## No. 3. — *The Coral Reefs of the Hawaiian Islands.*

By Alexander Agassiz.

Before giving the results of my observations on the Coral Reefs of the Sandwich Islands, it may be useful to recapitulate the salient points of the older theories of the formation of the coral reefs, from Chamisso's (1815–1818) to Darwin's (1842), as well as the modification of the latter by Dana (1838–1842, 1849), and to enumerate briefly the objections which have been made to the general application of the theory of subsidence to the special cases examined by later investigators, from Agassiz (1851) to the present time.

I need only refer to the earlier views of Forster, who imagined coral reefs to have been built up from the bottom of the ocean, a view which was naturally untenable after the observations of Quoy and Gaymard on the limits of depth at which corals apparently thrive, as well as the later observations of Ehrenberg on the coral reefs of the Red Sea.

Darwin, it should be remembered, examined only the Great Chagos Bank, and based his speculations on the observations he made on this single group, supplementing the knowledge, however, by a most exhaustive analysis of the observations and descriptions of others, and a most thorough examination of the hydrographic charts which had any bearing on the subject. But no naturalist has had opportunities to make a personal examination of the conditions of growth of corals and of coral islands such as have been enjoyed by Dana, as geologist of the United States Exploring Expedition. His Report on Coral Reefs and Islands, published in 1849, contains a full account of his own observations (1838–1842) on the Hawaiian Islands, the Society Islands, the Samoa and Viti groups, and his theories are based upon his own experience, far wider than that of any other writer on the subject. He has therefore drawn but little either from the descriptions of the voyagers of the early part of this century, or from the hydrographic charts, both of which form so essential a part in the Darwinian theory of coral reefs.

An examination of the hydrographic charts of the coral reefs, while interesting, can lead to no sound conclusion. Well as I know the Florida reefs and part of the Bahamas, as well as the majority of the West India coral reefs, I should hesitate to base any general conclusions upon an examination of these charts, much less to attempt any but very indefinite deductions for local phenomena or conditions.

It seems scarcely necessary to discuss the opinions of Wilkes,[1] who dismisses the whole basis of the theory of coral reefs, besides the special theory of Darwin, and who calmly says: "After much inquiry and due examination, I was unable to believe that these great formations are or can possibly be the work of zoöphytes; . . . I cannot but view the labors of these animals as wholly inadequate to produce the effects which I observed." There seems to be only one critical observation worthy of remark. When speaking of the formation of lagoons he suggests the possibility of the washing influx and efflux of the sea to carry off in the shape of mud or sand, or in solution, the strata underlying the central part of a lagoon. Wilkes further says: "It seems almost absurd to suppose that these immense reefs should have been raised by the exertions of a minute animal, and positively so to explain the peculiar mode of construction by which reefs of an annular shape are formed, when in nine cases out of ten they are of other figures." The last part of his statement seems to have been lost sight of in the discussions on atolls.

In striking contrast to Wilkes's opinions are the observations of Couthouy, one of the naturalists of the United States Exploring Expedition, who published in 1842 his views on the Coral Islands of the Pacific.[2] He suggests that corals are limited in their range of growth by temperature rather than depth, and that wherever this is not below 76° Fahrenheit, then, *cæteris paribus*, they will be found to flourish. Couthouy admits the correctness of the theory advanced by Darwin, and believes the great thickness of the reefs to have been produced by a gradual and long continued subsidence of the original shelf of coral, while the surface was maintained at the same level as at first by the unceasing additions made by the polyps. He also believes that the whole of Polynesia is at present slowly rising, and gives his reasons for believing in a former subsidence of a great continent, mainly based upon the identity of the volcanic and coralline rocks composing the majority of the islands of Polynesia. Couthouy describes the seaward side of the encircling reef of the Paumotu group as representing a succession of terraces or plateaus; the lowest of variable breadth, seldom exceeding one hun-

[1] Wilkes, Charles, Narrative of the United States Exploring Expedition, London, 1845, Vol. IV. p. 268.

