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ART. VI.—*The Coral-reef Problem and the Evidence of the Funafuti Borings;* by ERNEST W. SKEATS, Geological Department, University of Melbourne.

## *Introduction.*

INTEREST in the vexed problem of the origin of atolls and barrier reefs has been again stimulated during the last few years by the writings of the two Harvard geologists, Professors W. M. Davis and R. A. Daly. Davis* has reinforced Darwin's view of the origin of atolls in a series of papers, by amplifying and elaborating the evidence, first recorded by Dana, in favor of the subsidence theory which is yielded by the presence of drowned valleys and embayed coasts in many of the central islands surrounded by barrier reefs.

Daly,† elaborating and adding to the earlier work of Belt‡ and Penck,§ among others has propounded the "glacial-control theory of coral reefs," claiming that the Pleistocene glaciation by means of Polar ice caps locked up so much water that a lowering of level of the tropical seas of 50–100 meters occurred. The lowering of temperature is pictured as killing most of the corals, while prolonged abrasion of oceanic islands during the period of lowered sea level led to the development of wave-cut "reef platforms" which served as the foundations on which the existing atolls were built up when sea temperatures and sea level subsequently rose. The phenomena of drowned

* Davis, W. M., this Journal, xxxv, pp. 173–188, 1913; ibid., xl, pp. 223–271, 1915; Bull. Am. Geogr. Soc., xlvi, pp. 561–739, 1914; Proc. Acad. Sci., Washington, pp. 146–152, March 1915.

† Daly, R. A., this Journal, xxx, pp. 297–308, 1910; Proc. Amer. Acad. Sci., li, pp. 157–251, Nov. 1915; this Journal, xli, pp. 153–186, 1916; Nat. Acad. Sci., pp. 664–670, Dec. 1916.

‡ Belt, Quart. Journ. Science, xi, p. 450, 1874.

§ Penck, Jahr. Geogr. Ges. München, vi, p. 76, 1881. Penck, Morphologie der Erdolurfläsche, Stuttgart, ii, p. 660, 1894.

valleys and embayed coasts are by Daly attributed to rise of sea level and not to subsidence of the land.

Davis, in common with others, admits some change of sea level due to glaciation and subsequent melting of Polar ice caps, but doubts the quantitative significance which Daly attributes to it, and indeed, regards it as of minor importance. These indirect methods of enquiry have assumed much of their importance from the circumstance that the materials and constitution of normal atolls are not commonly available for direct examination except when subsequently elevated or explored by boring.

Some fifteen to eighteen years ago the writer, while a demonstrator under the late Professor J. W. Judd at the Royal College of Science, London, was concerned in the examination of coral limestones from upraised coral islands* and also made a large number of the analyses of the materials of the cores from the borings into the atoll of Funafuti. For some years he was handling the sliced cores of the latter bore and has examined most of the rock sections so ably described by Professor Cullis in the mineralogical part of the Funafuti report.† The writer's familiarity with the bore cores from Funafuti and his experience with limestones from upraised coral islands constitute his justification for contributing to the present discussion. The significance of the evidence made available by the publication of the very detailed and exhaustive examination of the Funafuti bores appears to have escaped many workers on coral reef problems or to have been misunderstood. This no doubt is partly to be attributed to the circumstance that the committee responsible for the work consisted of adherents of diverse views on atoll formation, and decided that the experts to whom the material was submitted should publish descriptions of the material but should draw no conclusions from the facts as to the mode of formation of the atoll. The writer believes he is correct in stating that these experts were unanimous in their views that the published descriptions supported Darwin's subsidence theory, and in fact were fairly susceptible of no other known explanation.

In this paper it is not proposed to discuss in detail the big problems raised by Prof. Davis or by Prof. Daly with the exception of three points raised by the latter, namely, the submarine profile of Funafuti, Daly's and Von Lendenfeld's views and diagrams of the development of coral atolls and the mechanism of the filling of "lagoon moats."

The author is principally concerned that more serious consideration should be accorded to the positive evidence provided by the examination of the bore cores which is published in the

* Skeats, Bull. Mus. Comp. Zool., Harvard, xlii. pp. 53–126, 1903.

† Funafuti report, Royal Society, London, 1904.

Funafuti report. In a succeeding paper he proposes to recall the attention of workers in this field to the support given to the subsidence theory of atoll formation by a consideration of the apparently unrelated problem of the origin and distribution of dolomite in coral and other limestones.

Some of these facts and the legitimate conclusions which follow from them were pointed out by Professor Sollas in 1905,* but subsequent writers on the subject have not commented on them and apparently have not realized their significance.

