

# AMERICAN JOURNAL OF SCIENCE

NOVEMBER 1927

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## A MIGRATING ANTICLINE IN FIJI.

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### DARWIN'S AND DANA'S EXPLANATION OF FIJI CORAL REEFS.

The Fiji Islands include a larger variety of coral reefs than any other island group in the Pacific. They are rich in fringing, barrier and atoll reefs at sea-level in various stages of growth, as well as in elevated barriers and atolls at various altitudes and in various stages of dissection. Darwin did not visit Fiji, but wrote on the basis of others' observations: "Most of the islands are surrounded by reefs, lying far from the land, outside of which the ocean is very deep";<sup>1</sup> and he assumed a slow subsidence of the islands to have taken place because he believed that such subsidence afforded the only means of developing barrier and atoll reefs from initial fringes; but he knew of no independent confirmation for his assumption. Dana, who as geologist of the United States Exploring Expedition saw many of the Fiji Islands, like Darwin made no mention of elevated reefs, but accepted Darwin's explanation for the sea-level reefs and provided for it a much needed and altogether new and independent confirmation; for he showed that the shore-line embayments, which persistently characterize reef-encircled islands, are necessary consequences of the subsidence during which the encircling reefs are assumed to have grown up. He wrote regarding the Fiji group as a whole: "Its northeast portion consists of immense barriers, with barely a single point of rock remaining of the submerged land; while in the west and southwest there are basaltic islands of great magnitude. . . . A large amount of subsidence is indicated by the reefs in every portion of the group."<sup>2</sup> Thus these two young naturalists who, while still

<sup>1</sup> Darwin, C., *The Structure and Origin of Coral Reefs*, London, 1842; see p. 161.

<sup>2</sup> Dana, J. D., *Geology. U. S. Exploring Expedition*, Philadelphia, 1849; see pp. 396, 398. See also my article: *Dana's Confirmation of Darwin's Theory of Coral Reefs*, this Journal, 35, 173-188, 1913.

in their twenties, made so great contributions to the coral reef problem, treated all Fiji as a subsiding region.

#### OTHER EXPLANATIONS OF THE FIJI REEFS.

At the close of the Darwin-Dana century, an opposite view was announced by Agassiz, the most experienced modern observer of coral reefs. He concluded, after examining many of the sea-level and elevated reefs of Fiji: "The islands of the whole group have been elevated and since their elevation have . . . . remained nearly stationary, exposed to a great and prolonged process of denudation . . . which has reduced them to their present height . . . It is upon the reef flats thus eroded or around the islands and islets which are the remains of a former period, that the corals of to-day have obtained a foothold . . . . They are not situated in an area of subsidence, but on the contrary in an area of elevation. The theory of Darwin and Dana is therefore not applicable to the Fiji Islands."<sup>3</sup> At a somewhat earlier date the observers of the "Challenger" expedition also had doubted the ability of Darwin's theory to explain the Fiji reefs. The Narrative of the Expedition states: "Throughout the Fiji Islands the three varieties of barrier, atoll and fringing reefs are distributed in such a manner as to render it difficult to understand how the two former have been formed [from the latter] by subsidence."<sup>4</sup> Murray, one of the "Challenger" staff, had a good sight of the well-embayed, reef-encircled, 30-mile island of Kandavu, the southwesternmost member of the Fiji group; and he wrote, without taking account of the island embayments: "It was here that, not being able to apply Mr. Darwin's theory in explanation of the phenomena of the Kandavu reefs, I commenced to doubt it altogether . . . . The more observations accumulate, the more does it seem to me probable that there never was a barrier reef or atoll formed after the manner required by Mr. Darwin's theory."<sup>5</sup>

Sir Archibald Geikie's position as a home student of the coral reef problem is significant. He had, shortly after Darwin's death, declared the subsidence theory of coral reefs

<sup>3</sup> Agassiz, A., *The Islands and Coral Reefs of the Fiji Group*, Bull. Museum Comp. Zool., 33, 1-167, 1899; see pp. 135-137.

<sup>4</sup> Narrative of the cruise of H. M. S. Challenger, London, 1885; see p. 508.

<sup>5</sup> Murray, J., *Coral Reefs*, Nature, 40, 222, 1889.

to be "one of the most impressive generalizations with which geology, fertile in such achievements, had yet astonished the world," and that "no more admirable example of scientific method was ever given."<sup>6</sup> Yet only the next year, and evidently in view of the opinions of the "Challenger" staff, he practically gave up that admirable theory as incompetent; for he then wrote, as if in regard to Fiji: "Upheaval has taken place even in areas where barrier reefs and atolls are in vigorous growth. Such an association of upheaval with an assumed general subsidence requires, on the subsidence theory, a cumbrous and entirely hypothetical series of upward and downward movements,"<sup>7</sup> and the theory should therefore be abandoned.

