickly. It has been the dominant destructive force in the denudation of Porto Rico and the Virgin Islands, while the ocean, hampered in its destructive work, has afforded every opportunity for the constructive work of organisms. Not only, therefore, does the concrete evidence of subsurface forms indicate that the ocean played a small part in the planation of the Virgin Islands platform, but the limited effectiveness of waves in eroding the shoreline at the present time indicates that subaërial erosion must be regarded as the chief factor in peneplanation in the past as well as in the present.

Following the dissection of the third cycle, the peneplane which had been formed was submerged, supposedly in Oligocene time as in Porto Rico, and a coastal plain was deposited. The coastal plain, now resubmerged, has no expression above sea-level, but must be inferred from the character of the platform surface. In the Sir Francis Drake Channel area, mesa-like ridges and terraces whose horizontal bases and irregular forms are characteristic of unfolded strata are undoubtedly Tertiary limestones. The flat tops of these submarine hills, measuring a mile in width and three or four miles in length without ten feet of relief, are their most significant feature. They are invariably leveled off five to eight, and usually six or seven, fathoms beneath the surface—a depth that accords with the upper wave-cut terrace which Vaughan has identified around the margins of so many of the islands. It seems probable that their broad, horizontal tops must have formed by moderate wave-action working on soft material with flat structure. These ridges and terraces in no way resemble recent growths of fringing and barrier reefs. They are not benches cut on Cretaceous rocks, because they are independent of structural trend and could not have developed in this situation on rocks as diverse in resistance as the oldland volcanics. No similar flats formed on oldland rocks anywhere in the islands at this level, even where exposed to vigorous wave-cutting. Subaërially dissected coastal-plain deposits alone could develop the form which they exhibit, but their flat tops must have been perfected by some wave planation which beveled their irregularities at a five-fathom baselevel. Adequate evidence, which will be considered on later pages, indicates that the sea worked about five fathoms lower before it reached its present level; so this stage in the physiographic history may be accepted in anticipation to explain the flat mesa tops. The depressions cut below the ridges represent the dissection which followed deposition and emergence of the coastal plain.

The assumption that a dissected coastal plain overlies the rocks of the oldland upon the submarine platform serves to explain many of its hills, ridges and escarpments which would otherwise be inexplicable. The banks north of Tortola and Saint Thomas, including Kingfish, Barracouta and Whale, bear no resemblance to coral reefs, as Vaughan has recognized.[18] The east-west elongation of Kingfish Bank might lead to the hasty conclusion that it is a structural ridge, dependent on the strike of the Cretaceous strata; but its elongation and the nature of its dissec-

[18] Vaughan, T. W.: Op. cit., p. 59.

tion are equally characteristic of an eroded coastal plain. Adjacent subsidiary eminences lying southeast of the main bank can be more readily comprehended as coastal-plain remnants than as oldland remnants. Vaughan interprets the banks as wave-cut terraces formed during a first stage of marine planation, but he has missed the fact that perfect flats occur on the ridges at 8 to 9, at 11 to 13 and at 19 to 20 fathoms—a variation impossible in normal wave-cutting, but common in the fluvial dissection of horizontal rocks. Other small elongate ridges are common on the platform, a strong one lying between Outer Brass and Hans Lollik islands. South of Saint Thomas and Saint John there are six or more between Frenchman Cap and Flanagan Passage, most of which attain a depth of 13 fathoms.

Marginal to the maximum depths of 26 to 35 fathoms at the southern border of the platform (but within the submerged fringing coral reef), there is a persistent, but breached, ridge that rises over 100 feet. It extends from a point southwest of Norman Island northeastward beyond Virgin Gorda. It resembles the outer drowned reef in its relationships, but is uniformly broader and is thoroughly dissected by young valleys which cut through it and expand within it into typical inner lowlands. The relationships of this ridge to an inner lowland within and to a deeper level of dissection and the fringing reef without, as well as its dissection, can be explained only on the assumption that it is a remnant of the coastal plain. At the northern margin of the bank, similar ridges occur and the drowned fringing reef is absent, Anegada being a striking example of a ridge that has been built up above the surface. As large-scale charts showing the northern edge of the bank are available only for the Culebra region, description of the northern drowned ridges will be deferred to Chapter IV, on Vieques and Culebra. It can not be proved, nor is it necessary to assume, that all of the small prominences rising above the surface of the submarine platform are coastal-plain remnants. Not a few of the isolated knobs are undoubtedly oldland rocks, which, like Frenchman Cap or Sail Rock, stand out above fringing Tertiary limestones; but the major ridges of the platform have every feature of a dissected coastal plain.

That the dissection of the coastal plain was fluvial, not marine, needs little further demonstration. The inner lowlands protected from wave-cutting, the deep valleys cutting through the ridges, the monadnocks rising above the level of dissection, and the divergent levels to which denudation has proceeded in various portions of the platform afford ample proof that marine planation, if it played any part at all, worked only in a limited way around the margins of the bank. Vaughan, however, is convinced that the formation of the platform as a whole is the result of wave-cutting at three levels. The validity of the upper and latest marine terrace seems assured, as will be further developed in the next section. His evidence for the lower terraces, at 16 to 20 and 26 to 34 fathoms, demands consideration. From the absence of the intermediate terrace off the Atlantic islands he assumes it was removed during the formation of the lower one, which it antedated. On the platform north of the islands, according to his view, the intermediate terrace, bounded seaward by a distinct wave-cut cliff, is found on Kingfish, Barracouta and Whale banks. The diversity of elevations found on these banks, however, is not characteristic of wave-cutting, and their seaward-facing escarpments may be explained as subaërially developed bluffs, while their southward-facing scarps and the valleys within them must be so explained. South of Jost Van Dyke and Tobago his intermediate terrace, protected by islands, could not have been wave-formed. Furthermore, the escarpment is not clear-cut between the islands and is absent in the broad western outlet of the sound. Between Hans Lollik and Dutchcap Passage the restricted occurrence of the "terrace" is again in direct association with islands whose presence means resistant oldland rock beneath and protection from erosion behind them.

The escarpment between Hans Lollik and Outer Brass is formed by a coastal-plain ridge; that in the vicinity of Salt Cay Passage is associated with a hooked ridge attached to Dutchman Cap; that in Savana Passage marks the divide between northern and southern drainage, when the platform was emergent. Elsewhere there is no scarp between the assumed intermediate and lower terraces, but the slope from 8 to 30 fathoms is gentle and more or less evenly graded. South of the islands there is no lower terrace between Sail Rock and Frenchman Cap, but occasional depression contours at depths of 25 to 28 fathoms indicate that the lower level was formed, and that much of the supposed intermediate level represents later deposition. East of Frenchman Cap the intermediate terrace is found only behind coastal-plain ridges and undoubtedly represents, as it does westward, later accumulations above the lower terrace. The escarpment between the two is always the escarpment formed by the ridges, which rise regularly above the assumed intermediate terrace level. From these facts only one conclusion can be drawn: that the intermediate terrace of Vaughan is not a wave-cut terrace, but where it exists at all, it represents the sum of two processes, namely, slower initial erosion behind barrier ridges of oldland or coastal-plain rocks, and more rapid filling in the same areas after submergence. That the lower terrace is not marine in origin has already been demonstrated.

In conclusion, the entire submarine platform owes its form to four distinct stages of physiographic development: (1) uplift of some 400 to 450 feet and early Tertiary peneplanation at this level; (2) submergence and coastal-plain deposition, presumably in Oligocene time; (3) late Tertiary emergence and fluvial dissection of the coastal plain; (4) submergence, the results of which will be outlined in the following sections.

