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THE CORAL REEFS OF TUTUILA, SAMOA

THE preparation of a detailed chart—not yet published—of Tutuila, Samoa, by the U. S. Hydrographic Office, and the studies made by various scientific specialists invited to the island by Dr. A. G. Mayor, director of the department of marine biology of the Carnegie Institution of Washington, have added greatly to the knowledge of that remote possession of ours in recent years. The chart, on a scale of about 1 : 50,000, shows the mountainous volcanic island to be surrounded by an extensive submarine bank, from one to three miles wide, somewhat shallower near its inner and outer margins than along an intermediate belt, where soundings of 60 fathoms occur. The shallower parts of the bank are interpreted as submerged fringing and barrier reefs, which are supposed to rest on a wave-cut platform now lying between 60 and 70 fathoms below sea level by reason of island subsidence. The present shores of the island are embayed and are bordered by well developed fringing reefs.

Dr. Mayor's latest Carnegie report contains a condensed statement by R. T. Chamberlin, entitled "The geological interpretation of the coral reefs of Tutuila, Samoa," the result of three weeks' observation there in July, 1920, from which the following extracts are taken:

The island of Tutuila is a volcanic pile whose slopes have been attacked by the sea until a broad wave-cut platform, 2 miles in width, has come to surround the island. This broad shelf of planation, originally cut in the volcanic rocks not far below the sea level, now lies at least (though probably not much more than) 400 feet below sea-level. . . . On the outer margin of the wave-cut platform, corals commenced to build a barrier reef, while a fringing reef grew outward from the shore. . . . Subsequently the island became progressively submerged. . . . Tutuila, therefore,

is consistent with the Darwin-Dana coral-reef hypothesis to the extent that a submergence of 400 feet has occurred since the corals began to form the old barrier reef; but in other respects it does not fit the requirements of that hypothesis, inasmuch as the barrier reef, instead of being built up several thousand feet from the slopes of a sinking island, is found to be rooted on a broad, wave-cut platform.

Dr. Mayor comments on Chamberlin's statement in part as follows:

> Professor R. T. Chamberlin, who made a special study of the relation between the reefs and the volcanic shores of the island, . . . finds that the ancient barrier and fringing reefs which once surrounded the island and are now drowned grew upon a platform which had been cut by the sea and afterwards submerged and not upon the unaltered slopes of the island. Thus the Darwin-Dana theory does not apply to Tutuila.

Chamberlin's summary concerning the origin of the reefs is excellent as far as it goes, and it is to be presumed that if he publishes a fuller account of his results he will then supplement the present brief statement with an explanation of the conditions which determined that Tutuila should be for a time reef-free and therefore exposed to abrasion before it became reef-encircled, and with a description of the high cliffs that must have risen at the back of the now submerged 2-mile platform and of their relation to the recently cut cliffs the base of which is close to actual sea level.

But excellent as the present summary is with respect to the reefs of Tutuila, neither the passage above quoted from it nor the passage quoted from Mayor's comment upon it does justice to Darwin's theory of coral reefs; for in so far as the quoted passages imply that the submerged barrier reef of Tutuila does not exemplify the "Darwin-Dana" theory, they hold good only for an imperfect, indeed an incorrect conception of that theory. As a matter of fact the Tutuila reefs, both submerged and at present sea level, exemplify certain special phases of Darwin's theory in a remarkable manner, as the following citations from his "Structure and Origin of Coral Reefs" (1842) will make clear.

In the first place, Darwin nowhere asserted that barrier reefs must be "built up several thousand feet from the slopes of a sinking island," or that they could not be built up from a "broad, wave-cut platform," as Chamberlin implies, or that they must grow up from "the unaltered slopes of an island," as Mayor assumes. All that Darwin's theory of barrier reefs and atolls demands is that a foundation of any form shall subside slowly enough for the reef to grow upward and maintain its surface at sea level. The form of the foundation is immaterial. It is true that the typical island profile which Darwin drew in two figures (pp. 98, 100), to represent a subsiding foundation on which a fringing reef would be transformed into a barrier reef and a barrier reef into an atoll, showed an island of a particular form, as graphic illustrations always must; but as this profile was modeled upon that of the island of Bolabola, a deeply denuded member of the Society group, it effectually disposes of Mayor's assumption that Darwin thought reefs grew up from "the unaltered slopes of an island."