[2] Joseph P. Couthouy, "On Coral Formations in the Pacific," Journ. Bost. Soc. Nat. Hist., 1842, p. 66.

dred and fifty feet, and declining rapidly seaward. These terraces as they recede from the sea become shallower and shallower, having at their extremity a sort of steep talus extending to the one next below it. This is probably due to the action of the surf, as the force of the sea becomes less and less where it is broken towards the shore line, though Couthouy is inclined to see in these terraces the effect of subsidence. But as he distinctly says that the outer terraces have only twelve to fifteen fathoms of water on them, about the limit of reef-growing corals, his explanation does not appear satisfactory even in the case of the terrace of Bellinghausen's Island, on which he found twenty-eight fathoms.

It seems much more natural to look upon the channels left, either in the barrier reefs or in atolls, as due to the original inequalities in the level of the foundation of the reef. The corals would naturally reach the surface soonest at the highest point, thus leaving passages which might at particular parts of the reef, and under certain local conditions, be gradually closed by the active growth of the corals, or might, on the other hand, remain open wherever the tides or currents rushed through them with sufficient force to check their increase, or where the silt was deposited in such quantities as to obstruct it.

It is interesting to go back to Kotzebue's Voyage, and to find in the chapter on the Coral Islands, by Chamisso, the following: "The corals have founded their buildings on shoals in the sea; or, to speak more correctly, on the top of mountains lying under water. On the one side, as they increase, they continue to approach the surface of the sea, on the other side they enlarge the extent of their work." [1] He noticed the more rapid growth of the coral where exposed to the action of the surf, and the obstacles to their growth in the middle of a broad reef, due to the amassing of shells and accumulation of coral fragments, and also to the formation of coral land by the cementation of the calcareous sand, gradually increasing in thickness till it is covered by the sea only during certain seasons of the year. He also noticed the formation of reefs more or less circular, with an interior sea, having a depth sometimes of thirty to thirty-five fathoms, which he explains from the action of the natural causes above enumerated.

Dr. Guppy [2] justly says in Nature: "The development of the new theory should be kept in mind. Chamisso seventy years ago advanced the view that an atoll owes its form to the growth of corals at the margin and to the repressive influence of the reef débris in the in-

[1] Kotzebue, Vol. III. p. 331, London, 1821.

[2] H. B. Guppy, Nature, March 15, 1888, p. 462.

terior; but this view gave no satisfactory explanation of the foundation of such a coral reef, and Darwin was driven to his theory of subsidence. The great defect in the way of Chamisso was, however, removed by Murray, who supplied the foundation of an atoll without employing subsidence, and investigation in the Florida Sea (Agassiz) and in the Western Pacific (Guppy) have confirmed his conclusions. The forms of reefs he attributed to well known physical causes. Both Semper and Agassiz have dwelt upon the importance of other agencies, and in our present state of knowledge it will be wisest to combine in one view the several agencies enumerated by them as producing the different forms of coral reefs. On the outer side of the reef we have the directing influence of the currents, the increased food supply, the action of the breakers, etc. In the interior of a reef we have the repressive influence of sand and sediment, the boring of the numerous organisms that find a home on each coral block, the growth of Nullipores, the solvent action of the carbonic acid in the sea-water, and the tidal scour. These are all real agencies, and we only differ as to the relative importance we attach to each. Future investigations will probably add others to the list, besides ascertaining the mode and degree of action of each case."