Submergence of the Submarine Platform

INITIAL SUBMERGENCE

Submergence of the submarine platform seems to have taken place in two stages. Initial submergence brought the sea approximately to the present 4½-fathom contour, at which, as a baselevel, some local marine planation and constructive work were accomplished prior to maximum submergence. The destructive work was limited to the formation of wave-cut terraces where conditions favored their development. Such conditions were found (1) where the materials upon which the sea worked were easily eroded, and (2) where the water offshore was sufficiently shallow for the floor to be built up rapidly to a level where wave-cutting became possible. Where the water offshore is deep, waves do not break; they accomplish no erosive work until a submarine talus slope is built up to a point where they may break. Upbuilding to the requisite level did not occur along much of the northern shorelines of the Atlantic-facing islands and a submarine terrace is absent. In fact, none has been formed at the level of later maximum submergence, and today the waves rise and fall ineffectively against the coasts of these islands. A terrace is similarly absent beneath many of the headlands of the southern coasts, but elsewhere it is present. Terraces or wave-beaten gaps appear to have been formed at the 4½-fathom water-level in the following places: (1) the spurs, ridges, mesas and terraces in western Sir Francis Drake Channel (Fig. 21); (2) the inter-island channel levels off northeastern Tortola; (3) the platform above which Fallen Jerusalem and Round Rock rise and the bench surrounding much of Virgin Gorda; (4) channels between Salt and Cooper islands, Lovango and Mingo cays, Mercurius Rock and Tobago, Outer and Inner Brass and other islands and cays; (5) distinct benches, bounded by escarpments south and east of Tobago; southwest of Inner Brass Island; in Windward Passage between Lovango Cay and Saint John; in the broad embayment on the southeast side of Peter Island; (6) small flats constituting the maximum elevations of Kingfish and Whale banks, Turtle Head and other submerged eminences rising above the platform; (7) terraces grading without perceptible escarpments into the outer and deeper portions of the platform—a feature commonly displayed off southern Saint Thomas and Saint John, where the outer portion of the bank is uniformly shallow. Many minor areas where a 6- to 10-fathom bench is present might be mentioned, but examples may best be multiplied by inspection of the charts of the area.[19]

Ever since its submergence, deposition has been in constant progress upon the platform, tending to be greatest in embayments. Within a relatively short time embayments are filled to sea-level by bar development and accumulation of alluvium in lagoons behind bars. Although the sea has been at its present level only a short time, judging from its erosive effects, nevertheless many of the smaller bays have been partly or completely filled. If a longer stand was made at the 4½-fathom level, bay-filling must have been extensive, and in the larger bays, where recent filling has not wholly buried the older deposits, depths of 4 to 6 fathoms should be prevalent. This is strikingly the case. Saint Thomas Harbor has maximum depths of 4¼ to 6 fathoms, although marginally it is filled to higher levels. With but slight modification, this is true of East Gregorie Channel, Santa Maria, Hull, Magens, Water-Smith, Redhook, Great, Saint James and Jersey bays, on Saint Thomas; of Coral Harbor, Saint John; of Road Harbor, Tortola; of South and eastern Gorda sounds, Virgin Gorda. A few smaller bays also afford additional illustration of the feature.

Concomitant with initial submergence of the platform was the upgrowth of coral reefs toward the water surface. The most conspicuous of the reefs whose development appears directly related to the early submergence is the drowned barrier reef at the southern edge of the bank. The normal depth within it is 22 to 34 fathoms, above which it rises about 100 feet as a long persistent ridge. It begins in a few broken patches at the edge of the bank four miles east of Pájaros Point, at the east end of Virgin Gorda, and develops into a slender reef which extends unbroken for 25 miles, to a point south of Norman Island (Plate II). There soundings have not been numerous enough to demonstrate its persistence, but it probably continues without a break some ten miles farther. Due south of Dittless Point, Saint John, it is breached; and westward, although constantly recurrent, it no longer possesses that degree of regularity and constancy which characterizes it to the northeast. South of Saint Thomas it has a patchy development; eastward, although occasionally suggested, it ceases to be a prominent feature in the submarine topography. It is a narrow ridge, usually less than 200

[19] Cf. charts, No. 905, U. S. Coast and Geodetic Survey, and No. 3904, Hydrographic Office, U. S. Navy.

yards wide above the twenty-fathom submarine contour, paralleling the edge of the bank at a distance varying from 200 to 500 yards. It apparently represents a coral reef which grew up with progressive submergence of the island group, but the cause of its death is somewhat mysterious. It is possible that submergence proceeded too rapidly for it to keep pace, and it thus suffered death by drowning. It certainly seems to have grown most vigorously and uniformly during the early stages of growth, and its poor development westward occurs in the shallower portions of the platform. Yet this explanation seems inadequate. Evidence which will be discussed in a later chapter, dealing with the submarine platform in the Culebra-Vieques area, indicates that subaërial dissection of the coastal plain occurred in late Tertiary time, and that its initial submergence took place immediately before the Pleistocene. In the Pleistocene the strandline undoubtedly underwent a series of oscillations during the five glacial stages, and according to Daly the maximum amount of water-withdrawal was some 30 fathoms. In any series of oscillations of this magnitude, the barrier reef must have been exposed above sea-level. Its death and the partial dissection which it has undergone toward the west can thus be accounted for as the result of emergence during one or more of the glacial stages. The formation of Anegada also appears to have been largely associated with the initial stage of the platform's submergence; but, as it constitutes a feature of the present level, it will be considered as a phase of deposition attaining its ultimate expression during maximum submergence.

Of the series of oscillations of the strandline during Pleistocene time, there is no decipherable record, although the effect of a migrating water-level over a group of extensive lowlands must have been considerable. The sea seems not to have been stationary at a single level long enough to have produced any decisive set of features. Modification of the platform surface, particularly by deposition and slight dissection during exposure, is probably the sum of Pleistocene work. The present level is postglacial, has not been of long duration, and has produced no very profound erosional effects, although active erosion and deposition are in process. Pleistocene geological work was probably comparable to that going on at present.

MAXIMUM SUBMERGENCE

The present shoreline of the northern Virgin Islands, except that of Anegada, is an embayed mountain shoreline[20] in a youthful stage of de-

[20] Cf. Johnson, D. W.: "Shore Processes and Shoreline Development," p. 173. New York, 1919. The terms "shoreline" and "coast" are here employed in a collective sense to embrace the shorelines and coasts of all the individual islands.

velopment (Figs. 5 and 6). The coast is characteristically steep, and in many places where it is not embayed the rocks are barely notched at the water-line. Beaches are absent along parts of the unembayed coast, but are beginning to form in many of these localities where the character of the rocks has facilitated the accumulation of talus. The embayments consist of short, steep-sided bays, whose upper reaches have been partly filled by bars and alluvial deposits. The amount of alluvial filling is closely dependent upon the relative sizes of the drainage areas contributing sediment to the bays, the areas and initial depths of the bays, and the degree of permanence of the intermittent streams. Numerous islands lie off the coast (Fig. 22), and many of the adjacent ones have been tied to the mainland or to each other by tombolos, consisting most commonly of large, worn coral fragments. It appears, then, that although the coastline is so young that portions of it have scarcely been notched, enough time has elapsed since the present level was attained for the for-

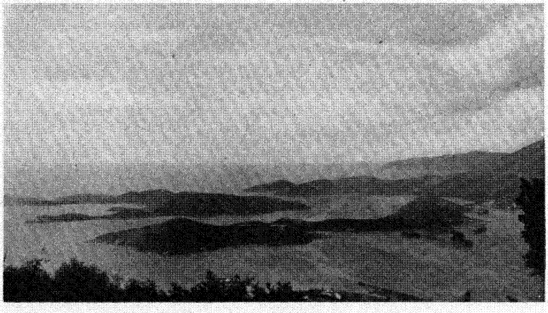

FIG. 22.—*The drowned coast of southern Saint Thomas*

mation of graded alluvial deposits at the heads of embayments and for the development of connecting beaches between a few neighboring islands. These features demand further description.

