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ART. XXXI.—*The Geology of the Lau Islands;* by WILBUR GARLAND FOYE.

OUTLINE.

INTRODUCTION.

THE following paper presents in outline a few of the more important results obtained during a geological study of the Lau Islands, Fiji. The study was made while a Sheldon Traveling Fellow of Harvard University and occupied the months between August and November, 1915. A complete account of the expedition will be published later as a Shaler Memorial report.

Geography.

The Lau group consists of fifty or more islands lying east of the two main islands of Fiji. They are scattered over 300 miles of the ocean floor from the 17th to the 21st parallels of south latitude and between the 178th and 179th meridians of west longitude. The average island is, perhaps, 4 or 5 miles in diameter and 300 or 400 feet in height. Vanua Mbalavu, lying at the west side of the lagoon inclosing the Exploring group, is one of the largest islands. It is 20 miles long and 1 or 2 miles wide.

PREVIOUS WORK.

J. Stanley Gardiner* of Cambridge University, England, E. C. Andrews† of Sydney, Australia, Alexander Agassiz,‡ and W. M. Davis§ are the scientists who have contributed the most to the geological knowledge of the islands.

GENERAL STATEMENT OF THE RESULTS.

The Lau islands are believed to have been formed by volcanic activity about the middle of the Tertiary period. They were later maturely eroded, submerged, and overlain unconformably by 300 to 500 feet of coraliferous limestone. Still later they were elevated, eroded, and a second period of basaltic eruptivity spread its debris over the eroded complex. In Recent times certain of the islands in which limestones are alone exposed have been eroded to submerged platforms by atmospheric solution and, aided by a recent subsidence, atolls have developed in their place.

CLASSIFICATION OF THE ISLANDS.

In a later paper a genetic classification of the Lau islands will be given, but for the purposes of this paper it is sufficient to distinguish:

1—Islands composed of limestone and volcanic rocks;
2—Islands composed of limestone alone;
3—Islands composed of volcanic rocks alone.

The members of group 3 are in general younger than the other groups and only two islands, Munia and Kanathea, were visited. Among the more important members of group 1, the Exploring Group, Tuvuthà, Lakemba, Ono-i-Lau, and Kambara were studied. Fulanga, Ongea, Vatoa, Wangava, and Vekai of group 2 were also visited. Of the islands just mentioned, Vanua Mbalavu of the Exploring Group and Lakemba will alone be described. The geological facts characteristic of these islands may be considered as typical of the other islands as well.

DETAILED GEOLOGY.

1. *Vanua Mbalavu* (fig. 1).

Vanua Mbalavu is nearly twenty miles long from N. to S. and of variable width. It is shaped something like a question mark and has its greatest width (2 to 3 miles) near the center

* J. Stanley Gardiner, "Coral Reefs of Funafuti, Rotuma, and Fiji," Proc. Camb. Phil. Soc., vol. ix, pt. 8, pp. 417–503, 1898.

† E. C. Andrews, "Limestones of the Fiji Islands," Bull. Mus. Comp. Zoöl., Harvard College, vol. xxxviii, 1900.

‡ Alexander Agassiz, "Coral Reefs of Fiji," Bull. Mus. Comp. Zoöl., Harvard College, vol. xxxiii, 1899.

§ W. M. Davis, "A Shaler Memorial Study of Coral Reefs," this Journal, vol. xl, pp. 223–271, 1915.

FIG. 1.

