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SCIENTIFIC SURVEY

OF

Porto Rico and the Virgin Islands

VOLUME IV—Part II

Geology of the Virgin Islands, Culebra and Vieques

Physiography, concluded—*Howard A. Meyerhoff*

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THE PHYSIOGRAPHY OF THE VIRGIN ISLANDS, CULEBRA AND VIEQUES

By Howard A. Meyerhoff

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CHAPTER III

THE PHYSIOGRAPHY OF SAINT CROIX

Geographic Outline

Saint Croix is the largest of the Virgin Islands. It is nineteen miles long from east to west, five miles wide through the western half of its length, narrowing to less than three miles from Christiansted eastward to Tague Bay, and to one mile in the easternmost two and a half miles of its length. The bank upon which it rests is considerably larger, being thirty miles long by five to eight miles wide in its outside dimensions (Plate III). The island is pushed so far into the northwestern corner of the bank that between Southwest Point and Ham Bluff on the west, and Ham Bluff and Salt River on the north, the submarine platform is at no place so much as half a mile wide, and in some localities it is wholly absent. On the north the sea-bottom deepens to 1000 fathoms within two or three miles of the island, and six miles north of Ham Bluff a sounding of 2412 fathoms is recorded. Westward, soundings are not available, but it is known that the bottom drops to 500 fathoms within three miles of the coast. Where Saint Croix narrows at Christiansted, the bank also contracts southward, but not so much; and from this point eastward the island is more centrally located. The platform north of the island is more than a mile wide from Christiansted eastward to Buck Island; there it bulges to the north again to a width of three miles. Beyond Saint Croix it narrows to a total width of four miles and extends east-northeastward for eight and one-half miles, where its bluntly rounded end rises sharply above depths of several hundred fathoms on the north, east and south. South of Saint Croix the bank varies between one and one-half and three miles in width.

The surface of the platform is broken by three small islands and by many small banks and reefs (Fig. 37). Protestant Cay is a small limestone island immediately off Christiansted. Green Cay, situated three miles east-northeast of Christiansted, is a low island, 500 yards long by 150 yards wide, composed chiefly of diorite, intrusive into Upper Cretaceous sediments and volcanics. Buck Island, located three miles east-northeast of Green Cay, is one mile long by half a mile wide, and is composed of Upper Cretaceous eruptives or their derivatives. East of Saint Croix the platform is broken on the southeast by a breached line of drowned ridges six miles long, which rise 25 feet above its floor; and on the north and east it is broken by Lang Bank, six miles long and three-quarters of a mile wide, curving southward at its eastern end in a broad hook. Lang Bank rises 35 to 50 feet above the inner surface of the platform, and 70 to 100 feet above the outer marginal depths. Fringing and barrier reefs are abundant along the south shore of Saint Croix and along the north shore from Salt River eastward.

The topography of Saint Croix is a decided contrast to that of any of the northern islands. It is divisible into three sharply contrasted portions: (1) a deeply dissected upland in the northwest, beginning one mile east of Frederiksted and extending northward to Ham Bluff and eastward to Salt River; (2) a wedge-shaped coastal plain (Part I, Fig. 4), narrow in the west and broadening eastward until it crosses the island two miles northwest of Christiansted in a series of dissected cuestas; (3) a maturely dissected area of rugged hills from Christiansted to East Point (Fig. 37). The threefold division is entirely dependent upon the underlying rocks, their structure and physiographic development. Further description of the topography will be presented in the discussion of the physiographic forms.

Physiographic Outline

As in the northern Virgin Islands, the physiographic history of Saint Croix has as its background an oldland of massive and bedded eruptives,

Fig. 37.—*The eastern oldland of Saint Croix, showing the submerged shoreline in the vicinity of Christiansted*

with interbedded sediments, chiefly limestones and stratified tuffs. They were more complexly folded than the similar rocks of the same age in the northern islands, although it might be more correct to say that the complexity of their folding is more in evidence. The rocks were intruded by diorites, but the intrusion does not have the extensive development that is found in Tortola, Beef Island and Virgin Gorda, or in western Vieques. Yet the small areas of deep-seated intrusives have produced sufficient effect upon the topography to warrant individual mention. During this stage of its history Saint Croix apparently developed as part of a larger unit, which embraced the northern Virgin Islands, Culebra, Vieques and Porto Rico.

Folding and uplift were followed by peneplanation, which reduced the oldland to a rolling surface of low relief, now represented in the upland in the northwestern part of the island. The peneplane produced is probably represented in the crests of the rugged hills east of Christiansted, but subsequent dissection has been so thorough that it may be assumed, mainly by inference, that the erosional surface was formed there. Peneplanation was stopped before completion by uplift; a new cycle of erosion was initiated, and fluvial dissection of the upland produced a lowland of late mature topography 800 feet below the upper level. The lowland was submerged and upon it was deposited a series of Tertiary coastal-plain deposits ranging upward to 600 feet in thickness. Differential uplift followed, accompanied by warping of the upland and coastal plain and succeeded by dissection of both. As a result of the uplift, the coastal plain seems to have been emergent to the edge of the bank, and the fluvial denudation which followed was deepest and most thorough in the areas at the eastern end of the present platform. Although conclusive evidence cannot be adduced, it seems likely that the block-faulting which isolated Saint Croix from the islands north and northwest occurred approximately at this time.

Depression followed, probably taking place in two stages, as in the northern Virgin Islands, the later one bringing the island approximately to its present level and producing the features of submergence which characterize its shoreline today. Reef growth has proceeded vigorously; valleys have been partly silted up and barred; and, on the whole, much of the shoreline exhibits considerable, but not complete, adjustment to the present level.

Detailed consideration will be given to each of the physiographic stages in the order of their development, as follows:

(1) The oldland.
(2) The upland erosional surface.
(3) The lower erosional surface.
(4) The coastal plain.
(5) The upraised and warped upland and coastal plain.
(6) The dissected coastal plain.
  (a) The emergent areas.
  (b) The submarine platform.
(7) The present coastline of submergence.

Wherever these events find counterparts in the physiographic history of the northern Virgin Islands, they will be briefly outlined and compared. Detailed consideration will be directed largely to the features which find no parallel in the northern group.

The Oldland

The origin and development of the oldlands of Saint Croix and of the northern Virgin Islands were essentially alike. From the correspondence in rock types and the genetic relationship of the geologic structures in both areas, the conclusion seems warranted that during their early history they were parts of a single land mass. Definite correlation of the rocks in both areas is quite impossible, for it is doubtful whether any of the beds are exact equivalents. The agglomerates, tuffs and related eruptives of andesitic composition are indistinguishable from those in the northern group. Between unfossiliferous rocks of this nature specific correlation from one locality to another is impossible, especially when lateral variation and lensing are common features. Among the Cretaceous sedimentary rocks of Saint Croix there are several limestones, some of which are fossiliferous. The small fauna yielded no species or genera which were common to the limestones of Saint Thomas, yet the assemblage is equally characteristic of the Upper Cretaceous. Although the rocks of both island groups are of the same age and were accumulated and later deformed in the same manner, they may not be strictly contemporaneous and equivalent. Contributory evidence of the correspondence in their history is found in the nature of the deep-seated intrusives. The intrusives of Saint Croix have a restricted occurrence, attaining importance only in two localities—in the Green Cay-Southgate region, three miles east of Christiansted, and in the Fountain basin, one and one-half miles southeast of Mount Eagle. In both localities rapid decomposition and disintegration have reduced them to lowlands. From their mineral composition, texture and relation to the surface volcanics, their genesis, it may be inferred, paralleled that of the intrusives of Vieques and the northern islands.

Except for the areas underlain by the intrusives, which have been easily eroded into lowlands, the various rock types composing the oldland have exerted but little influence upon the topography. They are divisible into the three types described for the northern Virgin Islands, but the erosional forms of the thinly stratified volcanics and sediments are the same as those produced on the massive eruptives and shallow intrusives. At Watch Ho (Vagthus Point) on the south shore of the island, three miles south of Christiansted, a series of vertical limestone beds have produced a vertical escarpment coincident with the bedding planes for a short distance along the coast; but even here, upon the summit of the promontory formed by the limestone, the effect of the thin bedding upon the drainage is lost. Other comparable examples of dip-slopes and escarpments along the shoreline upon the rocks of the oldland might be mentioned; but, on the whole, shorelines, drainage lines and ridges exhibit a supreme indifference to rock types.

ROCK STRUCTURES

The structure of the oldland was carefully studied and plotted by John T. Quin, F. R. G. S., long a resident of Christiansted and an enthusiastic student of some phases of the geology of Saint Croix. His study, although intermittent and undertaken only as a hobby, was extended over a long period of years and is based upon much more extensive observations than could be made in the relatively brief time which the writer had to survey the island. The present survey, therefore, affords but partial confirmation of Dr. Quin's observations throughout much of the island and supplements them elsewhere. In the main Dr. Quin's results, given in his work, "The Building of an Island,"[24] will be used in outlining the geological structure.

At the present time the oldland is represented in two large areas, subequal in size and separated by the thin prong of the Tertiary coastal plain which crosses the island one and one-half miles northwest of Christiansted. One block occupies the northwestern part of the island; the other, offset to the south, comprises the entire eastern half and includes Green Cay and Buck Island (Fig. 37). In both areas the geologic structure seems to be a comparatively simple system of folds, crowded in the eastern block, more widely spaced in the western. In the western section the dips indicate the presence of a single anticline and syncline, which plunge southeast, and whose axes trend N. 55°–60° W. The syncline cuts diagonally across the center of the block, and the anticline clips the southwestern quarter. Crest and trough are approximately three miles apart. No indications of other folds have been found, and the prevalently massive nature of the rocks makes the possibility of other large structures remote. Some minor faulting has taken place, but in no observed case was the throw greater than 100 feet. Contortion of strata with minor crumpling was noted, particularly at Ham Bluff. In the eastern half of Saint Croix three anticlines and synclines have been plotted by Dr. Quin. If his interpretations are correct, the folds are asymmetrical, with steep to vertical dips upon their southwestern limbs. The crests and troughs, whose axes strike N. 60°–75° W., are from one-half to three miles apart. They pitch southeast, but the pitch is not strong, as in the folds of the northwestern block.

[24] Quin, J. T.: "The Building of an Island, being a sketch of the geological structure of the Danish West Indian Island of Saint Croix, or Santa Cruz." Published by the author in Christiansted, Saint Croix, 1907. Map (frontispiece), and Chapter V, pp. 44-52.

These folds exert a negligible effect on the topography, although, locally, small sections of the coastline are determined by the strike of the rocks; for example, at Watch Ho on the south-central coast. The strike crudely parallels the coast from Prosperity to Salt River Point on the north shore, yet does not appear to mold its form. The northwesterly direction of the coast from Christiansted to Judiths Fancy conforms with the structural trend, but other evidence implies that the outline of this part of the coast was formed without reference to the structure. The valley from Great Pond through Lowry Hill to Altona Lagoon is the only major feature in the topography the direction of which seems to be a direct consequence of the trend of folding. It coincides with the crest of an anticline, but it is to be confessed that field

FIG. 38.—*The fault lowland, filled by coastal-plain deposits, in central Saint Croix*

observations bore out the interpretation only in the Fort Louisa Augusta peninsula, where the crest of the anticline is not excavated into a valley as it is to the southeast. In short, there is not a single important topographic feature the development of which can be referred with certainty to the underlying folds.

Minor normal faults are numerous, but, so far as could be observed, none of them has topographic expression. From a point a mile offshore the writer caught a suggestion of step-faulting and tilting in the rugged hills constituting the easternmost three miles of the island. Several successive hills, carved in complex structures, presented steep western fronts and gentler eastern back-slopes. As the impression was obtained only from one point off the north coast and was not confirmed, no confidence is placed in the opinion. Judging from Dr. Quin's observations, it seems equally possible that the hills are hogbacks.

The breach between the two areas of oldland rocks, filled by Tertiary limestones, appears to have been excavated on a major fault whose strike lies between north-northeast and northeast (Fig. 38). The evidence for faulting rests upon the following points:

(1) The presence of the only lowland which crosses the island, and which is now occupied by coastal-plain deposits whose accumulation it antedated.

(2) The structural discontinuity of the two blocks. If the anticlinal axes are projected from the eastern to the western areas, they meet no corresponding structures.

(3) The presence of limestone beds carrying the fossil Rudistes at Watch Ho on the south, and similar, but thinner, limestone strata at Judiths Fancy on the north. If these two limestones are assumed to be equivalent, their position indicates an offset of the western block to the north, of the eastern block to the south. If they are not equivalent, the presence or absence of corresponding limestones in the two blocks is not significant, because of the southeastward pitch of the structures.

(4) The southward flexure of the strike in the beds at Judiths Fancy. This feature may be drag caused by horizontal movement of the western block to the north.

(5) The presence of a broad coastal plain overlapping the southern margin of the western block upon a well-defined lowland; absence of both a distinct lowland and Tertiary deposits on the seaward margin of the eastern block.

The faulting appears to have occurred prior to the development of the lower erosional surface upon which the coastal plain rests. Save for this single line of weakness and offset, faults are not important as a cause of any topographic features of the present oldland areas. It is to be remembered, however, that the boundaries on all sides of Saint Croix bank are block-fault boundaries, those on the west and north, at least, being of comparatively late origin.

PHYSIOGRAPHIC DEVELOPMENT OF THE OLDLAND

The similarity of the Upper Cretaceous rocks composing Saint Croix to those making up the northern islands, in age, origin, lithology, structure and mutual relationships, is conclusive evidence that both regions were initially parts of the same land mass. The clear-cut fault boundaries north of Saint Croix and south of the northern Virgin Islands indicate profound block-faulting, which has formed between them a graben some 10,000 to 16,000 feet deep and but 24 miles wide.

The position of Saint Croix in the Mesozoic land mass before block-faulting is by no means certain. Whether it was merely a southern projection from the northern islands or a part of a substantial mass continuous with Porto Rico cannot be determined. Whatever its connections, they were maintained through the period of deposition, folding and injection of the rocks, and persisted through the periods of peneplanation which followed. In all respects the early history of the oldland of Saint Croix was similar to that of the northern Virgin Islands oldland.

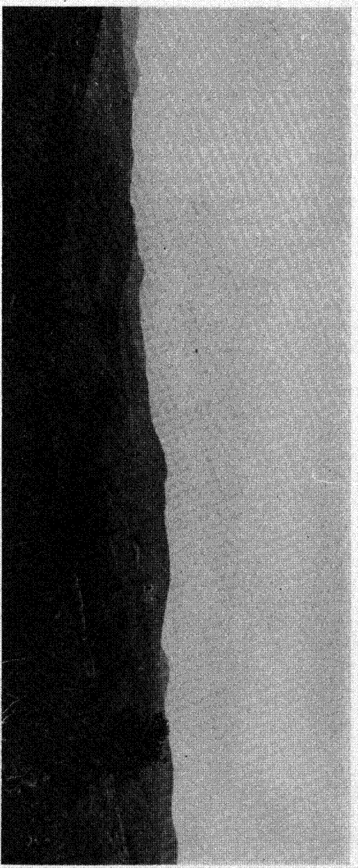


FIG. 39.—*Old upland erosional surface in the vicinity of Annaly, Saint Croix*

The Upland Erosional Surface

From Government Hill, Saint Thomas, the island of Saint Croix may be seen on clear days emerging partly above the southern horizon. In the center of the island in the vicinity of Christiansted, there is a broad gap, succeeded westward by a series of low rolling hills, a gap marking the position of Salt River, then a series of higher hills which rise and fall considerably, but which at no point drop below the horizon. The accordance of the tops of the hills in western Saint Croix is a noticeable feature. East of the Christiansted gap the hills are rugged; yet there, too, despite notches which pass beneath the horizon, the tendency is toward elevations which accord with the height of the western upland.

Actual study of the island corroborates convincingly the distant impressions obtained from Saint Thomas. The oldland which constitutes northwestern Saint Croix rises to a deeply dissected upland, which, prior to dissection, was a rolling surface of hills in an erosional stage of early old age (Fig. 39). The baselevel apparently was 750 to 800 feet above the present position of the sea, and above it rose irregular hills with 100 to 375 feet of relief. The most pronounced hill group is the Mount Eagle-Blue Mountain mass, whose maximum elevation is 1165 feet above sea-level. Bodkin, two miles west of Mount Eagle, is 993 feet high, and the other summits range between 825 and 925 feet in height. From any eminence or ridge upon the upland its once smoothly rounded slopes, characteristic of old age, are more convincing than when they are viewed from a distance or subjected to too minute analysis of topographic detail (Fig. 40). The deeply incised

FIG. 40.—*Small basin in the vicinity of Fountain estate, with the Saint Croix upland in profile*

valleys now dissecting its undulating surface are utterly discordant with its subdued and rounded forms (Fig. 41).

The upland surface marks the culmination of the earliest recorded erosion cycle. It appears to be equivalent to the Saint John peneplane of the northern islands, but this conclusion is open to question. In general it has not attained the degree of perfection which the peneplane possesses on Saint John, but it resembles the greatly dissected second-cycle level, as represented in eastern Saint Thomas (cf. Figs. 39 and Part I, 20). In elevation it is somewhat higher than the latter, but it is lower than the Saint John peneplane. There is, moreover, no intermediate erosion surface in Saint Croix between the upland and the lower peneplane upon which the Tertiary coastal plain was deposited. There are thus recorded but two erosion cycles, as compared with three in the northern islands. On the latter the Tertiary coastal plain is entirely submerged, but in Saint Croix it attains a maximum elevation of 600 feet above sea-level. If the comparative elevations of the coastal plains are considered to represent approximately the amount of differential uplift between the northern islands and Saint Croix, the upland, beginning but little more than 200 feet above the highest coastal-plain beds, would correspond to the second-cycle erosional surface, which lies about 300 feet above the submerged coastal plain in the northern Virgin group. If allowance is made for the greater thickness of the Saint

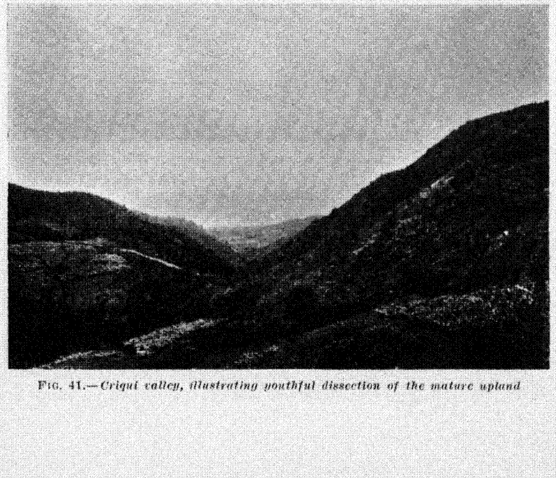


FIG. 41.—*Criqui valley, illustrating youthful dissection of the mature upland*

Croix coastal plain, the figures check very closely. On Vieques, where the coastal plain attains an elevation of 150 feet, the first-cycle peneplane is absent and the second lies at an elevation of 400 feet. The relation between the Tertiary and second-cycle peneplane there is thus the same as the relation between the coastal plain and upland in Saint Croix.