*Von Lendenfeld's and Daly's Diagrams of Atoll Development.*

Darwin's and Dana's diagrams of atoll development show a centripetal displacement of the outcrop of the reef of an atoll as the result of growth during subsidence. Von Lendenfeld† and Daly‡ have published diagrams showing a centrifugal displacement of the outcrop of the atoll reef during subsidence. This latter view can only be tenable on the assumption that the debris broken from the seaward face of the reef accumulates as a submarine talus *within the limits of coral growth*, and that fresh coral reef material grows upwards on that talus.

On "a priori" grounds the writer would expect the following factors to determine in large measure the nature of the submarine profile of an atoll.

1. The relative rates of subsidence and of upward growth of corals.§
2. Rate of abrasion of the seaward face of the growing reef by wave attack.
3. Rate of lateral regrowth of corals on the seaward side of the abraded reef.

With regard to the first point, if the rates of subsidence and of upward growth are nearly equal a very steep outer wall to the reef will develop and might continue for many hundreds of feet. If this were the only factor involved a slight centripetal shift of the outcrop of the reef would be expected, for only submarine talus formed within the limits of coral growth can sustain growing corals and these will fail to reach the surface. If the rate of subsidence is less than that of upward growth of coral, the latter will be checked on reaching sea level and more material will be abraded from the seaward face, submarine talus will collect and if within the limits of coral growth upward growth of coral on the talus will commence. The

* Sollas, The Age of the Earth, T. Fisher Unwin, London, pp. 121–132.

† R. Von Lendenfeld, Gaca, Jahrg. 26, 196, 1890; Westermann's Monatshefte, p. 505, Jan. 1896.

‡ Op. cit., p. 247.

§ One may neglect the case where the rate of subsidence exceeds that of upward growth of coral, since the atoll would in that case be drowned.

accumulation of talus will be slow and whether or no corals can grow from such a talus and reach the surface will depend on the submarine slope of the island, on the relation between the rates of supply of talus material, of subsidence, and of upward growth of coral. Any considerable accumulation of submarine coral talus necessarily involves extensive abrasion of the growing reef by wave action and considered by itself will cause a centripetal shift of the position of the outer reef-face at the surface. But here the second and third factors mentioned above, which involve the relative rates of abrasion of the reef face and repair by regrowth of corals, become important. Von Lendenfeld's and Daly's diagrams can only express the facts in the case of a reef in which the rate of subsidence is much slower than that of upward growth of coral, lateral abrasion of the reef-face and its repair are rapid and a large quantity of submarine coral talus accumulates at depths less than 15 to 40 fathoms giving a foundation for the seaward and upward growth of coral. In the writer's view the combination of these factors in the history of an atoll is likely to be exceptional rather than normal and the alternative view seems more probable that usually during subsidence the upward growth of coral will occur on dead coral reef and only as the result of occasional long pauses in subsidence or prolonged periods of very slow subsidence will sufficient talus accumulate to provide a foundation for coral growth. If this latter picture of the development of an atoll is correct, on the whole a centripetal shift of the outcrop of the reef will take place.

Davis* has discussed this question and defined the conditions under which centripetal or centrifugal shift of the reef may possibly take place. Let us turn from these "a priori" arguments to consider the facts so far as they may be disclosed by an examination of the submarine profile of Funafuti. The diagram shown in Daly's paper is not helpful in this connection for it is generalized and the vertical scale is exaggerated three times. In the Funafuti report several cross profiles are shown on the true scale and if we limit our attention to the part within 200 fathoms of the surface (slightly greater than the depth of the main bore) it will be noticed that the cross profiles show varying slopes. It may be noted here that the soundings showed that down to 400 fathoms from the surface round most of the island the average submarine slope is about 40°, a figure which must reach if it does not exceed the upper limit for the angle of rest of submarine talus. One profile, AA in the Funafuti drawings, between the surface and a depth of 200 fathoms shows the existence of 4 very steep walls with angles up to and exceeding 70° and one of these is over three hundred feet in height and slopes at 78°. Between

* W. M. Davis, Proc. Nat. Acad. of Sci., ii, pp. 466-471, 1916.

these steep slopes are several which are at much lower angles. These steep walls most probably represent the outer parts of the growing reef at various stages of development while the methods of formation of the intervening flatter slopes may be more debatable. The important point to note is that in the development of the Funafuti atoll we have evidence in the submarine profiles that there has been a centripetal not a centrifugal shift of the outcrop of the reef since the more deeply buried submarine steep walls representing former positions of the outer reef-face are further from the center of the island than those of more recent origin and shallower depth. An appeal to the facts as shown in the submarine profile of Funafuti indicates, therefore, that the development of that atoll is in general accordance with the diagrams of atoll growth originally published by Darwin and by Dana while Von Lendenfeld's and Daly's views and diagrams are clearly inapplicable to that particular atoll.

