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A TILTED-UP, BEVELED-OFF ATOLL

WHAT WOULD A TILTED-UP, BEVELED-OFF ATOLL LOOK LIKE?

IF an atoll were tilted up by deformational forces and then beveled off to low relief by degradational processes, its understructure would be laid bare. If the atoll reef had been formed on the margin of a shallow platform cut across a stationary, worn-down, deeply weathered volcanic island by the waves of the lowered and chilled ocean in the Glacial epochs of the Glacial period, according to Daly's Glacial-control theory, the revealed understructure would consist chiefly of volcanic rocks under a small thickness of lagoon deposits. If the atoll reef had been formed on the margin of a submarine bank that had been built up to small depth by pelagic calcareous deposits over a deep, non-subsiding volcanic foundation, according to the Rein-Murray theory, the tilted and beveled understructure should give evidence of such an origin by showing chiefly deep-water calcareous deposits on a volcanic mass of submarine eruption. If the atoll reef and its enclosed lagoon deposits had been built up to great thickness on a slowly subsiding volcanic island of subaerial eruption and erosion, according to Darwin's theory, the beveled understructure would declare this origin by showing chiefly shallow-water calcareous deposits above a volcanic base.

To make the latter case specific, let it be assumed that the original foundation of the atoll was a mountainous volcanic island of oval outline, about 50 miles long. If such an island sank slowly, while a barrier reef grew up around it and calcareous lagoon deposits were laid down in the "moat" enclosed by the barrier, until the island was wholly submerged, the barrier reef would become an atoll reef, as in Fig. 1. If such an atoll were tilted up at its southwestern end, and if the uptilted area were degraded to moderate or low relief, as in Fig. 2, the understructure would be well revealed. The upper beds would consist of lagoon limestones with occasional lagoon reefs, originally encircled by the marginal atoll reef; and the volcanic foundation would be laid bare beneath the limestones, if the uplift and the following degradation were of great enough measure. If a central area of the foundation were shown, the calcareous beds would there overlie the summits of the dissected volcanic range unconformably; but if only a marginal part of the foundation were shown, calcareous beds might there alternate in approximate conformity with tuffs and agglomerates, either because these volcanic

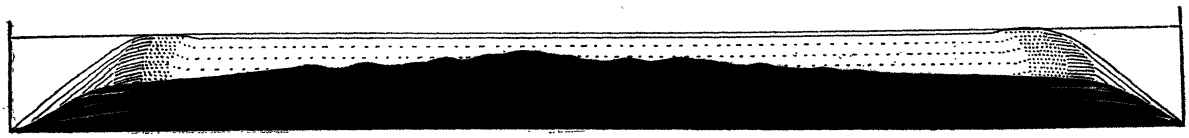

FIG. 1. Ideal section of an atoll on a volcanic foundation.

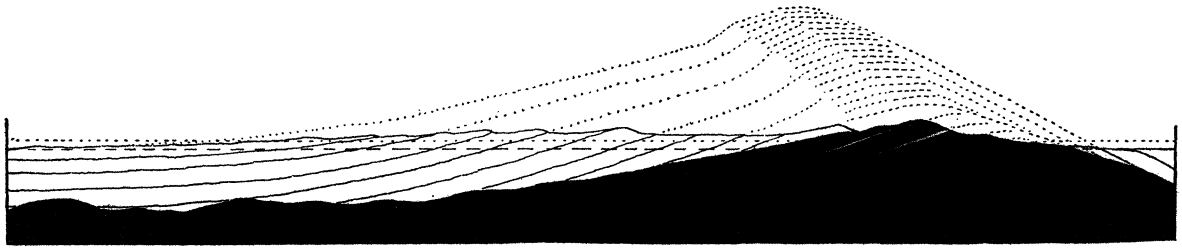

FIG. 2. Ideal section of a tilted-up and beveled-off part of an atoll, drawn on double the scale of Fig. 1.

beds were spread out beneath sea level, or because, if spread out above sea level, they were submerged by the subsidence of the island before they were much eroded during a long dormant interval when no eruptions occurred.