On the other hand, it may be pointed out that the Saint Croix upland approximates a peneplane more nearly than the upland surface of Tortola or Saint Thomas, and that for this reason the degree of penepla-

FIG. 42.—*The lower or third-cycle erosional surface, flanking the dissected upland*

nation, as compared with the Saint John peneplane, is not a valid criterion; that the coastal plain, thicker than in the northern islands, may have buried the second-cycle surface; or the latter may have been completely destroyed during later dissection to a lower baselevel. The weight of argument, however, favors the conclusion that the upland of Saint Croix corresponds to the second-cycle surface of the northern islands, and it will be considered hereafter to have that relation.

The oldland hilltops of eastern Saint Croix approximate the minimum elevations of the western upland and may be considered as a remnant which has since been very strongly dissected.

The Lower Erosional Surface

Peneplanation of the present upland was stopped by uplift of 700 to 800 feet, an amount which corresponds exactly to that which occurred between the second and third erosion cycles in the northern Virgin Islands. Denudation to the new baselevel proceeded until a rolling to rugged surface was formed (Fig. 42) and until only two small sections remained in which the earlier erosional level was preserved. Much of the lower surface formed is now buried beneath the Tertiary coastal plain; hence its nature cannot be accurately ascertained. The valleys cut into the upland represent no more than slender extensions which are not typical of the entire surface, and even the inner lowland areas, where the coastal plain has been stripped, are marginal to the original surface and can scarcely be considered typical. The marginal sections exposed locally in the inner lowland, where the Tertiary marls and limestones have been removed, are hilly and almost rugged. Their character is well displayed between Saint John estate, three miles west of Christiansted, westward to Little Fountain. Here contacts between the Cretaceous and the overlapping Tertiary, although usually obscured by surface wash, are not uncommon, and the boundary can everywhere be drawn with a fair measure of accuracy. The contact is found through a wide range of elevations, differing in short distances by so much as 150 feet. West of Little Fountain the marls and limestones abut directly against the escarpment between the upland and the lower erosional surface, burying the latter almost completely.

East of Christiansted much of the dissection of the Cretaceous upland was accomplished during this stage of physiographic history. More recent erosion has been engaged largely in removing the flanking coastal plain, a single patch of which still remains on the hill slope above Milord Point, while a few scattered Tertiary fossils were found half a mile or more inland at two other localities fronting the south coast. The coastal plain was, therefore, deposited along the margins of the eastern oldland block, and the surface upon which it rested was a rugged one of fluvial dissection, corresponding in age and development to the one underlying the Tertiary to the west. North of Saint Croix, Green Cay and Buck Island rise as monadnocks above the lower erosional surface and above whatever may remain of the coastal plain submerged beneath the marginal waters upon the platform.

The second erosion cycle recorded on Saint Croix is thus found in the surface upon which the overlapping Tertiary rests. In its relation to the Tertiary it is similar to Lobeck's lower peneplane on Porto Rico, and to the third-cycle peneplane of the northern Virgin Islands, to both of which it is equivalent in age and mode of origin. Its ruggedness is the outcome of fluvial dissection, which produced a late mature surface of low to moderate relief on the seaward portion of the bank, above which a few residuals rise, such as Buck Island and Green Cay; mature, rugged topography of moderate to high relief in the interior, such as the eastern oldland area and the southern and eastern borders of the northwestern upland; and the submature to mature dissection of the more remote areas, of which the northwestern upland is the only representative.

During the dissection of the upland several portions of the island yielded readily to denudation. The broad coastal expanses and the fault

FIG. 43.—*North coast of Saint Croix. Maroon Ridge in the foreground*

line between the northwestern and eastern oldland remnants (Fig. 38) were the largest areas reduced to lowlands, but several others deserve mention. Between Fountain and River a deep basinal valley over half a mile wide was eroded out (Fig. 40), in large part because of the presence of a diorite intrusion in the upper part of the valley. South of Mount Eagle, immediately east of the Fountain-River valley, is a small basin with an outlet to the south and a small pass to the southeast. No feature controlling its development could be detected. The broad depression from Southgate Pond across the island to Great Pond was developed partly on quickly disintegrated and decomposed diorite on the north, but on the south alluvial material has completely masked the underlying rocks. The rocks flanking the depression are all of volcanic derivation. All of the other valleys in the upland are of normal size and development.

Under ordinary conditions of fluvial peneplanation with equal distribution of rainfall on homogeneous materials, denudation is greatest at the coast and becomes progressively less inland. This relation holds for the southern, eastern and northeastern portions of Saint Croix. The northwestern upland, therefore, requires explanation as an abnormal feature. It was not completely reduced during the second cycle (of Saint Croix); yet the least reduced areas, from Mount Eagle to Maroon Ridge, constitute the northern coast of the island, notwithstanding the fact that they receive a heavy rainfall, and that their rocks are not superior in resistance. The margin of this part of the platform is a block-fault boundary. The faulting which formed it must have been of such recent date that scarcely any dissection of the coastline has occurred (Fig. 43). There is little or no submarine platform, no coastal plain, and no adjustment of drainage to the new coast. The streams dissecting the upland are more or less adjusted to gradients accordant with the contact between coastal plain and oldland; and although many of them head within a mile of the northern coast, they flow away from it toward the south. Absence of the lower erosional surface off northwestern Saint Croix, together with the other factors considered, forces the conclusion that these features are not absent because they never developed, for they must have developed. Their absence can be explained only as a result of comparatively recent faulting, whose date is tentatively placed as Pliocene.

Erosion of the lower surface proceeded no farther than late maturity on any part of the oldland, because the cycle was terminated by Middle Tertiary submergence, during which deposition of the coastal plain took place. Drowning seems to have exerted but little effect upon the rugged surface over which the sea advanced, for there is no evidence of wave planation or other marine modifications except deposition.

The Coastal Plain

Resting upon the erosional surface just described is a series of gently dipping coastal-plain deposits, consisting of a basal calcareous conglomerate, and alternating foraminiferal marls, firmly consolidated calcarenytes and fossiliferous crystalline limestones. They vary greatly in total thickness, but the variation is primarily the result of subsequent erosion and is only in part due to the irregularity of the surface upon which they were formed. Their maximum thickness is displayed in the series of outcrops from Golden Rock estate on the road between Christiansted and Judiths Fancy to the crest of Bulowminde. Golden Rock is 75 feet above sea-level and lies but little higher than the average elevation of the contact between the base of the coastal plain and the Cretaceous rocks which they overlap. Bulowminde is located on the top of a cuesta in which the coastal plain attains its greatest elevation, 590 feet. If allowance is made for erosion of the cuesta, the original coastal plain was not less than 550 feet thick, and was probably nearer 600. The fauna which was collected from the strata has not been studied; hence a final opinion of their age must be deferred to a later chapter of this report. Vaughan assigns them to three different geological horizons—Middle and Upper Oligocene and Lower Miocene.[25] Physiographic evidence impels the writer to date the entire formation tentatively as Oligocene. Its age, however, is of no moment in the present discussion and will be referred to noncommittally as Middle Tertiary, but in correlation the formations will be tentatively assigned to the late Oligocene.

Two lithologic features of the coastal-plain materials are of physiographic significance: the thin basal conglomerate containing fragments of oldland rocks, and the absence of oldland material in all the beds above the basal conglomerate. The conglomerate is the normal product of deposition by an encroaching sea upon a rugged fluvial surface; and, as might be expected, it is found only in the lower or valley portions of the contact, and is normally absent from the hills which the coastal plain buried. The nature and distribution of the bed indicate how slightly the underlying surface was modified during submergence and suggest that burial of the surface was rapid. The absence of recognizable fragments of oldland rocks from the balance of the coastal-plain deposits and the presence of but small amounts of clay derived from decomposition of the Cretaceous quartz-free volcanics indicate that comparatively little erosion of the oldland occurred during the formation of the coastal plain, and that the rate of limestone deposition was much more rapid than the rate of erosion in the adjacent land areas. During the final stages of deposition, it is to be remembered, sea-level was within 225 feet of the upland erosion level, and extensive erosion could not be expected. At the present time, despite the elevation of the Virgin Islands above sea-level, little land waste is being transported to the submarine platform areas to add to the accumulating coastal plain.

[25] Vaughan, T. W.: "Stratigraphy of the Virgin Islands of the United States and of Culebra and Vieques Islands, and Notes on Eastern Porto Rico." Jour. Wash. Acad Sci., Vol. XIII, 1923, p. 311.

Even on rugged shorelines where beaches are present, coral-sand accumulation exceeds rock-debris accumulation, and within ten yards of a headland coral-sand completely displaces rock fragments in the beach material. The only important deposits of rock waste of recent origin are fluvial and estuarine. Apparently the conditions of Middle Tertiary coastal-plain formation were analogous.

The Tertiary coastal plain of Saint Croix flanks the northwestern oldland in a narrow strip of increasing width from William estate, one and one-quarter miles north of Frederiksted, southward to Concordia estate. There the line of contact swings northeastward, and along the south side of the island the belt of Tertiary gradually broadens as the oldland narrows (Plate III). Starting with a width of one and one-half miles, it increases to four miles at Windsor and Morningstar estates, and immediately west of Christiansted it crosses the entire island. South of Christiansted it ends against the uneven surface of the oldland in an irregular series of cuestas (Fig. 38). In the lowland south of Catherine's Rest it has yielded place to alluvial material mixed with Tertiary limestone fragments; on the south shore it retreats westward around a low promontory of Cretaceous rocks which make the cliffs at Watch Ho. In the eastern half of the island coastal-plain deposits were found *in situ* at only one point—a small patch above Milord Point, on the south coast; but a few weathered Tertiary corals were picked up in the alluvium in two of the larger valleys fronting the Caribbean (north of Longford estate and in Cottongrove valley). On the northern side of Saint Croix the coastal plain is found at a single point,—an outlier of the southern belt, which extends completely across the island for a short distance on either side of Little Princess estate, northwest of Christiansted. Eastward no coastal-plain material was found, unless the limestone composing Protestant Cay should prove to be Tertiary. It is assumed to be Pleistocene or Recent because of its position within the present reefs, but it must be admitted in the absence of paleontologic evidence that Protestant Cay may be a remnant of the Tertiary which has survived later dissection. Along the northwestern upland there is neither a coastal plain nor a lowland upon which one might have rested.

Since its deposition the Tertiary has been deeply dissected and a considerable portion of it has been removed. Its present restriction to the south side of the island provokes an inquiry concerning its original extent. That it was developed on the northern flank of the northwestern oldland prior to faulting is a reasonable conclusion, but the outlines of the coast in that direction before the present fault-coast was formed are not known. East of Christiansted, however, neither the north nor the south coast has been directly affected by faulting since Middle Tertiary time. The relation of the coastal plain to this part of Saint Croix is, therefore, a legitimate field for inquiry. It was pointed out above that the oldland in northwestern Saint Croix was severed from the oldland in the east by faulting, which occurred before the formation of the lower erosion level. Erosion carved it into a lowland, and during Middle Tertiary it was filled with coastal-plain deposits (Fig. 38). The question arises whether later faulting along this line of weakness could have occurred, thus causing the paucity of Tertiary deposits in the eastern section of the island. Field evidence is decidedly negative. Although the coastal plain fills the faulted area and peters out rapidly east of it, the strata occur on both sides of the fault-line, while Cretaceous rocks rise as monadnocks through the Tertiary west of the line. The coastal plain has the appearance of a deposit formed in an embayment between promontories and is without specific relation to the fault. Moreover, the occurrence of Tertiary drift and of one small patch *in situ* on the southern slopes of the eastern oldland area is sufficient evidence to justify the assumption that it was formerly present along the entire southern coast of Saint Croix.

No field evidence was obtained at any point along the northern coast east of Christiansted favoring the view that the Tertiary was deposited marginal to the oldland. It is hoped that more detailed search will reveal residual patches and float that will prove its former existence. Even without field verification, the conclusion that the coastal plain was deposited there is inescapable. Foundation for the conclusion rests on the following points:

(1) The presence of the mature erosional surface, equivalent to that upon which the Tertiary was deposited on the south side of the island (Fig. 37).

(2) The extension of the lower coastal-plain beds to Little Princess estate and possibly to Protestant Cay, a fact which makes it very likely that the upper beds, at least, extended much farther along the north coast.

(3) The total thickness of the coastal plain, which is such that it must have occupied every portion of the lower erosional surface.

The removal of the coastal plain from this area need not be considered as complete; for, as will be shown when the submarine platform is discussed, some coastal-plain material still exists submerged. The removal of so much of it that none remains upon the eastern section of the island is not surprising when it is considered how narrow the eastern width of the entire Saint Croix bank is as compared with the southwestern. Thus in the first and second erosion cycles the eastern end of the island was thoroughly dissected, while in the western portion dissection was imperfect. Similarly, when the coastal plain emerged, dissection and removal were more thoroughly accomplished in the east, because the streams working headward from the north and south coasts had relatively short distances to go to establish gradients to the drainage divide.

The coastal plain is believed, therefore, to have extended completely around the island. Its width was variable and depended upon the width of the lowland developed prior to Tertiary submergence. Where this was narrowest, subsequent erosion has since largely or completely removed the deposits. Along the northern coast of the northwestern oldland area the coastal plain has been faulted into the graben between Saint Croix and the northern Virgin Islands.

Uplift and Warping of the Coastal Plain

The deposition of the coastal plain probably occurred in the Middle and Upper Oligocene, as on Porto Rico. No erosional break could be detected in the series, and they may be regarded, therefore, as a unit of accumulation. Following their formation, they were elevated at least 600 feet; but the movement was slightly differential and the amount of uplift differs from place to place by small elevations. The base of the Tertiary at the foot of the northwestern oldland lies at heights varying between 100 and 200 feet above sea-level. Elevations range but little above 100 feet from Wheel of Fortune estate east-northeastward to Fredensfeld, but at Windsor and locally in the vicinity of Dolby Hill the contact between Cretaceous and Tertiary reaches 200 feet. At Little Princess estate, on the other hand, the contact passes below sea-level. The irregularities are caused by the unevenness of the surface upon which deposition occurred, or have resulted from the removal of the coastal plain to varying distances from the oldland. None of them can be definitely traced to warping, which played too small a part in uplift to affect seriously the average level of the contact. Vaughan has identified the Tertiary near Wheel of Fortune as Middle Oligocene; that along the north shore west of Christiansted, as "probably Upper Oligocene." Physiographic evidence is at variance with this stratigraphic determination. The Tertiary west of Christiansted lies at a lower elevation than the beds at Wheel of Fortune, and the uplift of the coastal plain was not accompanied by any folding or warping sufficiently strong to justify the conclusion that Upper Oligocene beds on the east are at a lower elevation than Middle Oligocene strata on the west.[26]

[26] Stratigraphic and paleontologic evidence of the relative ages of these beds will be considered in an ensuing part of the report.

The uplift of the coastal plain was, however, accompanied by slight warping in a direction the reverse of that implied by Vaughan's stratigraphic determinations. The deformation produced a broad, shallow, semicircular structural basin between Kingshill and Beeston Hill. At no point were the strata observed to dip so much as five degrees. The principal movement was low arching along a northwest axis from Christiansted to Salt River Point, with a subordinate axis of arching from Fair Plain northward to Windsor estate. Erosion on the crests of these arches has produced cuestas, which form a semicircle around the structural basin between the two axes of uplift. Other cuesta development has had little or no reference to warping or folding, but is the result chiefly of the initial seaward dip of the strata.

Quin has reported westward dips up to 15° in the Tertiary along the west coast of Saint Croix. In two days of observations along the shoreline from Ham Bluff to West End Salt Pond the writer was unable to discover any dips of that magnitude. The strata dip consistently toward the west, but the amount is less than five degrees. The structure is apparently original and normal in deposits laid upon a seaward-sloping surface. It was hoped that steep dips formed by drag in block-faulting would be found and thus substantiate the belief that faulting has occurred at the west end of the island since coastal-plain accumulation. Dr. Quin's more extended observations may have brought to light a locality overlooked by the writer, but certainly the feature has a very limited development, if any.

With uplift of the coastal plain a few other minor flexures were formed in the Tertiary beds, including low arching in the Bethlehem-Fair Plain valley and in the Grove Place-Diamond-Enfield Green valley. It is scarcely detectable in the structures of the beds, but was sufficient for the development of shallow subsequent valleys flanked by cuestas. According to Quin there is structural evidence for arching along a northeast-southwest axis from Saint George Hill, at the southwestern corner of the upland, to Southwest Point. This arch has no physiographic expression, unless it explains the Southwest-Sandy points peninsula.

The structural undulations imparted to the Tertiary were shared by the oldland; but, because of the mature dissection of the upland in which drainage lines were well established, the low arching and depression made little determinable change upon its surface. Two features in the physiography of the oldland may, however, be the outcome of the post-Oligocene uplift. Between Mon Bijou and Little Fountain the coastal-plain limestones terminate at, or possibly are buried beneath, an alluvial fan made up of Cretaceous rock fragments which were washed out of Canaan valley. Gravels from the same source were also found at Glynn estate. The Bethlehem arch seems to have caused more rapid erosion in Canaan valley, and to have resulted eventually in deflection of the Canaan drainage into Salt River. On the west flank of this arch the drainage of Hermitage basin appears also to have been diverted from the Colquhoun-Mt. Pleasant valley through the low pass to the southwest. The arch detected by Dr. Quin through Saint George Hill may have deflected the Annaly-Mt. Stewart-Montpellier drainage from the Two Friends-Grove Place route to the southwest past Orange Grove. The stream capture which occurred here may have been facilitated by the uplift.

Dissection of the Coastal Plain

Erosion has worked upon different parts of the elevated coastal plain at such dissimilar rates of speed that the western portion has been dissected to an old plain; the central portion, to a late mature surface of low relief; the eastern portion southwest of Christiansted, to a mature surface of moderate relief. These three divisions, although distinct, are transitional, the mature forms passing imperceptibly into the old from east to west. Each division merits brief mention.

The Tertiary coastal plain west of Diamond and Enfield Green estates, as far as the Saint George arch, is well drained by intermittent consequent streams originating upon it or flowing southward from the oldland. The Tertiary west of the arch is poorly drained to the west or northwest. Much of this area has the aspect of a very young coastal plain upon which drainage lines have not yet been established. From a surficial examination of the topography, it was difficult not to assume that the southwest part of the island was made of younger materials which had but recently been uplifted above the sea. Insufficient paleontological work has been done up to the present time to enable the writer to have a first-hand opinion on this point; but, judging from the conclusions of other workers and from every line of field evidence, the Tertiary in the west is not younger than that east of the Diamond-Enfield Green valley. If anything, it is somewhat older, for the strata are continuous with the lower and older Tertiary strata in the coastal plain farther east. Removal of the higher resistant layers, which are still present in the east, has exposed soft marly limestones, whose uniform non-resistance to erosion makes the development of strong drainage lines impossible. Structural undulations have thus produced no decisive topographic effect, and the surface is a smooth seaward-sloping plain which gives little evidence of deep dissection. As solitary exceptions to the unbroken slope, the eastern margin of the town of Frederiksted ends in a limestone escarpment 40 to 50 feet high, facing inland upon a narrow lowland (Fig. 44), and the road from La Grange southward past Wheel of Fortune to Concordia passes through a poorly defined inner lowland bordered on the west by a breached and irregular cuesta.