At a little later date attention was called by Guppy, a most painstaking observer, to the elevated reefs of eastern Fiji, with the conclusion: "We cannot doubt that if those facts had been known to Mr. Darwin, he would never have placed the Fiji Islands in an area of subsidence."<sup>8</sup> Some years later the same observer's careful study of Vanua Levu, the northernmost and next-to-largest member of the Fiji group, led him to believe that the history of that well-embayed and reef-encircled island is "one long story of emergence," and that it "offers no evidence to support Darwin's theory."<sup>9</sup> At about the same time, Gardiner, who has examined many reefs in the Pacific and Indian oceans, including those of Fiji, wrote: "While it may be true that some reefs really owe their existence to upgrowth during the subsidence of the land round which they originally formed only a fringe, the great mass of facts collected in the past twenty years points out clearly and decidedly that such a method of formation can never have been anything else than rare and altogether exceptional."<sup>10</sup>

<sup>6</sup> Geikie, A., Charles Darwin, Nature Series, London, 1882.

<sup>7</sup> Geikie, A., Address (The origin of coral reefs), Proc. Royal Phys. Soc. Edinburgh, 8, 1-31, 1883; see pp. 28, 29; Nature, 29, 107-110, 124-128, 1883.

<sup>8</sup> Guppy, H. B., A Criticism of the Theory of Subsidence as affecting Coral Reefs. Scot Geogr. Mag., 4, 121-137, 1888; see p. 125.

<sup>9</sup> Guppy, H. B., Observations of a Naturalist in the Pacific . . . Vanua Levu, Fiji. London, p. 373, 1903.

<sup>10</sup> Gardiner, J. S., The Origin of Coral Reefs as shown by the Maldives, this Journal, 16, 203-213, 1903; see p. 204.

## A RETURN TO DARWIN'S EXPLANATION.

Evidently, if scientific conclusions were determined by authority, the unanimity of the above-cited experts as to the incompetence of Darwin's theory with regard to the reefs of Fiji would be decisive against it; but fortunately dissent from authoritative opinions is always in order in science. One of the first to express such dissent regarding the reefs of Fiji was Moore, a British hydrographer, who said: "I believe that it is not inconsistent with the theory put forward by Mr. Darwin that, in the same group, some islands should be rising and some falling at the same time; nor that an island should have fallen to a certain extent and then undergone a movement of upheaval. If this is so, there is nothing, as far as one can see, in the Fiji group, which disproves subsidence as the origin of barrier reefs,"<sup>11</sup> and he might have added, "or of atolls as well"; but this open-minded observer did not cite Dana's principle of shore-line embayments in support of Darwin's theory, much less did he adduce new evidence in favor of it. Yet a new and very effective means of testing Darwin's theory was approached a few years previous to Moore's statement regarding Fiji, and was established about the time of that statement; for it was intimated by Crosby in his study of the elevated reefs of Cuba<sup>12</sup> and explicitly stated by Walther in his investigation of the elevated reefs of the Sinai peninsula,<sup>13</sup> that the limestones of reefs which are built up over subsiding foundations must rest unconformably on the foundations. This excellent test, as well as that furnished by embayed shore lines, was subsequently applied to certain elevated reefs of Fiji in some detail by Foye and in more general manner at a little earlier date by myself. It gives strong support to Darwin's theory.

Foye concluded after an examination of a number of elevated reefs in eastern Fiji: "As far as observed, the elevated limestones of Fiji rest unconformably on eroded volcanic islands"; and he inferred that, although the limestones in many islands are now more or less dissected, they were formed as "atolls and barrier reefs." One of the most significant of

<sup>11</sup> Moore, W. U., *Coral Reefs*, *Nature*, 40, 203, 1889.

<sup>12</sup> Crosby, W. O., *On the Elevated Reefs of Cuba*, *Proc. Boston Soc. Nat. Hist.*, 22, 124-130, 1884.

<sup>13</sup> Walther, J., *Die Korallenriffe der Sinaihalbinsel*, *Abhandl. k. Sachs. Gesell. Wiss. Leipsig, Math.-Phys. Kl.*, 14, 437-506, 1888.

Foye's examples is Tuvuthá, a small island three by two miles across in eastern Fiji; he there made the capital discovery that the nearly level, moderately dissected, ring-like limestone crest of the island, 800 feet in altitude, encloses a "circular moat," inside of which an eroded central mass of volcanic rock rises from beneath the limestones to an altitude of 540 feet. Hence, before upheaval, this island must have been a small atoll. Inasmuch as the contact of the limestones on the volcanic foundation rocks was found to be unconformable, Foye concluded that the foundation of Tuvuthá "was formed by the mature erosion of an isolated volcanic peak. It was then submerged, overlaid by limestone and uplifted." He notes also that coral heads are to be seen in place in the limestones on most of the exterior slope of the island, and "in such relations that subsidence [during the formation of the limestones] is the most logical explanation of their position."<sup>14</sup>

Thus Tuvuthá, which is certainly one of the most competent witnesses as to the mode of atoll formation that has ever been summoned before the court of scientific inquiry, testifies unequivocally in favor of Darwin's theory. Moreover, as this island has been upheaved by deep-seated telluric forces that knew nothing of its existence and still less of its origin, it may be taken as representing the structure and hence the origin of various other atolls, especially in Fiji, that do not exhibit their foundation rocks, whether they have been uplifted or not. Hence these other atolls also may be regarded as having been formed by upgrowth on subsiding foundations, essentially as Darwin believed.