On Saint Thomas the character of the shoreline is dependent upon the drainage patterns which have developed in different portions of the island. The western shoreline, extending northwestward to West and Salt cays, is rectilinear and truncates the geologic structure. It is formed on one of a series of northwest-southeast fractures, which have already been described.[21] The western section of Saint Thomas from

[21] Ante, pp. 97-99.

Salt Cay to Santa Maria Bay is a simple fault-block tilted north, and except for the small drainage area of Fortuna Bay, on the south coast, its drainage has been largely controlled by the dip of the beds. With the single exception noted, the southern coast is a steep and rugged erosion scarp, which drops off sharply into six or seven fathoms of water. Locally talus has accumulated at the base of the cliffs, and upon it the waves are just beginning to form a boulder beach. The north shore is a 25° dip-slope, and notwithstanding the fact that wave erosion seems to be stripping the strata rapidly, beaches are found only at Sand, Botany,

FIG. 23.—*Inner and Outer Brass islands*

Bordeaux and Stumpy bays, which are sheltered from the direct attack of the Atlantic. Elsewhere conditions resemble those found on the south coast—talus accumulations alternating with steep slopes which descend steeply into deep water (five to eight fathoms).

The central block of Saint Thomas from Santa Maria Bay to Picara Point on the north, and from Perseverance Bay to Saint Thomas Harbor on the south, is deeply embayed. Along the north coast are two outlying islands (Fig. 23) and one of the deepest and most striking bays in the entire Virgin Islands group. The headlands between Vluck and Dorothea points have been cliffed by the Atlantic, but a narrow fringing reef protects much of the remainder of that section of the coast from erosion. Within the reef the rocks front the Atlantic in a weathered, discontinuous sea-cliff, which has undergone as much wave-cutting as the adjacent unprotected coastline. In a few of the embayments, notably at the head of Magens Bay, there has been some alluvial filling. The drainage lines on the northern slope and the arrangement of the headlands and islands strongly bespeak control by northwest-southeast fractures. The

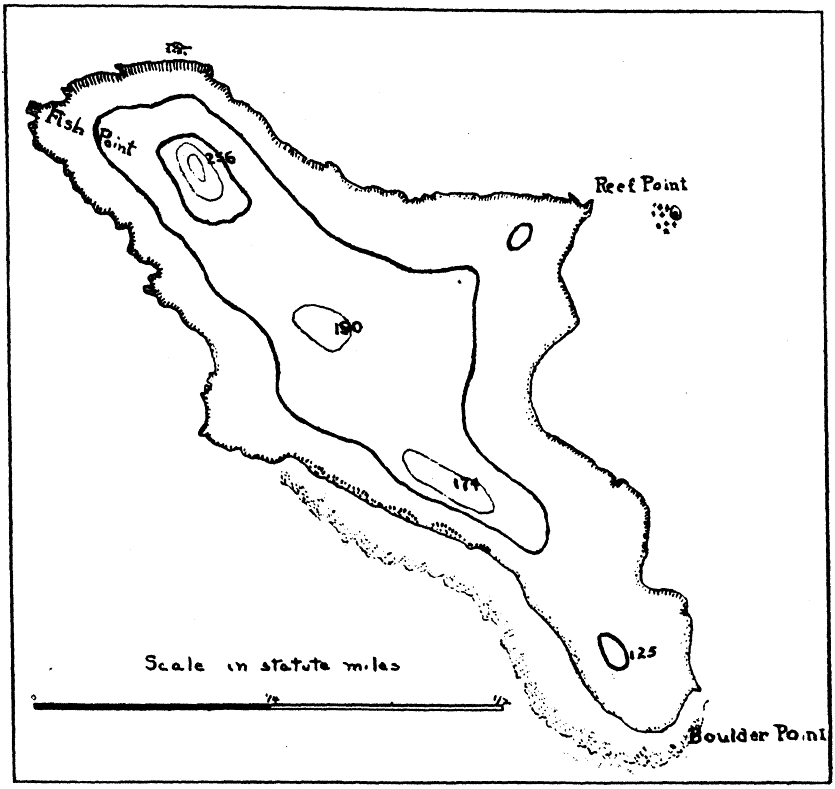

FIG. 24.—*Inner Brass Island, illustrating strike and fracture control of the southwestern shoreline*

physiographic features truncate the structure, for the strike is approximately N. 70° W., but the ravines and spurs trend about N. 45° W. The most striking fractural feature is Magens Bay (Fig. 16), a rectangular bay two miles long and one mile wide. The direction of elongation of the bay and its bounding promontories, Tropaco and Picara points, is almost exactly northwest, whereas their rocks strike N. 70° W. Similarly, the rectilinear shorelines on the southwest side of Inner Brass and