It is true that Darwin nowhere wrote anything about the denudation of Bolabola, but he was perfectly familiar with the fact that the slopes of volcanic islands are altered by erosion and abrasion. His geological philosophy was somewhat primitive, for he thought that many volcanic islands had been uplifted after their conical form had been produced by eruption, and that during the resulting emergence the sea cut valleys in the island slopes; it was, indeed, by this process that he accounted for the repeated breaching of certain original "basaltic rings," composed of outward dipping lava beds, and their conversion into a circuit of separated hills, such as characterize the islands of "St. Jago" in the Cape Verde group, St. Helena, and Mauritius. He also knew that "deep arms of the sea . . . penetrate nearly to the heart of some [reef] encircled islands," Raiatea in the Society group being mentioned as one of them; and the depressions occupied by such sea arms were surely understood

to be alterations from the original form of the islands. Hence there is no warrant whatever for thinking that Darwin's theory demands the growth of reefs on unaltered volcanic slopes.

The particular kind of alteration caused by the abrasion of circum-insular platforms was very properly not shown in his type diagram, because, so far as Darwin's observation and reading went, no barrier reefs were known to have grown up from foundations of that kind. He knew full well, however, that platforms might be abraded and that reefs might grow upon them; but he believed that, unless subsidence occurred, such reefs would differ from ordinary barrier reefs in having shallow lagoons behind them, as will be shown below.

Various passages in his book make it clear enough that no particular form of reef foundation was regarded as essential. Anything on which a reef might begin its growth would suffice. For example, Darwin wrote: "If the rim of a [non-subsiding] crater afforded a basis at the proper depth, I am far from denying that a reef like a perfectly characterized atoll might not be formed; some such, perhaps, exist; but I can not believe in the possibility of the greater number having thus originated" (89). And again: "A bank either of rock or of hardened sediment, level with the surface of the sea, and fringed with living coral, would . . . by subsidence be converted immediately into an atoll, without passing, as in the case of a reef fringing the shore of an island, through the intermediate form of a barrier reef" (101). Evidently, the prime element in Darwin's theory of barrier reefs and atolls was subsidence; no particular form of the foundation on which reef growth begins was assumed, except for purposes of graphic illustration. Such illustration always involves definite profiles; but the more general statements of the text show that definite profiles are not required.

Moreover, a careful reading of Darwin's book will discover that he clearly conceived the possibility of a reef growing up from the outer margin of an abraded platform, as now appears to have been actually the case on Tutuila; and that he gave this possibility little consideration, not because such a reef would not grow upward into a true barrier if the platform subsided, but only because he found no examples of it. He wrote:

> It will, perhaps, occur to some, that the actual reefs formed of coral are not of great thickness, but that before their first growth, the coasts of these encircled [non-subsiding] islands were deeply eaten into, and a broad but shallow submarine ledge thus left, on the edge of which the coral grew; but if this had been the case, the shore would have been invariably bounded by lofty cliffs, and not have sloped down to the lagoon channel, as it does in many instances (49).

Certain volcanic islands that Darwin had seen in the Atlantic, before he was concerned with the origin of coral reefs, had made him familiar with the visible occurrence of sea-cut cliffs; and the "broad but shallow submarine ledge" that must extend forward from the base of the cliffs was apparently familiar by inference. Thus he described St. Helena as surrounded by "enormous cliffs, in many parts between 1,000 and 2,000 feet in height," and added that "the swell of the Atlantic ocean has obviously been the active power in forming these cliffs." In various other reef-free islands he recognized "the prodigious amount of degradation, by the slow action of the sea, which their originally sloping coasts must have suffered, when they are worn back, as is so often the case, into grand precipices."[2] He does not explicitly announce the contrast between the "grand precipices" of volcanic islands that are not defended by encircling reefs, and the moderate slopes that lead "down to the lagoon channel" in nearly all reef-encircled islands; but he knew and correctly described both classes of islands.

In view of all this it is manifest enough that, if Darwin had at hand the facts now known about Tutuila, he would have said, in effect:

> Tutuila is an actual island which must formerly have been "deeply eaten into" by the sea, and which must then have been surrounded by a "broad but shallow submarine ledge" backed by

[2] "Geological Observations," 1844, 91, 128.

"lofty cliffs"; yet the very fact that most other barrier reef islands are not "bounded by lofty cliffs" but "slope down to the lagoon channel" shows that they have not been "deeply eaten into"; or if they have been then the resulting cliffs have been completely submerged by later subsidence.

His general scheme of upgrowing reefs on subsiding foundations therefore takes in without any difficulty the special case of an island around which a platform had been abraded.