According to the theory of subsidence, there is no limit to the thickness which a coral reef, rising out of deep water, may attain. It may rest upon rocks of any material situated in a region of subsidence, while naturally it would extend mainly vertically, its horizontal width being comparatively slight. According to the other theory, which does not call upon subsidence to explain the formation of barrier reefs or of atolls, the base of coral reefs, whether atolls or barrier reefs, may be any plateau or eminence, either volcanic or the product of accumulations of limestone banks, which have reached the requisite height for the growth of corals. The presence of such limestone banks and of eminences, either volcanic or other, which have reached the level at which corals will flourish is nowhere better exemplified than in the West Indian region, where we find atolls, barrier reefs, and fringing reefs in a region which is eminently one of elevation. In an area of elevation we may have comparatively thin reefs, forming a mere casing to the core upon which they have grown, as Guppy has shown in the case of one of the Solomon Islands.[1]

Mr. J. J. Lister, the naturalist of H. M. S. Egeria, Commander Aldrich, describes Christmas Island as being a succession of horizontal terraces, marking the pauses of its gradual elevation during which a

[1] Nature, December 29, 1887, p. 203.

fringing reef was formed.[1] There was a cap of coral limestone over the whole island ; the very top of the island, twelve hundred feet high, being a block of worn and undermined coralline limestone, then tiers of cliffs intervening between the top and existing sea cliffs. "Christmas Island thus appearing to be a remarkable instance of the complete casing with coral of an island, which, from the time that its first nucleus came within the reef-building zone, has been steadily subjected to a movement of upheaval varied by pauses, during which the cliffs were eroded by the sea."

That the volcanic nucleus has not been exposed is undoubtedly due, as has been suggested by Guppy,[2] to the fact that the upheaved island has not been exposed to denuding agencies for a sufficiently long period of time.

Murray,[3] who had unusually good opportunities for examining numerous coral reefs of the Pacific, published a remarkable paper on the formation of reefs in the Proceedings of the Royal Society of Edinburgh, in which he gives an explanation of the formation of channels between barrier reefs and the mainland band, and of the lagoons of atolls, based upon the solvent action of sea-water saturated with carbonic acid upon coral limestone. That this solvent action is a powerful factor in corroding the surface of coral reef, and carrying off surplus limestone in solution is not to be denied, but to consider it the principal cause of the formation of lagoons and of channels between barrier reefs is perhaps pressing the theory too far. It undoubtedly has acted in many cases powerfully enough to corrode the whole surface of reefs exposed to action of water so saturated with carbonic acid. I would refer specially to the surface of reefs like the fringing reefs of Honolulu, the corroded breccia reef rock found at many points of the Keys of Florida, and the evidence of the same action to be found on the shore deposits of coral along the whole northern coast of Cuba, where the shore reef exists parallel with the great Cuban barrier reef. Similar action, of course, is taking place constantly in limestone districts, through which waters saturated with carbonic acid percolate, forming caves and other cavities so characteristic of these formations.

[1] A similar condition of things exists at Barbados, where the volcanic reef centre crops out only on the summit of the island, and the sides of the cone are covered with coral reef terraces, which are one of the most characteristic features of the island as seen from the sea. A. Agassiz, Three Cruises of the Blake, figs. 39, 46.

[2] Nature, January 5, 1887, p. 223.

[3] Murray, John, Proc. Royal Soc. Edinb., 1879–80, p. 505.

Wherever in that region the fringing reef has attained any considerable width, we find that upon the portion nearer shore, where the corals once flourished, they have died because the extension of the reef towards the shore has excluded them from contact with the fresher sea-water outside. This part of the reef has been corroded and eaten off, or was dissolved, as Murray suggests, by the action of the carbonic acid held in sea-water, which absorbs a large amount of carbonate of lime.

But it should not be forgotten that this solvent action of carbonic acid in sea-water cannot be considered as the chief agent in the formation of barrier reefs. Take, for example, the case of the Florida reefs, or that of the great barrier reef of Australia. The former are so far from the neighboring chain of keys, and the latter so distant from the adjacent mainland, that such an explanation of the presence of the channel separating the one from the keys, the other from the shore, would involve the solution and disappearance of the reef itself.