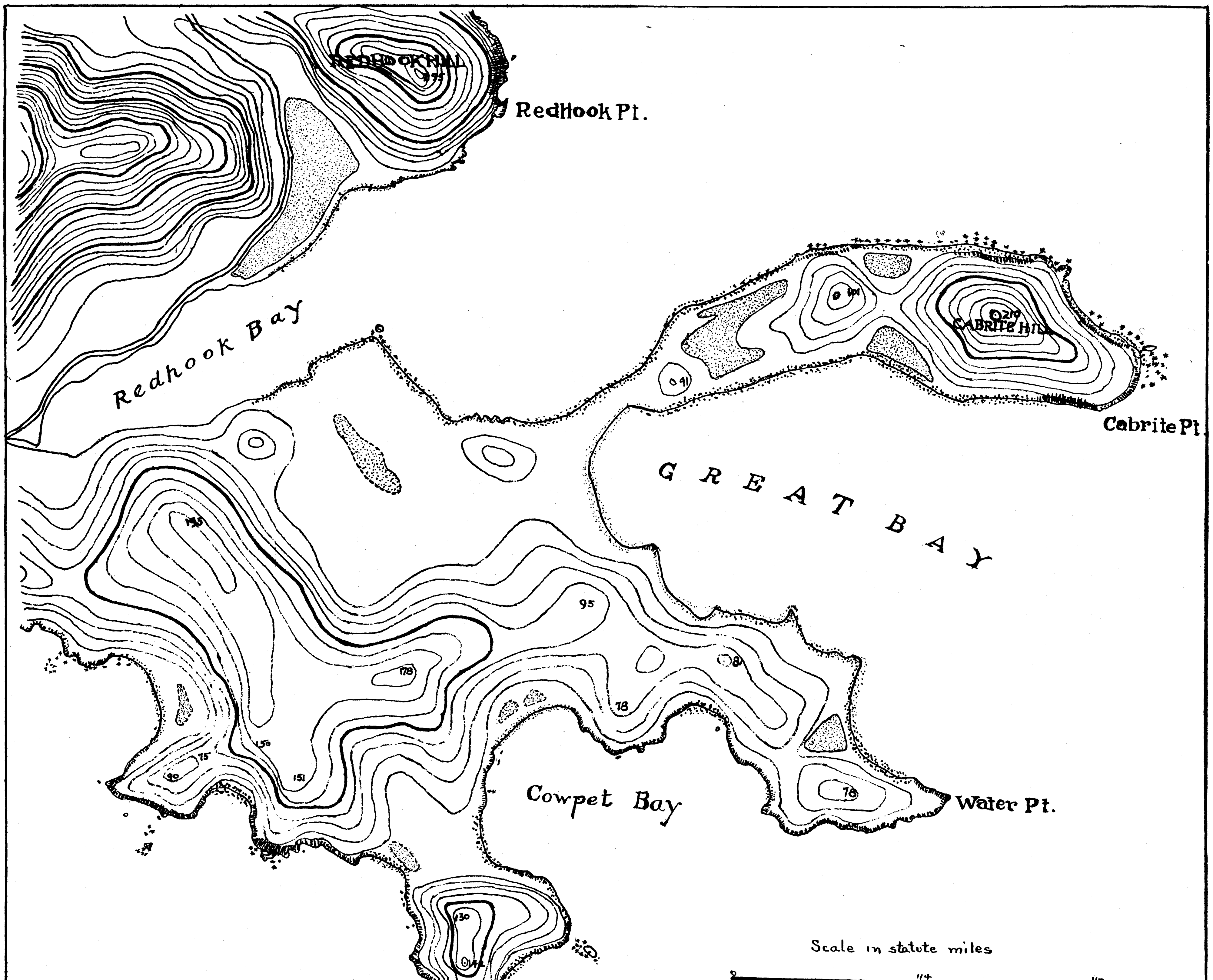

FIG. 25.—*Bar and lagoon development in the embayed shoreline of eastern Saint Thomas*

the northeast side of Outer Brass islands conform with the prevalent northwest direction of the major topographic features. An interesting conflict between fractural and structural control is in process on Inner Brass Island (Figs. 23 and 24). The trend of the southwestern shoreline is N. 45° W., but it is broken in its center by one-third of a mile of equally straight shoreline trending N. 67° W. The latter is controlled by the structure of the rocks, which consist of thin-bedded, indurated tuffs and tuffaceous shales, dipping 60° N. 23° E. and striking N. 67° W. The northern and southern ends of the island consist of more massive volcanics, in which structure is not evident and where fractures would naturally dominate the topography.

The northwest trend of topographic features exhibited on the north side of Saint Thomas is dimly in evidence south of the island's drainage divide, but terminates abruptly at the line of west-east lowlands, extending from Brewer Bay to Saint Thomas town (Figs. 12 and 22). The persistence of a continuous series of partly drowned lowlands and low passes in perfect alignment not only to Saint Thomas town, but eastward beyond Charlotte Amalie village, must be explained as the result of erosion along the crush zone of a fault. The line does not correspond to the structure of the rocks, which are massive, and the zone is not continuous along any single rock type which might be considered non-resistant to erosion. What appears to be a strong divergence of structure on opposite sides of the fault was noted and will be discussed in the section on structural geology. That it is a line of weakness along a fault-plane seems reasonably certain.

The erosion remnants south of the lowland extend southward in irregular, elongate peninsulas and islands, between which are deep bays (Fig. 22). The bays occupy old stream channels that were filled by alluvial material and coral sand at the 4½-to 6-fathom depth, when the water formerly rested at that lower level. Perfect beaches are developed at the heads of the bays and coves, and narrow pebble or coral-fragment beaches are developed along the steep sheltered shorelines, where weathering has kept pace with wave-erosion; but along the exposed shorelines of the longer peninsulas and islands, especially those facing east and south, the waves have cut high cliffs, at the foot of which is little or no beach. Locally the cliffs drop sharply into six or more fathoms of water offshore, and south of Water Island the depth is twelve fathoms. The fact that all of the channels and embayments except the diminutive Krum Bay are characterized by precipitous rocky sides or steeply sloping beaches, which within a short distance from the water-line attain a depth between six and ten fathoms, strongly favors the conclusion that their present bottoms are composed of alluvial filling in old valleys, largely deposited during the initial stage of submergence. Except at the heads of the bays, alluvial deposition to the present level has not progressed very far. Saint Thomas Harbor owes its depth and excellence as a port to the small amount of filling above the earlier level. Its inner east-west expansion lies within the lowland developed on the easily eroded east-west fault zone described above.

The southern fault-block of central Saint Thomas continues eastward as a massive upland, not sufficiently dissected to form a deeply embayed

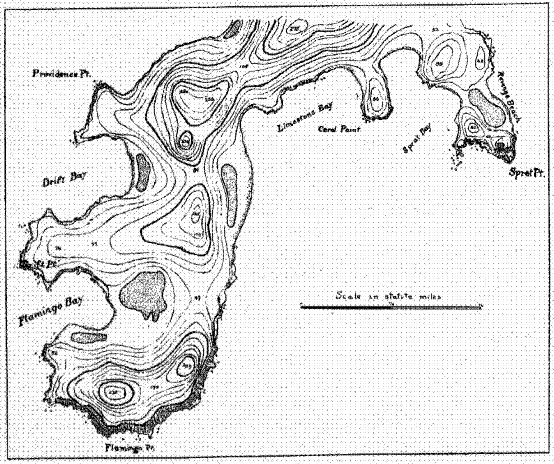

FIG. 26.—*Lagoon and bar formation and coastal erosion on Water Island*

coastline. Small alluvium-filled bays occur between Saint Thomas and Long Point, but the shoreline as a whole is characterized by steep wave-cut cliffs and narrow beaches with depths of four to seven fathoms immediately offshore. The interior is an upland strongly dissected along several zones of weakness, becoming progressively lower and more subdued eastward. In general outline the rugged shoreline of the north coast in eastern Saint Thomas displays no dominant controlling features, but, considered in detail, it is strongly modified by the east-west strike and northward dip of the underlying rocks. From Picara Point to Mandal

Point it consists of high cliffs, whose angle of slope is partly determined by the 60° dip of the rocks. As some of the erosion is taking place on comparatively massive beds and even across the stratification, dip and strike control is only partial. In spite of the apparent rapidity of wave erosion, there is no beach and scarcely any accumulation of debris at the

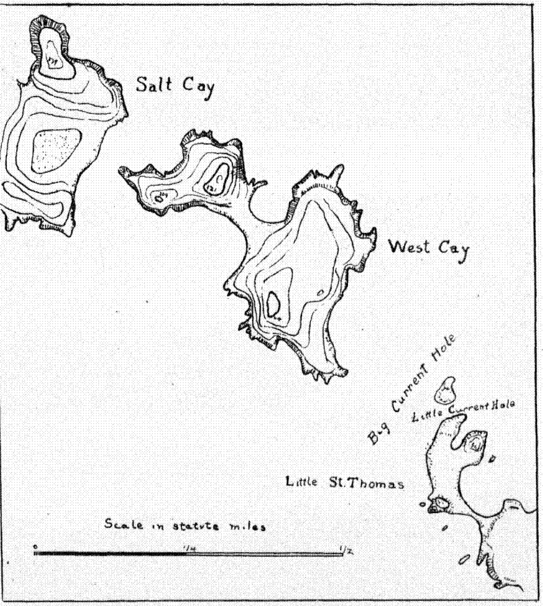

FIG. 27.—*Tombolo development west of Saint Thomas*

foot of cliffs which drop into six and one-half fathoms of water. Southeast from Mandal Point embayments are more common and the shoreface slopes less abruptly to the six-fathom depth.