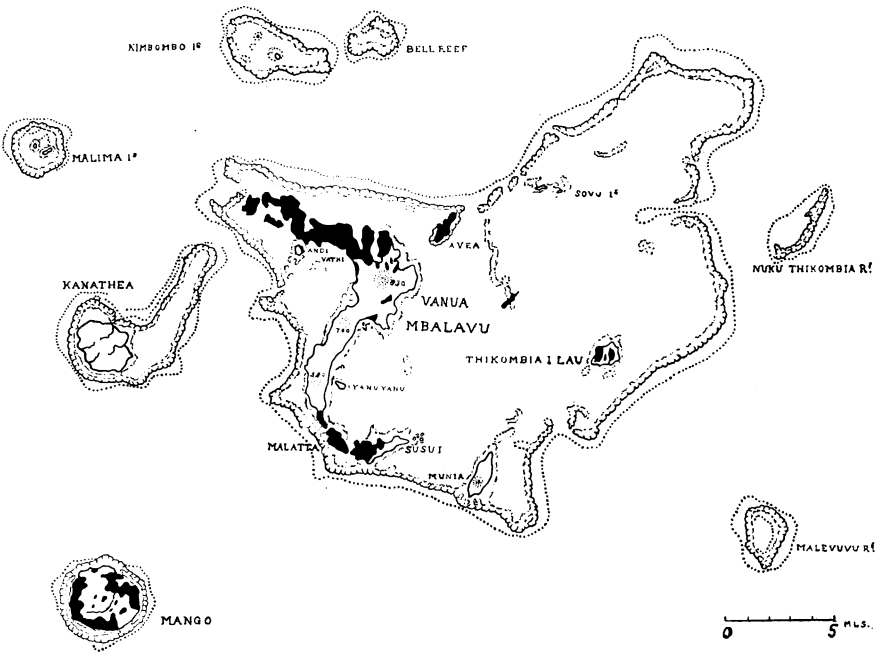

FIG. 1. The Exploring group and adjacent Reefs and Islands.
Black = elevated limestone.

FIG. 2.

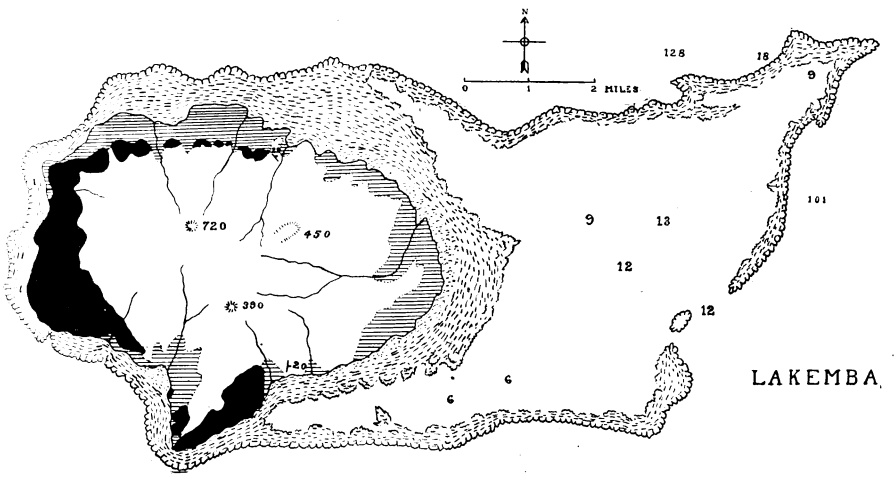

FIG. 2. Island of Lakemba.
Black = limestone. White = andesite. Lined = coastal flat.

of the upper curve. Here, near the center of the island, is situated its highest peak, Koro Mbasanga, which rises 930 feet. North of this peak the country slopes down in wide, spoon-shaped valleys to a limestone platform, having a broken surface which forms the northern end of the island. The average elevation of the platform is 350 feet. It swings southward on the western side of Koro Mbasanga and terminates just west of the peak, wedging out along the shore.

Southward from this peak a broken ridge forms a serrate backbone to the island. The map shows hills 500 and 700 feet high along this ridge, but the usual altitude is but 300 or 400 feet. The hills are low and rounded.

At the southern end of the island the low ridge dips southward beneath a small area of limestone standing at an elevation of about 300 feet. The peak, Koro Mbasanga, has an amphitheater-like depression on its eastern side. The southern limb of the ridge inclosing the amphitheater was followed southward and it was found that lavas from this peak had overflowed an area of limestone and baked it red. The limestone was a foraminiferal variety containing little or no coral. Just north of Koro Mbasanga a similar limestone, but silver-grey in color, was found in patches overlying an eroded volcanic surface. Here it included bits of the underlying rock and formed an undoubted basal layer.

From the facts just recorded it was inferred that an eroded surface of volcanic rocks had been submerged and overlain unconformably by limestone. The evidence was inconclusive, however, as to whether the limestone had been elevated and eroded before the extrusion of the volcanic rocks of the second period. This question was answered by exposures in the small island of Andivathi, lying off the northwestern coast of Vanua Mbalavu within the upper curve of the question mark.