We are inclined to look upon the depth and extension of the ridge or plateau upon which a barrier reef first establishes itself as the chief cause of its growth and final form. Such a plateau having reached the level at which corals flourish, the reef begins to grow, and its distance from the mainland or from the adjacent islands is thereafter determined by the contour lines of the submerged extension of the land seaward or landward. Nevertheless, the effect of the relatively clear or muddy water on the sea and land faces of the incipient barrier reef cannot have failed to exercise an important influence on its seaward or landward development.

Murray [1] clearly shows that the solution of dead carbonate of lime shells and skeletons by sea-water is as constant as its secretion by living organisms. He considers it probable that on the whole there is more secretion than solution, and that there is at the present moment a vast accumulation of carbonate of lime going on in coral areas no one familiar with the subject will deny. This secretion diminishes with the depths, while the rate of solution perhaps increases under pressure. He compares it to the action of aqueous vapor in the atmosphere over land surfaces. When precipitation is in excess of evaporation fresh-water lakes are formed; when evaporation, on the contrary, exceeds it, salt lakes are formed in inland drainage areas.

The discussion on the theory of solution which has taken place in "Nature" between Reade and other geologists, does not appear to cover the ground. The objections are mainly made by investigators who know

[1] Nature, March 1, 1888, p. 414.

little of coral reefs from their own observations, some of whom have ignored or flatly denied facts which can hardly be dealt with in so summary a fashion.

According to Reade,[1] it seems very evident that if we accept the dissolution theory for the origin of coral lagoons, it seems impossible to believe in the building up of calcium carbonate, or volcanic platforms, or other peaks, from varying and unknown depths to the levels necessary for the growth of coral reefs. If, on the other hand, we believe that platforms are so built up, it appears equally destructive of the dissolution theory of lagoons.

In "Nature" of September 21, 1880, Mr. Reade says: "I think the theory Mr. Murray sets forth, — that the cones or peaks on which he considers atolls have been formed have been levelled up by pelagic deposits, and thus brought within the limits of reef-building coral growth, — a very far-fetched idea."

In the same journal, Darwin says: "I am not a fair judge, but I agree with you exactly that Murray's view is far-fetched. It is astonishing that there should be rapid dissolution of carbonate of lime at great depths and near the surface, but not at intermediate depths, where he places his mountain peaks."

It is surprising that Reade[2] should have attempted to throw doubt on the existence of calcareous submarine banks. The submarine banks are not, as Mr. Reade seems to think, due to the tests of the pelagic fauna alone. A submarine peak is not built up by the pelagic fauna, but it is built up by the carcasses of the Invertebrates that live upon it, and for which the pelagic fauna serves in part as food. Certainly, the amount of limestone and shells of pteropods alone in some regions is very much larger than any estimate made by Mr. Reade. The large number of well known limestone banks of great thickness and extent should make such a discussion unnecessary.

The "pelagic cemetery" is farther down, and not on the surface, and I would refer Mr. Reade to my article on the Florida Reefs, in the Memoirs of the American Academy of Arts and Sciences, 1883, as well as to the "Three Cruises of the Blake," for such proof as has thus far been obtained regarding the existence of these huge masses of limestone banks, eminently fitted, as I think I have shown, to form the base of such coral reefs as those of the West Indies, of Florida, of the shores of Cuba, and of the great Alacran and other reefs on the Yucatan Bank.

[1] T. Mallard Reade, Nature, March 22, 1888, p. 489.

[2] Nature, April 5, 1888, p. 535.

The following are the principal experiments which have been recorded regarding the solvent action of sea-water on corals. According to Mr. Robert Irwine,[1] dead or rotten coral of several species of Porites, exposed to sea-water of 1.0265 specific gravity, and of a temperature of from 70° to 80° Fahrenheit, was found to be soluble to the extent of 5 to 20 ounces to the ton. We have no data to show how far this capacity of solution is in excess of the deposition of limestone due to the corals themselves, or to the sand and débris carried into the lagoons or the inner part of the reefs. No observations have been made regarding the amount of carbonate of lime existing in lagoons, and in the sea-water on the sea face of a reef.