The east end of Saint Thomas was formerly deeply embayed and was flanked by several small islands. The initial irregularity of the coastline

FIG. 28.—*Little Saint Thomas and West Cay*
Savana Island in the background

FIG. 29.—*Wave-beaten gap between Grass and Mingo cays*

has been in part modified by the alluvial filling at the heads of Water and Redhook bays and Mangrove Lagoon, and by the connection of several of the islands to the mainland by tombolos, as at Coki, Cabes, Cabrite (Cabrita), Pretty Clip and Deck points (Fig. 25). Numerous lagoons have developed as a result of the formation of bay bars, which are chiefly of the mid-bay variety, as in Mandal and Water bays, though some are of the bay-mouth type, as south of Redhook Hill. Lagoons have also been formed in enclosures between double tombolos, as, for example, the westernmost lagoon in the Cabrita Point tombolo.

Bars and tombolos have developed elsewhere on the mainland of Saint Thomas and on the off-lying islands. Bay bars have formed lagoons at the heads of bays on Salt Cay, in Fortuna and Perseverance bays, and in profusion on Water Island (Fig. 26). Tombolos connect the two halves of West Cay (Fig. 27), Little Saint Thomas and the mainland, with the formation of a lagoon (Fig. 28), Hassel Island and the mainland (now cut by an artificial channel to secure drainage of Saint Thomas Harbor), Sprat Point with the rest of Water Island, with the formation of a lagoon (Fig. 26). On Saba Island a cuspate bar is responsible for the development of the two lagoons on its north side. It will require but little prolongation of this bar to form a tombolo connecting Turtledove Cay and Saba Island.

From Thatch Cay, just north of the eastern end of Saint Thomas, eastward to Fort Recovery, Tortola, there is a narrow belt, twelve miles long and not more than two miles wide, where features show complete domination by the underlying rock structure. The rocks within it are well stratified tuffs, tuffaceous shales and limestones. Throughout this belt stratification is more consistently pronounced, and massive agglomerates and intrusives are more generally absent than elsewhere in the northern islands; hence the structure exerts strong influence on the topography. The beds strike nearly true east-west and dip approximately 65° north. The result is an alignment of east-west islands and peninsulas, the most striking of which is the chain of islands embracing Thatch, Grass, Mingo (or Senia) and Lovango cays, which stretch five miles across the northern end of Pillsbury Sound. Congo Cay, immediately north of Lovango Cay, is another strike island consisting of marble (Fig. 15). Although Thatch and Grass cays are separated by a channel 16 fathoms deep, the other members of the group are barely detached. Between Grass and Mingo cays, in fact, the detachment is scarcely complete, for the Atlantic ground-swell breaks heavily upon the broken rocks which clutter the narrow gap (Fig. 29). On Grass Cay wave-cutting has pushed the wave-cut cliff back nearly to the crest of the island (Fig. 30), and not far from its western end piling breakers from heavy seas almost wash over a low notch which they are rapidly widening. The exposed northern faces of these islands are steep dip-slopes which the breaking waves have little difficulty in stripping (Fig. 31). The isolation of the group is unique. The members drop sharply to a narrow

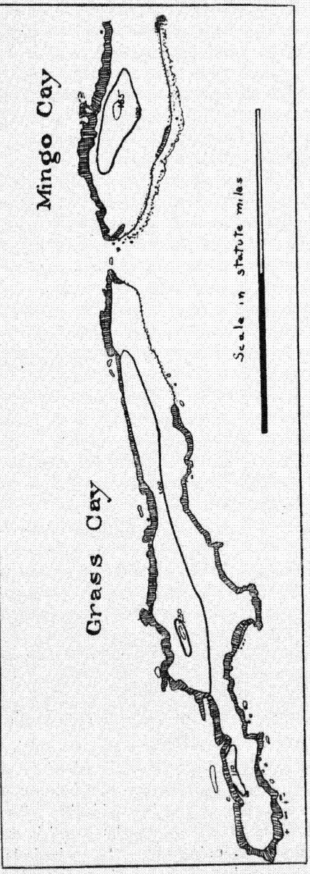

Fig. 30.—*Partly submerged hogback, breached by wave action and worn back nearly to its divide*

bench five to eight fathoms below the water-line, and this drops abruptly to a depth of 11 to 17 fathoms .1 to .5 mile offshore. The bench and the greater depth are found on all sides of the chain, even in the narrow channel between them and the mainland of Saint Thomas. The initial development of the group was fluvial; it is a breached hogback rising above the old peneplane. The narrow terrace on its flanks is marine, cut during initial submergence of the submarine platform.

Other examples of islands and peninsulas in linear arrangement are enumerated on page 97. The influences of structure are apparent elsewhere, especially in the alignment of Tobago and Jost Van Dyke with the northern portion of Tortola; but in these islands the rocks are massive and little of the detailed topography is directly referable to the underlying structure, which is rarely in evidence. On Salt, Cooper and Ginger islands the rocks include bedded tuffs, tuffaceous shales, shales and a bed of limestone, all of which are more or less continuous through the three islands. The attitude of the rocks plays only a moderate part in their topographic features, partly because the strata have been intruded by irregular knots and stringers of diorite. The east-northeast elongation of the northern half of Ginger Island, however, depends entirely on the strike of the thin-bedded indurated sediments and sill-like injections which compose it.

Parts of Saint John are deeply embayed, especially at East End, where a curving neck encloses Coral Bay and its three northern arms (Fig. 6). Indentation is less conspicuous along the northern coast, where very few north-south valleys have cut across the pronounced east-west structure of the folded sediments, but the western and southern shorelines are characterized by the many irregularities which follow upon drowning of young valleys. A number of the embayments have a square or rectangular form, typified in Great Cruz Bay (Fig. 32). The development of these bays began with deep incision of young, steep-graded valleys into the upland. With the first stage of drowning they were filled up to the present four-to six-fathom level, except in a few large, deep estuaries, such as Coral Bay. With drowning to the present level mid-bay bars have commonly developed, and at the present time alluvium has completely filled some of the bay-heads up to the bars, while in others small unfilled lagoons still exist between bars and valley-filling. Opposite the valleys with large drainage areas the filling has been entirely completed or is almost complete, while opposite short valleys lagoons are still common. As a result of their compound erosional and depositional history, the present form of the drowned-valley embayments is characteristically rectangular, being squared off inland by mid-bay bars. Ideal development of the form is found in Great Cruz Bay (Fig. 32) and Chocolate Hole. The shape of Magens Bay on Saint Thomas is similarly explained (Fig. 16). The resulting square or rectangular form gives an erroneous impression of structural control: but generally the structure is not an important factor, except in one or two cases where valleys had been eroded on the outcrop of weak beds.

The shoreline of Saint John presents no new features. Narrow, steeply sloping beaches are more persistent than on Saint Thomas, but at several points along the north and south shores there is no beach, and wave-cut cliffs drop into four to seven fathoms of water. Fringing coral reefs are growing in isolated patches along the northeast side of East End Peninsula and in the vicinity of Reef Bay, on the south shore; but the most extensive growth is found along the west shore of Coral Bay. Patches of reef are found elsewhere, and off the northwest coast, in addition to small fringing reefs, a large barrier reef has formed half a mile from land near the edge of the bench of initial submergence. Lagoons are common, and most of them are developed, as on Saint Thomas, between mid-bay or bay-mouth bars and alluvial bay-head filling (Fig. 32). Double tombolos have formed at half a dozen points along the north, west and south shores, the larger and more striking being at Hawknest Point (incorrectly called "Hognest" on the charts), on the northeast coast; Turner Point, on the west; Ram Head, on the southeast; and Turner Point, in Coral Bay. Lagoons exist between the bars in all of these cases, but the one behind Hawknest Point is shallow and is not perennial.