*The Filling of the "Lagoon-moat".*

Daly* attaches much importance to the mechanism of the filling of the "lagoon-moat" in atolls. He claims that, according to the subsidence theory of atoll formation, the fairly shallow and relatively flat lagoon floors which are commonly met with, imply advanced filling of the lagoon to depths of scores, hundreds or possibly thousands of meters. The filling mechanism according to Daly involves two factors, sediment and active transportation of that sediment. On this basis he claims that the lagoon floors should not be flat but should slope away from the sources of supply of sediment, i.e. the reef-face and the central island in the case of barrier reefs in course of development to atolls. Further he claims that the supply of sediment is quite insufficient unless in the case of all atolls a very prolonged pause has followed subsidence. He favors the view that the "lagoon moats" really represent wave-cut surfaces or rock platforms developed by the erosion of pre-existing islands while the sea level stood lower than it does at present. Davis† has criticised this theory of wave-cut platforms as the support for modern atolls from the point of view among others that enormous periods of time would be necessary to develop level rock platforms in the case of islands some of which must have been 20 to 30 miles in diameter. The writer is more particularly concerned with Daly's criticism of "moat" filling previously stated above. It will be noted that although Daly quotes Darwin's view that the "moat" is slowly filled through the accumulation of detritus and shells and skeletons of organisms inside the reef, in his discussion of the mechanism of

* R. A. Daly, Proc. Nat. Acad. Sci., ii, pp. 664-670, 1916.
† W. M. Davis, Bull. Am. Geogr. Soc., xlvi, p. 646, 1914.

"moat" filling he ignores the activity of organisms and develops his destructive criticism on the assumption that the moat is filled entirely by means of transported and deposited sediment. While it may be granted that Daly's criticism would have some force if sediment were the only factor in moat filling, the argument is very seriously weakened if not completely vitiated by ignoring the part played by organisms. One of the best established facts in modern work on coral reefs is that any effects due to solution from lagoon waters, which was an important element in Murray's picture of the development of lagoons, is negligible in amount and quite overbalanced by organic growth and the deposition of sediment. In fact measurements show that the lagoons of many atolls are becoming shallower owing to these causes. If it can be shown that the growth and deposition of organisms within the waters of the lagoon are quantitatively much more important than the deposition of sediment the weight of Daly's destructive criticism would be removed and the relatively flat floors of many lagoons could be attributed to the deposition of organisms. To decide between the opposing hypotheses the appeal is to the facts so far as they are known. The Funafuti report* again provides the most definite evidence of the nature of lagoon deposits. Two bores were put down from the waters of the lagoon and penetrated to depths of 113 and 144 feet respectively below the floor of the lagoon. The record of the deeper boring, ⌊, shows that of the material from the first 70 feet between 80 and 95 per cent consists of loose uncemented fronds of the calcareous alga, Halimeda; below 70 feet the organisms are cemented by calcite into a white limestone and for about 20 feet consist of about one third of Halimeda and two thirds of foraminifera. In the lower 50 feet the rock is mainly composed of corals and foraminifera while Halimeda is scarce. It will be noted that for the first 60 feet the filling of the lagoon "moat" consists of loose fronds of Halimeda practically devoid of sediment; below this level the calcite cement, small in amount, may or may not represent recrystallized calcareous sediment. At Funafuti, therefore, it is clear that of the two factors, organisms and sediment, which have filled the lagoon "moat", the organisms are of overwhelming importance. The deposits of Halimeda in the upper part of the lagoon bore must have been accumulated fairly rapidly since from the floor of the lagoon down to a depth of 35½ feet the fronds of Halimeda were still sufficiently preserved to show the peripheral cells on decalcification. We may therefore conclude, at any rate, so far as Funafuti is concerned, that Daly's objections to the subsidence theory of atolls so far as they are based on difficulties connected with the filling of the lagoon "moat", have no weight

* The Atoll of Funafuti, London, 1904, pp. 310-315.

for the predominant factor, the activity of calcareous algæ, foraminifera, corals, etc., has been completely overlooked.