Similarly, Vanua Mbalavu, one of the reef-encircled Exploring Isles in eastern Fiji not far from Tuvuthá, appears to be an elevated and dissected almost-atoll; for there, as is shown by both Foye's and my own observations,<sup>15</sup> a maturely eroded volcanic summit surmounts by a small measure the limestones that rest unconformably upon its flanks. Hence this uplifted almost-atoll also testifies for Darwin's theory. Furthermore, in western Fiji, where elevated reefs are almost wanting, sea-level barrier reefs encircle many maturely dissected volcanic islands, the well-embayed shore lines of which attest their subsidence while the barrier reefs were growing up around them.

<sup>14</sup> Foye, W. G., *Geological observations in Fiji*, Proc. Amer. Acad. Arts and Sci., 55, 1-145, 1918; see pp. 10, 56-58.

<sup>15</sup> A Shaler Memorial Study of Coral Reefs, this Journal, 40, 223-271, 1915.

Moreover, this Darwinian origin for barrier reefs has been independently and conclusively demonstrated by Marshall's recent and truly admirable investigation, subsidized by the Bishop Museum of Honolulu, of the raised barrier reef of Mangaia in the Cook group, where the reef limestones are clearly seen to rest unconformably on the eroded slope of their volcanic foundation; and therefore just as Tuvuthá and Vanua Mbalavu reveal the origin of many atolls and almost-atolls, so Mangaia, an impartially selected example of its class, reveals the origin of many barrier reefs and confirms the above-stated inference based on the embayed barrier-reef islands in western Fiji.

In view of all this, it is to be believed that Vanua Mbalavu, which first subsided in an early phase of its history when its now elevated limestones were accumulating and which has since then been elevated, is now subsiding again; for along with its smaller companions, which also show limestones resting unconformably upon eroded volcanic foundations, it is surrounded by a large sea-level barrier reef, the thickness of which, as determined by the depth of the lagoon floor over which it rises, measures in one part of its circuit about 500 feet. Such a barrier may be designated as of a second generation of upgrowth. Little Tuvuthá is likewise encircled by a sea-level barrier reef of a second generation; but as this barrier is close-set, the recent submergence that it indicates must be of small amount. Thus Moore's idea that diverse movements of subsidence and upheaval have taken place in Fiji is abundantly justified.

#### INCOMPETENCE OF ALTERNATIVE THEORIES.

With this justification of the instability of the Fiji Islands in mind, it is impossible to regard them as having long been stable, as they are assumed to have been in Daly's Glacial-control theory.<sup>16</sup> Indeed, quite apart from the evidence for instability given by embayed shore lines and unconformable limestone contacts in various parts of the Fiji group, geological studies of the large, northwesternmost island, Viti Levu, by Andrews in 1900, Woolnough in 1903 and 1907, Foye in 1918 and Brock in 1924, give independent demonstration of its long continued changes of level; and thus make instability highly

<sup>16</sup> Daly, R. A., *The Glacial-Control Theory of Coral Reefs*, Proc. Amer. Acad. Arts and Sci., 40, 157-251, 1915.

probable for the group as a whole. Moreover, the absence of cliffs on various Fiji islands that are bordered only by fringing reefs—for example, on the southwestern coast of Viti Levu, the northeastern end of Vanua Levu, and the southeastern side of Ngau—testifies against the occurrence of low level abrasion, such as the Glacial-control theory assumes to have taken place while the ocean was lowered and chilled and the defending reefs were killed in the Glacial epochs. It is true that the depths of Fiji lagoon floors are as a rule roughly accordant, but the rule has many exceptions; and in any case it is not permissible to explain their accordance as the result of low-level abrasion on islands that have been essentially stable since Preglacial time, as the Glacial-control theory demands, because the Fiji islands show so many indications of recent instability. That theory is therefore not acceptable, except insofar as its factor of low-level abrasion finds application in the marginal belts of the coral seas, as I have shown elsewhere.<sup>17</sup>