Good reasons may be given for believing that the peculiar case of completely submerged platform-back cliffs, just alluded to, is a very probable one; for wave-cut platforms and cliffs presumably occur as normal features in an early, pre-reef stage of young volcanic islands; and their rarity to-day is best explained by the strong subsidence of the islands since the platforms were cut; but the discussion of this question would lead away from the matter here under consideration.

Another passage from Darwin's book, directly following the one above quoted about the possibility of reefs growing on the coast of an island that has been deeply eaten into by the sea, is pertinent here, as it explicitly considers the growth of a reef upon a platform margin and the depth of the resulting lagoon:

> On this view,[3] moreover, the cause of a reef springing up at such a great distance from the [non-subsiding] land, leaving a deep and broad moat within, remains altogether unexplained.

Or otherwise phrased: If a reef sprang up from the outer margin of a broad platform, cut by waves around a still-standing island, the enclosed lagoon could not be so broad and deep as barrier-reef lagoons usually are, unless subsidence had occurred along with reef growth. The quoted statement is not so clear as Darwin's writing generally is, but the modified phrasing here suggested is believed to represent his fuller meaning; it is certainly consistent with the context. In any case, Darwin clearly knew that a platform could be abraded around a volcanic island and that such a platform must be backed by cliffs; and he further believed that, if a reef grew up on the margin of the platform, the lagoon thus enclosed would not have the depth of most barrier-reef lagoons; but that if the abraded island subsided and the reef grew higher, the depth that is usually found in barrier-reef lagoons would thereupon be produced. According to the present understanding of the coral-reef problem, it is precisely the occurrence of such subsidence that puts a stop to further abrasion by making reef-growth on a platform margin possible; but Darwin did not detect this point, nor did he see that the opportunity for abrasion of platforms around volcanic islands in the coral seas is best provided, as above mentioned, when the islands are young and high, with simple, non-embayed margins, so that a large amount of detritus shall be washed down from their steep slopes to the shore, where its accumulation in beaches inhibits coral growth and permits abrasion. Indeed, this explanation of the condition under which the abrasion of a platform may occur is not mentioned even in Chamberlin's summary, though its omission there may be due rather to the conciseness of the summary than to a rejection of the explanation. The explanation has, however, a considerable theoretical importance in giving reasonable consideration to an early pre-reef stage of island development that has been generally overlooked;[4] and it was in view of this explanation that the common occurrence of completely submerged platform-back cliffs was above suggested as probable in barrier-reef islands; but the platforms associated with these submerged cliffs need not have been nearly so broad as the submerged platform of Tutuila.

It may be added that the opportunity for platform and cliff cutting on Tutuila can not be advisedly ascribed to the inhibition of coral growth by the lowered temperature of the lowered Glacial ocean, as is postulated

[3] A footnote in Darwin's book at this point reads: "The Rev. D. Tyerman and Mr. Bennett . . . have briefly suggested this explanation of the origin of the encircling reefs of the Society islands."

[4] "Clift Islands in the Coral Seas," *Proc. Nat. Acad Sci.*, II., 1916, 283–288.

in the Glacial-control theory of coral reefs; for if the Tutuila platform had been cut to a width of a mile or two in volcanic rock under such conditions, similar platforms should have been cut around other volcanic islands, and the tops of the platform-back cliffs should be visible to-day above normal sea level; but as a matter of fact such partly submerged cliffs, or plunging cliffs as they may be called, have not been often detected; besides Tutuila, the other best known examples are Tahiti and the Marquesas islands, as will be further told below.

To return to Darwin's text: a further examination of it discovers a remarkably close parallel to the actual condition of Tutuila, as the following statement will show. The Tutuila barrier reef is now drowned; its successor is a fringing reef on the marginal slopes of the abraded island; and these slopes are, according to Mayor, steeper than the sides of the valleys by which the island is dissected. Now in view of the association of fringing reefs with rising or stationary coasts in Darwin's theory—as it is ordinarily quoted—it might be thought that the occurrence of the Tutuila fringing reef around a subsided island contradicted his views. But that such is not the case is made clear by this prophetic sentence:

> If during the prolonged subsidence of a shore . . . an old barrier reef were destroyed and submerged, and new reefs became attached to the land, these would necessarily at first belong to the fringing class (124).