Eastward, however, the dissection of the coastal plain is marked, and its topographic expression is the outcome of differential erosion, con-

FIG. 44.—*Tertiary cuesta at the eastern edge of Frederiksted*

trolled by the underlying geologic structure, on beds of unequal hardness. The most prominent feature developed is the semicircular cuesta that begins on the southeast at Beeston Hill and extends northwest, then west, passing south of Saint John estate, thence southwestward to Bonne Esperance. The escarpment rises 450 feet above the low plain on the northeast to an average elevation of 500 feet and attains a maximum height of 590 feet immediately north of Bulowminde. Seen in profile, the cuesta appears as a series of benches or steps (Fig. 45), the most prominent of which lies approximately 350 feet above sea-level. The benches are capped by the more resistant semicrystalline limestones and porous but well-consolidated calcarenytes, while the marls and earthy limestones form the gentle intermediate slopes. On the back of this semicircular cuesta the drainage is radially inward, but notwithstanding the concentration of run-off toward the center of the basinal structure, no dominant central valley has been formed. Instead, each small valley maintains its independence and opens out on a rolling plain with a low, varying inclination toward the south. The only strong valley lies south of the cuesta, which it truncates. It trends southwestward through subdued cuesta-like valley-walls between Anna's Hope and Work and Rest estates, appearing to have been eroded upon a low, poorly defined

FIG. 45.—*Terraced Tertiary cuesta and lowland near Morningstar estate*

anticlinal roll in the Tertiary strata. It has assumed partial control of the consequent drainage on the back slope of the basin north of it.

The curved lowland at the base of the cuesta (Part I, Fig. 2) is not an inner lowland, for its surface is underlain by Tertiary strata whose thickness and weakness facilitated their deep and extensive excavation. Between Lebanon and Morningstar estates—in fact, as far east as Saint John estate—a broken line of low Tertiary hills rises on the northern rim of the lowland. They represent a dissected cuesta, overlooking on the south the broad plain at the base of the main cuesta, on the north a diminutive inner lowland which is little more than a series of short ravines eroded at the base of the Cretaceous upland (Fig. 46). The northern cuesta has been breached by even the least important of the intermittent mountain streams, which cut through it and enter the larger lowland beyond. In consequence, the inner lowland, if it deserves the designation, consists merely of a succession of dry ravines tributary to the larger valleys developed normal to its trend. Northeastward it acquires local importance, where Salt River accidentally tapped it as it eroded headward toward the larger lowland on the south (Part I, Fig. 2).

Between the cuesta-lowland section of the coastal plain and the old plain in the west, there is a centrally located portion of moderate relief. Its dissection has been accomplished by the Bethlehem-Fair Plain stream system, the largest drainage unit on Saint Croix. During the field survey for the present report all the members of this system were dry except the upper portion of the main valley, in which there was a small,

FIG. 46.—*Low dissected cuesta and inner lowland at Windsor estate*

irregular flow a short distance above and below River estate. Most of the drainage from the eastern half of the oldland north of the coastal plain enters this stream system; comparatively little of it enters the Salt River system, which drains the Tertiary lowland described above. In the central coastal-plain area, in fact, the identity of the lowland has been lost by the removal of most of the higher Tertiary beds, and the streams make their way across the seaward-sloping plain in shallow consequent valleys. The Bethlehem-Fair Plain valley apparently owes its location to erosion on the crest of a very low north-south arch. On the east it is flanked by Kingshill ridge; on the west, by a ridge that is broken south of Golden Grove estate by a tributary valley. The tributary has captured the River-Castle Burke drainage, which formerly flowed due south through the wind gap near Fox estate, and has more recently extended its conquests farther west to the intermittent stream which flows out of the lowland past Hard Labor estate. The latter originally passed between the Tertiary hills upon which Adventure and Mt. Pleasant estates are located. Further piracy appears imminent; for, in the soft limestones in which the ill-defined valleys of these intermittent streams are cut, stream capture takes place easily. The Bethlehem-Fair Plain system alone is firmly established and will naturally be the beneficiary. On the northeast Salt River is a rival whose future development will initiate a struggle for supremacy between the two expanding systems. The divide between them at the present time is low and vaguely defined, consisting of a plain more than half a mile square in which there are not twenty-five feet of relief.

In the preceding discussion the coastal plain has been considered under three natural divisions: an old plain on the west, a mature to old plain centrally located, and a maturely dissected area of moderate relief on the east. The divisions merge; there are no clear boundaries. Explanation of the different degrees of dissection which characterize these divisions is not far to seek. From the Cretaceous upland north of the coastal plain, most of the run-off drains south upon the coastal plain. It follows that the amount of run-off reaching the coastal plain is roughly proportional to the area of the upland; hence where the upland is broadest (on the west), there has been a maximum amount of run-off upon the coastal plain, and a maximum amount of dissection has thus taken place. With decrease in the width of the upland eastward, the amount of coastal-plain dissection is less. Where the northern upland ends at Salt River, all of the drainage is indigenous to the coastal plain and comparatively little erosion has taken place. As the amount of decrease in the width of the upland is regular, so, too, is the proportion of decrease in the degree of dissection.

While the coastal plain of the western half of Saint Croix was undergoing fluvial denudation, the corresponding deposits on the north and south sides of the eastern half of the island were completely stripped from that part of the lower erosional surface which is at present emergent. Erosion was not restricted to the coastal plain, and it may be assumed that valleys in the oldland were re-excavated, deepened, broadened and extended at the same time. In the west the rate of valley-deepening in the hard Cretaceous volcanics seems to govern the rate of removal of the coastal plain. Most of the valleys are accordant on both sides of the contact between coastal plain and oldland, but rapid removal of the Tertiary north of Fredensfeld has caused aggradation. Gravels extend from the mouth of Canaan valley out upon the coastal plain to Mon Bijou and Glynn estates, and alluvial deposits have been similarly formed elsewhere.

The Submarine Platform

The submarine platform surrounding Saint Croix is the drowned border of the subaërially dissected coastal plain. It is less than ten fathoms deep except beyond the eastern end of the island, where it ranges between 10 and 20 fathoms, with readings more than 20 fathoms at its eastern tip. Along the north coast from Ham Bay to Salt River Point and southeast to Long Reef its greatest width is 1000 yards, with an average of 400 to 500 yards, while off Maroon Ridge it is practically absent. On the west coast, from Ham Bay to Southwest Point, it is barely 600 yards wide. Elsewhere around the borders of the island its width varies from one to three miles, and beyond East Point it extends east-northeastward for nine miles, narrowing gradually from five and one-half miles down to three and terminating in a bluntly rounded end (Plate III). On all sides it stops abruptly at an escarpment 1000 to 6000 feet high, which sharply delimits its seaward margin.

The character of the platform surface does not differ greatly from place to place. It has a very gentle, and in most localities uniform, seaward slope, which is broken by many reefs and shoals, and in the east by a few large banks. Two oldland monadnocks, Green Cay and Buck Island, rise above it to the surface, the latter attaining an elevation of 330 feet above sea-level. The reefs, both growing and dead, include barrier and fringing types. Growing reefs extend almost continuously from Southwest Shoal, about one mile off Long Point on the platform south of the island, to East Point. Beginning as barrier reefs a mile offshore, they gradually close in upon the shoreline, which most of them fringe from Watch Ho Point eastward. Small fringing reefs are present even along the northwest coast, but from Salt River Point eastward coral growth is almost continuous, being especially abundant in the shallow water surrounding Buck Island. On the southern platform an irregular line of dead reefs rises 15 or 20 feet above the bottom. Off the west coast the narrow platform is unmodified.

The banks which rise above the surface of the platform east of Saint Croix differ from the reefs in having larger dimensions and in rising from greater depths. They are found near the margin of the platform almost completely enclosing a submerged basin six miles long and two to three miles wide. Lang Bank, the largest, begins two and one-half miles north of East Point, extends for six miles along the northern rim of the platform, there bending south and ending at the southern rim. Its greatest width is less than a mile. Near the southern margin of the platform three corresponding banks, without names, extend from the latitude of East Point toward the southern end of Lang Bank. Two of them, each two and a half miles long by half a mile wide, are separated by a low gap scarcely 25 feet lower than their crests, which lie 6 to 9 fathoms beneath the surface. The outer slopes of all the banks are moderately steep escarpments to a depth of 20 fathoms or more, then very steep to 200 fathoms or deeper. East of Lang Bank the platform continues in a crescent-shaped terrace one mile broad and 14 to 29 fathoms deep, rimmed at its outer edge by narrow breached ridges (Fig. 47). Within the banks, on the other hand, there is locally a low escarpment at the crest, but generally the surface slopes evenly and gently to depths of 16 to 19 fathoms in the center of the basin.

The submarine platform off the western, southern and northern coasts of the island offers strong contrasts to that of the northern Virgin Islands, in that (1) it is much narrower; (2) it is shallower; (3) the beaches deepen gradually offshore,—there are no steep slopes or escarpments (the northwestern fault-coast is excepted from this statement); (4) the modifications of its surface are restricted to reefs, broad ridges or banks being absent. East of the island, however, the platform is not essentially different, except in shape, from parts of the northern Virgin Islands platform,—for instance, south of Saint John. Points of resemblance are found in the width and the depth, and in the flat-topped banks rising above the surface of the platform. The analogies afforded by this eastern area are sufficient to justify the conclusion that the history of the entire platform was closely parallel to that of the more extensive platform surrounding the northern islands. The nature and origin of the contrasts found in the other parts of the platform will be considered first.

The platform off the southern coast, between Southwest and Watch Ho points, is an extension of the old plain of erosion developed on the coastal plain on the adjacent land. Its angle of slope is less, but the decrease has resulted in part from slow accumulation of coral sand and of debris washed from the island. There is no escarpment between land surface and platform except the low cliff cut recently by waves. Continuity of the coastal plain beneath the platform is the chief cause of the form which the latter exhibits. Deposition upon its surface, although considerable, has not succeeded in greatly modifying its character. East of Watch Ho Point the depth of the platform is four to six fathoms immediately outside the line of reefs and increases offshore to depths greater than those found westward. The tendency of the platform to increase in depth toward the east is significantly related to the offset of the oldland to the south and to the contraction in the width of the island. The Tertiary coastal plain deposited upon this portion of Saint Croix was, after uplift, more deeply dissected than that to the west, and the greater depth of the platform is probably the expression of the greater dissection and perhaps of slightly greater submergence. Similar generalizations might be made for the platform off the north coast from Long Reef to the latitude of East Point. Its surface has been considerably built up by reefs and accumulations of coral sand, especially in the vicinity of Christiansted and Buck Island; but elsewhere its surface, six to ten fathoms deep, is smooth and gently undulating. These portions of the submarine platform constitute a young marine plain of deposition, apparently built up upon an old plain of fluvial denudation. Lack of any features of marine erosion eliminates the possibility that wave-cutting was responsible for its formation. Whatever work has been accomplished by the sea is depositional in character and has occurred comparatively recently.

The eastern end of the submarine platform (Fig. 47), although it is modified by accumulations of coral sand, preserves all the characteristics of a fluvially dissected coastal plain. The horseshoe-shaped rim of banks, with their steep outer slopes and gentle back slopes, invite a comparison with the Beeston Hill-Bonne Esperance cuesta in central Saint Croix. The outer slope is more than a debris slope, because it is strongest at the eastern end of Lang Bank, where it rises above the comparatively flat crescent-shaped terrace described above. It is not a wave-cut cliff, because in the same locality an outer line of ridges would have prevented wave-cutting at its base. In every particular except the accidental character of its shape, it resembles the submerged coastal-plain ridges south of Norman and Peter islands on the northern bank. The basin within it attains a maximum depth of 19 fathoms near its center and 16 fathoms near its western end. Recent deposits have filled whatever outlet the basin may have had, for the deepest channel leading from it is but 13 fathoms deep.

It is doubtful if the comparison between the banks and the Beeston Hill-Bonne Esperance cuesta can be pressed very far. The latter owes its origin to arching along two axes tangential to the escarpment. There are no grounds for assuming that the entire eastern margin of the bank was upturned. Furthermore, if the platform has been dissected by fluvial erosion to the base of the banks (25 to 30 fathoms), denudation would normally be greatest at the sea border, as is the case of the coastal

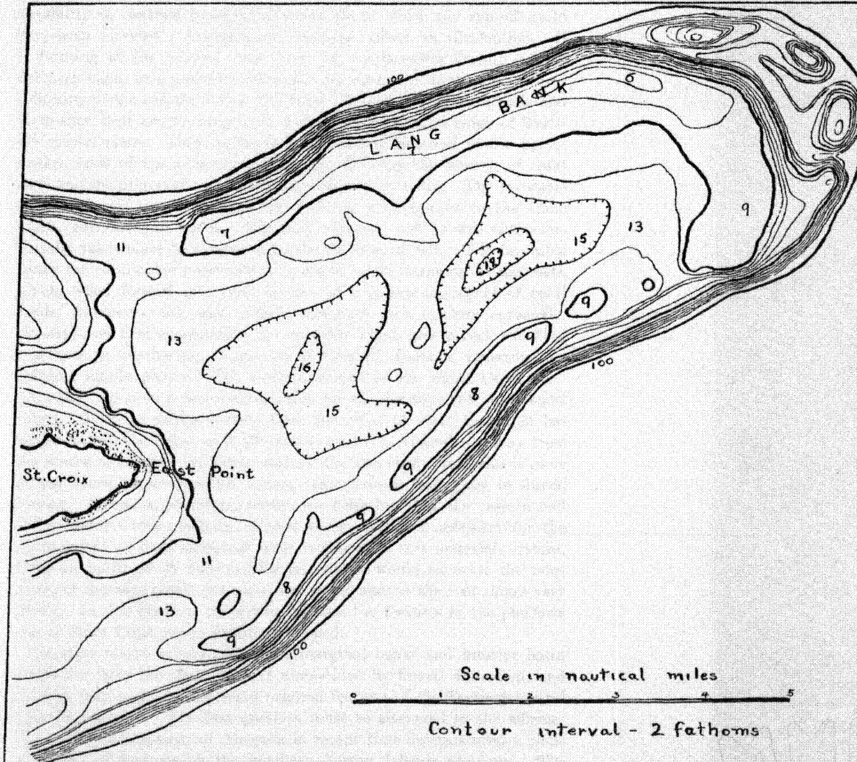
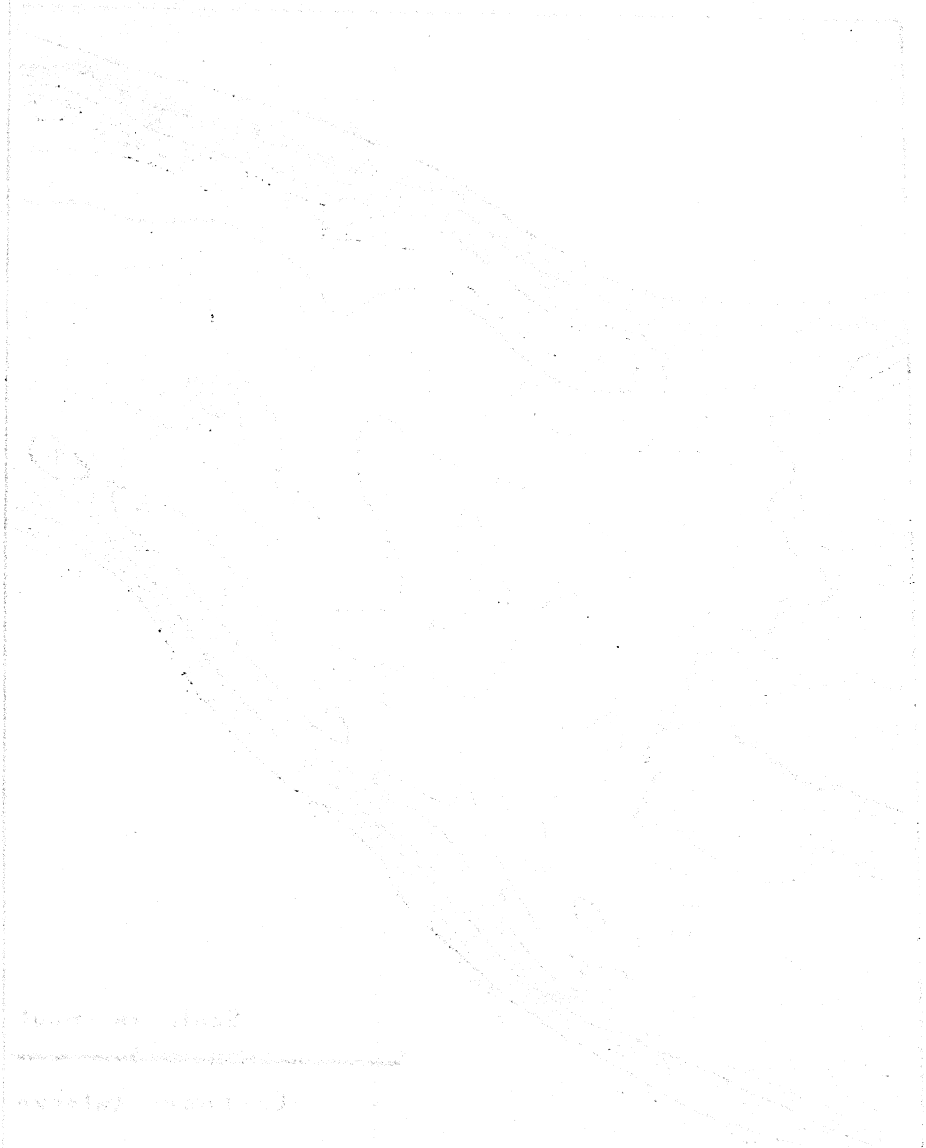


FIG. 47.—*Contoured surface of the submarine platform east of Saint Croix, showing marginal banks and interior basins*



plain farther west. Under ordinary circumstances the banks would have been removed unless the material composing them was of exceptional durability in contrast to adjacent materials to which the run-off could have been diverted. Anegada will, perhaps, afford an illustration. It is forming at the present time near the northeastern margin of the northern bank, in a position and under circumstances analogous to those obtaining at the eastern end of the Saint Croix platform. Anegada and Horseshoe Reef are growing upon a drowned unreduced ridge of Tertiary coastal plain. There seems to be something inherent in the northeastern ends of the submarine platforms favoring the growth of coral reefs and the preservation of the ridges which they build. The favorable factor for reef development is the location with respect to the trade winds, currents and waves. The most vigorous reef growth characteristically takes place to windward in the trade-wind belt. The favorable factor for coral-ridge preservation is found in the make-up of the reefs, which, when formed into rock, consist of a porous aggregate of coral heads, fragments and sand, firmly cemented with calcium carbonate. Porosity and firm cementation are qualities which give a rock excellent resistance to weathering, as the use of Bedford, Indiana, limestone for building amply proves. The eastern margin of the Saint Croix platform has thus been a favorable location for the development of resistant ridges. The fine debris derived from the ridge by wave clastation has settled within the ridge, as is illustrated again in Anegada. Away from the source of calcium carbonate cement, the fine clastic material is more or less dense, impervious and poorly cemented—an easy prey to fluvial erosion. There is, therefore, reason for believing that the eastern end of the Saint Croix platform satisfies every condition necessary for the development of hard marginal coral ridges with soft materials within. With an uplift of 30 fathoms, fluvial erosion would excavate the non-resistant deposits inside the reefs, but would reduce the reef-ridges very slowly. In this manner, the writer believes, the features of the platform east of Saint Croix were initially developed.

Question might arise whether the marginal banks and interior basin would not have the same form if unmodified by fluvial dissection, and whether they could not represent original features of the Tertiary coastal plain as they are. The first question must be answered in the affirmative. The development of Anegada in recent time has produced a similar group of features on the northern Virgin Islands platform. The second question must be answered in the negative, for deposition of a Tertiary coastal plain in this area must have been as rapid as it was westward, if not more rapid, because of the conditions which encouraged marine life. At present the ridges lie 25 or more feet beneath sea-level and are probably not more than 150 feet thick, compared with 550 to 600 feet of coastal-plain deposits at Bulowminde. Reduction by subaërial erosion is the only explanation; greater submergence is a contributory but inadequate factor.