The larger part of Andivathi is composed of andesite agglomerate and ash dipping 30° E. The western beds, representing the lower members of the series, are of coarse agglomerate with vesicular blocks of lava a foot or more in diameter. The upper beds become increasingly finer and show many small fragments of pumice. The total thickness of these beds is about 200 feet. The eastern side of Andivathi is composed of elevated coraliferous limestone. Both ash and limestone are cut by a network of basic dikes, the largest observed being 20 feet in width. It is deeply lateritized and outcrops as a long, well-defined depression in the limestone into which it was intruded. The limestone stands up in nearly perpendicular walls on either side of the depression which was once filled with the dike, indicating that in this climate the igneous rock weathers more rapidly than the sedimentary. On the N.E. side of

Andivathi ash beds rest on an irregular surface of limestone and dip S.E. toward the eroded and nearly vertical walls of limestone, forming the coast of Vanua Mbalavu less than a hundred yards away. The irregularity of the surface beneath the ash makes it apparent that the limestone was elevated and eroded before the volcanic rocks of the second period were extruded.

The central ridge south of Koro Mbasanga is more deeply lateritized than the rocks of the highest peak, and bits of silicified coral often occur in the laterite. The writer inferred that the corals were residuals of a limestone cover which once mantled the volcanic rocks. The andesites, lateritized to a depth of 20 feet or more, strengthen this inference since it is apparent that they are of a very different age than the rocks of Koro Mbasanga. A petrographic study shows that the latter rocks are olivine basalts whereas the former are andesites.

The limestone area at the northern end of the island covers 10 to 12 square miles. Its surface is very irregular and in places almost impassable because of the tangled mass of solution remnants. It is covered with a red residual soil, having an average thickness of one or two feet. Skeats found that 17 limestones from this district showed less than 1/10th of one per cent of insoluble matter. It follows that the limestone lost by solution must be reckoned in hundreds of feet.

The general elevation of the limestone plateau is 300 to 350 feet. Nearly perpendicular walls bound this area along the coast and in these walls may be traced a slight folding of very low curvature. There is no evidence here that the limestones have been deposited on the eroded stumps of Tertiary strata, as Agassiz's theory would postulate. Coral heads occur in place from top to bottom of these cliffs and are usually surrounded by a paste of shell and coral rubble similar to that filling in around the heads of a modern reef. Since these cliffs are higher than the vertical limit within which corals grow beneath the sea, and since, moreover, they must have retreated laterally, as well as vertically, by solution and wave-cutting, the writer sees no escape from the conclusion that they were formed by vertical subsidence.

Distinctive features of the limestone of the island are the narrow fingering bays, inclosed by nearly vertical walls of limestone, extending far inland. Many of the bay-heads rest against the volcanic rocks and the writer believes that underground solution cavities, formed along the contact between the limestone and volcanic rocks, have in most cases been the initial stage in the production of such bays. Most of the rainfall percolates easily into the porous limestone and flows away to the sea on the surface of the volcanic rocks. Large solution

cavities are thus formed and the collapse of their roofs gradually develops the ramifying bays. The writer does not agree with Davis that these bays are necessarily evidence of subsidence in sub-recent times.

2. *Lakemba* (fig. 2).

The island of Lakemba was probably never completely covered with limestone. The volcanic surface, reaching a maximum elevation of nearly 800 feet, is composed of well-rounded, mature forms. The rocks are deeply lateritized and support a scant vegetation.

Along the boundary of the volcanic area are isolated remnants of elevated limestone which once encircled the island. These remnants unconformably overlie the volcanic rocks and rise to a maximum elevation of 320 feet. Near the northern side of the island spur-ridges 100 feet high and their intervening valleys are covered with a mantle of shell and coral rubble containing volcanic pebbles. Traced west and south, this basal deposit is transitional upward into coral-reef limestone.

The remnants of limestone decrease in altitude along the coast towards the eastern side of the island. They reach a maximum elevation, as noted above, of 320 feet at its northwestern side but do not occur on the side hills of the eastern half.

These facts show that the island, bearing an unknown number of andesitic cones, underwent nature erosion and subsided. The mature topography was not entirely submerged since 400 feet of the island still remained above sea-level. The sunken portion was overlain by 320 feet, or more, of coraliferous limestone and was later uplifted.

The disappearance of the limestone from the eastern side of the island may be explained in two ways. It may be due to more rapid solution on the rain side of the island, or it may be due to tilting during uplift. If erosion were the cause it would seem that the rainy side of the island should show a more mature topography than the dry side. It is significant that the topographic forms on the western side show greater erosion than on the east. This fact, with others, leads the writer to believe that the island has been tilted toward the east.