That is precisely the case at Tutuila. Evidently, it is immaterial whether the "old barrier reef" here mentioned had been formed by upgrowth from the slopes of a non-abraded, subsiding island, or by upgrowth from the margin of a platform on an island that subsided after the plaform had been abraded. Darwin's suggested explanation is excellent; it was only because he found no examples of fringing reefs thus produced that he did not pursue the suggestion further; but fringing reefs of this kind abound in the Philippine Islands.[6]

If it be true that the submerged barrier reef of Tutuila was formed on a subsiding platform of marine abrasion, one or two miles in width, the cliffs at the back of the platform should have been 1,000 feet or more in height. Hence the upper part of their faces ought still to be visible after a subsidence of some 400 feet; and it should therefore be on the now submerged part of the cliff faces that the present fringing reefs of Tutuila have been formed. Mayor's accounts of Tutuila tell, however, of narrow platforms backed by steep cliffs a few hundred feet in height that have been cut close to present sea level since the submergence of the barrier-reef platform. It would therefore seem that these new cliffs must have been cut in the slanting faces of the earlier and greater cliffs after their partial submergence. This relation of the two sets of cliffs has not been mentioned, as far as I have learned, by any observer on Tutuila; it is a "flier" of my own,[7] based on the dimensions of the new cliffs and platforms as reported by Mayor. The relation of the height of these cliffs to the breadth of the platforms at their base suggests that the inclination of the preexisting spur-end surfaces in which the new cliffs have been cut was much steeper than the ordinary radial slope of the spurs on a dissected volcanic island, but not steeper than the precipitous descent which the earlier-cut, spur-end sea cliffs might have had at the back of their two- or three-mile platform; and as the cliffs at the back of so wide a platform must have had some such height as 1,000 feet, the upper part of their slanting faces should be still visible as plunging cliffs after a 400-foot subsidence. Furthermore, the idea that the new cliffs of Tutuila are cut in the earlier ones gains some support from photographs of Tutuila by Mayor, and from photographs of the Marquesas islands by Iddings; for these islands appear to resemble Tutuila in many respects, although their submerged platforms, the presence of which is indicated by a few soundings in front of their plunging cliffs, are

[6] "The fringing reefs of the Philippine Islands," *Proc. Nat. Acad. Sci.*, IV., 1918, 197–204.

[7] "The islands and coral reefs of Fiji," *Geogr. Journal*, IV., 1920; see p. 218.

not yet well enough known to warrant any statement as to whether they bear submerged reefs or not; and although new sea-level fringing reefs are not yet developed on the Marquesas cliffs, for Mayor reports the growth there of only separate corals on the cliff faces below sea level. A corollary of this last-mentioned fact is that the submergence of these islands must be more recent than that of Tutuila.

Had the old barrier reef of Tutuila not been drowned by a too rapid submergence—possibly the result of subsidence at an ordinary rate reenforced by the Postglacial rise of ocean level—it would have to-day formed a sea-level barrier reef enclosing a fine lagoon; and it would have thus imitated the barrier reef which surrounds Tahiti, where the island spurs are strongly cut off in plunging cliffs between embayed and mostly delta-filled valley mouths, thus indicating that the visible barrier reef of Tahiti, like the submerged barrier reef of Tutuila, has grown up from an abraded, cliff-backed platform. It may be parenthetically added that the form of the larger valleys of Tahiti, now embayed and delta-filled, suggests some such measure as 600 or 800 feet for the submergence of the inferred cliff-base platform; also, as the Tahiti reef now reaches sea level and as most of the drowned-valley embayments there are filled with deltas, that island must have been submerged less rapidly and less recently than Tutuila. And to this it may be added that the submergence of Tutuila must, as already noted, have been less recent, but perhaps not more rapid than that of the Marquesas, where not even fringing reefs are yet formed; and finally that local subsidence of these different islands, varying in rate and in amount from place to place, and not a synchronous and uniform rise of the ocean, must be taken as the cause of their non-synchronous and non-uniform submergences.

But if this view concerning barrier reefs be correct, it might be objected that neither the submerged barrier reef of Tutuila nor the sea-level barrier reef of Tahiti was formed according to Darwin's theory, because according to that theory—as it is usually quoted—barrier reefs are supposed to have developed from on-shore fringing reefs, while the Tutuila and Tahiti barrier reefs appear to have developed from off-shore, platform-margin reefs. Yet even this contingency is provided for in Darwin's wonderfully well reasoned discussion, as may now be briefly pointed out.

