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THE FORMATION OF THE LESSER ANTILLES

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The Islands.—The island chain of the Lesser Antilles extends in a curve about 500 miles in length between Porto Rico and Trinidad, and includes 25 larger members with an uncounted number of smaller ones. Most of the islands are of volcanic origin, now in various stages of dissection; but five of the larger islands and two small ones consist wholly of calcareous strata, and five others are composed of both volcanic rocks and calcareous strata. Vieques and St. Croix, southeast of Porto Rico, and Barbados, east of the southern part of the chain, are of other origins. The following inferences regarding the history of the islands are based on observations made during a voyage in October and November, 1923, and on a study of all available charts and published articles. A fuller statement is in preparation for publication elsewhere.

The Circuminsular Banks.—Many of the islands are associated with submarine banks, from 20 to 40 or 50 fathoms in depth. The largest of these extends 80 miles eastward from Porto Rico with a width of 25 or 30 miles, and bears the mountainous Virgin islands, five of which are from 3 to 11 miles in length; but not St. Croix, which rises from a much smaller bank of its own, farther south. The second largest bank is at the other end of the chain, next north of Trinidad; it has a length of 98 miles and a breadth of from 10 to 17 miles, and includes the mountainous island of Grenada as well as the little Grenadines. Other island-bearing banks will be mentioned below. Besides these, a few additional banks, mostly of moderate or small size, are charted without islands; the largest of these is Saba bank, 33 by 20 miles.

Relation of Islands and Banks.—In general, the younger a volcanic island the smaller the bank around it; the older the island, as indicated by the stage of its dissection, the larger the associated bank. Thus Saba island, near the bank of the same name, is a young, moderately clift volcanic cone, 3 miles across and 2820 feet high, with a bank less than a mile wide around it. The long bank from which Statia, St. Kitts and Nevis rise appears to have been formed in association with the older, much degraded elements of those islands; their lofty younger cones are believed to have been built up on the bank after it had assumed nearly its present dimensions. The Virgin islands are of so ancient eruption that they are all elaborately dissected; some of them are mere skeletons; their bank is of large size. The little Grenadines are also elaborately dissected and rise from the northern part of a large bank; Grenada, on the southern part of the same bank, is of later origin and was probably piled up after the bank had been formed around small islands, like the Grenadines, of earlier origin, which are now buried beneath the new island.

Subsidence of Islands and Building of Banks.—All the maturely dissected volcanic islands have been more or less submerged since their eruptive growth was completed and while their dissection was advancing. This is shown by the embayments which enter the valleys or by the delta plains which replace the embayments. The submergence is ascribed to island subsidence and not to Postglacial ocean rise, because the embayed valleys are so maturely widened and, in a number of instances, their estimated rock-bottom depth at the bay mouth is so great that it is believed they could not have been excavated only during the Glacial epochs of lowered ocean level. Hence the banks around these islands have been built up by aggradational processes upon subsiding foundations. This makes it probable that, in the case of banks that bear no islands, the island foundations have been completely submerged.

The Islands Were Reef-Protected while the Banks Were Aggraded.—Coral reefs are at present imperfectly developed on the submarine banks, chiefly as discontinuous fringing reefs well back from the bank borders; but inasmuch as the inter-bay headlands have been only moderately and recently clift, it is believed that, during most of the period of island dissection and subsidence and hence during most of the period of bank aggradation, the islands have been protected from cliff-cutting by vigorous barrier reefs. It is only lately, and probably during the Glacial epochs when the temperature and level of the ocean were somewhat lowered, that such reef protection failed and that the headlands were clift. The fact that many of the headland cliffs plunge to a small depth below present sea level favors this view.

The Banks Represent Reef-Enclosed Lagoon Floors, Formed According to Darwin's Theory and Modified by the Processes of the Glacial-Control Theory. The Lesser Antillean banks are therefore interpreted as having been formed by the aggradation of lagoon floors that were enclosed by up-growing barrier reefs over slowly subsiding volcanic foundations, essentially according to Darwin's theory of coral reefs; but the barrier reefs are thought to have been cut off by low-level abrasion, the lagoon floors are suspected of having been somewhat planed down, and the headlands are believed to have been moderately clift, when the corals of the protecting reefs were weakened or killed by the slightly reduced temperature of the lowered ocean in the Glacial epochs, as postulated in Daly's Glacial-control theory. The reef foundations, however, are not supposed to have been stable, as is also postulated in that theory; and the 30-fathom measure there accepted for the lowering of the Glacial ocean has not been confirmed by observation.