AN ACTUAL ISLAND THAT APPEARS TO BE A TILTED-UP AND BEVELED-OFF ATOLL

Now there is a certain island measuring about 12 miles across, which has been examined by several geologists and which exhibits, in a series of volcanic and calcareous beds inclined to the northeast and at least 8,000 feet in total thickness, a structure very much like that just inferred for a tilted-up and beveled-off atoll built up from a subsiding foundation. Its southwestern or basal quarter is occupied by volcanic rocks, including lavas, agglomerates and ash beds, which are as a rule inclined moderately to the northeast, and which are overlaid in apparent conformity by a series of cherts, tuffs and limestones, several thousand feet in total thickness, dipping 10° or 15° northeastward and occupying the remaining three-fourths of the island. The basal district of relatively resistant volcanic rocks, stripped of its former calcareous cover, is worn down to submountainous relief; the highest summit is near the southwestern coast; it is largely composed of deep-lying lavas and has an altitude of 1,330 feet. The overlying volcanic beds more to the northeast, composed largely of agglomerates and tuffs, are etched out in a series of discontinuous cuestas, trending northwest-southeast, with strong slopes on their outcrop side and gentler slopes on their dip side.

The larger district of calcareous and other strata is reduced to low relief, except that its cherts and its more resistant limestones, both occurring in discontinuous beds of lens-like form, surmount the worn-down lowlands of weaker tuffs and marls in discontinuous cuestas, again with their scarps to the southwest and their dip slopes to the northeast. One of the cuestas, formed on a low-lying chert bed, rises with a length of two or three miles near the submountainous volcanic district, from which it is separated by a well-defined subsequent valley, evidently excavated along a series of weak strata, presumably tuffs. The limestone cuestas rise in the northeastern third of the island, and are separated from the chert cuesta by a rather broad medial lowland which traverses the island obliquely from coast to coast. So much for the form of the island: let its origin as indicated by its structure be next inquired into.

THE BASAL VOLCANIC ROCKS

The southwestern district appears to represent the marginal part of a volcanic island that was built up chiefly by subaerial eruptions; the lower agglomerates are interpreted as subaerial deposits: the lower tuffs contain no marine fossils as far as known, and are only rarely interbedded with thin calcareous lenses holding marine fossils. The island thus formed must have subsided during the later stages of its volcanic activity at least, for according to the latest and fullest geological report (1923), the higher volcanic beds, a thousand feet or more in thickness, include "water deposited and stratified tuffs . . . . with intercalcations of [locally developed] marine and fresh water limestone. . . . . At intervals during the deposition of these beds there must have been long periods unbroken by any volcanic eruptions. This is proved by the existence of beds of marine limestone and chert enclosing remains of corals which can not flourish except in waters free from external detritus." Various shallow-water molluscs are also preserved in these beds. Next follows a rather heavy series of fresh-water cherts with thin beds of limestone and marl; the cherts contain a large amount of silicified wood, "both monocotyledons and dicotyledons . . . sometimes . . . a foot in diameter," and "abundant

fresh-water gasteropods." These beds are supposed to have been deposited in ponds near the base of intermittently active volcanoes; they imply that, in spite of earlier subsidence, the temporarily submerged flanks of the island were built up again above sea level by later eruptions.

The cherts are followed by a heavy series of weaker beds and these are covered by deposits of gravels of moderate thickness, including pebbles of volcanic rocks and silicified wood. "The heterogeneity of the deposit would point to its being a beach deposit laid down under the influence of strong currents and tides in an epoch of subsidence between the [preceding] fresh-water lagoon phase and the [following] more open water limestone phase;" and these overlying limestones clearly prove that, in spite of previous upbuilding of volcanic eruptions, the island was eventually submerged by subsidence. Their testimony deserves fuller consideration.