The reef on the western side of Lakemba is narrow and fringing but sweeps far out and includes a lagoon 8 or 10 miles wide on the northeastern side. The mouths of the rivers on the eastern side are deeply embayed. The width of the western reef would suggest that it has been established in sub-recent times by uplift, whereas the eastern reef has either been long established or recently submerged. The recent uplift of the western coast would favor a tilting to the east.

In this connection it is important to note that the Lakemba lagoon has a maximum depth of 14 fathoms, the Aiwa lagoon slightly to the southeast, 21 fathoms, and the lagoons of the Argo reefs, 15 miles to the east, have a depth on the western side of 20 fathoms, on the eastern side of 35 fathoms. These lagoon depths are much greater than the average for the Lau Islands and may possibly be attributed to the eastern tilting movement described above.

Application of the Results of the Expedition to Coral Reef Theories.

From the facts just stated it is apparent that the elevated limestones of the Lau Islands were deposited on an eroded surface of volcanic rocks which subsided in accordance with the principles of Darwin's theory. It has been questioned whether this process explains the development of modern atolls. Alexander Agassiz inferred that coral banks similar to the Florida banks were the result. Likewise Daly considers atolls as special, post-Pleistocene, forms of coral reefs.

According to Daly, Kambara is an atoll which developed on a platform carved on Tertiary limestones, during the Pleistocene, and which has since been elevated. The coraliferous limestones of the island now stand at an elevation of 400 feet, or more, above the sea. Since the rise of the waters after the Glacial period, as stated by this writer, was between 250 and 300 feet, it would seem that there should be evidence of an unconformity between the Tertiary platform and the post-Pleistocene reef exposed in the sea-cliffs; no evidence of such an unconformity was seen either in Kambara or any similar island, although the cliffs have been cut back sufficiently to expose such unconformities if they were present.

That the uplift of the limestone islands is comparatively recent in date is apparent from the fact that the included corals are Pleistocene or Recent. Their age was kindly determined for the writer by Dr. T. W. Vaughan. Assuming that Fulanga owes its atoll form to post-Pleistocene growth on a Pleistocene, wave-cut platform, this platform should now stand near the present sea-level, as the summit of the uplifted atoll-rim is 240 feet above that level. It is apparent, therefore, that the present level lagoon, which is from 10 to 12 fathoms in depth, cannot be ascribed to Pleistocene wave-cutting. Hence it is inferred that atolls developed as a result of the subsidence of the Tertiary volcanoes.

The limestone rim of Lakemba has the appearance of a barrier-reef formed during subsidence. The exact location of the reef-edge is not known, for it is almost impossible to recognize ancient reef-edges in masses of elevated limestone. If the

observations of the writer are correct the growing reef is continually being destroyed and its débris cast into the lagoon; the reef grows on a mass of its own waste containing only a limited number of coral heads *in situ*. There is more chance of the rounded heads of the lagoon being preserved than the fungus-like growth of the reef-edge.

There is, therefore, positive evidence of subsidence in the Lau islands, and very good evidence that barrier reefs and atolls were developed during such subsidence. Thus far the Darwinian theory is supported, but the irregular uplifts and subsidences negative the idea of a general depression of the Pacific islands, a further conception of the theory. The earth movements are here irregular and seem to be confined to individual foci whose instability is the result of isostatic adjustment of large fault blocks, of secular cooling after volcanism, or of the transfer of large quantities of molten rock from the interior to the exterior of the earth's crust.

There is another method by which atolls develop. The limestone islands are rapidly eroded to sea-level by atmospheric solution. Evidence of this process may be seen in the diminishing limestone masses within the lagoons of many of the Lau islands. By tidal-scour and wave action, platforms are developed slightly below sea-level. Examples of such platforms may be seen about Fulanga and Ongea. It is significant, however, that most of these islands have lagoons 10 to 15 fathoms in depth. Such depths cannot be ascribed to erosion but must be the result of recent submergence. In time, the erosion of the elevated limestone of Fulanga will lead to the development of an atoll of the second generation replacing the older uplifted mass.

In conclusion, it should be stated that the evidence from the unstable islands of the Lau Group should not be given too wide application. The writer is convinced that the Glacial-control theory has a large body of facts in its favor but these facts are gathered from other, more stable, portions of the earth's surface.

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