Unlike Anegada, the ridges do not now support actively growing reefs;[27] yet, since the submergence which followed their dissection, a considerable amount of material has been deposited on the floor of the basin within them. This material could not have been derived from the adjacent island, yet it could scarcely have been derived from the ridges by marine erosion at the present sea-level. Again, an analogy must be sought in the northern platform. At the southern margin of the latter is a drowned reef whose growth was connected with a slightly lower sea-level during late Tertiary time, and whose death was caused by exposure during the Pleistocene. The submerged ridges on the eastern section of the Saint Croix platform rise to a fairly uniform height of six to nine fathoms, as if they had all formed at a wave-base five or six fathoms beneath the present surface, either by coral growth to that level or wave-planation to it, or both. Either process would have supplied a source of material to account for the deposits in the basin. There are other grounds for postulating a temporary wave-base at a level some five fathoms beneath the present water-line:—(1) North and south of the eastern half of Saint Croix the platform maintains a level of six or more fathoms immediately offshore. Unlike the platform surface to the west. this area appears to have been formed at a lower level and has not yet been built up toward the present water surface by accumulation of clastic material. (2) Off the northwestern fault coast, where a narrow platform is present, it is regularly five to eight fathoms deep. It appears to be a wave-cut terrace whose formation was possible only when the waves were cutting at a lower level on the island's flanks. (3) Finally, the features of drowning exhibited in the coastline of the island are such as would form with a small amount of submergence and not with the total amount of submergence represented by the present depth of the eastern part of the platform.

The final problem which the platform presents for solution is the origin of the differences in its depth and character at the eastern end and in the portions flanking the island. The gradually increasing depths of its surface from west to east, beginning approximately at Watch Ho and Christiansted, suggest downward tilting of the eastern

[27] Notations on the charts indicate that there is some scattered coral growth on Lang Bank, but it has not yet assumed importance.

portion. The decreasing elevation of the Cretaceous upland in the western oldland area apparently supports this view, although the more thorough dissection which it has undergone is an equally plausible explanation for its lower altitude. The nature of the coastal-plain dissection south of Christiansted indicates that arching occurred in this region; it would follow that depression occurred to the east, but whether it was enough to explain the features of the eastern platform is not known. Furthermore, the deformation seems to have preceded dissection of the coastal plain and in that case would not bear on the problem. The only alternative hypothesis which can be offered to explain the difference in the eastern and western platform is slight down-faulting; but its case is weak. There are not sufficient data for a final conclusion.

From the evidence considered, the history of the submarine platform appears to have been a phase of subaërial coastal-plain dissection, followed and complicated by submergence and marine deposition. Beginning with the formation of the coastal plain upon the lower erosional surface of the oldland, the balance of its history may be summarized as follows:—(1) uplift and fluvial dissection of the coastal plain, with the production of an old plain on whose eastern surface a few residuals were left only partly reduced; (2) partial submergence, followed by reef-growth and deposition; (3) temporary emergence during the Pleistocene; (4) resubmergence to the present level.

The Present Level

The principal features which have developed during the sea's present stand include continued dissection and removal of the coastal plain, the development of the shoreline, and the growth of coral reefs upon the submarine platform. Dissection of the coastal plain has already been discussed; attention may, therefore, be restricted to the other two features. In its relative simplicity the shoreline of Saint Croix offers a strong contrast to the irregularly distributed, deeply embayed and oddly shaped islands of the northern Virgin group; yet it is the result of a series of events probably no fewer in number than those responsible for the present forms of the northern islands. The reasons for its apparent simplicity are many, but those of chief importance are closely related to the different varieties of shoreline exhibited; hence the types of shorelines and their synthesis to produce the composite outline of the island will be considered jointly.

The present form of Saint Croix represents the synthesis of three types of shorelines whose origins are dissimilar. The only features they share in common result from recent slight submergence. The southern coast from Sandy and Southwest points eastward to Watch-Ho has been formed by marginal submergence of the fluvially dissected coastal plain. By the processes of denudation the higher strata of the coastal plain were removed with considerable uniformity over much of the surface adjacent to the coast, especially west of Krause Lagoon. The surface has little relief, and even the intermittent streams have eroded very shallow valleys. Their courses from the upland are less incised southward, and for the most part the southerly slope of the strata near the coast is so uniform that only locally does the run-off show a marked tendency to concentrate in well-defined valleys. The result is that the run-off is commonly little more than a sheet-wash during heavy rains, and erosion goes on at a comparatively uniform rate over the entire seaward portion of the coastal plain. Because of the absence of strong valleys, drowning of the coast has not produced the usual deeply embayed shoreline, and only a few localities offer positive evidence of submergence. Drowning has produced a diminutive bay, into which drain the two intermittent streams entering Long Point Bay about half a mile north of Long Point. The Bethlehem-Fair Plain stream widens for over half a mile above its mouth. When the locality was visited in April, 1924, the stream bed was dry, but the lower valley was filled by more or less isolated pools of salt water for more than a quarter of a mile from the shore. Depression has been responsible also for cutting off the meander behind the beach. The width and arc of the meander are not in accordance with the greater width of the present estuary—a feature to be expected if the mouth of the stream has been widened by the influx of salt water concomitant with drowning. Wherever the sea has found higher strata to work upon, it has cut low cliffs, and the entire southern shoreline of the coastal plain is a series of sand beaches along the lower portions of the plain, interrupted by low wave-cut cliffs whose height is rarely more than ten feet and never as much as twenty feet. The best are found in the vicinity of Long Point and at Cane Garden Bay, where Tertiary hills of moderate elevation front the coast. The irregularities of the shoreline, although of small dimensions, have undergone so little modification that they still possess all the characteristics of youth.

The form of the southern shoreline is considerably modified by fringing and barrier-reef growth. Krause Lagoon is partly enclosed by a barrier reef, the eastern half of which is exposed, the western half still submerged and growing. Sand has accumulated along the seaward margin of the dead portion and is building up a cuspate bar outward toward a growing coral patch 300 to 400 yards offshore. The position of the eastern half of the reef above water suggests recent slight emergence as the last stage in the island's history. Further evidence bearing on slight emergence will be discussed in following paragraphs.

The Sandy-Southwest points peninsula requires special consideration. It is an anomalous protrusion from the southwest corner of the coastal plain, enclosing two lagoons, one of considerable size. The form of the peninsula is simpler than that of the adjacent southern coast and its origin seems to have been more recent. It rises less than twenty feet above the level of the sea and is composed of firmly consolidated lime-sand, bordered seaward by a beach of unconsolidated sand. The form and nature of the peninsula indicate that it developed by continued outgrowth of bars into an advancing double cuspate foreland, which has since been upraised. The material composing it is unfossiliferous, and its age cannot, therefore, be stated; but it is thought to be Pleistocene. The consolidation of the lime-sand is a normal process occurring at the upper reaches of the waves along all the present beaches, where by evaporation of the water in the pore spaces between grains a calcium carbonate cement is precipitated. The result is a very solid rock, firmer than most of the poorly unconsolidated Tertiary marls. It seems probable that the peninsula was formed by the forward building of bars through the agency of confluent coastal currents. The interbar depression was ultimately cut off from the sea, and West End Salt Pond was formed. The elevation of the peninsula above sea-level is the result of emergence, possibly connected with the formation of the structural arch whose axis, according to Quin,[28] extends from Saint George Hill to Southwest Point. The inner shores of the lagoons approximate the form and position of the older coastal-plain shoreline before modification (Fig. 48).

The western shoreline is exceedingly regular in outline. At the south it extends from Sandy Point in a broad sweeping curve until it joins the older Tertiary shoreline south of Frederiksted. A beach of coral sand borders the consolidated material of the peninsula, whose low, flat surface is not more than fifteen feet in elevation. At the south end of Frederiksted there is a low sea-cliff less than ten feet high, but in general a cliff is absent where the western shoreline is formed upon the coastal plain. The coast curves broadly in the vicinity of Frederiksted, and thence trends N. 17° W. in an almost straight line two miles long. At Sprat Hole the Tertiary ends against the Cretaceous volcanics, which border the sea northward from that point. The character of the coast changes abruptly with the change in rocks, from low and flat to rugged and high; for the oldland rises rapidly to elevations of 750 feet within

[28] Quin, J. T., Op. cit., pp. 44-52.

a mile from the shore. Shallow re-entrants and low wave-cut cliffs become somewhat more numerous, but for the most part there is a beach of unconsolidated alluvial material, whose devolpment has considerably modified the original irregularities. The extent of the modification can

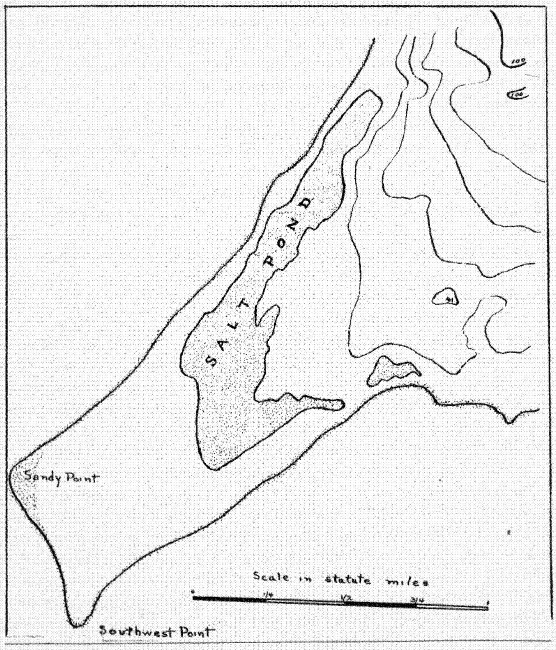


FIG. 48.—*Sandy-Southwest points peninsula, southwestern Saint Croix*

be appreciated by contrasting the present shoreline with the hundred-foot contour (Fig. 49). There is usually a steep but regular rise from the sea to an elevation of twenty feet, above which the slope gradually assumes the form characteristic of fluvial dissection. With the passage of the shoreline from the coastal plain to the oldland, there is a change in the width of the submarine platform offshore from an average of 600 yards to 300 yards. The width of the platform above the ten-fathom contour seems to be a fair measure of the amount of marine planation which has taken place since the western margin of the platform was formed; thus it is wider on the easily eroded material of the coastal plain, but narrow where it adjoins the oldland, which was reduced more slowly because of its height and the hardness of its rocks. Coral growth has not obtained a foothold on this side of the island, and accumulation of material has been a negligible factor in modifying the submerged surface.

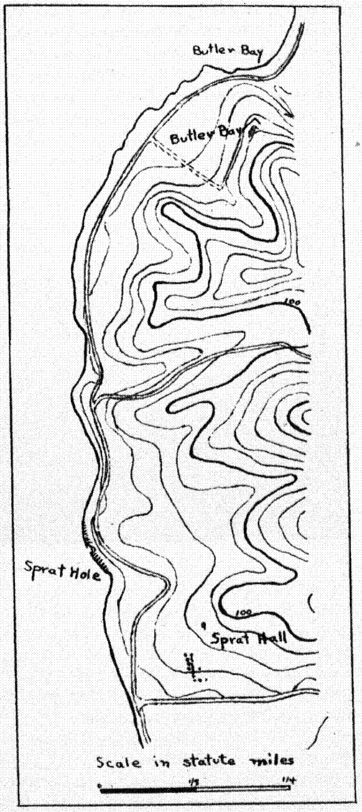


FIG. 49.—*Contrast of coastline and fluvial erosion surface in western Saint Croix*

The north coast from Ham Bluff to Baron Bluff (Part I, Fig. 3), a distance of six miles, offers an interesting mixture of forms. Along a mile of it, between Ham Bluff and Annaly Bay, no submarine terrace is present, but the steep rock walls of Maroon Ridge (Fig. 43) descend into the ocean, with little change of angle, to depths of 100 fathoms. The shoreline is in extreme youth and has been little more than notched; it is characterized by high sea-cliffs which are completely inaccessible from land or sea, while above the water-line the flanks of the ridge are scarcely gullied. Eastward from Annaly Bay the coast changes. The upland is somewhat dissected; and short, steep valleys descend to the sea (Fig. 50), forming at their mouths shallow re-entrants, along which are narrow beaches (Part I, Fig. 3). Between the small embayments are high rocky stretches, usually cut into impassable sea-cliffs. In places the presence of a narrow rock bench a little above mean tide level, but within reach of the higher waves, suggests recent slight uplift of the coast; but the extreme difficulty of travel along much of the shoreline made careful examination of the nature and origin of these benches

FIG. 50.—*Annaly valley and bay, north coast of Saint Croix*

impossible, and the question of their significance, however suggestive of emergence, cannot be regarded as settled. The submarine platform along this portion of the coast is narrow but constant, varying in width between 300 and 500 yards. From Wells Bay eastward beaches become more numerous, while wave-cut cliffs are restricted to the more prominent headlands, of which Baron Bluff is the easternmost. Between Lavallee and Rustoptwist estates there is a broad flat, filled with alluvial deposits, which have been washed down from the upland in a network of short, steep, converging valleys and spread out between the ridges on either side. The material has nearly filled what was once the largest embayment along this part of the north coast. The mode of development was the normal one: a bar formed across the mouth of a re-entrant, alluvium filled the landward side, and in between there was formed a lagoon, which now holds water only in rainy months. Alluvial filling is, apparently, almost completed. Another arresting feature of the north coast is an asymmetrical, triangular facet along the coast west of Wells Bay (Part I, Fig. 3). A spur from the upland is truncated by the coastline and descends to the sea at a 40° angle from an almost knife-like crest 895 feet high.

It has been postulated that the northern coast from Ham Bluff to Baron Bluff is a young fault-scarp. The hypothesis is fully borne out by the physiographic evidence. The following are the critical points:—(1) the limited development of the submarine platform, present as a narrow strip where the dissection of the upland has permitted the short, youthful valleys (Fig. 50) to carry and deposit land waste along the shore, absent where the upland has undergone least erosion; (2) a shoreline in its initial to youthful stage of development (Part I, Fig. 3); (3) the narrow watershed on the north side of western Saint Croix, as contrasted with the broad watershed on the south side of the dissected oldland; and (4), in consequence of the asymmetrical divide, short, steep valleys on the north (even these are absent along Maroon Ridge, Fig. 43), in contrast to the longer, more mature valleys on the south. One characteristic physiographic feature is missing: a rectilinear shoreline. Few block faults are simple, however. The fault boundary of the Highlands in southeastern New York, for example, consists in places of a series of short faults with different strikes occurring in a zone which has a linear trend. The faulting north of Saint Croix may, therefore, be zonal and somewhat irregular, the outline of the coast conforming with the irregularities.

The northern shoreline between Baron Bluff and Christiansted is hybrid. Salt River has been drowned and dismembered, and, unlike the other drowned river mouths in the Virgin Islands, the estuary is a comparatively broad, open one (Part I, Fig. 2), two fathoms deep, and only partly silted up along the sides, where short intermittent tributaries enter it. Filling seems to have been in part retarded by the screen of mangroves which grow around the edges, and in part prevented by the perennial flow of Salt River, which maintains an open channel into the sea. Reefs are growing across its mouth, and sand derived from them fills the outlet to a depth of one fathom, but complete closure cannot occur. The shoreline southeastward from Salt River Point to Christiansted consists of unconsolidated sands margining the rocks of the oldland at the north, a narrow strip of the coastal plain in the central portion, the oldland rocks again in the vicinity of Christiansted. In the neighborhood of Judiths Fancy the otherwise low coastline is interrupted by hills of folded Cretaceous volcanics, which front the sea in wave-cut cliffs. The isolation of the hills, which are cut off from those westward by a flat plain of poorly consolidated, partly reworked material of Tertiary age, indicates that they were Tertiary islands, formerly covered by the coastal plain, which has since been stripped from them.

The rest of the shoreline, from Christiansted on the north and Longford estate on the south, is a physiographic unit. It has been formed by the submergence of the maturely dissected oldland with the formation of embayments which vary between one and two and one-half fathoms in depth (Fig. 37). Altona Lagoon, the largest one maintaining an open connection with the sea, was caused by submergence of an east-west valley. Other major features are the broad basins in which Southgate and Great ponds are located, initially formed by rapid erosion upon a granitoid intrusive, which probably underlies the greater part of the two areas. Submergence caused the deep embayments, bars developed between the headlands bounding them, and alluvium has filled a large part of the depressions. The lagoons situated between the alluvium and the bars are large, but are only one to two feet in depth, and in dry weather Great Pond sometimes dries up completely. Both lagoons are, therefore, all but filled. Farther east the island narrows, the valleys are shorter, and initial re-entrants were, in consequence, not so large. The bar-lagoon stage of development was omitted in the shortest valleys; and in several instances where lagoons formed, they have subsequently been filled, only four small lagoons remaining unfilled in this part of the island. Sandy, evenly concave beaches alternate with long stretches of rocky, wave-cut promontories, which in many places tower more than fifty feet above the sea. As much as half of the coast is composed of wave-cut cliffs.

Coral-reef growth upon the submarine platform has already been mentioned, but a résumé of its nature and significance is pertinent to the features of the present level. Along the northern fault-coast coral growth has barely obtained a foothold. Scattered heads have acquired a footing among the rocks south and east of Ham Bluff, but they cannot be classed as true reefs. A thin, fringing reef growth begins on the north coast at the mouth of Salt River and continues in patches to Big Princess estate. Thence Long Reef, barely submerged, extends away from the shoreline at a low angle, continuing subparallel to the coast in Scotch Bank. The reef thus formed encloses Christiansted "harbor," a small anchorage from two to five fathoms deep, between Protestant Cay and Fort Louisa Augusta, to which access is obtained through a natural.

tortuous channel seven fathoms deep. The balance of the sand-filled lagoonal area behind the reef is less than two fathoms in depth. Whatever harbor Christiansted may be said to have owes its origin to the barrier reefs, which threaten to take that which they have given. The channel is so narrow and tortuous that only short vessels can make the turns, and for this reason the port of call for larger boats is Frederiksted, where anchorage is found on the exposed bank. Coral growth is abundant but scattered between Green Cay and Buck Island, the latter being bordered on all sides except the southwest by a fringing reef, while irregular growth northward has formed a shoal more than a mile broad. The mainland to the south is also protected by a fairly regular reef, part barrier, part fringing, from Mary's Fancy to East Point. On the south coast, a barrier-fringing reef extends with a few short breaks from East Point to Great Pond Bay, west of which coral growth is less regular. A drowned reef of older origin parallels the coast at a distance of two miles, extending to the western margin of the submarine platform.

The reefs surrounding Saint Croix have furnished an abundant supply of coral sand to the surface of the submarine platform and to the sandy beaches along the coast. The coral growth and derived clastic material have, in consequence, modified greatly the original surface of the submarine platform and have often been instrumental in producing terrace-like effects in places where sand and land-derived waste have accumulated in horizontal deposits within the reefs. The deposits which are now being made are forming a new coastal plain, and their mode of formation is like that which produced the Tertiary coastal plain.