Not only the Glacial-control theory as developed by Daly, but also the various other theories adopted in place of Darwin's by Murray, Geikie, Guppy, Agassiz and Gardiner must be set aside; for all of them assume non-subsiding islands, and therefore none of them can account for the close association of reef upgrowth and island subsidence in the reefs of Fiji and of other island groups, as proved by embayed shore lines and unconformable limestone contacts. Had the above-named students of the coral reef problem shown that such shore lines and contacts can be explained without island subsidence, the case would have been different; but they did not do so. They left their discussions seriously incomplete, especially on the deductive side, and their conclusions are therefore untrustworthy. True, Guppy, Agassiz and Gardiner made brief mention of embayed shore lines, but chiefly to discredit them as affording valid evidence of subsidence; and while Daly recognizes such shore lines as indicating subsidence, he dates the subsidence as Tertiary and as therefore irrelevant to recent reef upgrowth. But Murray and Geikie made no mention of embayed shore lines in their discussion of reef origins; and not one of the above named investigators referred at all to unconformable limestone contacts, although the evidence for subsidence given by unconformities has been established since

<sup>17</sup> The marginal belts of the coral seas, *Proc. Nat. Acad. Sci.*, **9**, 292-296, 1923; also this *Journal*, **6**, 181-195, 1923.

the time of Hutton and Playfair. Nearly all text books and manuals of geology are similarly uncritical in their treatment of coral reef origins. Even the article on coral reefs in the eleventh edition of the *Encyclopedia Britannica*, which might be expected to present an up-to-date view of the old problem is silent concerning the embayed shore lines of reef-encircled pelagic islands and of reef-fronted continental coasts, as well as concerning unconformable limestone contacts beneath elevated reefs; perhaps because the article was written by an observer whose chief experience was with sea-level atolls, the lagoons of which contain no embayed volcanic islands and the surface features of which afford no satisfactory evidence as to their submarine structures.

If inquiry be made into the reasons for the inattention of the above-named observers to the evidences of reef origins which are here given prime importance, it will appear that, excepting Daly, they were all of biological rather than of geological training and experience, and also that they were singularly indifferent to the consequences of their theories with respect to the continental coasts or islands which the reefs fringe or front. They were, indeed, more concerned with island-encircling reefs than with the islands which the reefs encircle. All of them, including Daly, had observational acquaintance with elevated reefs, but none of them ever raised the question as to whether the island shore line, which such reefs fronted while they were forming, was a simple shore line of emergence or an embayed shore line of submergence. Furthermore, although the coral seas afford numerous examples of both sea-level and of elevated fringing reefs which wrap unconformably around salient spurs, and although the embayed valleys between such spurs, clearly of erosional origin, must have been partly drowned by submergence before the fringing reefs were formed, no attention was paid by the above-named observers to the evidence of submergence thus provided. Yet such fringing reefs illustrate, quite as well as sea-level barrier reefs around embayed islands, a condition of reef formation that has been determined by a relatively rapid subsidence of the reef foundations, as Darwin appears to have understood;<sup>18</sup> and although he knew of no examples of the kind, they abound in the Australasian archipelago. Nevertheless the interpretation of elevated fringing reefs in the manner here outlined has not been recognized by any of the observers above-named,

<sup>18</sup> *Loc. cit.*, 1842; see p. 124.

evidently because they disregarded or insufficiently considered the physiographic development of the reef-fringed islands. Furthermore, the small thickness ordinarily possessed by elevated fringing reefs, which has been cited as arguing against the great thickness of sea-level barrier and atolls reefs built up during slow subsidence as postulated by Darwin's theory, really has no such application; for their small thickness is the result of a short period of growth during a still-stand pause after a rapid and often great, reef-inhibiting subsidence, as I have elsewhere shown.<sup>19</sup>

On the other hand sea-level atolls, to which Agassiz in particular gave much attention, are inscrutable structures: they are stubbornly silent as to the nature of their foundations and the condition of their upgrowth. It is only from the internal structure of atolls as revealed by borings, or from the contact of their limestones with the foundation rocks as observed in elevated atolls, that their origin can be inferred. Yet even the results gained from the borings in the atoll of Funafuti in the Ellice group of the torrid Pacific<sup>20</sup> have not been so generally accepted as giving confirmation for Darwin's subsidence theory as they should have been, because the experts who reported upon them were, according to Skeats,<sup>21</sup> instructed by the committee of the Royal Society in charge of the work to state only the facts that they found, and not their inferences based on the facts. In consequence of this restriction, it is probable that many readers of the report have failed to perceive the evidence for subsidence and reef upgrowth that is given by the fact there stated, that only shallow-water foraminifera occur in the main boring, nearly 1,200 feet deep in the atoll reef, while deep-water foraminifera are found at corresponding depths on the exterior slope of the atoll. It should therefore be believed that this sea-level atoll has been formed, in its upper 1,200 feet at least, by upgrowth during the slow subsidence of its foundation. Its evidence for Darwin's theory antedates that given by Tuvuthá, Vanua Mbalava and Mangaia by ten or more years.