Mr. W. G. Reid, in a paper read before the Royal Society of Edinburgh, February 6, 1888, observed that the solubility of carbonate of lime increased with pressure.

Mr. James G. Ross[2] detailed in "Nature" other experiments showing a considerable amount of solution. In a species of Oculina 0.0748 gramme was lost, from a specimen weighing 16.3164 grammes, in twenty days. In another case, 0.1497 gramme was lost in thirty days by a mass of Madrepora weighing 15.334 grammes. The above experiments would both indicate the possibility of a very material deepening of a lagoon by the solution of the coral. At such a rate of solution, a lagoon four miles in diameter might be deepened one fathom in a century.

The rotten condition of the old shore reef of Havana,[3] completely honeycombed as it is, shows how rapidly limestone is acted upon by sea-water. The rotten reef rock of the Everglades, soaked by brackish water, which is often accumulated in large bodies behind the old reef ranges, has been described by Professor Agassiz. This water, saturated with carbonate of lime, often rushes out with considerable volume after a storm, and produces great havoc with the shore fishes of the adjoining reef. Their dead bodies often line the shores of the Florida reefs for miles, when there has been such an outburst of water saturated with carbonic acid. The existence off shore of bands of sea-water similarly saturated with carbonic acid may explain the great destruction of fishes which so often takes place in fishing vessels carrying their catch from the Florida Reef to Havana. It will have been noticed by all who have ever seen a coral sand beach, or a breccia beach, or a beach composed

[1] Nature, March 15, 1888, p. 461.

[2] Nature, March 15, 1888, p. 462.

[3] See Three Cruises of the Blake, Fig. B, p. xii.

of larger fragments of coral and reef limestone, that the constituent parts of the beaches were, as could easily be seen by the eye, invariably corroded far beyond the condition to which the sand or breccia, or larger fragments, could be reduced if merely subjected to the triturating agency of the rollers. An analysis made by Prof. F. W. Clark, the chemist of the United States Geological Survey, of such fragments, either as sand or in all intermediate stages up to fragments of coral, or coral limestone, showed very clearly that the chemical composition of the pieces was practically the same.

The only analysis known of the chemical constituents of the sea-water of the lagoon of an atoll is given as determined by Messrs. Stillwell and Gladding,[1] from which it would appear that the amount of chlorine was considerably larger than the amount given in the latest analysis of Dittmar, and that the water of the lagoon is fresher than that of ocean water.

It may not be out of place to mention here, that there is a most excellent figure and plan of an atoll in an account of Caroline Island,[2] by Prof. E. S. Holden, the director of the American Eclipse Expedition of 1883. Not only is the description of the atoll admirable, but the illustrations of the various parts of the island are most characteristic, including one of the best figures perhaps of a bird's-eye view of an atoll. A map also accompanies the description, but unfortunately no soundings are given.

Lagoons without openings are perhaps older lagoons, in which the openings have from local causes been gradually closing, and from the porous nature of the surface coral rock there still remains a chance for the exchange of waters from the interior to the exterior of a reef.

Jukes,[3] who in 1845 surveyed the Great Barrier Reef of Australia, came to the conclusion that the "northeast coast of Australia has either been slightly elevated, or that it has at least not suffered any depression during a long period of time." From this he has satisfied himself that, wherever we find coral reefs rising abruptly from unfathomable depths, they must necessarily have been produced by the depression of the sea bottom, the corals building on upwards as the bottom was slowly sinking, so as to keep the upper portion of the reef always within the required depth. The depression of the bottom, according to this view,

[1] Mem. Nat. Acad. of Science, Vol. III. p. 96.

[2] Report of the Eclipse Expedition to Caroline Island, May, 1883, Mem. Nat. Acad. of Science.