In concluding the consideration of the present level a few summary statements appear necessary. The apparent simplicity of the shoreline of submergence is due entirely to the land forms which produced it. Part of the northern coast is a fault-scarp, which suffered little fluvial erosion before it was submerged to the present level. The southern coast is a partly stripped coastal plain, upon which subaërial erosion proceeded so evenly that no valleys developed to cause embayment. The remaining eastern part of the island is a re-excavated lowland margin, which was formed initially by early Tertiary fluvial erosion and was later covered by a coastal plain which has been removed. Most of the short valleys dissecting the remnant of upland were too steep for the formation of deep re-entrants upon submergence, and many of those formed have since been filled by alluvium, which has obliterated the lagoons formed behind bay-mouth and mid-bay bars. Hence even in this portion of the island the shoreline has been greatly simplified. Modification of the shoreline by wave erosion is gradually coming to an end, because much of the coast is now protected by fringing and barrier reefs. Their protective influence indicates that subaërial erosion is the dominant factor in denudation in regions where coral growth flourishes, and their effect as a check on wave erosion explains why marine planation has played so little part in the physiographic history of Saint Croix. At the present time the reefs are not merely protecting the mainland from wave-attack, but the living and drowned barrier reefs are serving as walls within which a new coastal plain is being built up. It is possible that the present shoreline of submergence has been modified by very slight emergence. The rock benches on the north coast and the elevation of the Southwest-Sandy points peninsula may be evidences of recent slight emergence, but this possible event requires additional confirmation.

CHAPTER IV

THE PHYSIOGRAPHY OF VIEQUES AND CULEBRA

The Oldland and Its Peneplanation

A. K. Lobeck visited the islands of Vieques and Culebra in the course of his physiographic survey of Porto Rico in 1916-1917, and he has sketched the main features of their development and present form in connection with the physiography of Porto Rico.[29] In this chapter their history will be discussed in the light of the physiography of the Virgin Islands, with which their topographic forms are, surficially at least, more obviously related. Their history begins with an oldland of Cretaceous volcanics and sediments which were intruded, folded and elevated. Peneplanation followed; and, although the even crests of the islands plainly represent a peneplane, Lobeck's conclusions raise a question as to which erosion cycle was responsible for the flat upland to which both islands rise. A brief summary of the relations of the two islands will assist in solving the problems of correlation.

Both islands rise above the same submarine platform upon which the northern Virgin Islands are situated. Culebra, the more northerly and easterly, lies ten miles south of the northern margin of the platform and eight miles west of the nearest of the Virgin Islands. It is separated from Vieques on the south by an equal distance, from Porto Rico on the west by seventeen miles. It is flanked by a number of small islands: on the east and northeast by Culebrita Island and Northeast Cay; on the northwest by several rocks and diminutive cays, of which Fungy Bowl is the largest; on the west by Luispena Cay, The Sisters,

[29] Lobeck, A. K.: "The Physiography of Porto Rico," pp. 314, 320, 324, 356, 373-374.

Cross and Cactus cays. Virgin Passage between Culebra and Saint Thomas exhibits depths that are characteristic of the deeper levels of the platform, shallowing from 25 or 30 fathoms on the north to 12 and 17 fathoms between Culebrita and Savana islands. It is thus a normal feature of the submarine platform. The depths surrounding Culebra average seven or eight fathoms immediately offshore, and are reached by steep but not precipitous slopes from the shoreline. Greater depths are attained within short distances of the coast, for the bank drops from the seven- to ten-fathom bench surrounding the island to 25 fathoms within one and one-half miles northward; to 16 fathoms within an equal distance southward. Vieques Sound, between Culebra and Vieques, averages 14 to 16 fathoms in depth.

Vieques, situated one to two miles from the southern margin of the bank, is second in size only to Saint Croix among the islands considered in the present study, measuring eighteen miles in length and four miles in width. Integrally related to it are five small cays located within half a mile of the coast. It is completely bordered by a beach which slopes gradually to the depths of the surrounding platform. Off the eastern half of the island the latter is 12 to 14 fathoms deep both on the north and south; eastward the depths are greater, while westward and northwestward soundings of 8 fathoms or less are prevalent to Porto Rico.

The rocks of the oldland on both islands are of the usual types. Culebra is composed entirely of surface volcanics and shallow intrusives, most of them massive, but with a few thin-bedded, stratified members well displayed on the east side of Flamingo Point. The structure of the rocks is gently undulating but nearly flat. On Vieques the rocks display more variety. From Isabel Segunda eastward to Porto Salinas and Salina del Sur, where they are overlapped by Tertiary strata, the rocks consist of folded, indurated surface volcanics with a lesser amount of interbedded crystalline limestones. Surface volcanics continue westward in a narrow strip, half a mile wide, along the north coast to the base of Punta Arenas. Except for this strip and a narrow belt of overlapping Tertiary coastal plain deposits in the south-central peninsulas of the island, the western half of Vieques is underlain by a granitoid intrusive, not essentially different from that found on Virgin Gorda. The topographic forms produced by the two types of oldland rocks are strikingly different. The eastern half of Vieques is rugged, with a fine-textured topography in which the dissection appears to have followed structural lines. Examination was not sufficiently thorough, however, to establish any detailed relationship between surface features and geologic structure; but the strikes of the stratified material are approximately northwest, and it was noted that many valleys and ridges showed similar trends. Hill alignment and crudely parallel valleys and ridges are best displayed south and southwest of the abandoned "central" at Le Brun stack. The northwest direction of the Ensenada Honda shoreline is also suggestive of structural control, but the inaccessibility of southeastern Vieques made a visit to that portion of the shoreline impracticable. The western half of the island is coarse-textured; the surface forms are smooth and rounded, lacking the angularity that is seen in the volcanics to the east.

Culebra rises to a maximum elevation of 650 feet in Mount Resaca, which is located in the north-central part of the island. Dolphin Head is 551 feet high, but none of the other elevations are much greater than 400 feet. In Luispena Cay the central hill rises to a height of 476 feet, but the other cays have maximum elevations less than 350 feet above sea-level. In Vieques Mount Pirata at the western end of the island is the only conspicuous monadnock, attaining a height of 981 feet. From Culebra or from the mainland of Porto Rico, the skyline of the western half of Vieques appears remarkably even, and in the less reliable close-up view obtained from any of the hills east of Mount Pirata the accordance of the hill-summit elevations is striking. The highest is 594 feet, but nearly all of them approximate 500 feet. The significance of this constant level is in no way nullified by the fact that barely ten per cent. of the entire surface rises above the 400-foot contour, because the hills are well distributed through the central and northern parts of the island and are also represented in the southern part west of the coastal plain. Viewed from Culebra, the low, broken skyline of the eastern half of Vieques stands in striking contrast to the smooth regularity of the western half. Heights of 300 feet are prominent, and most of the passes cutting through the island are less than half that elevation. Only Mount Jalobre, west of Salina del Sur, stands at a height comparable with the hills of the west.[30]

In his interpretation of the significance of the persistent higher elevations in Culebra, Lobeck frankly admits the absence of decisive criteria but assumes that "the tops of the hills roughly indicate the upper level"[31] of Porto Rico. Because in Vieques the Tertiary coastal plain overlaps a lowland cut below the level of the even-crested hills, Lobeck expresses the opinion that there also the hill summits represent the upper peneplane. From the point of view of the physiographer whose study was

[30] Cf. Lobeck, Op. cit., Fig. 40, p. 374; U. S. Coast Pilot, Porto Rico and Virgin Islands, Dept. Commerce, U. S. Coast and Geodetic Survey, Serial No. 164, 1921, Fig. 1.
[31] Lobeck, A. K., Op. cit., p. 314.

restricted to Porto Rico, such a conclusion is inevitable. In Porto Rico the upper and lower peneplanes are such outstanding features that intermediate levels of small area appear insignificant by comparison and are likely to be overlooked. To the Virgin Islands physiographer, with small residual areas to study, the impress of shorter erosion cycles assumes greater importance because they affect a much larger proportion of his province. Eastern Porto Rico imposes an additional difficulty in the correlation of its land-forms with those of Culebra and Vieques. In the monadnock group of the Luquillo Mountains it can hardly be said that the upper peneplane is represented at all, except possibly in a few flat-topped spurs, 1400 to 1600 feet high, protruding beyond the mountain mass and locally flanking the headwaters of the streams which are working headward from the present baselevel. Dissection has destroyed nearly every trace of the upper peneplane. East of the mountain mass from Cape San Juan to Humacao (probably farther, but the writer's observations were limited to this section), there is a series of low hills rising between the playas and constituting the stream divides, which attain elevations of 400 to 600 feet. The accordance of these hills is particularly imposing when observed from northwestern Vieques, from Palominos Island, and from the lighthouse at Cape San Juan. They are given scant attention by Lobeck and possibly too much by the author.[32] They do not represent the upper peneplane, which, if it is present at all, has only fragmentary representation in the spurs on the mountain flanks at 1400-1600 feet. According to Lobeck's physiographic map of Porto Rico the Luquillo Mountains drop off sharply at their eastern border to the level of the lower peneplane, whose surface is broken by numerous hills and ridges rising above it. Lobeck has not considered it significant that these lower hills and ridges approximate a common level, although he recognizes that they cannot represent the upper peneplane. Yet, if Mount Pirata is excepted, scarcely a single hill on Vieques or Culebra rises higher than the general level attained by the low hills of eastern Porto Rico. If, then, the Vieques-Culebra summits indicate the upper peneplane, it would follow that the latter is depressed 1000 feet in the ten miles or less which separate Vieques from the mainland of Porto Rico. Plainly some other explanation than the tentative suggestion made by Lobeck must be sought for the accordant summits of the two islands.

The following possibilities suggest themselves:—

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[32] These hills will be discussed more fully in a subsequent report on "The Geology of the Fajardo District," to be published as Part III of Volume II in the Scientific Survey of Porto Rico and the Virgin Islands series.

(1) That the upper peneplane has been faulted or flexed down between Porto Rico and Vieques.

(2) That the even hill summits of Culebra, Vieques and the Naguabo-Fajardo area represent a peneplane contemporaneous with the upper peneplane of central and western Porto Rico, but lower in elevation because it was formed by short streams working into the oldland close to the coast. According to this view the peneplane would be developed at higher levels with increasing distance from the sea.

(3) That the Vieques-Culebra upland, together with the hills and ridges of the Naguabo-Fajardo area, consists of second-generation monadnocks rising above the lower peneplane. Accordance of summits would result merely because of the subequal rate of erosion affecting all areas more or less alike.

(4) That the Culebra, Vieques and Naguabo-Fajardo ridges represent an intermediate peneplane equivalent to the second-cycle level identified in the northern Virgin Islands from discordant tributaries, broken main-valley gradients, interior basins and coastal rock benches. If this theory is to be accepted, it must account for the fact that the erosion surface, meagerly developed in the adjacent Virgin Islands, has an extensive development in this area.

As each one of these interpretations has some plausibility, they require independent consideration, especially as Lobeck inclines to the view that the hilly interiors of Culebra and Vieques are to be correlated with the upper peneplane of Porto Rico.

(1) The upper peneplane has been faulted or flexed downward between eastern Porto Rico and Vieques. West of the Luquillo National Forest the upper peneplane is approximately 1500 to 1800 feet in elevation, ending southward in the ridge, 2000 to 2500 feet high, which overlooks the Caguas lowland. The only locality west of the Luquillo Mountains where faulting might have occurred is in the broad, deep valley of Rio Canovanas, whose headwaters have even cut a comparatively low pass in the high southern ridge. But remnants of the peneplane are found east and south of the Rio Canovanas lowland, as noted by Lobeck, and are probably present in the spurs east of the Luquillo Mountains. Extension of the peneplane across this deep valley eliminates all possibility that it is a fault valley, east of which the upland might be found at a lower elevation. East of Rio Canovanas there are no topographic features, such as lowlands and rectilinear truncation of structures or of surface forms, which would suggest large-scale faulting. The eastern coast of Porto Rico is an irregular shoreline of submergence lacking the rectilinear outlines of a fault coast, and submarine contours

between Porto Rico and the eastern islands reveal the platform as an area of submergence whose surface could not have been faulted. The intrusive diorites in western Vieques appear to be continuous with the rocks of the Yabucoa-Humacao area in the adjacent part of Porto Rico. Hence between Porto Rico and Vieques there is neither a topographic nor a geological break. Faulting, therefore, is not likely and is certainly impossible on a scale large enough to account for the difference of 1000 feet in the upper peneplane on the mainland and the erosion surface in the islands.

It is true that the Saint John peneplane of the Virgin Islands is at an average elevation of 1000 feet, as compared with 1500 to 2000 feet for the upper peneplane in eastern Porto Rico. If the two surfaces were formed contemporaneously, as the writer believes they were, warping or tilting of the peneplane must have occurred. If it could be proved to have taken place east of the Luquillo Mountains, the explanation of the Vieques-Culebra upper erosion surface could be simply solved. Such a solution might also be extended to include the Naguabo-Fajardo hills, which are certainly comparable in form, altitude and time of origin with those of the islands. But there is no evidence of flexure on the eastern flanks of the Luquillo range. On the contrary, a very close study of the region with this problem in mind offered convincing proof that the upper peneplane is not wholly absent, as stated by Lobeck,[33] but is represented in several isolated, deeply dissected spurs and in one extensive area due east of El Yunque. The erosion escarpment between these upper flats and the Naguabo-Fajardo hill levels renders it certain that the latter represent a later and lower surface of denudation. Because of their apparent genetic relationships, the hills of eastern Porto Rico and of Vieques and Culebra cannot be explained as features of diverse origin; therefore, monoclinal flexure of the upper peneplane between Porto Rico and the eastern islands is not admissible. Instead, the tilting which has depressed the island section east of Porto Rico about 1000 feet was gentle and even. The uplift which occurred after deposition of the Tertiary coastal plain was 500 feet greater at Lares than at Corozal,[34] and at least 250 feet lower between Canovanas and Rio Grande than at Corozal—a total of 800 feet in 65 miles. Tilting of the coastal plain downward toward the east was accomplished by a subequal amount of tilting in the upper peneplane. If the angle remains constant still farther eastward, the surface of the upper peneplane would coincide with the Saint John upland in the Virgin Islands. There is no basis for assum-

[33] Lobeck, A. K.: Op. cit., p. 314.
[34] Lobeck, A. K.: Op. cit., p. 327.

ing irregularities in tilting, and no reason, therefore, for including the upper levels of the islands between Porto Rico and Saint Thomas in the upper peneplane.

(2) The even hill summits of eastern Porto Rico, Culebra and Vieques may represent a peneplane contemporaneous with that of western Porto Rico, but lower because it has been pushed back headward toward the Luquillo mountain mass by short streams operating closer to the sea than the rivers west of the mountain mass. If the spurs on the eastern flanks of the mountains represent the upper peneplane, as was conjectured above, this explanation cannot hold. It appears unlikely, also, in view of the fact that the elevation of the Saint John peneplane accords rather exactly with the eastern projection of the tilted upper peneplane of Porto Rico.

(3) The Vieques-Culebra hills, together with those in the Naguabo-Fajardo area, are merely monadnocks rising above the lower peneplane. According to this interpretation they are not referable to an intermediate baselevel, but attain subequal altitudes because of the uniformity of fluvial erosion acting on more or less homogeneous materials. The arguments against this view must be discussed largely in connection with the factors favoring the fourth hypothesis. But the distribution of the even-topped hills, often without reference to drainage lines or distance from the sea; and the old character of the surface where the intermediate elevations occupy broad areas, in strong contrast to the relative youth of more recent dissection, are two strong points against the view that regularity of skyline is an accidental development. Forms produced in a single cycle of erosion have simply graded slopes and show uniformity in development. Youthful dissection of an old surface indicates rejuvenation.

(4) The Culebra-Vieques hills represent an erosion cycle in which the baselevel was intermediate between the upper and lower peneplanes. The probability of an intermediate or second erosion cycle is favored by several lines of field evidence: (a) Except for the marginal dissection and the pronounced lowland between Great Harbor and Flamingo Bay, most of Culebra rises to a flat upland, 300 to 400 feet high. Compared with the character of the upland surface the recent dissection is young, except in the Great Harbor-Flamingo Bay depression. (b) In Vieques the postulated level is best represented in the hill and ridge crests in the western half of the island, where the rocks are granitoid intrusives. Normally, the coarse-grained intrusives are reduced to lowlands with relative ease, and there are no peculiar features in the Vieques quartz-diorite which make it resistant to erosion. The fact that this

area of intrusive rock forms one of the largest continuous expanses of the erosion level under consideration and contains, besides, the highest monadnock east of the Luquillo Mountains foot-hill belt (Mount Pirata) does not necessarily imply greater resistance to erosion, but may perhaps be attributable to a greater initial mass to be reduced and to a location remote from drainage lines. The intermediate upland surface formed upon this rock type is smooth and rolling; the small valleys which are cut into it, and which are working headward toward the drainage divide, are young and steep-sided. In eastern Vieques where the island is narrow, subsequent dissection has lowered the surface generally below 250 feet, Mount Jalobre alone rising above 400 feet. Greater erosion in this part of the island was facilitated by its narrowness and by the presence of limestones interbedded with the volcanics. (c) The distribution of hills of similar height in western Vieques appears to be more regular and widespread than a haphazard development of monadnocks with subequal elevations above the lower peneplane would render possible. The same statement holds for the hills and ridges on different kinds of rocks in eastern Porto Rico. (d) The existence in the northern Virgin Islands[35] of an intermediate erosion level of restricted development, which is present in Savana Island (Part I, Fig. 28), only seven miles west of Culebra, leads to the expectation of a parallel erosional stage in Vieques and Culebra. Persistent and widespread areas in eastern Porto Rico at a similar altitude render inevitable the conclusion that this stage in the physiographic history of the Porto Rico-Virgin Islands bank was general and is of greater importance than has hitherto been recognized. The extent of its development in Porto Rico has not yet been determined beyond the Fajardo District, but presumably its development would be least where conditions least favored dissection of the upper peneplane or most favored the formation of the lower, or third-cycle, peneplane. Probably a restudy of the areas termed by Lobeck the "Rugged Foothill Belt," as well as of the Lower Peneplane,[36] will further extend its boundaries.

From several lines of evidence the conclusion seems warranted that the region between Porto Rico and the Virgin Islands has been susceptible to rapid and extensive erosion throughout its history. It was one of the first areas to be reduced during the first cycle of erosion; and upon renewed uplift the upper peneplane was destroyed, and a new surface of fluvial denudation was cut nearly 1000 feet below the first. Later the second-cycle surface was all but completely destroyed,

[35] Ante, pp. 39-42.

[36] Lobeck, A. K.: Op. cit., Fig. 3, facing page 305.

remnants of it being well preserved only in Culebra and Vieques, which presumably were farthest removed from most active fluvial erosion. Indication of such a location is supplied by the presence of residuals in both areas, which rise as monadnocks toward the elevation of the upper peneplane—Mount Pirata on Vieques, and Mount Resaca on Culebra. No final hypothesis can be advanced to explain why the entire area should have been an easy prey to erosion. As western Vieques is underlain by a normally weak granitoid intrusive identical, or closely allied, with a similar intrusive in southeastern Porto Rico, the drowned reentrant between Punta Yeguas, Playa de Naguabo and Punta Arenas is probably underlain by quartz-diorite. This portion of the bank might thus be explained as a drowned lowland worn in easily eroded rocks. There is no basis for believing that a similar explanation holds for the bank north and east of Vieques, for the intrusive is not encountered again for nearly forty miles (in Buck Island, south of Saint Thomas). The northwest-southeast alignment of topographic features between Culebra and Magens Bay, Saint Thomas, has already been described and attributed to faults of small displacement. The distribution of these faults, which are most abundant in the portion of the bank now most widely submerged, implies that structural weakness was in part responsible for the deep erosion east of Porto Rico and north of Vieques. Granted the non-resistance of the region to erosion, the present position of the island residuals is logical: Vieques, located near the southern margin of the bank because low precipitation developed it farthest from the dominant northern drainage; Culebra, located on fairly dense resistant rocks with nearly horizontal structure, possibly marking the center of a synclinal trough, midway between two old major drainage systems.