THE OVERLYING CALCAREOUS ROCKS

The subsidence, already measuring thousands of feet since the formation of the lowest intercalcated coral-bearing limestone beds in the tuff deposits, must have been long continued, for above the gravels and separated from them by a slight disconformity, comes a great upper series of Oligocene marls and limestones, at least 1,500 feet thick, and very probably thicker still if the uppermost beds which now lie under water off the northeast coast are included. In view of this date for the deposition of the upper strata, the basal volcanic rocks may be of Eocene eruption. According to the report of 1923, the limestones contain "a fossil fauna as noted for its variety as for its abundance. . . . This fauna is essentially a marine one and consists of compound corals, lamellibranchs, foraminifera, calcareous algae, gasteropods and echinoderms. . . . . The commonest lamellibranchs are species of Ostrea and Pecten, the former often reaching a very large size. The algae are chiefly represented by species of Lithothamnion. . . . The compound corals are represented by genera too numerous to mention." The presence of corals within the area of the limestones makes it probable that the outer margin of that area was rimmed by a coral reef, and that the limestones are lagoon deposits. An earlier observer (1919) notes that a fossil coral reef which he found at the disconformable base of the heavy limestone series "grew upon a basement that had been subaerially eroded and was later depressed below sea level;" and that the overlying limestones were "deposited in shoal water on a flattish floor."

There can be no question that a long-continued subsidence was in slow progress while these overlying beds were accumulated, for their fossils are similar throughout; and it is highly probable that, as above implied, the "flattish floor" on which the beds were deposited was that of a shoal-water lagoon enclosed by an upgrowing barrier or atoll reef.

The heavy sedimentary series as well as the underlying volcanic series is here and there entered by dikes, and is in at least one locality interrupted by agglomerates, which are interpreted as having been poured out upon the underlying beds and buried by the overlying beds; but the small volume of these high-level volcanic rocks of late intrusion or eruption is negligible in comparison with the great volume of the sedimentary series. Hence, while the earlier phase of the long-continued subsidence witnessed a more or less frequent production of volcanic agglomerates and ash beds alternating with occasional marine calcareous deposits, the later phase of the subsidence was accomplished, as far as the part of the original mass now seen in the beveled island is concerned, almost without eruptions and was rarely disturbed even by deep-seated intrusions. During this later phase, the original volcanic island seems to have been wholly submerged, for limestones and marls alone were then deposited. Their accumulation was at last interrupted, at least for the southern part of the atoll now represented by the island, by an uptilting which introduced an era of erosion still in progress. As the upper limestones are of Oligocene date, the era of tilting and erosion probably occupied the remainder of Tertiary and later time.

THE TILTED-DOWN PART OF THE ATOLL

The non-emerged part of the atoll is to-day represented by an extensive submarine bank, 5 miles wide on the east and 10 miles on the west of the island, and extending over 30 miles to the northeast; on the farther part of this bank a small and low limestone island, probably of Pleistocene deposition and of recent uplift, is found. It is eminently possible that the northeastern part of the atoll was tilted down when the southwestern part was tilted up; and if so, reef upgrowth and lagoon deposition may have continued in the northeast, thus building up the present bank, while the uptilted southwestern area was suffering degradation; but it is also conceivable that, as Fig. 2 suggests, a gentle flexure separated the uptilted southwestern part of the atoll from a little depressed northeastern remainder. With these possibilities, however, we are not especially concerned.

THE EMBAYED SHORE-LINE AND THE HEADLAND CLIFFS

After the era of degradation was well advanced on the uptilted island, a submergence of moderate measure took place, shown by the change from the broken to the dotted sea-level line in Fig. 2, for the present

shore-line is elaborately embayed. This involved a significant diminution in the size of the island, for its probable northeastward extension in a worn-down lowland now makes part of the shallow submarine bank, above mentioned. The embaying submergence is ascribed to actual subsidence of the maturely degraded island—not to the Postglacial ocean rise into valleys eroded on a still-standing island, while the ocean was lowered in the Glacial epochs of the Glacial period—because the valleys that are occupied by the present embayments even in the more resistant volcanic rocks are thought to be too broad to have been eroded during those epochs.

The headlands of the degraded and embayed island are moderately cut back in cliffs, but the recession of the cliffs is so small that their abrasion can not have been in progress for nearly so long a time as that occupied by the subaerial erosion of the widely opened and partly embayed valleys; for it is well assured that unrestricted abrasion of oceanic islands is a rapid process compared to their subaerial degradation. Hence valley erosion must have been begun relatively long ago and must have continued for a relatively long period, while cliff abrasion must have been a late and brief process.