Sea-level barrier reefs also are, like atolls, silent as to their origin, so long as the reefs alone are examined. I have made conscious test of this point while standing on various Pacific

<sup>19</sup> Subsidence rate of reef-encircled islands, *Proc. Nat. Acad. Sci.*, 12, 99-105, 1926.

<sup>20</sup> The Atoll of Funafuti, Royal Society of London, 1904.

<sup>21</sup> Skeats, E. W., The Coral-Reef Problem and the Evidence of Funafuti, this *Journal*, 45, 81-90, 1918.

barrier reefs with my back turned, physically as well as mentally, to the islands that the reefs surround; for under such limitation of observation and inference all theories of reef formation seem to be equally competent. But as soon as the reef-encircled islands are examined, all still-stand theories of reef formation are excluded, because they cannot account for the features of the islands, particularly their embayed shore lines, however well they account for the features of the reefs. Hence while there is, of course, abundant material for study in the organic assemblages on coral reefs, that study will not reveal the conditions under which coral reefs have been formed. It is only from the islands or coasts back of the reefs that such revelation is to be expected. The problem of reef origin is therefore largely geologic and physiographic rather than biologic; the reef-building organisms have had to accept the conditions offered by their foundations, according as the foundations rose, stood still or subsided.

The net result of all this is that many of the earlier studies of coral reefs afford no safe ground for theorizing as to reef origins, because the evidence given by the most competent and outspoken witnesses—the reef-encircled islands—was not there brought forward. When that evidence is duly considered, it testifies—apart from certain exceptional cases—strongly for island subsidence in association with reef upgrowth, even if the reefs are to-day elevated above sea-level. Hence, as above intimated, all the theories from which the slow subsidence of reef foundations is excluded must be discarded in favor of Darwin's older theory; for under that theory embayed shore lines and unconformable limestone contacts are, even though the author of the theory did not know it, inherent, inevitable consequences of the conditions and processes which the theory postulates; and under that theory, furthermore, several other highly significant matters—especially the disposal of the large volumes of detritus that have been eroded from maturely dissected, reef-encircled islands, as well as the non-cliffed, mountain-top form of the islets of almost-atolls—also find complete explanation, as I have shown in earlier articles.<sup>22</sup> In these various respects, Darwin's theory succeeds where all other theories fail; and its success is all the more remarkable in that most of the special matters which it accounts for so well were

<sup>22</sup> Subsidence of reef-encircled islands, *Bull. Geol. Soc. Amer.*, 29, 489-574, 1918. The small islands of almost-atolls. *Nature* 105, 292, 293, 1920.

wholly unknown when the theory was invented nearly 90 years ago. But careful distinction should be made between Darwin's coral reef theory and his erroneous application of the theory to the whole of Fiji, which led him to believe that all the islands of the group have subsided.

The more closely the geological history of Fiji is investigated, the more clearly is it seen that Darwin's theory of reef formation is merely a generalization of those phases of Fiji history in which subsidence permitted reefs to be built up, as I propose to show in the following pages. Wherever and whenever subsidence took place at a not too rapid rate it was accompanied by reef upgrowth, except where and when the outwash of island detritus was excessive, or where and when an upgrowing atoll became too small for further upgrowth. Not only so, the elevated and the sea-level reefs of southeastern Fiji are not confusedly intermingled, as has been implied in various accounts of them and as they truly enough seem to be at first sight. On the contrary, they are rather systematically arranged, as will be shown in the next following paragraphs; and the various upward and downward movements, during which the reefs of the southeastern part of the archipelago have been formed and uplifted, are by no means "cumbrous and entirely hypothetical," as Geikie feared, but are relatively simple and well substantiated, as will be shown in later paragraphs.

#### THE SEA-LEVEL AND ELEVATED REEFS OF SOUTHEASTERN FIJI.

When the many unlike reefs of south-central and south-eastern Fiji are examined deliberately, it is found that they may be arranged in four or five, roughly north-south belts,<sup>23</sup> each of which trends a little west of north and in each of which the reefs are, with explainable exceptions, all of a kind. The first belt, about 100 miles in length by 30 in width in the south-central part of the group, may be called the Ngau belt after one of its members. It includes six well dissected volcanic islands, in which the occurrence of embayed shore-lines and sea-level barrier reefs suggests a simple, one-phase history of island subsidence and reef upgrowth, still in progress. I had opportunity of inspecting all the islands of this

<sup>23</sup> A fuller account of these island belts is given in my book, *The Coral Reef Problem*, shortly to be published by the American Geographical Society of New York.

belt during my visit to Fiji in 1914, and some account of them is given in one of my more general essays.<sup>24</sup> The elevated reefs next farther east were for the most part aside from my route and the following accounts of them are therefore taken from the records of other observers, chiefly Agassiz and Foye, and from large-scale hydrographic charts.