The Lesser Antilles Lie in the Marginal Belt of the Atlantic Coral Seas.—The absence of vigorous, bank-border barrier reefs around the island-bearing banks of today and of vigorous atoll reefs around the island-free banks is ascribed to the position of the Lesser Antilles in the marginal belt of the Atlantic coral seas, where the temperature of Postglacial time is thought to be not quite so high as that of Interglacial and Preglacial time.[1] Some of the banks have been shown by Vaughan[2] to be slightly benched at several levels, as if by abrasion in the rising Postglacial ocean.

Contrast between the Lesser Antillean Bank Reefs and the Typical Reefs of the Pacific Coral Seas.—The existing bank reefs of the Lesser Antilles, as here interpreted, are novices of recent establishment, and therefore not the direct successors of the infered bank-border, lagoon-enclosing barrier reefs of Preglacial time. The two sets of reefs—the earlier ones of large depth, the later ones of very small depth—are probably separated by a surface of abrasion which truncated the earlier established reefs, and which serves as a foundation for the island-fringing novices of today. In this respect, the novice reefs of the Lesser Antilles are unlike the veteran barrier and atoll reefs of the Pacific coral seas; for there the reefs of earlier date do not appear to have been cut away in the Glacial epochs; and the present reefs, with their exterior slopes descending into deep water, are the direct successors of the earlier ones. It is only in the marginal belts of the Pacific coral seas that novice reefs of new establishment are found, comparable to the novice bank reefs of the Lesser Antilles.[3]

Second-Cycle Islands.—The Lesser Antillean islands which are composed of volcanic and calcareous rocks, or of calcareous rocks alone, have evidently suffered uplift; they and their submarine banks are therefore at present in a second cycle of development. They appear, however, to have been formed, before their uplift, in the same manner as the islands and banks which have not been uplifted. Insofar as their calcareous areas have subsequently been worn down to lowlands and submerged, or abraded to low-level platforms in the Glacial epochs, the resulting banks may be treated as of a second generation. Several of these second-cycle islands merit brief description.

Two Uplifted Atolls.—Marie Galante, an independent member of the Guadaloupe group, is a limestone island, 9 miles in diameter, with a very even upland profile at a height of 670 feet. It is little dissected, and appears to represent a recently uplifted bank or atoll; it is bordered by a narrow bank. Sombrero, a narrow limestone island a mile long and from 25 to 40 feet high, rising from a 3-by-4 mile bank, has been well described by Julien,[4] who interpreted it as the remnant of an uplifted atoll which was originally about as large as the present bank.

A Tilted and Partly Re-leveled Atoll.—Antigua and Barbuda, with the 30-mile bank between them, are believed to represent a tilted and partly re-leveled atoll. The atoll appears to have been tilted up in the southwestern or Antigua area, perhaps to a potential altitude of 8000 feet, and then worn down to moderate or low relief; but tilted down to a moderate depth and then built up again in the northeastern or Barbuda area. The beveled volcanic and calcareous rocks, dipping 10° or 15° northeast all across the Antigua area, have been well studied a number of geologists, most recently by Earle;[5] their reports give repeated evidence of island growth during a long period of slow subsidence, first by eruptive processes to a thickness of 5000 feet or more, later by calcareous sedimentation in Oligocene time to a thickness of at least 1500 feet. Confirmation is thus found for the inferences above stated concerning the origin of the banks that have thus far escaped tilting. The calcareous strata presumably represent lagoon deposits, at first enclosed by a barrier reef,[6] but later, when the volcanic island disappeared, by an atoll reef.