The cliff faces that were cut in resistant rocks plunge below present sea level; and it is therefore believed that these cliffs have been partly submerged. It is also believed, in view of the long period of valley erosion without cliff cutting, followed by a short period with cliff cutting, that the cliffs were cut by low-level abrasion during the temporary depressions of the ocean in the Glacial epochs of the Glacial period, as will be further stated below; and hence that their partial submergence to-day is largely due to Postglacial ocean rise, and not alone to island subsidence. Similar cliffs cut in weak-rock headlands appear to have been recently cut back farther at present sea level, and are therefore not now seen as plunging cliffs. If the plunging, hard-rock cliffs really represent nearly all the work that abrasion could accomplish, while reef growth was inhibited in the Glacial epochs of lowered ocean temperature and level, then it is all the better proved that nearly all the much greater work of eroding the now-embayed valleys took place during a higher stand of the island in Preglacial time, and that their embayment is due to island subsidence of late date.

The discontinuous fringing reefs that to-day skirt the island shores, as well as the alluvial delta plains that extend inland from the present bay heads and the beaches that swing in curves concave seaward between the volcanic headlands of the southwestern coast, are all believed to be chiefly of Postglacial date. Their Interglacial predecessors would have been largely removed by low-level erosion in the Glacial epochs. It is interesting to note that the beaches, although occupying reentrants between headlands of volcanic rocks, are composed largely of calcareous sand, which must therefore have been swept in from the off-shore bank.

Evidence for the Former Existence of an Atoll Reef

Although the uptilted limestones of the supposed atoll include, as already noted, a number of coral reefs of small thickness which may be regarded as having been intermittently formed in the lagoon area, the enclosing atoll reef, which should be of continuous growth and of great thickness, has not been identified. The discovery of such a reef in the strata of an uptilted and beveled-off island would be a very agreeable confirmation of the belief that its limestones were deposited in the lagoon of an ancient atoll; but the position of the tilted limestones with respect to their ancient volcanic foundation and to the present-day circuminsular bank is such as to make even the expectation of such a discovery unreasonable. The margin of the atoll lagoon where an encircling reef should be found would now stand either high in the air along the southwestern side of the island, where it must have long ago been destroyed by erosion as indicated in Fig. 2, or a few miles off shore in the submarine bank east or west of the island, where after degradation and low-level abrasion it must now be submerged out of reach of observation. The strata of the island being lagoon strata, only discontinuous lagoon reefs are preserved in them.

So long as the atoll reef is not directly shown to have existed, it may not be apparent why the limestone area of the island should be interpreted as representing a reef-enclosed lagoon, instead of a rimless bank. Several reasons for the adopted interpretation may be adduced. In the first place, the presence of fossil coral reefs in the tilted limestones shows that temperature and other conditions were fitted for the growth of reef-forming corals during the period of limestone deposition; and this makes the occurrence of an encircling reef plausible at least. In the second place, the small measure of headland cliff-cutting already noted around the island shore in comparison with the large measure of valley erosion over the island surface demonstrates that, after the period of uptilting, the resulting island must, in spite of the discontinuous development of fringing reefs around it to-day, have been well protected by fringing or barrier reefs during most of its long period of erosion; and a similar demonstration of the former long-continued presence of protecting barrier reefs is furnished by other maturely dissected and well-embayed but little cliffed volcanic islands not far

away. Thus the presence of bank-margin reefs during the earlier period in which the now tilted limestones were accumulated, already shown to be possible by the occurrence of bank or lagoon reefs in the limestones, is made reasonable by the inferred presence of protecting bank-margin or barrier reefs during most of the later period in which the tilted limestones were degraded. Reefs appear to have been wholly absent only during the Glacial epochs of lowered sea level, when the headland cliffs were abraded. In the third place, a neighboring island, composed wholly of limestones evenly uplifted to a moderate height, has been ingeniously interpreted (1867) as representing the lagoon deposits of a former atoll, the marginal reef of which has been cut away by the sea since its uplift. Evidently, the inferred occurrence of a former atoll in the neighborhood of the tilted-up and beveled-off island gives support to the belief that it also was an atoll before it was uptilted. But even if the upper calcareous strata accumulated on a rimless submarine bank, the accumulation must have taken place in shallow water upon a slowly subsiding foundation, and not upon a deep and stationary foundation, shoaled by aggradation as postulated in the Rein-Murray theory.