Some 40 or 50 miles east of the Ngau belt and across the open Koro Sea, is a second north-south belt—the Kambara Belt—110 miles in length by 20 or 30 in breadth, consisting of nine elevated and non-dissected atolls, several hundred feet in altitude, none of which show volcanic rocks in their central basins; but this belt includes also the maturely dissected volcanic island of Thithia, which bears discontinuous and apparently unconformable reefs on its flanks, well above sea-level. If it be agreed, as certainly seems reasonable, that the atolls of this belt were formed like Tuvuthá, which stands a little farther to the east, they must have had a two-phase history; first, a phase of subsidence and reef upgrowth, which was carried past the barrier reef stage of the Ngau belt to the atoll stage here so well represented; second, a phase of upheaval, which must have been recently and rapidly accomplished because the raised atolls are so little dissected. A still-stand pause has followed the upheaval, for the raised atolls are now fringed with well-developed sea-level reefs, although fringing-reef terraces are not found on their emerged flanks. Evidently the movements of the Ngau and the Kambara belts have not agreed; for although the present phase of subsidence in the Ngau belt repeats the first or subsidence phase in the Kambara belt, these corresponding phases were not synchronous. Thithia appears to have been so high that it was not submerged when its neighbors were.

The Kambara belt includes also a number of minute islands of small height, surrounded by sea-level fringing reefs. When the atolls of this belt stood at sea-level before their recent elevation, the small islands in the belt must have been completely submerged; for, precisely on account of their small size, any reefs that attempted to grow upward from them would have soon been reduced to mere pinnacles, which could not stand the assault of the ocean waves. Hence the submergence of these small islands was not due to rapid subsi-

<sup>24</sup> The Islands and Coral Reefs of Fiji, *Geogr. Journ.*, 55, 34-45, 200-220, 377-388, 1920.

dence, such as that to which the drowning of various good-sized atolls, like those of the Darwin Hermatopelago or Sea of Banks north of Fiji is most reasonably ascribed, but to their extinction by reduction of diameter during reef upgrowth. They were, however, rescued from their temporary submergence when the elevation of the belt took place. I have suggested that such small islands should be called "resurgent."<sup>25</sup>

About 10 miles farther east is the north-south Ongea belt, comprising a good number of uplifted, strongly dissected and well embayed limestone islands, surrounded by sea-level barrier reefs. The Exploring Isles, including Vanua Mbalava and its smaller companions above described, are among the few members of this belt in which the unconformably underlying volcanic foundation rocks are visible. If the other members of the belt have suffered the same changes of level as these Isles, the belt must have had a three-phase history; the first phase beginning with the subsidence of the eroded volcanic foundations and the upgrowth of first generation reefs to the almost-atoll or atoll stage; the second phase including the upheaval and erosion of the limestone reefs on the volcanic foundations; and the third phase renewing the movement of subsidence and thus embaying the dissected limestone islands and permitting the upgrowth of second-generation barrier reefs, now at sea-level. The first or subsidence phase of the Ongea belt thus corresponds to the first phase in the Kambara and Ngau belts; the second or upheaval phase of the Ongea belt corresponds to the second phase of the Kambara belt, but no such phase is represented in the Ngau belt; and the third phase of the Ongea belt is not represented in the Kambara belt. Evidently while the successive phases in the three belts are similar, they are not synchronous: they are earlier in the Ongea than in the other belts.

Fulanga, nearly the southernmost member of this belt, stands a little to the west of the line of its fellows: its elevated reef is breached and its emerged lagoon floor is somewhat dissected and embayed; hence it seems to be, by reason of its westward position, not very far entered upon the third phase of dissection and renewed subsidence, which characterizes the other members of the Ongea belt. Tuvuthá also stands well to the west in the northern part of this belt; and judging by its

<sup>25</sup> Extinguished and resurgent coral reefs, *Proc. Nat. Acad. Sci.*, 2, 466-471, 1916.

small measure of dissection and its close-set barrier reef, it is only just entering on the third phase of renewed subsidence, but has not yet advanced so far in that phase as the other members of the Ongea belt have.

Next east of the Ongea belt is the Argo belt of sea-level atolls or almost-atolls, about 70 miles long by 20 miles wide. As some of the almost-atoll islets are here composed of limestone, the members of this belt seem to be farther advanced in the third or dissection-and-subsidence phase of a three-phase history than are those of the Ongea belt; hence the two earlier phases, namely, reef-forming subsidence and reef-revealing upheaval presumably antedate the corresponding phases in the Ongea belt. Next east of the fourth or Argo belt is an imperfectly developed fifth or Malan belt, represented by a few submerged reefs and banks. It may therefore be suggested that the subsidence which has gone so far as to produce the almost-atoll and atolls of the Argo belt has here advanced somewhat farther and faster, so as to submerge the reefs and convert them into submarine banks; but the banks here occurring are too few in number to give good assurance of this suggestion.