The Lower Peneplane

The coastal-plain deposits of Vieques rest upon a hilly surface of fluvial denudation, which has been correlated by Lobeck with the lower peneplane of Porto Rico (Fig. 51). Only its marginal and more rugged portions are now exposed where the coastal plain has been removed, but it extends as a surface of low relief beneath the Tertiary and beneath Vieques Sound, Virgin Passage, and the area north of Cordilleras Reefs and Culebra. It was formed as a result of uplift of the second-cycle peneplane still represented in the hills and uplands of Culebra and Vieques. Again, as in the second erosion cycle, the entire area between the Luquillo Mountains and Saint Thomas was reduced rapidly toward the new baselevel, until only the masses forming the hills of eastern Porto Rico, Vieques and Culebra remained as monadnocks. The surface has been buried beneath coastal-plain deposits, which mask its form not only on Vieques, but also in the entire expanse which now constitutes the submarine platform. It is thus impossible to learn anything about the surface detail that has direct bearing upon its origin; yet, aside from the rugged surface exposed on Vieques and the deep depression in Great Harbor and Flamingo Bay, several considerations point to the fluvial origin of the surface. One of the largest sections reduced during this third erosion cycle was the lowland now forming Vieques Sound, which is, and was at the time of its formation, sheltered from wave attack. There is no means of estimating how much marginal erosion was accomplished by wave action; but denudation was dominantly fluvial and seems to have been accomplished largely by a ramify-

FIG. 51.—*Partly submerged inner lowland and dissected Tertiary coastal plain, south-central Vieques*

ing river system with headwaters in the Luquillo Mountains, in the low divide between western Vieques and Ensenada Honda, Porto Rico, and between Culebra and Vieques. The protected position of most of this region from wave attack and its conformance to the plan of a river system seem convincing evidence of its fluvial origin. The narrow lowland south of Vieques, where stream development was unimportant, is proof of the ineffectiveness of the sea as a factor in forming the surface. The small cays surrounding Culebra are monadnocks, indicating a rugged topography which could not have existed, much less have formed, under the persistent attack of waves.

The third cycle of erosion was of nearly as great duration as the second, producing a group of connected lowlands and marginal valleys from 500 to 600 feet below the upper level of Culebra and Vieques. As in the Virgin Islands, these lowlands served as a basement upon which the Tertiary coastal plain was deposited, and are thus contemporaneous with the lower peneplane of Porto Rico.

The Coastal Plain

The Tertiary coastal plain has a very limited representation in the Porto Rico island group. No Tertiary deposits are found on Culebra, although they undoubtedly underlie the Cordilleras Reefs to the west. The distribution of Tertiary limestones on Vieques, however, is significant of their former widespread occurrence over a large part of the entire submarine platform area. Their best present expression is on the central part of the southern coast, from Porto Real to Chiba Cay in

FIG. 52.—*Tombolo separating Porto Real and Ensenada Sombe, Vieques. Tertiary headland in background*

Ensenada de la Chiba (Fig. 51). The inner limits of the coastal plain are marked by a line of bays, including Ensenada Sombe, Porto Mosquito, Porto Ferro and Ensenada de la Chiba (Plate IV). All are disconnected bays occupying the partly drowned inner lowland (Fig. 52) and are connected with the Caribbean by narrow mouths, cutting through the cuesta which rises about 100 feet above sea-level. When originally deposited, the limestones abutted against the irregular front of the Cretaceous hills, resting upon the uneven fluvial surface of the third-cycle peneplane, from which they have been partly removed. At present they are about 125 to 140 feet thick, and it is doubtful if they were much thicker when formed. It is therefore unlikely that they covered much more of the island at this point; they did not cover any portion of the second-cycle peneplane.

Tertiary limestones and marls, 160 to 175 feet thick, compose the east end of Vieques from Porto de Salina and Salina del Sur to Punta Este. The narrow isthmus between the two bays connecting the coastal plain with the mainland is the partly drowned inner lowland, whose surface is further covered by shallow lagoons. The somewhat greater thickness of the deposits appears to be the result of less stripping during recent erosion than occurred along the south shore.

The third occurrence of Tertiary consists of a patch barely two acres in extent; yet of the three Tertiary areas it is the most significant. It is located on the north shore at Punta Caballo, midway between Isabel Segunda and Punta Arenas. The strata underlie a low hill which projects from the general coastline sufficiently to form the only prominent headland between Punta Mulas at Isabel Segunda and Punta Arenas at the western end of the island. It cannot be doubted that it is the sole surviving remnant of a large expanse of coastal plain which once covered all of Vieques Sound. The thickness represented at Punta Caballo is not more than fifty feet. There is no pronounced inner lowland, for the deposits rest against the oldland hills which front upon much of the northern coast. The latter is developed on the Cretaceous volcanics and locally upon semiconsolidated alluvial deposits of post-Oligocene age, and consists almost throughout its length of gentle northward slopes, cut by rejuvenated valleys. The slopes end at the shoreline in a wave-cut cliff 20 to 30 feet high. The coastal section appears to be the erosion scarp between the second- and third-cycle peneplanes. It formerly served as the inner valley-wall of an inner lowland, from which all of the coastal plain except the patch at Punta Caballo has been stripped. Before dissection and removal of the cuesta, the alluvial deposits mentioned above were deposited, and they now front the coast because the cuesta has been reduced. The failure of the coastal plain to rise above the surface of Vieques Sound elsewhere is due largely to the amount of dissection it has undergone; in part, perhaps, to a smaller amount of initial accumulation.

The original extension of the coastal plain is merely a matter of conjecture, yet the limits of conjecture are so narrow that a fairly convincing conclusion can be reached. During the development of the third-cycle peneplane broad fluvial lowlands were formed in Vieques Passage, in Vieques Sound, in Virgin Passage and in the area north of Culebra and the Cordilleras Reefs, while a narrower one was formed south of Vieques. The relative breadth of the lowlands depended upon the structural and textural weaknesses of the underlying Cretaceous rocks, the rainfall distribution and the arrangement of drainage systems. After their formation they were submerged to a level somewhat below the surface of the second-cycle peneplane. Coastal plain deposition ensued; and, if the deposition now in process on the submarine platform may be regarded as typical, accumulation of material was greatest near the shoreline, where it consisted of coral-reef growth and bars; it was less within the reefs, and least on the offshore sides of the reefs. It became proportionately less at greater distances from the shoreline, where most of the accumulations were composed of the lime-sand and mud derived from the reefs. In this manner a coastal plain is accumulating around Anegada today; and, judging from the distribution of coral heads in the Oligocene deposits in Saint Croix, these seem to have formed in an analogous way. This method may be considered to apply to the Tertiary of Vieques and the entire bank between Porto Rico and the Virgin Islands. The present inner lowlands on Vieques, according to this interpretation, were sites of accumulation of clastic material whose source was the oldland on the one hand, the reefs and bars on the other. The amount of accumulation from both sources was probably little less than along the reefs. In the open water beyond the reef zone accumulation was probably much slower, and the ultimate thickness of the deposits, less. Subsequent uplift of the coastal plain led to its dissection. The reef material, consisting of firmly rooted coral heads with interspersed calcium carbonate debris and cement, has proved most resistant to erosion and now forms most of the uneroded coastal plain on Vieques. The areas within the reefs and bars, composed of poorly cemented debris, were rapidly eroded into inner lowlands; the seaward areas of deposition, filled largely with uncemented lime-sand and mud, were likewise rapidly denuded localities, initially of lower elevation.

The present distribution of the Tertiary on Vieques is thus explained. That it has been wholly removed from the bank which is now submerged is not at all likely. It is assumed, therefore, that much of Vieques Sound, Virgin Passage, Vieques Passage and part of the northern section of the bank are underlain by remnants of the coastal plain, partly veneered by subsequent deposits. Complete absence of erosion remnants of the coastal plain on the fringes of Culebra and on the adjacent islands can be explained as the outcome of more vigorous erosion in the northern drainage areas, where rainfall tends to be slightly heavier, and a somewhat greater amount of submergence at the present time.

Uplift and Dissection of the Coastal Plain

Some of the factors affecting the dissection of the coastal plain after its uplift were discussed in the last section in considering its original extent. There remains for consideration the mode of dissection. The amount of uplift was not less than 350 or 400 feet, an amount represented by the present depth of the platform and the elevation of the coastal plain deposits above sea-level. Most of the erosion which occurred after uplift was restricted to the soft Tertiary marls, and in consequence the lowlands were re-excavated, while a comparatively small amount of erosion occurred in the harder rocks of the oldland. The drainage established upon uplift was consequent, the greater part of it having a general northerly direction, deflected, however, by the position of Culebra, and modified by local variations in the contour of the surface. The easily eroded marls were rapidly but not completely reduced to new lowlands between Vieques, Porto Rico and Culebra, while the more resistant reef limestones surrounding Vieques were cut by young valleys. Behind them the less resistant material was dissected by headward-working subsequent streams, which have formed strong inner lowlands from Porto Real to Ensenada de la Chiba in southern Vieques (Figs. 51 and 52), and from Salina del Sur to Porto Salinas near the eastern end of the island. There were thus formed elongate inner lowlands, with young, narrow valleys as outlets through the retreating cuesta. As a result of these features submergence to the present level has formed the pouch-shaped harbors along the southern coast.

The recency of the removal of the flanking coastal plain in other portions of Vieques is amply attested by the presence of gravel-clay alluvial deposits, many of which are now marginal along parts of the coast. They are especially well developed in the valley one and a half miles west of Esperanza and between Punta Caballo and Resolucion. The materials have been derived almost wholly from waste from the oldland rocks. Where they have been formed by disintegration of the diorite in western Vieques, they consist of coarse arkoses, with subordinate amounts of hornblende, quartz and clay; where they have been derived from the andesitic volcanic rocks, as in eastern Vieques, they consist largely of graywacke-clays. They fill the larger valleys of the oldland and form conspicuous accumulations in the inner lowland of southwestern Vieques, where their arkosic character and low clay content make them an important water-bearing sand. They exhibit good stratification, yet in their mode of occurrence appear to be of simple fluvial origin. They are older than the drowning which is now a feature of the coastline and are at present undergoing dissection. There is no evidence that greater submergence of the island occurred, and they cannot be explained as deposits made while the sea stood at a higher level. They appear to have resulted from temporary aggradation during maximum emergence of Porto Rico and the Virgin Islands bank, which was accompanied by rapid denudation of the oldland cores. Aggradation took place in the lower portions of valleys cut into the oldland, and particularly in the inner lowlands. The marginal alluvial deposits now found along the north coast in western Vieques are believed to have been accumulated in an inner lowland and have since been left exposed to coastal erosion by complete removal of the Oligocene limestones and marls. A surprising proportion of the surface material of Vieques below the elevation of the intermediate peneplane consists of alluvial deposits so formed, but in Culebra alluvium underlies only a small portion of the lower levels. Some was noted in the valley between the heads of Great Harbor and Flamingo Bay, but much of this is comparatively recent. Other deposits were observed at the heads of the embayments of the southeastern section of the island. None of these deposits are marginal, and there is no indication that they formed within the cuesta in an inner lowland.

Probably the dissection of the coastal plain is not the outcome of a single stage of uplift and denudation, succeeded by drowning. There seems to have been initially a moderate amount of uplift, followed by partial excavation of the old lowlands, youthful dissection of the marginal coastal plain, and formation of cuestas and inner lowlands where the nature of the Tertiary deposits permitted. A second maximum uplift inaugurated such active erosion upon the oldland monadnocks of Culebra and Vieques, that aggradation of the valleys and inner lowlands occurred and was succeeded ultimately by degradation of the entire platform. Later submergence has largely stopped erosion, except for the slow denudation in process on Vieques and Culebra, while deposition is again going on in all of the submerged areas.

The Submarine Platform

Fluvial dissection of the coastal plain effected the re-excavation of the third-cycle lowlands, whose submergence has produced the submarine platform. The submergence appears to have occurred in two stages, the second of which is responsible for the present level. The history of the Culebra-Vieques submarine platform is an integral part of the history of the northern Virgin Islands platform; and, as the latter's development has been fully treated in the second chapter of the present report, only the special features found in the Culebra-Vieques region require discussion.

Perhaps the most striking feature brought out by a study of the surface of this part of the bank (Part I, Plate II) is the absence of any "submarine terraces," whose occurrence is described by Vaughan in the adjoining Virgin Islands bank. There are, it is true, a large number of shoals which rise from depths ranging between eight and eighteen fathoms, and which are now submerged to subequal depths, usually five or six fathoms. How far these shoals represent comparatively recent growths of coral reefs or flat-topped mesas of the dissected Tertiary coastal plain, it is impossible to determine. Aside from the shoals the bank appears to express simplicity and unity of development. Prominent submerged escarpments are few and are limited to the eastern ends of Vieques and Culebra, the northern side of Culebra and the Cordilleras Reefs, with a subordinate scarp on the south side of the latter and low scarps on the flanks of the shoals. Here, also, as in the northern Virgin Islands, the margin of the bank is an abrupt drop to depths of several hundred fathoms both north and south. It is accentuated in most localities by a narrow drowned reef or by broader shoals rising above the platform at its brink, although along the northern edge the shoaling usually occurs one to four miles within the rim. The entire surface of the bank is modified extensively by coral growth and by sand and mud deposits, which make it difficult to restore the erosional surface developed by fluvial dissection of the coastal plain. In a general way, however, the original surface of denudation can be approximately determined.

The floor of the platform is exceedingly level over large areas. Nearly 100 square miles of Vieques Sound have less than 30 feet of relief; and approximately 150 square miles of the northern part of the bank, lying between Icacos Cay and Virgin Passage, and between the northern edge of the bank and Cordilleras Reefs and Culebra, present gently sloping to flat surfaces. The slope is northward and varies from 0–15 feet per mile. These two flat expanses are separated by Cordilleras Reefs and Culebra; they merge into Virgin Passage on the east and terminate westward in the shallow water, broken by reefs, shoals and islands, off Porto Rico. There the irregularity of the surface, in marked contrast to the more extensive level stretches to the east, bespeaks imperfect dissection, complicated by coral growth on the drowned hilltops. The level area of central and eastern Vieques Sound slopes gradually from a depth of 8 to 12 fathoms off Vieques and Porto Rico to depths of 16 to 17 fathoms in the central and northern portions of the sound inside Cordilleras Reefs. The deepest areas are basinal because of the irregular deposition of clastic materials on the bottom in recent time. Although a young marine plain of deposition is being formed, the flatness of the surface is not due to the accumulation of sediments, but is rather the outcome of the earlier dissection of the horizontal coastal plain. Ample proof of such an origin for the sound is afforded by the behavior of submarine contours at its mouth between eastern Vieques and eastern Culebra. Depths of 85 to 90 feet persist almost to the outlet of the sound, but end against a low submerged ridge which rises 20 to 50 feet above the surrounding surface. The ridge is long and narrow, extending from the Tertiary cuesta on eastern Vieques to the shoals east of Culebra. The ridge is broken by a gap, 84 feet deep, three and a quarter miles north of the coastal plain on Vieques, and by a broader gap, 80 feet deep, two miles from Culebra; but elsewhere it is continuous. South of the southern break, the western slope, though gentle, is steeper than the eastern. The form and outline of this ridge, as well as its position and its connection with the coastal plain on eastern Vieques, strongly imply that it is part of the Tertiary coastal plain, eroded to greater depth than the strata on Vieques; and that it is a

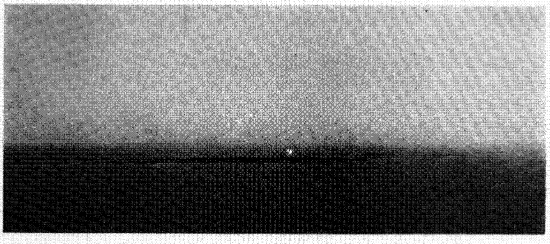

FIG. 53.—*Icacos Cay and Cordilleras Reefs islands*

low cuesta facing inward upon the Vieques Sound lowland. The gap near the center is an old valley which was cut through it in the course of its dissection. The characteristics to be expected of a dissected coastal plain are also found immediately east of the ridge and southeast of Culebra in Grampus Shoals and their prolongations.