Absence of an Encircling Reef To-day

If the now uptilted limestones were reef-encircled during their deposition, it might be expected that the beveled-off island and its northward continuation in a shallow bank should be encircled by an off-shore barrier reef to-day, even if they were without reefs during the Glacial epochs. So they should be, if they were situated in a warmer part of the ocean; but they happen to lie in the marginal belt of the coral seas, where they and their neighbors are, even in the present Postglacial epoch, bathed in waters that are hardly warm enough for the vigorous upgrowth of bank-margin reefs, although they do permit the formation of discontinuous fringing reefs near the island shores. This is a general aspect of the problem which I have treated elsewhere[1] and will therefore not enter upon here; it involves the conclusion that Postglacial time is not so favorable for reef growth around these islands as Preglacial and Interglacial times were; a conclusion which finds support in various studies of the climate of those time-intervals based upon Glacial and Interglacial deposits in other regions.

The Tilted-up and Beveled-off Atoll is Antigua

The island which is here interpreted as a tilted-up and beveled-off atoll has not been named thus far, because I have wished the reader to consider the problem it involved independently of any opinions he may have previously formed about the island itself. Now that the problem has been set forth, the mask of anonymity may be discarded: the island is Antigua in the Lesser Antilles, and the observers above quoted may be identified among others in the list given below by the dates of their published articles.[2] The volcanic base is of early Tertiary eruption; the atoll superstructure is of mid-Tertiary deposition; and the revelation of the atoll structure is due to later Tertiary tilting and erosion. The neighboring island that was interpreted half a century ago as an evenly uplifted and much abraded atoll is Sombrero.[3]

Confirmation of the idea that protection of the Antigua coast by encircling reefs has long been prevalent and that the temporary absence of such reefs occurred only during the Glacial epochs of the Glacial period is given by the Virgin Islands as well as by St. Lucia and several other members of the Lesser Antillean volcanic chain, where the hard-rock headlands between the embayments which enter mature valleys eroded in the same hard rocks are only moderately cut back in plunging cliffs.

The thickness of the volcanic and calcareous strata seen in the beveled surface of Antigua is at least five and probably eight times as great as the depth of the famous boring in Funafuti atoll of the Ellice group in the central Pacific; and the opportunity for the study of atoll understructure is immensely superior on Antigua to that afforded by the small boring-core from Funafuti, the interpretation of which has produced rather more dissension than demonstration; for the successive deposits of Antigua, from the lowest volcanic beds to the highest limestones, are open to examination in many outcrops along the strike of the strata over distances of from 5 to 12 miles. The evidence that they give for long

[1] The marginal belt of the coral seas. *Amer. Journ. Sci.*, vi, 1923, 181-195.

[2] P. T. Cleve. "On the geology of the northeastern West India islands." Handl. Svensk. Vetensk. Akad., ix, 1871.

J. C. Purves, "Esquisse géologique de l'île d'Antigoa." Bull. Mus. roy. hist. nat. Belg., iii, 1884, 273-318.

J. W. Spencer, "On the geological and physical development of Antigua." *Quart. Journ. Geol. Soc.*, lvii, 1901, 490-505.

A. P. Brown, "Notes on the geology of the island of Antigua." Proc. Acad. Nat. Sci. Phila., 1913.

T. W. Vaughan. " . . . An account of the American Tertiary, Pleistocene, and recent coral reefs." U. S. Nat. Museum, Bull. 103, 1919, 189-524.

K. W. Earle. "Report on the geology of Antigua." "Antigua," 1923.

[3] A. A. Julien. "On the geology of the Key of Sombrero." Ann. Lyc. Nat. Hist. New York, viii, 1867, 251-278.

continued and relatively slow subsidence is indisputable.