Second-Cycle History of the Antigua-Barbuda Atoll.—As the Antigua-Barbuda atoll appears to have been formed in Oligocene time, the uplift and erosion of its Antigua area presumably occupied a considerable part of later Tertiary time. After the erosion was so well advanced that the weaker calcareous beds were worn down to lowlands and the more resistant volcanic rocks were reduced to submountainous forms, the resulting island was further diminished in size by subsidence, which increased the area of the bank of second generation and embayed the island shore line; the evidence for this seond-cycle subsidence, like that for the first-cycle subsidence above described, is found in the form of the embayed valleys. During most of the time that the erosion of Antigua was in progress, it must have been, again as in the case of the first-cycle islands, protected from abrasion by encircling reefs; for here, as in the other islands, the subdued headlands between the broadly opened and partly embayed valleys are but little clift; yet here again, as in the other islands, the fact that the headlands were somewhat clift after they had gained essentially their present forms points to the occurrence of a relatively recent and brief interval, probably coinciding with the Glacial epochs of lowered ocean level and temperature, when reef protection failed. At present, novice reefs are found on the Antigua-Barbuda bank of second generation, similar to those on the banks of first generation.

Classification of the Lesser Antilles.—An ideal scheme of island development may now be outlined in terms of which the islands of the Lesser Antilles may be genetically classified. The scheme includes one complete cycle of island history and part of a second cycle. The first cycle opens with the eruptive upgrowth of a volcanic island, presumably on a slowly subsiding foundation; as the cycle advances the island may be increased in size by new eruptions, which for a time more than make good the loss of size caused by erosion and subsidence; then after eruptions cease, the submarine slopes of the slowly subsiding and diminishing island are more and more encroached upon by accumulating lagoon deposits within an upgrowing barrier reef; and when the island is wholly submerged the barrier becomes an atoll reef enclosing an island-free lagoon. A small episode of reef abrasion and of headland cliffing occurs at whatever stage of the cycle is attained when the Glacial period is encountered. The second cycle, introduced by upheaval or uptilting, may interrupt the first cycle at any stage in its progress. The second-cycle island thus exposed to developmental changes is not a young and growing volcano, such as was formed at the beginning of the first cycle, but an uplifted barrier reef with a central island or an uplifted atoll without a central island, and is composed of calcareous strata on a volcanic foundation; it then, with or without renewed volcanic activity, runs through a sequence of erosional changes associated with subsidence and renewed reef growth, again with an episode of abrasion when the Glacial period is encountered. Evidently, an island now well advanced in the second cycle was originally formed by volcanic eruption at a much earlier geological date than an island now at the beginning of its first cycle: but as the island in the second cycle is, after its time of upheaval, again subject to subsidence, it is inferred that young, first-cycle islands are also as a rule formed during the subsidence of the ocean floor.

According to this scheme, Saba is a small young island, probably of Pleistocene eruption. The Saints, next south of Guadaloupe, are a small group of maturely dissected, partly submerged, and moderately clift volcanic residuals, 5 miles over all, rising from a well defined bank, 8 or 10 miles across. Redonda, between Nevis and Montserrat, is a small, clift residual, less than a mile in diameter, rising from an imperfectly charted bank of moderate size; Redonda is therefore taken to be an abraded, almost-atoll islet. The small island-free banks close this simple series. Another series may be made of larger islands and banks. Montserrat includes a maturely dissected cone, probably of Pliocene eruption, adjoined on its clift northern side by a 2-mile bank, and overlapped on its southern side by the nearer members of a group of much younger cones, by which the island was increased perhaps ten-fold in size; the bank around their shores is of insignificant width. As already intimated, Statia consists of a deeply dissected cone on the north, in part overlapped by a young and loftier cone on the south; St.Kitts consists of several small volcanic residuals tied together by sand reefs and adjoined on the north by a group of lofty young cones; Nevis consists of three maturely dissected residuals, over and around which a loftier young cone has been built up; the bank 47 miles in length, above which these three composite islands rise, was probably formed as a barrier-reef lagoon floor on the flanks of the subsiding older elements of the group, and the newer cones were later built up on it. The occurrence of large slabs of limestone, some of them over a hundred feet across, on the flanks of the younger cone of Statia[7] and of Brimstone hill,[8] a small parasitic cone on a larger young cone of St.Kitts, supports this view. Dominica, Martinique, St.Lucia and St.Vincent are composite islands of larger size; their cones and mud-flows of later eruption, now moderately dissected, probably cover to a greater or less extent their earlier-formed banks as well as the still earlier erupted and much denuded smaller cones, during the subsidence of which the banks were built up. The deeply eroded and partly submerged Grenadines probably had, as already suggested, similar companions on the site of the later formed and much larger island of Grenada, the addition of which near the western side of the large bank that had been aggraded during the subsidence of the earlier islands explains the narrowness of the bank on that side. The deeply eroded and elaborately embayed Virgin islands have probably lost much of their original area by subsidence, for their bank is very large. Part of the bank foundation may have been, before any volcanic cones were built upon it, a hilly lowland of deformed and eroded continental rocks extending eastward from Porto Rico, for patches of such rocks are still visible. A slight and recent uplift at the eastern end of the Virgin bank has produced Anegada island, wholly of limestone; it is an aberrant feature, suggesting the introduction of a second cycle of island-and-bank development.