Dissection of the Saint John upland is dendritic, with entire freedom from structural control. The deepest valley on the island, however, seems to have been eroded on a fracture. It extends due north from

FIG. 31.—*Grass Cay in profile, showing the steep northern dip-slope*

Reef Bay, heading in the lowest pass in central Saint John. Across the divide another steep valley continues due north. The deep cut thus eroded straight across the island is made the more striking by its high, steep, linear western wall. The absence of other valleys resembling it indicates that its genesis is not accidental; and, although minor faulting is suspected, no field evidence of faulting or strong jointing could be found. The east-west depressions paralleling the north coast are small subsequent valleys, but they play a minor part in the island's drainage system.

The British islands multiply examples of the coastal features found on Saint Thomas and Saint John, but contribute no new ones. Jost Van Dyke offers a steep, rugged slope to the Atlantic, with its base 15 to 18 fathoms below sea-level. The submerged marine terrace was never formed. Off Dubois and Rough points, on northern Tortola, and at the northern ends of Guano and Great Camanoe islands the submerged terrace is also absent, but elsewhere it is regularly present. Northern Jost Van Dyke and north central Tortola are scarcely embayed, probably because the shoreline parallels the strike and represents roughly a steep dip-slope on massive agglomerate beds that have undergone little dissection. For the rest, the shorelines are typically indented by sub-rectangular to irregular bays (Fig. 13), which are found alike on large and small islands. The drainage pattern is dendritic, so far as the erosion of narrow elongate islands has allowed, and appears at practically no point to be dependent upon rock structure. A unique feature of erosion was found on the northern side of Ginger Island, where the sea-cliff has been cut back nearly to the drainage divide of the northern strip of the island. In the process there has been developed an almost perfect facetted spur between two ravines which drain south.

Tombolos are unusually numerous in the British islands. Belmont Point, on the north side of West End Peninsula, Tortola, is tied to the mainland by a double tombolo which encloses a large lagoon. Paired islands tied by double or single tombolos seem to be as common as isolated islands. Great Thatch Island (Fig. 33) is composed of two rocky nuclei tied by a tombolo. In like manner the northwestern part of Guano Island (Fig. 34) is attached to the eastern part, northern Great Camanoe to southern, eastern Scrub to western, and northern Cooper to southern. Salt Island consists of three former cays now joined, and in this island the tombolos, one of which is triple, enclose two lagoons. Beef Island is composed of at least four former islands similarly united, and at its northeast end the juncture seems to have been effected by a triple or quadruple tombolo which encloses two lagoons. On the north shore of this island a cuspate bar, which encircles a small lagoon, is growing outward toward a coral reef immediately off the point of the bar. Lagoons are abundant on all the British islands, and, except for those found between double and triple tombolos, they are usually of the bay-mouth and mid-bay types. Fringing and barrier reefs also are extensively developed, particularly on the south and east sides of many of the islands.

The physiographic development of Virgin Gorda is dependent upon its rather special origin, although it shares the general features of a rugged and deeply embayed shoreline with the other members of the group. It consists of a central block two miles square, to which are attached a crudely rectangular peninsula on the southwest and a narrow, rugged and irregular neck to the east. The southwestern peninsula (Fig. 19), whose rolling surface was formed during the second cycle of erosion, is attached to the central block by a long neck and a slender

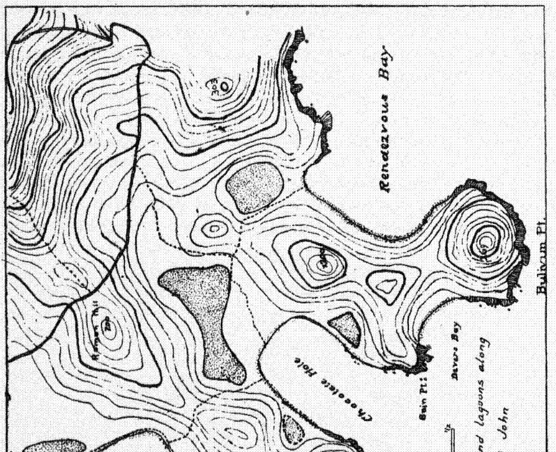

Fig. 32. Rectangular bays, bay bars, and lagoons along the southeastern coast of Saint John

tombolo. The peninsulas and central block are composed of a granitoid intrusive, whose weathering into huge rectangular blocks along the southwest coast and in Fallen Jerusalem has afforded the large, open joint planes which make the so-called "natural baths." On the northwest, northeast and southeast corners of the block are remnants of the tuffs and agglomerates which were invaded by the intrusive. The islands off the north coast (Fig. 35), as well as the Dog Islands, to the west, are also agglomerates and tuffs which formed the country rock prior to intrusion. The structure of these surface volcanics has been obliterated by induration; but their distribution with respect to the intrusive and the perfect dome shape of the central block suggest very strongly that the latter is a stripped laccolith, with upturned edges of the arched tuffs and agglomerates remaining upon its margins. The eastern peninsula was an offshoot of the laccolith with uncertain relationships to the rocks which it underlay. At the southeastern corner of Gorda Sound it is breached (Fig. 35), but a double tombolo ties its western and eastern halves. Extensive reefs are growing off many portions of the Virgin Gorda coast. East of the southern peninsula they threaten soon to form a slender lagoon between Copper Mine Point and Tady Bay, and on the west to form an outer enclosure beyond the bar which shuts in the long lagoon north of Spanish Town.

RECENT SLIGHT UPLIFT

The possibility of recent slight uplift in the northern Virgin Islands was recognized from two lines of evidence. At several separated points along Sir Francis Drake Channel, on the north shore of Mingo Cay facing the Atlantic, and elsewhere less prominently, narrow, horizontal rock or gravel benches are found less than three feet above mean tide-level. Some of these benches are awash except in the calmest of weather, but their outer edges are above the level at which active wave-cutting occurs at any time.