[3] Jukes, J. B., Narrative of the Surveying Voyage of H. M. S. Fly, Vol. I. p. 311.

has occupied a far longer period than that during which the northeast coast was either stationary, or had been slightly elevated. He urges the parallelism of the outline of the Great Barrier Reef with that of the northeast coast as evidence that the circumstances which modified the outline of the coast likewise determined the general outline of the reef, while subsidence would most assuredly produce the results observed on the northeast coast of Australia if the rate of growth of corals were absolutely identical with that of the subsidence of the bottom of the sea. With our present knowledge of the mode of coral reef formation, it seems unnecessary to explain the existing state of things by a subsidence coincident in rate with the growth of corals, when observation plainly shows us that there has been only a slight elevation or a stationary condition of the coast line. Starting from the conditions Jukes imagines to have existed before the subsidence took place, only leaving the coast nearly at its present level, we can imagine a fringing reef to have been formed slowly, and to have little by little extended seaward, advancing more slowly as the depth increased, while the talus for the upper limits of coral grew, it increased in thickness, and to have ended in a barrier and inner reef with channels very much like the reef we find to-day.

Is it credible that, along the whole length of the northeast coast of Australia, the subsidence should, for a length of over one thousand miles, be so nearly identical in amount as to have ended in forming parallel to it the Great Barrier Reef? The same question is one which must be answered not only for Australia, but for all the atolls and barrier reefs in the Pacific and other regions where such reefs exist.

We have all over the world many positive proofs of the elevation of the land, sometimes on a gigantic scale, as in South America, for instance, up to nearly three thousand feet. Neither can we deny that there are many points, especially in the Pacific Ocean, where are to be found areas of subsidence; but it is by no means proved that this subsidence has been the main cause of the formation of atolls or of barrier reefs. In fact, all the later investigations of coral reefs have, without exception, rejected Darwin's theory of subsidence as explaining the formation of reefs, and they have looked to other causes, which seemed to them more natural, as probably more efficient in the growth of reefs. The question is not whether subsidence has taken place even in the areas where atolls or barrier reefs occur, — this may be considered as proved, — but whether this subsidence has absolutely kept pace with the rate of growth of corals. It is remarkable that Darwin, who is so strongly opposed to all cataclysmic explanations, should in the case of the coral reefs cling to a theory which is based upon the disappearance of a Pacific continent,[1] and be apparently so unwilling to recognize the agency of more natural and far simpler causes.

Granting that during the secondary period the great East India islands were connected with Asia, and that there had been in the early tertiary period a great subsidence, which may have extended throughout some parts of the Pacific to the time of the formation of modern coral reefs, — granting even that the summits of the islands now existing indicate plateaus upon which the various archipelagos of the Pacific are based, and point to a former extent of land far greater than now projects above the surface of the sea, and also that the islands of the Pacific mark a general subsidence along a line extending from the southeast to the northwest, as is urged by Dana, — yet there is nothing in all this to show that the subsidence has been the main cause of the formation of atolls and barrier reefs, while the existence of such a subsidence in its turn derives its strongest proof, with many writers, from the existence of atolls and barrier reefs. As long as we can in so many districts explain the formation of atolls and of barrier reefs by other causes, fully sufficient to account for the numerous exceptions to the theory of Darwin, which have been observed by so many investigators since the days of Darwin and Dana, it seems unnecessary to account for their presence by a gigantic subsidence, of which, although we may not deny it, we can yet have but little positive proof.

Dana has been led to reconsider the earlier and later observations, and has given his results in the American Journal of Science.[2] He most distinctly rejects Darwin's hypothesis, that the slow subsidence upon which he counted to form atolls and barrier reefs from fringing reefs involved the whole central Pacific, besides other large areas, a Pacific continent having disappeared through subsidence.