The three examples of second-cycle islands already described appear to have reached the atoll stage of their first cycle before their second cycle was opened by uplift. Marie Galante was a moderate sized atoll before its recent uplift; now it is a little dissected island-upland, surrounded by a narrow bank of second generation. Sombrero was a smaller sized atoll before uplift and has suffered a greater loss since uplift, thus giving it a wider bank of second generation. The large Antigua-Barbuda atoll was tilted long ago; and in its southwestern area of greatest uplift, it has been degraded about as much since the time of tilting as the volcanic foundation had subsided before that time; its bank of second generation is well developed. A similar history may be suggested for St.Bartholomew, St. Martin and Anguilla, with their large bank; and also for Grande Terre and Desirade and their bank; but the history of the latter group seems to have been complicated by the addition of the lofty volcanic range of Guadaloupe on the west long after the formation of an earlier volcanic foundation, on which as it subsided the limestone islands were aggraded.

The scheme on which this classification is based will doubtless need various modifications before it is complete, but it is believed to be substantially correct.

[1] W. M. D. "The marginal belts of the coral seas." *Amer. J. Sci.*, **6**, 1923 (181–195).

[2] T. W. Vaughan. "Physiographic features of the Virgin and northern Leeward islands." *J. Wash. Acad. Sci.*, **6**, 1916 (53–66).

[3] W. M. D. "Drowned coral reefs south of Japan." *Proc. Nat. Acad. Sci.*, **9**, 1923 (58–62).

[4] A. A. Julien. "On the geology of the key of Sombrero." *Ann. Ly. N. H. New York*, **8**, 1867 (251–278).

[5] K. W. Earle. *Report on the geology of Antigua.* Antigua, 1923. This includes a bibliography of 22 titles.

[6] J. C. Purves. "Esquisse géologique de l'île d'Antigoa." *Bull. Mús. hist. nat. Belg.*, **3**, 1884 (273–318). This observer recognizes that Antigua reached the barrier-reef stage (307) but does not mention the possibility of its having become an atoll.

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

[8] P. T. Cleve. "On the geology of the north-eastern West India islands." *Handl. Svensk. Vetensk. Akad.*, **9**, 1871.

RADIO FOG SIGNALS FOR THE PROTECTION OF NAVIGATION; RECENT PROGRESS

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The second president of the National Academy of Sciences, Joseph Henry, then chairman of the Lighthouse Board, between 1872 and 1878, made extensive investigations of sound in its application to fog signals. In the 50 years since that time little progress has been made in meeting the defects for fog warning purposes of sound signals transmitted through the air. Recently, however, the progress in another branch of physical science, electricity, in which also Joseph Henry was a pioneer, has permitted a broader solution of the fog signal problem, which could little have been anticipated in Henry's time.

The radio fog signal, which has come into actual use within the last three years, in conjunction with the radio compass, is likely to prove one of the greatest advances yet made in providing aids for the guidance of mariners. The radio compass, also perfected in the last few years, is probably the most important navigational instrument provided for use on shipboard since the invention of the magnetic compass. The navigator is most in need of help during fog and thick weather. Of all the former aids and navigational instruments, there were available to him in time of