The nature of Cordilleras Reefs, the barrier between Vieques Sound and the northern lowland, demands careful consideration. It consists of a long, narrow ridge with faint beginnings three and a half miles north of Luquillo, Porto Rico, attaining excellent development one mile north of Cape San Juan and continuing to Cactus Cay, three and a half miles west of Culebra, a total distance of twenty miles. It rises above sea-level in Las Cucarachas, Los Farallones, Icacos, Ratones, Lobos and Diablo cays, and in Hermanos and Barriles reefs, as well as in other diminutive unnamed islands (Fig. 53). The eastern half of the ridges rises from a base 80 to 100 feet below sea-level to a flat-topped

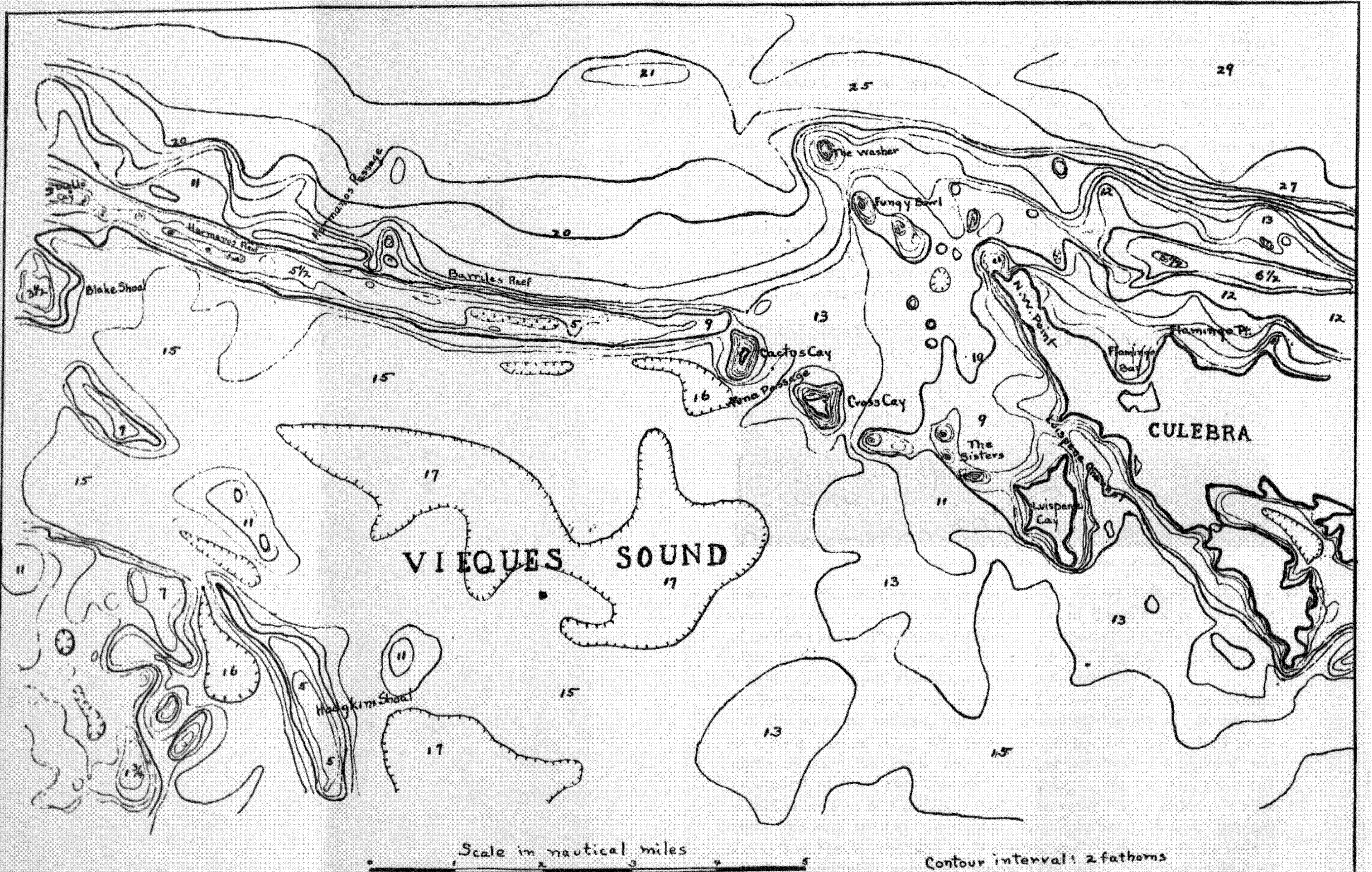

FIG. 54.—*Northern Vieques Sound and the eastern half of Cordilleras Reefs, showing the submarine topography*

summit averaging 30 feet below sea-level, but it attains the surface in numerous small rocks in Barriles and Hermanos reefs (Fig. 54). Along many miles of its length it is a double ridge whose northern and southern members are separated by a trough of slightly deeper water. When it is double, one ridge (commonly the southern) is strong; the other, weak and broken. In the eastern half of its extent the entire ridge rises from the platform base in a moderately steep escarpment on the north, and in an almost equally prominent escarpment on the south; but in its western portion the southern escarpment is low and gentle, sinking gradually to the shallow depths (less than 11 fathoms) off the Porto Rico mainland. East of Blake Shoal the southern escarpment is uniformly simple. On the north the scarp is simple only in its eastern portion (the Barriles Reef section), where it drops from five fathoms at the crest of the reef to seventeen fathoms. From Hermanos Passage westward, it changes to a low compound slope with an average declivity of one degree. In the vicinity of Hermanos Reef and Diablo Cay it slopes evenly and gently north-northwestward to a depth of 12 to 14 fathoms; at this level the declivity increases to two degrees to a depth of 21 fathoms; then flattens out to a slope of five feet to the mile toward the northern margin of the platform. The crest of the ridge varies between a half mile and a mile in breadth; the base, from one to two miles (Fig. 54).

The use of the name "reef" for the Cordilleras ridge is misleading. It suggests coral-reef origin, and although some coral heads were observed in active growth at scattered localities along its crest, they appear to have played but little part in its origin. Examination was made of the rocks composing the islands which rise above the reef. Although it is believed that these rocks do not compose the ridge to its base, they suggest some strong analogies to features found in the northwestern part of the Fajardo District of Porto Rico, where origins and geological history were plainly decipherable. Icacos, Ratones, Lobos and Diablo cays are made up of consolidated thin- to medium-bedded lime sandstones or calcarenytes, which exhibit strong cross-bedding. The perfection of sizing and rounding of the grains, as well as their purity, implies æolian origin, which, however, the irregularity of the cross-bedding does not fully confirm. The white color of the formation and the irregularity of its cross-bedding make it stand in strong contrast to the San Juan formation of Porto Rico, which is buff-colored and regularly cross-bedded. Yet in the peculiarity of its position, degree of consolidation, and perfection of sorting it resembles the San Juan formation so closely that it will be considered an equivalent formation of wind-blown origin. From the data available, contemporaneity of origin may be assumed for both formations. A similar conclusion concerning their age and origin has been reached by Lobeck.[37]

In northern Porto Rico the San Juan formation is invariably associated with the coastal plain. In the Arecibo District the association is direct; but in the northeastern San Juan and northwestern Fajardo districts the formation—a long ridge paralleling the coast—rises higher than the coastal plain on which it rests, and so stands above sea-level, whereas the underlying coastal plain deposits have been submerged. The San Juan formation thus serves as a barrier behind which are embayments and lagoons. The easternmost outcrop of the San Juan formation is at Punta Vacia Talega, about two miles west-northwest of Loiza, although the coastal plain is probably buried beneath the surface at least as far as the mouth of Rio Grande. If the San Juan ridge on Punta Vacia Talega and the more westerly peninsulas on which it outcrops be projected eastward, the line of projection is found to coincide with the Cordilleras Reefs. This suggestive alignment, worth little if considered by itself, acquires significance when taken with the other evidence that implies the equivalency of the San Juan formation of Porto Rico and the rocks of the Cordilleras cays.

Uplift and dissection of the coastal plain took place in Miocene time; the age of the San Juan formation is considered tentatively as Pleistocene, and its origin is associated with resubmergence of the coastal plain after its dissection. A question immediately arises: Were Vieques Sound and the northern platform excavated as continuous lowlands during Miocene and Pliocene time? If so, or if not, what is the relation of the Cordilleras Reefs calcarenyte to the coastal plain?

In the city of San Juan, its type locality, the San Juan formation has a thickness of not less than 100 feet, but in other localities a thickness of 50 feet is the average. It is doubtful whether any of the Cordilleras Reefs formation is more than 50 feet thick, but the entire ridge rises 100 feet above the platform. It appears likely, therefore, that it rises above a base of Tertiary material. A study of the submarine contours with a view to establishing the late Tertiary drainage lines upon the platform indicates that the Cordilleras Reefs barrier existed through the late Tertiary period of dissection, although subsequent deposition upon the surface of the bank makes accurate interpretation impossible. Drainage from western Vieques, Vieques Passage and eastern Porto Rico (south of Rio Fajardo) seems to have been directed northeastward and eastward across Vieques Sound lowland, passing out

[37] Lobeck, A. K.: Op. cit., pp. 348 and 362.

upon the northern lowland through Tuna Passage valley, three miles west of Culebra, where superposition is suggested (Fig. 54). The most deeply dissected portion of the Vieques Sound lowland lies in the north, sometimes at the foot of Cordilleras ridge, as might be expected if the ridge is a cuesta formed upon coastal-plain materials with a gentle dip to the north. Rio Fajardo may have joined this drainage system on the north, although the present depths suggest a northwest course for it through San Juan Passage. The drainage of Culebra, eastern Vieques and the eastern lowland seems to have found an outlet through the low ridge between the eastern ends of the two islands, making its way southeastward to the Caribbean. In Virgin Passage drainage appears to have been north and south, the divide extending from the southern margin of Culebrita slightly north of east to Savana Island. A spur extended southeast from the main divide to Sail Rock. In western Vieques Sound several of the shoals, such as those between Hodgkins and Blake shoals, appear to represent not recent coral accumulation, but incompletely reduced remnants of the horizontal coastal-plain sediments. To what extent the other shoals may be of similar origin is not determinable from the data at hand, but might be learned from field examination of the rocks which protrude above the surface of the sound.

The northern and Virgin Passage areas of the platform have a simple surface, presumably erosional, but modified by deposits which have filled in most of the drainage irregularities. Their average level is slightly lower than that of the Vieques Sound lowland, as might be expected from their proximity and direct relation to the late Tertiary baselevel. Yet the marginal ridges along their outer limits near the edge of the bank need consideration. The simplest interpretation of their origin is, of course, that they are barrier reefs, later in origin than the surface of the bank, and consisting of reefs that grew during late Pliocene or early Pleistocene submergence. Exposure or drowning terminated their development. This explanation seems applicable to the marginal ridge south of Vieques, where the narrow ridge encloses undrained basins, whose origin could not have been a normal feature in fluvial dissection. The series of ridges near the edge of the bank north of Cordilleras Reefs, Culebra and Virgin Passage offer a striking contrast in several respects to the reefs along the southern edge of the bank. The latter hug the margin of the platform and are continuous with its outer slope. They are narrow, rarely exceeding 300 yards in width, and commonly measuring less than 200 yards; and they ape every bend and angle of the platform boundary. They are amazingly persistent, extending more than 30 miles south of the Virgin Islands without a single gap cutting through to the base of the reef, although there is moderate variation in the depth of its crest below sea-level. (These statements do not apply to the broken ridges south of Virgin Passage.) To the regularity and simplicity of the southern reefs, the ridges near the northern margin present the following contrasts:

(1) They are situated at varying distances inside the edge of the bank, rarely less than a half mile, commonly as much as two miles.

(2) Their northern slopes are not continuous with the steeper outer slope of the platform, but have a declivity of less than two degrees.

(3) Their trend conforms imperfectly with the trend of the platform margin, and most of the local flexures in each are independent.

(4) The northern ridges are uniformly broader than the southern reefs, a width of one mile being common; they are also more complex, exhibiting a variety of spurs and re-entrants.

(5) They are not persistent. Nowhere do they extend more than ten miles without a gap cutting through to their base, and shallower gaps are of common occurrence.

Several similar ridges are found four to ten miles south of the edge of the platform north of Virgin Passage, while south of Virgin Passage three analogous isolated ridges or mesas occur along the border of the bank. The ridge three and a quarter miles east of Vieques is most prominent.

From the contrasts enumerated it seems reasonable to conclude that a distinction must be made between marginal reefs and marginal ridges. The latter appear to represent partly dissected remnants of the coastal plain, whereas the reefs represent post-Tertiary accumulations of coral growth. This tentative explanation is offered for whatever it may be worth, to explain the strong divergence in the two types of marginal barriers.

Culebra and its dependent cays occupy an isolated position, standing in strong relief above the surrounding submarine platform. On the west and south, the depth of the bank is 12 to 15 fathoms; on the east, it is 12 to 25 fathoms, increasing regularly from south to north. North of the island there is, in succession, a descent of 12 fathoms to a narrow trough parallel to the coast, a ridge rising to a maximum of 5½ fathoms also paralleling the coast a mile offshore, a low cliff 30 feet high facing the Atlantic, then a gentle northward slope to 13 fathoms; finally, a moderate to strong descent to the deeper platform level, which is here 26 to 28 fathoms deep.

The isolated position of Culebra seems to be the result of three factors: (1) the strength of the rocks composing it; (2) the structure of the rocks which lie nearly horizontal, and which probably form a shallow synclinal trough or basin;[38] (3) an assumed favorable position with regard to late Tertiary drainage lines. The alignment of cays on the western side of the island, such as the Cactus-Luispena series and the Fungy Bowl-Northwest Point chain (both independent of the northwest fracture system), seems to depend upon structure, but difficulty of access to the outer cays made it impossible to verify this assumption. The shoals on the northern and eastern flanks of Culebra may be interpreted in two ways: (1) They may be developed upon Cretaceous rocks dipping inward toward the axis of the syncline, with erosion scarps facing outward. North of the island the absence of a strong inward-facing scarp and the comparatively steep northward-facing scarp below the 13-fathom level favor this interpretation. (2) They may be dissected Tertiary coastal-plain deposits—a view favored by the steep inward-facing scarp bounding Culebrita Reef on South Channel, and by the apparent continuity of the shoals east and southeast of Culebra with the coastal-plain ridge extending southward to Vieques. In either case the concentric arrangement of shoreline, channels and shoals is satisfactorily accounted for. Theoretically, the criteria on which a decision between the alternatives could be made are so sharply defined that a ready conclusion might be expected from examination of the charts. Decision is rendered difficult, however, by the inadequacy of information contained on the small-scale charts. The conclusion suggested by the available data is that north of Culebra, where the dominant scarp faces away from the island, the shoal is formed upon Cretaceous volcanics; that east and southeast, where the most prominent scarp faces inward and the lower outward-facing scarp appears to depend largely upon accentuation by modern coral growth, the shoals are developed upon submerged coastal-plain deposits.

All considerations indicate that the development of the submarine platform from Porto Rico to Virgin Passage was the outcome of uplift of not less than 350 feet, following deposition of the coastal plain. The dominant factor in the formation of the platform was fluvial dissection, operating effectively upon the newly deposited coastal plain, less effectively and more slowly upon the harder and remoter oldland rocks. As a

[38] The conclusion that the structure of Colebra is synclinal is put forth tentatively, because it could not be completely verified by field observations. The rocks are essentially massive without observable dip or strike, except on the shoreline southeast of Flamingo Point, where gently undulating stratified volcanics showed no constancy in amount or direction of dip. The conclusion is based on the presence of a westward-dipping Cretaceous cuesta in the eastern part of the island, and the semicircular arrangement of islands, shoals, channels and escarpments from the northern to the southeastern side of the island.

rough estimate, at least nine-tenths of the bank now under water was covered by the coastal plain, and it is believed that Tertiary limestones, much reduced in thickness, still cover a large portion of the platform floor. There is no conclusive evidence that marine planation played any part except on the outer mile or two of the northern edge of the bank. If it could be proved that the marginal ridges are of comparatively recent reef origin, there would be grounds for assuming that marine planation might have been effective as far south as the Cordilleras Reefs and Culebra escarpments, but this possibility is not demonstrable. A series of profiles across the bank from south to north shows three apparently recurrent levels or terraces—an upper one at 4 to 6 fathoms, an intermediate one at 12 to 17 fathoms (Vieques Sound), a lower one at 23 to 30 fathoms (Part I, Plate II). The upper one appears to be of late origin and will be discussed in the next section; the other two have been interpreted by Vaughan as the result of two distinct periods of marine planation. The present study has attempted to disprove the view that the platform was developed in two cycles, and to prove that it was formed during a single cycle in which marine planation was of no importance. The platform floor has been modified to a considerable extent by post-Tertiary deposition, especially in Vieques Sound, where land-derived sediments, coral growth and coral fragments, without means of egress to the more open portions of the bank, have been actively altering and building up the surface. Less extensive but important modifications have been made in Virgin Passage and on the bank north of Cordilleras Reefs and Culebra.

The genesis of the platform appears to have been in no way related to depression of the ocean level during Pleistocene glaciation. Vaughan in his study of this area[39] seems not to have taken into account the pre-Pleistocene history of the platform. His paper is primarily concerned with the so-called outer flats, particularly those north of Cordilleras Reefs and Culebra, and the corresponding ones north of Saint Thomas, Saint John and Tortola. According to his interpretation a submarine flat was formed at depths of 17 to 20 fathoms, followed by emergence and wave planation of the platform at depths of 26 to 34 fathoms along its seaward margins, succeeded by submergence to the 6- to 10-fathom level. His evidence has already been outlined in considering the development of the platform in the northern Virgin Islands. He says in part: "The escarpment extending from the islands north of Culebra Island, east of Porto Rico, across the Virgin Passage, and along the north side of Saint Thomas, and the escarpment on the face of the

[39] 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, No. 3, pp. 53-66.

outlying shoals can be explained in no other way:" namely, than as a wave-cut cliff at the landward margin of a submarine plain, "developed when sea-level was about 20 fathoms, or slightly more, lower than now."[40] Against this assertion it must be contended that the escarpment does not exist in Virgin Passage; that it exists north of Saint Thomas only off islands and promontories—never between them—and that such an escarpment would have developed north of Culebra and Cordilleras Reefs by normal fluvial erosion because of the structure and strength of the rocks and their position with respect to drainage lines during erosion. In describing the platform north of the Virgin Islands, Vaughan ascribes to Barracouta, Kingfish and Whale banks an origin other than that of coral growth.[41] These banks or shoals resemble the marginal ridges north of Cordilleras Reefs and Culebra in contour and in their relation to the platform. All of them, it is thought, are remnants of the Tertiary coastal plain. With these serving as buffers to the sea, manifestly the sea could do little work toward developing a sea-cliff behind them. Marine origin, therefore, for any portion of the platform except the narrow and irregular bench outside (north of) the marginal ridges appears unlikely. The formation of the platform lowlands was accomplished mostly before Pleistocene time, subsequent to formation of the coastal plain in Oligocence time and its emergence shortly thereafter. Submergence to the six- to ten-fathom level may have taken place before the Pleistocene, but the migratory nature of the strandline during five stages of withdrawal and return of the water, corresponding to the five glacial advances, makes very doubtful any assumption that extensive marine planation was accomplished at definite levels during Pleistocene time.

Submergence of the Submarine Platform

The embayed shorelines of Culebra, Vieques and eastern Porto Rico, as well as the relations of the smaller islands to the coasts, are ample proof of submergence. Whether the submergence is the result of a single change from the level at which the platform was formed, or of more than one shift in level, is the chief problem connected with this stage of physiographic history. Two lines of evidence may be used to reach a conclusion: marine erosional levels and depositional levels. The former may be expected on the seaward margin of the land areas, especially those facing the Atlantic; the latter may be looked for in the coral reefs whose growth was connected with the submergence of the platform, and also in protected areas where clastic materials have accumulated.

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[40] Vaughan, T. W.: Op. cit., pp. 59-60.
[41] Vaughan, T. W.: Op. cit., p. 59.

One mile north of Culebra, and separated from it by a channel 12 to 13 fathoms deep, is a rocky bank which joins Northeast Cay and Culebrita to the east and southeast, and which, because of this relation, was considered above to consist of Cretaceous volcanic rocks. Its flat crest ranges only from 5½ to 7 fathoms, but descends to 9 fathoms in the channel which separates the ridge from Northeast Cay. It slopes gently, but not quite evenly, northward to a depth of 11 to 13 fathoms, where there occurs a distinctly sharper escarpment to 26 or 28 fathoms. A corresponding gentle northward slope from 5½ to 11 fathoms is found north of Northeast Cay, and a flat is developed between 4 and 12 fathoms between Culebrita and Palada cays. Where Cordilleras Reefs have not been breached and are not modified by recent coral growth, their summit is uniformly level at 5 to 6 fathoms (Fig. 54). Where islands are present, as at Diablo Cay or at Northeast Cay, the descent from sea-level to 6 fathoms is very abrupt and has all the characteristics of a wave-cut cliff. The low northern slope of Cordilleras Reefs is presumably due to the dip of the coastal-plain sediments which compose it, as discussed in the previous section. But the slope may have been modified or perfected by marine planation. Marine erosion forms a wave-cut cliff approximately at sea-level and forms a graded wave-cut terrace below sea-level. The presence of these features 25 to 30 feet below sea-level indicates a stand of the sea at that elevation sufficiently long to plane off platforms as much as a mile across. The level is recurrent in many localities, chief of which are numerous shoals (including Hodgkins) in the western part of Vieques Sound and local stretches along southern Vieques.