A second and more widespread criterion was observed in the relation of beaches to wave-cut cliffs, and of the cliffs to the present erosion level. Beaches are most common along the southern coast and in the shallower protected portions of the northern coast, especially in the British islands, where some of the present beaches rise at angles of 10° to 20° from the water and abut against wave-cut cliffs six or more feet above the water-level. The breaking waves, naturally small in the more sheltered stretches under consideration, fail to reach the rock cliffs at the inner margin of the beach. That this relation is of very recent origin is indicated by the fact that on steep cliffs, plainly cut by wave erosion, young vegetation

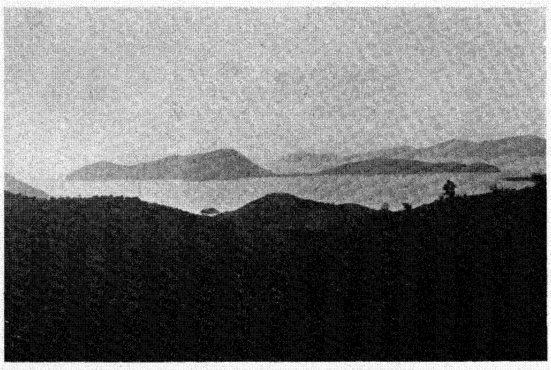

FIG. 33.—*Great Thatch Island*

FIG. 34.—*Guano Island and a section of the northern coast of Tortola*

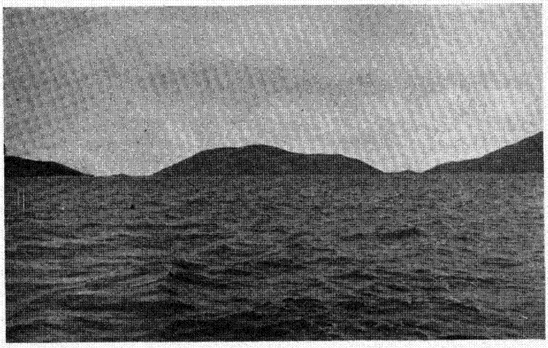

FIG. 35.—*Gorda Sound, Virgin Gorda*

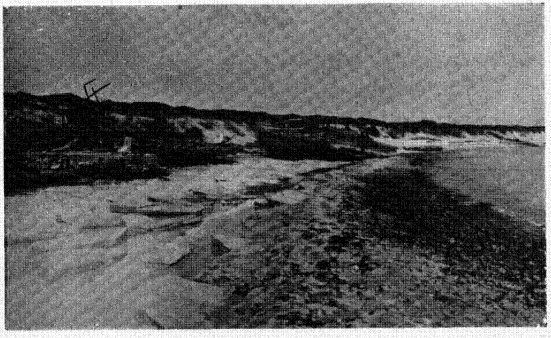

FIG. 36.—*The dune ridge along the north shore of Anegada*

has taken hold and is existing undisturbed down to the upper level of the beach. Subaërial weathering of the wave-cut cliffs, on the other hand, has scarcely begun, for no talus has accumulated at their bases and the rocks have a comparatively fresh appearance that is unusual for surfaces exposed long to tropical weathering. It is barely possible that such a feature could result as a normal phase of shoreline development. It is true that development of a beach retards wave erosion and may temporarily stop it, but not with deep water immediately offshore, to which accumulating debris may be readily transported. The steep angle of the beach above and below the water-line and the widespread occurrence of overgrown wave-cut cliffs, even on headlands, are facts which favor the conclusion that recent uplift rather than normal shoreline development is responsible for the condition. Locally the growth of coral reefs has stopped wave-cutting, but not in any of the areas in question.

A third line of evidence, which was not thoroughly investigated because its possibilities were not realized, lies in the recent change of water-levels in lagoons. The writer retains a distinct impression from field observation that the water surface in lagoons appeared to have undergone recent recession. The fact was laid entirely to the long drought from which the islands have been suffering; hence no systematic study was undertaken to determine whether the change had in any measure been uniform or permanent. The high elevation of many of the tombolos and bay bars above sea-level was also noted. In some cases the bar sands and coral fragments rise 20 feet above the water-level. Although in a few instances—for example, the tombolo between central Virgin Gorda and Spanish Town Peninsula—the wind has piled the sand into dunes, in the cases of the coarser beaches, as on Great Thatch Island, wind action is out of the question as an explanation of their present height.

From the apparent slight elevation of beaches, the growth of young vegetation on fresh wave-cut cliffs, and the occasional presence of wave-cut benches slightly above sea-level, it is tentatively concluded that the northern Virgin Islands have undergone very recent slight uplift.

ANEGADA AND OTHER REEFS

Dependent upon the present level of the sea for their growth and extension, yet in some cases growing out of a long past, are the coral reefs which modify the surface of the submarine platform. Their growth and the clastation which usually follows death have furnished most of the deposits that have accumulated upon the surface of the bank since the Tertiary limestones were first laid down upon the lower peneplane. Many of the living reefs are small barrier or fringing reefs directly associated with individual islands. Their lengths are usually a few hundred yards, and they grow particularly well in the shallow water above the six-fathom bench, if sheltered from the direct attack of the Atlantic. None of them compare with the submerged barrier reef margining the platform at the south. The more important of them have already been mentioned.

Along the northeastern margin of the platform, however, is a group of reefs in vigorous growth, within part of which lies Anegada, a recent and growing addition to an accumulating coastal plain. The island of Anegada is nine miles long and averages a little more than a mile in width. Through the west-central portion its surface is cut up by five lagoons, four of which extend nearly across the width of the island. The three largest ones are connected by narrow channels and maintain a single, narrow, open connection with the sea to the south. On the north a low ridge of coral sand, partly wind-blown, separates them from the Atlantic (Fig. 36). Eastward the island curves broadly to the southeast, paralleling the edge of the platform, which lies about two miles off its north shore. The easternmost portion of the island is also cut by lagoons, one of which maintains an open channel to the southwest. The rest of Anegada consists of limestone, grading from dense, poorly consolidated fine lime-sand and mud along the southern shore to a firmly consolidated basement of locally fossiliferous lime-sand in the interior, and ending at the north shore in a line of low sand hills mostly or entirely of dune origin. The southern and central parts are flat and reliefless; the northern hills, rising to a height of 30 feet, form the highest elevations on the island.

An unbroken series of coral reefs or huge isolated coral heads completely surrounds Anegada. Off the north coast the band of reefs and coral heads varies from 200 to 1300 yards in width. On the south it averages two miles, and much of the active coral growth is going on more than a mile from the shore. The shallow water between Anegada and the southern reefs, which is three fathoms deep, is filling with a deposit of fine coral sand and lime-mud, continuous with that making up the south shore. At no point on the island were coral remains found as a constituent of the rocks, which are wholly clastic in origin, although derived from the reefs. Fragments of the Cretaceous rocks of the oldland are also absent. Anegada seems not to be an emerged reef, but a coastal-plain deposit in active formation, made of lime-mud and sand, filling in an inter-reef area. Although accumulation is progressing most rapidly around and within areas of active coral growth, it is also going on upon the platform south of the island, where the water deepens gradually from four fathoms immediately off the southern line of coral heads to 11 and 12 fathoms north of Virgin Gorda. A few reefs and prominences charted as "rocky" break the otherwise perfect slope; but terraces and escarpments, characteristic of the submarine floor farther west, are absent. Soundings and actual inspection of the shallower water[22] show that the entire bottom is composed of coral sand and mud. Gradually increasing depths west of Anegada also indicate slow accumulation of sand and mud in that direction. The island thus represents the maximum accumulation of coastal-plain limestone around coral heads and reefs, while to the south and west material is being spread out in nearly horizontal deposits, which thin away from the source of clastic reef material.

Horseshoe Reef is formed by the junction of the reefs which lie north and south of Anegada and which converge beyond its southeastern end. The reef extends from the island without interruption for eight miles due southeast, terminating 1½ miles from the edge of the submarine platform, where the latter turns toward the southwest. A right-angle spur 3½ miles long extends southwestward from the reef at this point, again paralleling the edge of the platform and ending in Hermanos Reefs five miles east from Pájaros Point, Virgin Gorda. In the spur of the main reef is a single heap of dead coral, "The White Horse," less than a hundred yards in diameter, rising about three feet above the surface of the water. The balance of the reef is submerged, but breaks heavily in all weather except perfect calms.