As far as I have learned, only one earlier observer, Purves, a Belgian geologist, has regarded Antigua as a tilted-up and beveled-off reef-enclosed island, and even he does not appear to have explicitly stated that it reached the atoll stage of development, although he comes so near to describing such a stage that one must suppose he understood it, mentally at least. His most definite statement is as follows:

La puissance de cette vaste formation calcaire indique qu'elle s'est déposée pendant une longue période d'affaissement du sol qui a suivi l'extinction de l'activité volcanique et pendant laquelle des récifs de coraux très-étendus se sont librement établis autours des bancs formés par les matériaux volcaniques éjectés lors des dernières éruptions. Ces roches, actuellement visibles, ne représentent pas la substance même du récif, car, pendant la formation du dépôt, ce récif devait être situé à une distance considérable de la côte. Ces amas de marnes et de calcaires avec leur masse de débris de coraux détachés mais très-bien conservés, de bois flotté et échoué, de coquilles et d'orbitoides, représentent évidemment le dépôt particulier que l'on voit encore de nos jours se former par l'accumulation entre la barrière de récifs et les côtes d'une île affectée d'un mouvement d'affaissement lent et continu ('84, 307).

In spite of this clear indication of the association of the Antigua limestones with an ancient barrier-reef system and the explicit recognition that the ancient reef is not now visible, the island has not gained the reputation that it deserves as a tilted-up and beveled-off atoll. Several observers of later date than Purves do not make so close an approach to imputing this origin to it as he did.

Antigua has many features of interest, which I enjoyed seeing during a ten-day visit in November, 1923. Its lower lands of fertile calcareous soil have long been cleared and cultivated, sugar cane being the chief crop. English harbor, an embayment on the southern coast between slightly cliffed headlands of submountainous form, back of which rises a well-defined tuff cuesta, was at one time strongly fortified as the chief British naval base in the West Indies; it was there that Nelson refitted his fleet after an engagement with the French in an early year of the nineteenth century. St. Johns, the chief town of the island to-day, was an excellent center for my excursions, which were all the more pleasant from the competent guidance by hospitable officials and residents with whom I made acquaintance. The town lies at the head of an open embayment which enters the northwestern end of the broad medial lowland worn down across the island on the weak beds between the cuestas of the underlying cherts and the overlying limestones; the other end of the medial lowland is entered by Willoughby bay, across which the limestone cuesta on the north affords a delightful view. Many of the physiographic features above described may be reviewed to advantage from the crest of the main chert cuesta which serves as a delightful Belvidere near the center of the island; and not the least interesting consideration that might be broadly enjoyed in the prospect there opened or more closely reviewed during an examination of the inclined tuffs and limestones in their many outcrops would be the contemplation of the island as a tilted-up and beveled-off atoll; but the conscious contemplation of Antigua as of that origin was denied me; for in spite of my ten-day exposure to the contagion of the infectious facts, a four-month period of unconscious incubation elapsed before the explanation of the facts as here presented "broke out" upon me. It then appeared that the deep understructure of the island agrees, as far as it is now revealed, in every essential respect with the understructure that an atoll, formed according to Darwin's theory of slow upgrowth from a slowly subsiding foundation, should possess.

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THE FISHERIES BIOLOGICAL LABORATORY, WOODS HOLE, IN 1923[1]

WHEN the laboratory was opened on June 20 three investigators of the bureau's regular staff who had been at the station during the greater part of the preceding winter and another who had arrived early in June were already there engaged in investigations which had begun at or through the laboratory in the preceding summer and continued without interruption.

The temporary official staff of the station consisted of the director and one scientific assistant. The laboratory enjoyed the hearty cooperation of Superintendent W. H. Thomas and the general staff of the station under his direction. Invaluable service to the director and to investigators was rendered by Robert A. Goffin, collector, and by the fisheries steam launch, *Phalarope*, with Robert Veeder as master. Helpful service was rendered in the office and library by Allan A. Graffin, and in art work by Kenneth G. Phillips, under the War Veterans Bureau. In addition to the *Phalarope*, employed for longer trips, two smaller launches and a number of rowboats were available.

In all, there were in the laboratory 28 investigators and assistants, of whom 14 were engaged upon official work and 14 upon independent studies. There fol-

[1] Published by permission of Mr. Henry O'Malley, United States Commissioner of Fish and Fisheries.