*The evidence of organisms from the main Funafuti bore.*—The careful, precise, and monumental work of Dr. Hinde on the materials from the borings at Funafuti provides a wealth of information on the organisms which built up that atoll. From his report, from Prof. Judd's general report on the materials, and from a personal communication from Mr. F. Chapman, now paleontologist to the National Museum, Melbourne, who sliced all the cores, and examined the foraminifera, the writer selects the following statements as bearing on the question of the origin of the atoll.

Dr. Hinde reported that in the upper 180 ft. of the boring, whose coral reef origin no one has questioned, about one-fifth of the organisms consisted of corals, the remainder consisting of calcareous algæ, foraminifera, and other organisms.* In the lower third of the boring from 750 ft. to the bottom at 1114 feet the corals form a larger proportion of the whole rock, but, even here, are considerably exceeded by the foraminiferal and fragmentary rocks. Between 600 ft. and 748 ft. coral casts are more numerous and Halimeda is abundant. He further stated that 27 genera of corals were recognized in the main boring, all of which belong to well-known reef-building forms, most of which still exist on the reef, and in the lagoon at Funafuti 35 genera of foraminifera are recognized in the main boring, of which only 7 are of importance as rock-formers, and they are still flourishing on the present reef or in the lagoon.

Prof. Judd† states that the corals which occur are sometimes *upright and in the position of growth*, but very frequently broken and fragmentary, this being true of all parts of the core from the top to the bottom. So far as could be made out the corals are as often "in situ" in the lower as they were in the upper parts of the core.

Mr. Chapman,‡ whose opinion is of great weight, as he did all the slicing of the cores, as well as from his position as an expert in the study of foraminifera, states that "throughout the bore the corals were found in the position of growth. Pocillopora was found in the boring down to 750 feet. In the living state at Funafuti it occurs from 30–180 ft.

*Coeloria* occurs in the bore from 340–1114 ft. 6 in., and is found living at 42 ft.

*Alveolina boscii* was found in the bore down to a depth of 700 ft. In soundings it is found commonly in shallow water down to 30 fathoms, below which it is rare.

The delicate megalospheric form of *Orbitolites complanata* in its reproductive stage was found in the lowest cores of the bore in the condition in which it lives in the shallow waters of

* Funafuti Report, pp. 333–334. † Op. cit., p. 173.
‡ Personal communication.

coral reefs. This material could not have tumbled down a talus bank and have been preserved loosely and intact. Moreover, it is associated in this lowest core of the boring with other evidence of shallow water conditions.

Halimeda, now living in the lagoon to the depth of about 200 ft., was found in the cores at 660 ft., proving a subsidence of nearly 400 feet."

Prof. Judd also stated that careful search was made to see if deeper water organisms mixed with those building up the reef could be detected in the cores.

If any part of the bore represented material fallen from above such an admixture of shallow and deep-water forms must have occurred. Not a trace of deep-water forms was found in the lower or any other parts of the Funafuti bore. Dr. Hinde's carefully drawn up lists show that from top to bottom the same organisms occur, sometimes plants, sometimes foraminifera, sometimes corals predominating, but in the whole depth bored the same genera and species of these various groups of organisms take their part in the building up of the mass.

Moreover, as Judd states, not a trace of Orbitoides or other Tertiary fossils such as occur and have been recorded, by the writer among others,* at Christmas Island in the Indian Ocean, and at Mango and Namuka in the Fiji group in the Pacific Ocean, was found from top to bottom of the boring.

*Textural features of the boring.*

If any part of the boring had passed through a submarine coral talus, its coarse fragmentary condition and bedded character should have been recognizable. Prof. Judd† reports that "nowhere could a stratification, such as might be expected in a talus formation, be found, but only such irregular accumulation of detrital materials as takes place between and around the corals, and these appearances were presented at many points from the top to the bottom of the bore hole, whenever consolidated rock could be examined."

Dr. Cullis‡ in his valuable report draws attention to and figures remarkable stalagmitic coatings to cavities in the limestone of the bore, chiefly formed of fibrous calcite, sometimes of alternating layers of calcite and dolomite, and these are found at intervals, not only in the upper part of the bore in the case of the fibrous calcite, but also from a depth of 815 ft. down to the bottom. This material from its appearance and occurrence as a lining of cavities is strongly indicative of rapidly deposited carbonate under conditions of supersaturation such as occur under very shallow water conditions or even between

* Skeats, Bull. Mus. Comp. Zool., Harvard, xlii, June 1903.
† Op. cit. pp. 174–175. ‡ Op. cit. pp. 392–420.

high and low tide level. Dr. Cullis also draws attention to the mineralogical change from aragonite to calcite in the materials of the upper part of the bore cores. In the top cores aragonite is freely represented in the corals, and certain other organisms, and as chemically deposited carbonate. With this occurs calcite in the form of organisms and as chemically deposited material. At about 100 ft. in depth it is noted that less aragonite and more calcite are represented due partly to the deposition of calcite instead of aragonite and partly to conversion of aragonite to calcite. Below 100 ft. this mineralogical change is more noticeable, and at 150 ft. practically all aragonite has gone, the lowest depth at which it has been recognised being 220 feet.