The immediate origin of Anegada and Horseshoe-Hermanos reefs is apparent from the relations of the island and reefs on the one hand and the reefs and platform margin on the other; but the island and reefs have a past whose history is not so easily deciphered. Study is made unfortunately difficult by the lack of large-scale charts showing depths between Anegada and Barracouta Bank. The small fauna which was collected from the surface limestones of the island has not yet been identified, and statement of its age must be deferred to a subsequent part of the present volume. From its general aspect, however, the fauna is thought to be either Pleistocene or early Holocene, probably equivalent in age to the San Juan formation. With the limitations imposed by inadequate charts and stratigraphic information, the conclusions concerning the origin of Anegada herewith offered are admittedly tentative.

The island and the reefs constitute an accumulating coastal plain and are using the imperfectly dissected Tertiary coastal plain beneath them as a base. The depths of the platform northeastward from Tortola are everywhere less than those which have been described to the west. Beginning with the northern exit from Sir Francis Drake Channel, the platform is

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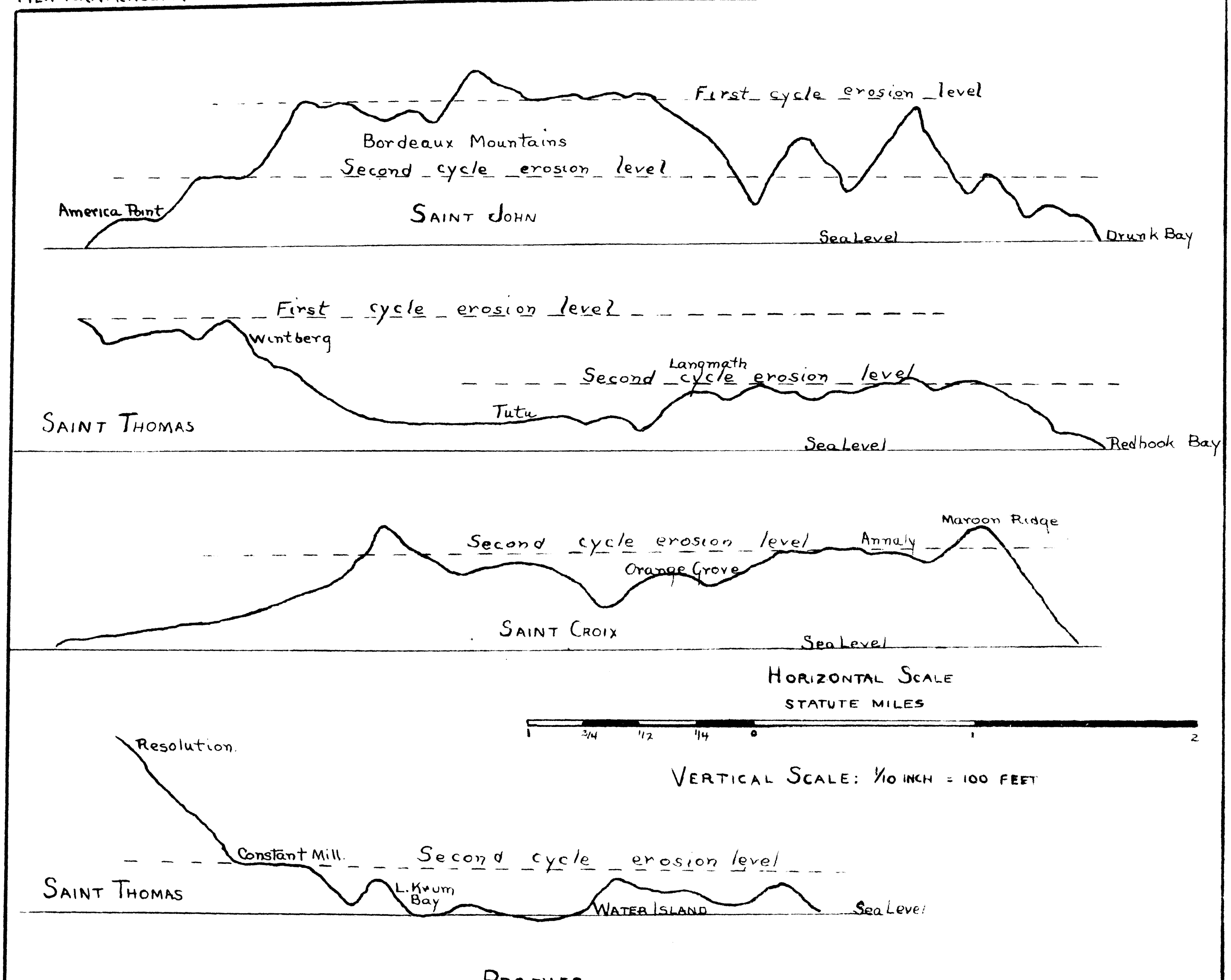
[22] The clarity of the water usually permits clear sight of the bottom to depths of six and seven fathoms on calm days, and the color of the water may lead to safe inference regarding the character of the bottom to depths of ten fathoms.



Profiles

Illustrating the development and relation of first and second erosional levels on the Oldland

PLATE II a.

less than 14 fathoms deep. Northward and northeastward it shallows to less than ten, culminating finally in Horseshoe Reef and Anegada. The gentleness of slope and the smoothness of the floor indicate even accumulation over considerable length of time. If only for the reason that comparable accumulations are not found elsewhere, it is unlikely that all of the accumulating material has been deposited during the initial and maximum submergence of the submarine platform. It must be concluded, therefore, that remnants of the Tertiary coastal plain underlie the one of recent origin. The remnants were left at the margins of the bank, where, as in the case of the ridges at the edge of the bank farther west, superior resistance to subaërial erosion left flat-topped mesas well above the average level of the platform. During initial submergence these ridges were drowned a relatively small amount, and their depth beneath the surface was ideal for rapid growth and extension of reefs. A young coastal plain was thus rapidly built up on the old, although its formation was interrupted temporarily by the withdrawal of water from the platform during Pleistocene glaciation. The position of Anegada above sea-level seems to be due to recent slight uplift, slightly greater in amount than that which has affected the rest of the northern Virgin Islands.[23]

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[23] Since the writer's study of the physiography of the Virgin Islands, Culebra and Vieques has gone to press, William Morris Davis has published "The Lesser Antilles" (Amer. Geog. Soc., 1926). This work includes a brief and generalized consideration of some phases of the physiographic development of the Virgin Islands (pages 109-127, and 138-143). Professor Davis' book approaches the subject with a purpose different from the writer's, and no consideration could be given to the details of the chronologic development of the land forms. Although he does not utilize the significant probability that the recent aggradation of the Virgin Islands bank has used a Tertiary base, and that the northern Virgin Islands as well as Vieques and Saint Croix are, what he terms, "second cycle islands," several of his conclusions anticipate those offered in the present report. Among the more significant are the following: (1) the importance of fluvial erosion in developing the initial submarine platform; (2) the probable pre-glacial date of its origin, with minor Pleistocene modification; (3) the relative unimportance of marine abrasion in its origin; (4) the importance of barrier reefs and lagoonal aggradation by marine organic detritus in giving the bank its present form. The writer can not agree with several minor conclusions, especially on points in which he had the advantage of more extended field observations; for example, that low-level abrasion has played any significant part in the development of Anegada. It is with regret that Professor Davis' significant and important contribution must be dismissed with such brief mention.

PARTS ISSUED

VOLUME I (complete in four parts, with index).

Part 1. History of the Survey, by N. L. Britton.
Geological Introduction, by C. P. Berkey.
Geology of the San Juan District, with colored map, by D. R. Semmes.

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