Whether subsidence is going on now, or has ceased after the formation of atolls, which he ascribes to it, seems immaterial. The point at issue is, how far is it possible for atolls and barrier reefs to begin in an area of limited extent without a constant alternation of elevation and subsidence. It seems to me that the rocky islets dotting the interior of Kaneohe Bay could as well be cited as proof of subsidence, as the rocky

[1] This part of the theory of Darwin, which seems a natural corollary of his explanation of coral reefs, is most emphatically rejected by Dana, Am. Journ. of Science, Vol. XXX. p. 90, 1885, and previously also in his Geology of the Exploring Expedition, in 1849.

[2] Am. Journ. of Science, August, 1885, p. 89, and September, 1885, p. 169.

islets which dot the great lagoon-like waters of the Gambier group, "leaving scarcely any doubt in the mind that the islets were the emerged points of sunken lands; and if this is evidence of subsidence, then the atoll [of Keeling] which he [Darwin] examined was proof of further subsidence, that is, one that had continued to the disappearance of the sinking peaks." This is the proof which Darwin believed to be almost certain evidence of subsidence.

Dana adds, as an argument in favor of subsidence, the existence of deep fiord-like indentations in the rocky coasts of islands, both those inside of barriers and those not bordered by reefs. Certainly this is a most unsafe method of reasoning, unless accompanied by sounding in the fiords to show the continuation of the slope of erosion. As to the non-existence in the ocean now, and the extreme improbability of the existence at any time, of submarine volcanoes or chains of mountains having their numerous summits within a hundred feet of the surface, which has been a favorite argument against the possibility of a volcanic base for reefs, the recent deep-sea soundings of the Atlantic in volcanic districts, like that off the west coast of Africa by the Talisman, have shown the existence of numerous peaks and submarine banks, which in the track of oceanic currents would soon be built up to the level at which corals can thrive, and produce the very conditions denied by Darwin. A similar state of things has been developed by the soundings of the Blake in the West Indies.

Dana mentions the great width of a reef as an indication of subsidence. I am unable to see the force of that argument. It seems merely to indicate the great length of time which has elapsed since it began to build. We might take for granted the evidence of subsidence as deduced by Dana for the Tahitian group and for the Samoan group, for instance, and yet we should not have the proof that this subsidence was coexistent with the formation of the different kinds of reefs.

If, as is supposed, we can have submarine banks of limestone formed upon volcanic mountains or other steep slopes, the steepness of the slope off the coral reef, does not argue anything in favor of subsidence. I do not see that the large débris offer positive proof of subsidence, if they have, as Murray supposes, gradually rolled down the steep talus of the sea face of the reef, and have, as is certainly the case in the Sandwich Islands, formed the surface, which may be of great thickness. Dana infers, from the statement I made in regard to the former connection of the Windward Islands[1] with South America, that there has been a sub-

[1] Bull. Mus. Comp. Zöol., 1879; Am. Journ. of Science, XVIII. 230, 1880.

sidence. It may also be that erosion has been amply capable of washing away the land connections, and forming the banks on which the islands rest as it were.

As to there not being any mound now approaching the ocean surface in the western border of the Gulf Stream, the past history of the Gulf Stream itself, of the Florida Plateau, and of the formation of the Keys of Florida and of the present reef, seem to me to furnish just such a foundation for reef-building as is required by Dana. The Mosquito Bank, the Yucatan Bank, and the smaller banks between Honduras and Jamaica, are all proof that immense limestone banks are forming at any depth in the sea, or upon pre-existing telluric folds or peaks, constituting banks upon which, when they have reached a certain depth, corals will grow. Is it claiming too much for erosion to say that some of the volcanic peaks may have been washed away and swept into the sea? Certainly this is not the case in any region where there is a rainy season. The Sandwich Islands themselves, greatly modified as they have been by erosion, furnish the best evidence that isolated peaks may have completely disappeared. A careful perusal of Dana's own account of the effect of erosion on their topography, and of Captain Dutton's later examination, shows how powerful a factor they regard erosion to have been in these islands. And if we go farther towards the equator, or to the region of cyclones and tornadoes, the action of erosion will be found to be far more powerful than in the Sandwich Islands, which are on the very edge of the rainy season district.