This mineralogical change involving a change in the appearance of the rock cores, it will be noted, is gradual and not abrupt, but it is probably responsible for certain erroneous conclusions to be mentioned below. Summarizing the evidence of the organisms and of the textural features of the main boring at Funafuti it may be stated that all the organisms belong to recent forms, most of the species are still living, nearly all are forms which only live in the shallow water of the reef and lagoon, many of the reef-forming corals in all parts of the bore, including the lowest cores, occur upright, in the position of growth, no deep-water types of organisms were found and no Tertiary forms.

No evidence of coral talus and no true sign of bedding was noticeable although carefully sought for. Stalagmitic linings to cavities in the coral limestone, such as might be expected to be deposited in very shallow or tidal waters, occurred at intervals down to the bottom cores, while the change from aragonite to calcite in the material of the core involving a change in the appearance of the rock occurred gradually between the depths of 100–150 ft., and was complete at a depth of 220 ft.

It will be noted that the above facts are completely at variance with the view expressed by Agassiz* in his paper on the Coral Reefs of the Tropical Pacific. Therein he remarked as follows: "The boring at Funafuti reached 1114 ft. It passed at first through the modern reef rock material and below that must have, judging by analogy, penetrated either an underlying mass of Tertiary limestone or have passed through the mass of modern reef rock forming the outer talus of the atoll of Funafuti."

Prof. Daly† in his paper on the glacial control theory of Coral Reefs after discussing Von Lendenfeld's view of the development of an atoll by centrifugal displacement of the outcrop as sinking progresses, states: "If Von Lendenfeld's

* Mem. Mus. Comp. Zool., Harvard, xxviii, pp. 21, 22, 1903.
† Daly, Proc. Amer. Acad. Sci., li, p. 247, 1915.

view is correct, the massive reef of a large atoll must lie unconformably upon talus of indefinite depth. Hence the Funafuti borings could not, in any case, have penetrated massive reef material in situ to a depth greater than about 45 meters." Again, at p. 218, he states: "the boring at Funafuti showed massive coral to persist to a depth of about 46 meters. Below that depth the log of the boring suggests that it passed through talus material all the way to the bottom at a depth of 340 meters. This conclusion was reached by the writer after a careful study of the Funafuti report, issued by the Royal Society of London; a subsequent inspection of a duplicate set of the core material has tended to confirm the opinion." These statements of Agassiz and Daly require some comment. The underlying mass of Tertiary limestone beneath a shallow reef, pictured by Agassiz, and the reef platform required by Daly's hypothesis cannot be recognized in the Funafuti boring.

Prof. Daly's opinion, after an examination of the report and of a duplicate set of core material, that below 46 meters the bore continued in talus material to the bottom, appears to the writer to be in conflict with the published facts and with the views of the experts who examined the material. It would involve a sharp, unconformable break at 46 meters below the surface between the coral reef rock and the underlying talus. The evidence on the contrary shows similar organisms and texture above and below this depth, and the only change noticeable near this depth is a gradual mineralogical change from aragonite to calcite between 100–180 ft.

*Conclusions*

The conclusion is reached, based on the examination of the organisms and textures from the bore and the submarine contours of the island of Funafuti, that the only hypothesis of origin capable of correlating and accounting for all these facts is the subsidence theory of Darwin. Supporting evidence of the shallow-water origin of all the material and therefore subsidence of the land will be brought forward in a succeeding paper dealing with the formation of dolomite and its distribution among coral and other limestones.

The conclusions to be drawn from this summarized statement of observations, both positive and negative, seem to the writer to be clear, namely, that the whole material of the atoll from the surface down to the bottom of the core at 1114 ft. 6 inches is essentially homogeneous in origin and organisms, and all of it was formed in shallow water. This necessarily involves either a subsidence of the land to the extent of 1114 ft. or possibly while the bulk of the material was formed during subsidence, a small portion may be due to growth during a post-glacial rise in sea level.