If baselevel remained at the 5- or 5½-fathom level long enough for the planation of terraces one mile wide, considerable filling of embayments must have been accomplished. Because dissection had proceeded to a much lower baselevel prior to submergence, fairly deep embayment of the larger valleys occurred, and alluvial filling followed when these were drowned. Deposition during this stage of development must have been far more extensive than that which followed upon the final submergence, which occurred so recently that comparatively few of the normal effects have had opportunity to develop.[42] It follows, then, that the depth of water in many of the embayments will offer testimony for or against a baselevel at 5 or 5½ fathoms. Thus, in eastern Vieques. Ensenada Honda encloses two depressions, one at the eastern side 4 to 6 fathoms deep, connected with the sea by channels less than a fathom

[42] Compare the width of the wave-cut terrace formed during the final submergence. where recent slight uplift has exposed it: Lobeck, A. K., op. cit., Fig. 37, p. 367; Fig. 38, p. 369; Johnson, D. W., Shoreline processes and shoreline development, frontispiece

deep; the other on the western side, 4 to 4½ fathoms deep, with a narrow outlet of 3½ fathoms. Salina del Sur is 3½ to 4½ fathoms deep, with a slender channel connection of equal depth to the southeast. In Culebra most of Great Harbor shows soundings of 4 to 7 fathoms, with water 13 fathoms deep immediately outside the narrow mouth. Flamingo Bay, almost completely enclosed by shallow water, has depths of 4 fathoms in much of its center. South Channel affords a very striking case of partial filling: south of Culebrita a narrow belt nearly one mile long is consistently 12 to 14 fathoms deep, while the outlets to the north and south have been filled to depths of 6 or 7 fathoms. Other examples might be taken from eastern Porto Rico (*e. g.*, Ensenada Honda); but those given suffice to show that in the larger bays and channels which were cut deeper than 5 fathoms during late Tertiary dissection, submergence was accompanied by alluvial filling, which tended to build up their bottoms to a depth of 4 to 6 fathoms. All of the smaller bays and parts of the larger ones have been built up higher than this depth during the greater submergence which followed, but the evidence of the existence of a lower base of deposition has not been fully destroyed.

South of Vieques there is a narrow drowned reef at the margin of the platform, analogous in all respects except in length and regularity to that described south of the British Virgin Islands and Saint John. The reef was built up to 6 fathoms in places, although an average depth is 8 to 10. Its growth was apparently contingent upon submergence to the five-fathom level, and its death was probably not the result of sudden drowning to the present sea-level, but of exposure during temporary withdrawal of the water during Pleistocene glaciation. From these three lines of evidence; namely, (1) marine planation, (2) alluvial filling of drowned valleys, and (3) growth of a marginal reef south of Vieques and Vieques Passage, all to a baselevel at an approximate depth of five fathoms, it seems certain that submergence was accomplished in at least two stages, one to the level just described in preglacial time; the other to the present level in postglacial time.

A special phase of the earlier submergence was the formation of dune sands above high-tide level along the crest of the Tertiary cuesta which underlies Cordilleras Reefs. In discussing the origin of the San Juan formation on the Cordilleras Reefs, Lobeck[43] relates its formation to the submergence which brought the strandline to its present position. So far as the Cordilleras Reefs occurrence of the San Juan formation is concerned, however, its origin must have antedated the latest submergence. Similar sands are forming today above high water along

[43] Lobeck, A. K.: Op. cit., pp. 361-366.

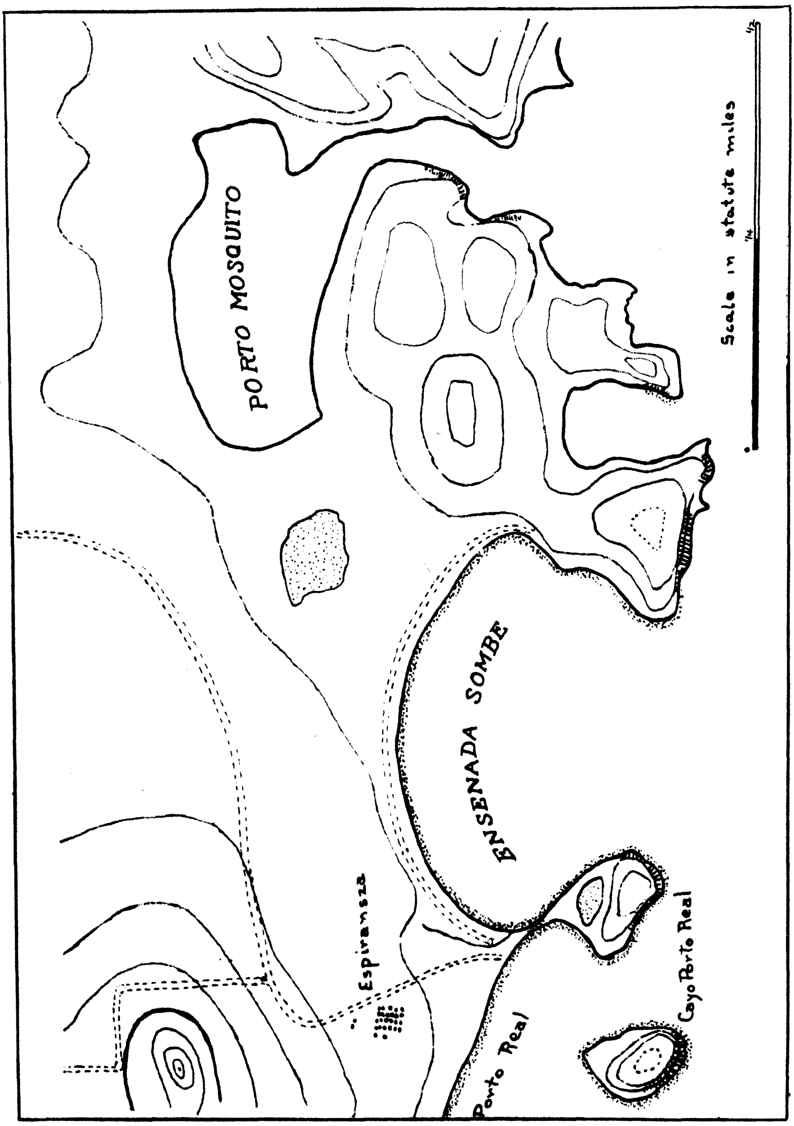

FIG. 55.—*Discontinuous bays partly occupying the inner lowland of southern Vieques*

extensive stretches of sandy beach, often on a scale comparable with the extent of the San Juan formation. The dune sand forming the ridge along the northern shore of Anegada is an example which in all respects is analogous to the Pleistocene dune deposits of the Cordilleras Reefs. The Anegada sands are unconsolidated and have been derived from the clastation of coral heads and limestone in the adjacent waters. They rise above a comparatively recent section of the coastal plain and lie entirely above the level of high tide. The Cordilleras Reefs calcarenyte, it may be assumed, underwent similar development in the Pleistocene along the crest of the unsubmerged Tertiary cuesta. Its consolidation occurred with post-Pleistocene submergence, by which it was carried partly beneath the water-level. The thickness of the dune sand may be estimated as the sum of the elevation of the islands composed of it and the 25 to 30 feet which now lie below sea-level, a total of not more than 75 feet.

It seems probable, also, that final removal of the Tertiary cuesta which surrounded Vieques, and behind which alluvial material had accumulated, was largely effected while the sea stood at the five-fathom level.

The Present Level

The final drowning of 30 or 33 feet, which brought the sea very nearly to its present level, produced few effects which have not already been encountered in the northern Virgin Islands. The filled, or partly filled, embayments again became areas of alluvium and sand accumulation, and most of them have been built up in part above the five- to six-fathom level of earlier deposition. The inner lowlands of southern and eastern Vieques were drowned, with the production of discontinuous flask- and bowl-shaped embayments (Fig. 55). These are sometimes all but connected by shallow lagoons, such as that between Porto Ferro and Porto Mosquito, and the two between Salina del Sur and Porto Salina. A few of the shallow bays have had bars formed across them, as at Playa Grande, Vieques, where a bay-mouth bar encloses a large lagoon, and at Flamingo Bay, Culebra, where a mid-bay bar forms the seaward side of a small lagoon. The lagoons in the vicinity of Punta Arenas appear to have formed as a result of bar formation by littoral currents moving northwest along the west coast and west along the north coast, with the spreading and piling of the sand by wind, and probably with slight broadening of the bars by very slight emergence. The converging littoral currents from the north and west shores of Vieques are building Punta Arenas northwestward into Arenas Bank, a lime-sand bank, one and a quarter miles wide at the base, tapering gradually to a slender point three miles northwest of its unsubmerged extremity—Punta Arenas (Plate IV). The development of Arenas Bank, bar formation and partial filling of the embayments are the chief depositional effects of the latest submergence; but others merit mention. Double tombolos connect the point between Porto Real and Ensenada Sombe with the mainland (Figs. 52 and 55), the northern and southern hills of Luis-pena Cay with the central block of the island, the Cape Passage peninsula of Culebrita with the rest of the island, and Point Soldado with the peninsula forming the southwest side of Great Harbor. Upon numerous shoals in Vieques Sound, and around portions of Vieques and southwest Culebra, coral heads and small reefs are growing vigorously, but elsewhere this activity is unimportant. Graded beaches have been developed around most of Vieques and southern Culebra, but on the north side of Culebra (except along Northwest peninsula) a beach is rarely present, depths of four to nine fathoms occurring close inshore. The filling of the drowned lowlands has, of course, continued, but there is no means of differentiating the results accomplished before and since maximum submergence.

Some erosion has also been accomplished toward the present baselevel. The fluvial erosion cannot be distinguished from that of the preceding level, but the amount is presumably small. Marine erosion, however, has accomplished considerable work in central and western Vieques and on the Cretaceous headlands and Tertiary cliffs in the eastern portion of the island. Large areas of the island slope moderately toward the coast, but the slope is truncated by a wave-cut cliff, 15 to 30 feet high, which has been cut indiscriminately in Cretaceous volcanics and intrusives, Tertiary limestone and late Tertiary or Pleistocene alluvium. The higher cliffs are usually associated with the limestones and alluvium, which, presumably, have been cut back farther because of their inferior resistance. It is a striking fact that none of the cliffs observed are now being actively worn back, but usually front upon narrow wave-cut terraces, strewn with coarse debris. The terraces are commonly awash where narrow and formed upon rocks, but they extend beyond the wash of the waves where broad and developed upon alluvium. Recent slight emergence has thus exposed the wave-work accomplished during maximum drowning, so that the amount can be accurately measured. The wave-cut terrace varies in width in direct proportion to the degree of consolidation of the material upon which it was cut. On the alluvium along the coast of northwestern Vieques it may be as much as 30 or 40 yards wide, though usually less. In the limestone areas along the south shore it is rarely more than four or five yards wide and is often absent.

particularly on headlands, where a steep, narrow beach may take its place. In the Cretaceous intrusives and volcanics it is only rarely present as a distinct bench, but is replaced by a steep, narrow beach, grading upward to a wave-cut cliff beyond the reach of present wave-cutting. On Culebra, where only Cretaceous volcanics are present, there is little visible result of recent marine erosion. Steep beaches occasionally occur, except along the north coast, where the depth of water offshore has thus far prevented wave erosion. For this reason, also, evidence for recent slight emergence is meager. On the cays of Cordilleras Reefs wave-cutting at the level of maximum submergence proceeded vigorously and was apparently responsible in large part for the broad shallow-water areas, less than one fathom deep, surrounding several of the larger cays. The smaller ones suffered most of their erosion at the pre-Pleistocene level, and characteristically drop off into five or six fathoms of water without any higher terrace developed upon their flanks. In some cases, at least, their surfaces represent the marine terrace of maximum submergence.

Recent Slight Emergence

In the preceding section the fact was brought out that the Vieques-Culebra area has undergone very recent uplift of not more than ten feet. For convenience, the evidence will be briefly summarized without additional discussion.

(1) Narrow wave-cut terraces, varying in width with the type of material in which they were formed, occur locally above the wash of the waves.

(2) Wave-cutting has ceased on practically all of the wave-cut cliffs (except in northern Culebra, where apparently it never began), which are now above the reach of the waves within high beaches or the terraces described above.

(3) The height and declivity of many of the beaches fronting wave-cut cliffs indicate that they are but partly graded to the present sea-level and were formed initially at a higher elevation.

(4) Bars and tombolos, whose materials are unmodified by wind action, show a width and elevation that is not compatible with normal development at the present water-line.

CONCLUSIONS

Except for minor points of difference in the land-forms of the Virgin Islands, Saint Croix and the Culebra-Vieques area, the physiographic history of all three areal divisions has been essentially alike.

So close is their relation that their physiography could have been treated under another areal grouping with equal propriety. Thus, Culebra might have been included with the northern Virgin Islands, for, like them, it lacks an emergent coastal plain. Saint Croix and Vieques, both of which are partly overlapped by Tertiary coastal-plain deposits that are absent on the other islands, are closely related not only physiographically and geologically, but botanically as well. They could with good reason have been considered jointly, for their chief differences are largely the result of unequal amounts of coastal-plain dissection and submergence. It is not surprising to find a close relationship between the land-forms of Culebra and Vieques and those of the northern Virgin Islands. The fact that they all rise from the same shallow platform, directly connected with eastern Porto Rico, is in itself indication that their development has been closely parallel and has been similarly parallel with that of Porto Rico. That the land-forms of Saint Croix, notwithstanding the island's present isolation, should also display the same succession of events not only is surprising, but has a significant bearing upon the tectonic history of this part of the West Indies. The characteristics and even the elevations of its land-forms are comparable in every respect with those of the islands to the north. A review of the physiographic forms on all of the islands and their relation to those of Porto Rico will serve to emphasize the unity of their development.

The Upper Cretaceous history of vulcanism and subordinate sedimentation, terminated by orogeny and uplift, was the same from the western end of Porto Rico to Virgin Gorda (Part I, Fig. 1), and from Tortola and Jost Van Dyke to Saint Croix. A large, single oldland was formed, and during early Tertiary time it underwent three cycles of erosion, the first two terminated by uplift, and the third by submergence. The first cycle formed the upper peneplane of Porto Rico and the Saint John peneplane of the northern Virgin Islands, leaving but few residual monadnock groups rising above the fluvial surface which was formed. The second cycle[44] caused the destruction of much of the earlier peneplane

[44] Since the present report went to press, the writer has spent four months in Porto Rico, studying the geology of the Arecibo district. In that portion of Porto Rico a late Tertiary erosion-level was discovered beveling oldland rocks and coastal plain alike, and lying about 800 feet below the first-cycle peneplane. Its relationships led to the suspicion that it might be the equivalent of what has been considered the second-cycle erosional surface in this report, and subsequent field work changed the suspicion to a certainty. The late Tertiary level was not identified by Lobeck, and in the Arecibo district its extensive development at the expense of the first-cycle peneplane led him to confuse the two. It appears, therefore, that the physiographic history of the area as outlined in the present report must be revised to the following succession:

1. First cycle—upper (Saint John) peneplane.
2. Second cycle—lower (sub-coastal plain) peneplane.
3. Coastal-plain deposition.

and produced an old erosional surface approximately 700 feet below the first. Thus, the upper peneplane was completely destroyed in Saint Croix and in the Culebra-Vieques area, and the uplands of these islands represent the second cycle erosional surface. The third cycle formed the lower peneplane of Porto Rico and a mature to old surface which extends beneath the coastal plain on Saint Croix and Vieques, and which underlies remnants of the coastal plain on the submarine platform. Formation of the lower peneplane was followed by deposition of a coastal plain in the middle Tertiary, and during late Tertiary time uplift exposed the coastal plain marls and limestones to dissection. The Tertiary deposits were formed in the entire area now constituting the submarine platforms of the islands, and the features of the platform-floor can in many cases be identified as fluvial forms of a dissected coastal plain. Toward the close of the Tertiary differential movement or warping caused submergence of the eastern Porto Rico and Virgin Islands regions, while western Porto Rico remained elevated. The submergence increased in magnitude as far east as Tortola, and there was formed a series of littoral features of marine erosion and deposition, which have been submerged an additional five fathoms since the Pleistocene.

Not only are all the physiographic events recorded in the land-forms of Porto Rico, Saint Croix and the northern islands, but the land-forms are spaced vertically at subequal distances. Thus, there is not a variation of as much as 200 feet in the relations of first-, second-, and third-cycle erosional surfaces in any part of the region. Only the levels developed by the two final stages of submergence are out of line and fail to parallel the earlier land-forms. The upper peneplane descends from an elevation of 2,000 feet in Porto Rico to 1,000 feet in Saint John. Similarly, the second-cycle surface descends eastward a corresponding amount. The third cycle, or lower peneplane, and the base of the Tertiary descend from an elevation of 600 feet near Lares to more than 200 feet below sea-level off Tortola. In a similar manner, the second- and third-cycle surfaces and the base of the coastal plain descend some 400 or 500 feet between Saint Croix and the northern Virgin Islands. On the other hand, the five-fathom level of wave erosion and marine accumulation is parallel to the present surface throughout all the islands

4. Uplift, warping and peneplanation of the coastal plain.
5. Uplift, second cycle of coastal-plain dissection.
6. Submergence, as outlined on preceding pages.

The findings of the season's field work were presented before the Geological Society of America in December, 1926, and will appear in print, it is hoped, in 1927. Further treatment of the subject will be published ultimately in the report on the geology of the Arecibo district in Volume II, Part IV, of the Scientific Survey of Porto Rico and the Virgin Islands.

and, like the present sea-level, bevels the earlier land-forms indiscriminately.

From these relations it appears that the entire Porto Rico-Saint Croix-Virgin Islands area developed as a unit until the late Tertiary dissection of the coastal plain was accomplished. Before the Pliocene-Pleistocene submergence, the entire region was tilted downward toward the northeast, and presumably at this time (Pliocene) the block-faulting occurred which separated Saint Croix from the northern islands. The last, or maximum, submergence has affected the entire region alike only because it involved a general shift in the strandline, and not a differential change in elevation in any of the islands.

BIBLIOGRAPHY

The excellent and full summaries which Professor Kemp has given in Part I of this volume, of the literature bearing directly on the geology of the Virgin Islands, would appear to make further bibliographic material superfluous. In the text of "The Physiography of the Virgin Islands, Culebra and Vieques," moreover, quotations and citations of opinions from other authors have been accompanied by footnote references to their works.

It will be noted, however, that two-thirds of the references in the footnotes are to works which have not been included in Professor Kemp's bibliography, because they are not concerned directly with the geology of the Virgin Islands, Culebra and Vieques. It was inevitable that a study which involves not merely local physiography but correlation of land-forms over a wider geographic area, would be forced to call upon literature dealing with a narrower scientific field, but a broader geographic field. The references which have been used include only a few of those reviewed by Professor Kemp, but embrace many which had no place in his summary. There has been, furthermore, no occasion to mention in footnotes many such works which were consulted, and which in all fairness merit mention. A bibliography appears, therefore, to be necessary, the more because it will assemble in a single section references to all the literature employed in the present physiographic study. Inasmuch as the physiographic history hinges upon the tectonic history of the Antilles, several titles dealing with this subject are included, even though they have not been helpful in any phase of the present work. The bibliography submitted thus includes:

(1) Works dealing specifically with the geography and physiography of the Virgin Islands, Culebra and Vieques.

(2) Works furnishing data concerning the geology of the Virgin Islands and Porto Rico that contributed to physiographic interpretations.

(3) Studies concerned with the physiography of Porto Rico and other Antillean islands, with which correlation has been made.

(4) Papers or longer contributions pertaining to the tectonic history of the West Indies.

(5) General geologic works, or articles dealing with specific areas other than the West Indies, from which analogies have been drawn.

The titles are arranged alphabetically by author, without classification and without critical comment. For other works dealing with the geology of the Virgin Islands, the reader is referred to Professor Kemp's splendid summary of the literature in Volume IV, Part I.

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