#### A WESTWARD MIGRATING ANTICLINE IN FIJI.

If the movements suffered by the several belts above described are now compared, it will be seen that, as already intimated, they are similar in the sequence of their inferred phases, as far as they go; but that the corresponding phases do not agree in time of occurrence. The phases of the western belts occur later than the corresponding phases of the eastern belts; and this clearly suggests the westward propagation of a broad and shallow wave-like deformation of the ocean floor, in which the wave-length, from crest to crest, is to be measured in several scores of miles and the wave height, from trough to crest, in only a few thousand feet. In other words, the changes of level in the several belts all appear to be caused by the slow westward migration of a broad and low ocean-floor anticline, preceded and followed by shallow ocean-floor synclines.

This may be made clearer with the aid of Fig. 1, in which vertical dimensions are greatly exaggerated. The background block represents an early position of the migrating anticline; the middle block, a later position; and the foreground block,

the present position. The islands and reefs are conventionally drawn in much magnified, symmetrical forms. The initial stage of a young volcanic island in the Ngau belt at the beginning of its one-phase history is shown at the left end of the back block. As the island, while suffering dissection, is approached by the preceding syncline it subsides slowly, is

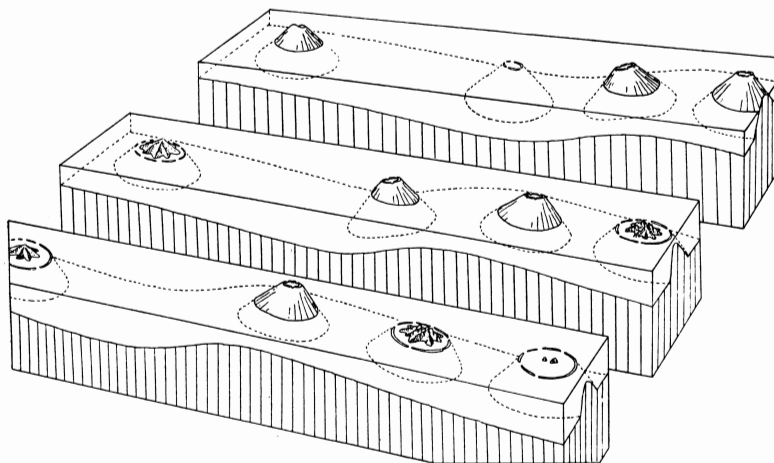


Fig. 1.

diminished in size and gains a slightly embayed shore line while a close-set barrier reef grows up around it, as shown at the left end of the middle block. As the syncline comes nearer, the subsiding island is further diminished in size while the reef-enclosed lagoon widens to its present measure, as shown in the fore block.

For the Kambara belt a final stage of the first or subsidence phase has been reached when its members became atolls in the trough of the preceding syncline, as shown at mid-length in the back block. The second or upheaval phase was entered on when the approach of the anticlinal front raised the atoll to half height in the middle block; and the culmination or present stage of this phase is represented in the fully upheaved atoll on the crest of the anticline in the fore block. The highest member of this belt is Vatu Vará,  $1\frac{1}{2}$  miles in sea-level diameter and 1,030 feet in altitude. Only one other raised atoll in the open Pacific, namely Eua, the southeasternmost

member of the Tonga group, stands higher. The small amount of erosion suffered by Vatu Vará as well as by the other uplifted atolls of its belt indicates a rapid upheaval, as if the front of the advancing anticline were steep. Rapid upheaval is also indicated by the absence of fringing-reef terraces in association with several corniced shore lines which Andrews has reported on the limestone slopes of Vatu Vará; but following the rapid upheaval, a still-stand pause, such as might well be associated with the passage of a flat-crested anticline, is indicated, as already noted, by the growth of good fringing reefs around the present shore lines of the uplifted atolls.

For the Ongea belt, the mid-stage of its second or uplift phase is represented by a moderately elevated atoll on the front of the anticline in the back block: and the final stage of that phase is represented by a fully elevated atoll on the crest of the anticline in the middle block. The present, well-advanced stage of its third or renewed-subsidence phase is shown by a dissected and embayed limestone island encircled by a second-generation barrier reef on the rear slope of the anticline in the fore block. The Argo belt is represented at the close of its second or upheaval phase by a fully emerged atoll on the crest of the anticline at the right end of the back block; at the mid-stage of its third or renewed-subsidence phase by a dissected atoll encircled by a second-generation barrier reef on the rear slope of the anticline in the middle block; and at the present, far-advanced stage of the renewed-subsidence phase by an almost-atoll of second generation in the trough of the following syncline in the fore block. The small banks of the Malan belt are not shown.