It is true that Darwin's type figure represents the initial stage of reef growth as an on-shore fringe around a rather steeply sloping island border; and that the fringe is transformed, as subsidence progresses, first into a barrier reef and later into an atoll; and from this it has been generally inferred that, when Darwin described barrier reefs and atolls as developed from fringing reefs, on-shore fringes must have been meant. But a closer examination of his text leads to a different conclusion. His chapter on fringing reefs defines them in a manner that appears to have been generally overlooked. He included in that chapter not only reefs closely attached to the shore of their islands, but also other reefs "not closely attached." Several off-shore reefs on the shelving sea floor of Mauritius and off the east coast of Africa are there presented as examples of detached fringing reefs:

> On the western side of Mauritius . . . the reef generally lies at the distance of about half a mile from the shore; but in some parts it is distant from one to two, and even three miles (52).

Again, on the eastern coast of Africa,

> For a space of nearly forty miles, from lat. 1° 15′ to 1° 45′ S., a reef fringes the shore at an average distance of rather more than a mile, and therefore at a greater distance than is usual in reefs of this class. . . . In the plan [small chart] of Mombas (lat. 4° S.) a reef extends for thirty-six miles, at the distance of from half a mile to one mile and a quarter from the shore (56).

None of these off-shore reefs has "an interior deep-water channel," but only a shallow one. It is therefore by the absence of a deep lagoon and in spite of the detachment of these reefs from the shore that they are, in Darwin's terminology, classed as fringing reefs and distinguished from barrier

reefs. Whether modern observers will adopt his terminology in this respect or not is aside from the point here at issue. The fringing reefs which Darwin regarded as the early stage of barrier reefs may have been either on-shore reefs or off-shore reefs; but if off-shore, the belt of water between them and the land must have been shallow. This is made perfectly clear by his explicit statement:

> Fringing reefs on steep coasts are frequently not more than from 50 to 100 yards in width; they have a nearly smooth, hard, surface, scarcely uncovered at low-water, and without any interior shoal channel, like that within those fringing reefs which lie at a greater distance from the land (55, 56).

These citations leave no doubt that, when the now-submerged barrier reef of Tutuila was first formed at a distance of a mile or two from the cliffed inner border of its shallow supporting platform, it would have been classed by Darwin as a fringing reef, because the "enclosed water channel" was then of small depth. But when subsidence continued and permitted reef upgrowth to such a height that the enclosed water channel or lagoon was increased in depth, then Darwin would have called it a barrier reef, as modern observers are united in doing.

The principle here involved is, however, of no great importance, because it was not Darwin but his successors who have emphasized the supposedly necessary sequence of fringing reef, barrier reef, and atoll, as a consequence of the theory of subsidence. Darwin's own discussion recognized this succession as characterizing the typical example of a subsiding island, like Bolabola; but he explicitly recognized other sequences in less typical cases. If the original reef foundation had been a bank close to sea level, the initial fringe would have become an atoll, as subsidence progressed, "without passing . . . through the intermediate form of a barrier reef," as a quotation (101) already made shows clearly enough. Or if a reef grew up from the rim of a still-standing submarine crater of proper depth, a possibility which Darwin explicitly recognized (89), an atoll would be formed without the preliminary formation of a fringing or a barrier reef. The point of all this is that Darwin conceived many conditions under which coral reefs might be established and transformed, and did not restrict himself to a special form of reef-foundation or a fixed sequence of reef development, even though he understood that the most probable explanation of the majority of barrier reefs is by the more or less intermittent upgrowth of fringing reefs from subsiding foundations, and that the best explanation of most atolls is by similar upgrowth from subsiding barrier reefs.

The object of this article is to point out that the full meaning of Darwin's broad discussion can not be condensed into a rigidly conceived theory, beginning with an island of a certain shape and proceeding through a perfectly definite sequence of transforming reefs. His treatment of the problem was far broader than that, as the citations given above must suggest, and as various other citations would confirm. Far from being inconsistent with his broadly conceived theoretical discussion, the reefs of Tutuila as described by Mayor, Chamberlin and others are remarkably close exemplifications of some of its most significant special phases.

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A NOVEL MAGNETO-OPTICAL EFFECT

EARLY in April, 1921, while my son, Malcolm Thomson, was operating, in a building of the River Works plant of the General Electric Co., a resistance welder for closing the seams of steel Langmuir mercury vacuum pumps, in which work the current is applied and cut off at about one half second intervals, there was noticed by one of the working force, Mr. Davis, who happened to be favorably located, a peculiar intermittent illumination of the space near the welder as the current went on and off. My son at once placed himself in a similar position and saw the novel effect, and noted a number of conditions accompanying it, perhaps the most important being that a single turn loop from the welding transformer to