Thus interpreted, the full emergence of the Argo belt in the back block was of earlier date than the full emergence of the Ongea belt in the middle block; and still more earlier than the full emergence of the Kambara belt in the fore block. There is, however, no belt of sea-level atolls west of the Kambara belt corresponding to the back-block stage of the Kambara belt. The expected locus of such an atoll belt is the open Koro Sea, which is island- and reef-free, except for Tova, a three-mile atoll about midway between Vatu Vará which belongs in the Kambara belt on the east and Totoya, a caldera-ring, reef-encircled island in the Ngau belt on the west. The reason for this may be that but one island ever existed in that inter-

mediate area; but it may be also that a number of atoll-crowned islands in the area have been drowned by sinking in the synclinal trough at a more rapid rate than that of reef upgrowth. If so, such drowned atolls should be discovered at moderate depths by soundings. While such discoveries are awaited, Tova may be taken as provisionally establishing the existence of an atoll belt between the Ngau and the Kambara belts.

The absence of a belt of partly uplifted and west-tilted atolls on the anticlinal front next west of the Kambara belt, corresponding to the west-tilted, half-height atoll inferred for the Kambara belt in the middle block and to the similarly tilted atoll inferred for the Ongea belt in the back block, may likewise be because no atolls were ever formed there; and this is not improbable because the anticlinal front is believed to be much narrowed by its steepness. No atolls with east-tilted rims are seen to-day in the Ongea belt on the rear of the anticline, because the rims of the uplifted atolls there have been destroyed by erosion. It is possible, however, that the originally level strata of the lagoon limestones, which are, as Darwin long ago pointed out, likely to survive longer in an emerged and dissected atoll than its encircling reef, may show a gentle eastward dip; but this possibility has not yet been shown by observation to be actuality, perhaps because no observer of the Ongea-belt islands has had the possibility in mind.

There are, nevertheless, two or three indications of eastward tilting in the dissected Ongea belt. One seems to be found in Lakemba, a volcanic island, five by four miles across and 720 feet high, 50 miles south of the Exploring Isles. According to Foye this island bears unconformable reef limestones up to heights of 320 feet on its western but to less heights on its eastern slope; and a barrier-reef loop, which becomes only a fringe on the west side of the island, extends six miles to the east. These features were taken by Foye, before the scheme of the migrating anticline was invented, to mean that Lakemba had suffered an eastward tilting; but the difference in height of the unconformable limestones on the two sides of the island may perhaps be due to post-upheaval erosion. Another and clearer indication of a slight tilting movement, appropriate to islands on the rear slope of the anticline, is given by the eastward slant of the large lagoon floor within

the Exploring-Isles barrier reef; it deepens from 20 or 30 fathoms on the west to 70 or 80 fathoms on the east in a distance of 25 miles. Agassiz called attention to this exceptional fact but without explaining it by a migrating anticline, as is here proposed. He also noted that the little dissected rim of Fulanga, which has already been mentioned as a southern member of the Ongea belt a little displaced westward toward the Kambara belt, and which should therefore according to the anticlinal scheme be just beginning its third or renewed-subsidence phase, is inclined gently to the east; and inasmuch as the eastern or windward side of atoll rims is usually better built up to sea-level than the western side, this inclination has some significance; but not so much as the slanting floor of the Exploring-Isles lagoon.

Another test of the hypothesis of the migrating anticline might be furnished by soundings of the area concerned, but unfortunately the charted soundings there are so few that they prove nothing. Indeed, even if they were numerous, it would be necessary to assume that the former depths of the sea bottom had been nearly uniform if it were expected that the present depths should show the effects of anticlinal deformation; and such an assumption is hardly permissible.

#### THE MIGRATING ANTICLINE AND DARWIN'S SUBSIDENCE THEORY.

The scheme of a westward migrating anticline is avowedly theoretical; but it has the confirmatory merit of bringing order out of confusion and of coördinating a large variety of sea-level and elevated reefs in a comparatively simple manner. The "upward and downward movements" which the scheme involves are geologically agile rather than "cumbrous," and far from being "entirely hypothetical" they seem to me to be well warranted by simple inferences from observed facts. Moreover the scheme was not invented to give support to Darwin's theory, but in order to explain the various changes of level that the islands and reefs of the region appear to have suffered when interpreted under the guidance of Tuvuthá and Vanua Mbalavu. Yet the scheme gives excellent support to the old theory, which rides over the migrating anticline as easily as a staunch vessel rides over a heavy sea. Here again, therefore, we have one of those many cases in which Darwin's

theory demands no special consideration, but in which it takes its place most unconcernedly in the history of a region, as worked out by ordinary geological methods. In doing so, it explains not only the facts which it was invented to explain—namely, the derivation of barrier and atoll reefs from fringing reefs—but also a great number of unexpected facts that were wholly unknown when it was invented. Its capacity to explain these facts, all of which might have been anticipated long ago if the consequences of the theory had been worked out deductively, is most commendable. Indeed, the vigorous competence and the irrepressible vitality of the old theory are so well proved by its success in meeting the demands of the migrating anticline in Fiji and of other movements elsewhere, that in spite of the many obituaries written over it in the past forty years, it may be expected to regain in the coming half century the worldwide acceptance that it enjoyed for a generation a hundred years earlier.

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