It is somewhat surprising that, in the discussion which has lately been carried on in the English reviews,[1] by the Duke of Argyll, Huxley, Judd, and others, regarding the new theory of coral reefs, no one should have dwelt upon the fact, that, with the exception of Dana,[2] Jukes,[3] and others who published their results on coral reefs soon after Darwin's theory took the scientific world by storm,[4] not a single recent original investigator of coral reefs has been able to accept this explanation as applicable to the special district which he himself examined. It is interesting to note that, however widely Darwin's theory was accepted and spread in all text-books of Geology, neither L. Agassiz,[5]

1 "Nature" and "Fortnightly Review."

2 Dana in 1838–1842; "Corals and Coral Reefs," in 1872.

3 Jukes in 1845, Narrative of the Surveying Voyage of H. M. S. Fly, Vol. I. p. 31, 1847.

4 Darwin in 1842, "The Structure and Distribution of Coral Reefs"; Darwin's Coral Reefs, 1874, 2d edition.

5 Agassiz, L., U. S. Coast Survey Reports, 1851 and 1866; also Methods of Study (popular sketch). See Vol. VII., Mem. Mus. Comp. Zoöl.

who examined the Florida Reefs in 1851, nor Joseph Leconte,[1] his assistant, who published subsequently views somewhat different from those of L. Agassiz, nor E. B. Hunt,[2] who promulgated a theory of the formation of the Florida Reefs, nor A. Agassiz, who spent several seasons in parts of Florida, on the Florida Keys, and on the Tortugas, was able to accept Darwin's theory as offering an explanation of the formation of the great reef extending from the Tortugas to Cape Florida.

Agassiz, while in general he accepted Darwin's theory as applicable to atolls, yet gave, in 1851, (Report of United States Coast Survey, republished with additions in the Memoirs of the Museum of Comparative Zoölogy,) an account of the Florida Reefs, showing the living reef outside of the lagoon, and its position with reference to the line of Keys. I subsequently gave a number of sections of the same reef from the Coast Survey maps,[3] showing the formation of a barrier reef actually going on, where the reef foundation grows lower and lower, and where we need not have recourse to the theory of solution for the formation of a lagoon. The lagoon we can actually trace from its broadest point at the Rebecca shoal, where the reef is submerged, to its narrowest point at the northern extremity of the reef.

Leconte accepts the theory of subsidence as a satisfactory explanation of the formation of atolls in the Pacific Ocean; but in Florida, which he visited with Professor Agassiz in 1851, he agrees with the latter in his account of the formation of a barrier reef where there has been no subsidence, and then he points to the Gulf Stream running parallel with the trend of Florida, as the agent which has deposited the great mass of the Florida bank below the level at which corals can grow. But there is no evidence that the Gulf Stream ever ran in the direction assumed by Leconte. Agassiz also accepted the theory of subsidence as generally explaining the formation of the different kinds of coral reefs, though in his account of the formation of the Florida Reef he does not go beyond the depths at which reefs grow, and says nothing of the substructure or foundation rock. In February, 1878,[4] I called attention to the exist-

[1] Am. Jour. Science, XXIII., May, 1857, p. 46, "On the Agency of the Gulf Stream in the Formation of the Peninsula and Keys of Florida," by Joseph Leconte; also Elements of Geology, New York, 1878.

[2] Hunt, E. B., Am. Jour. Sci., 1863, Vol. XXXV. p. 197.

[3] In the Tortugas and Florida Reefs, Memoirs of the American Academy, Vol. XI., 1883.

[4] Agassiz, A., Letter No. 1 to C. P. Patterson, Supt., on the Dredging Operations of the U. S. Coast Survey Steamer Blake, Bull. Mus. Comp. Zoöl., V., No. 1, 1878.

ence of a great atoll, Alacran Reef, on an area of elevation on huge limestone banks such as those of Yucatan.

Leconte insists on the fact that the Florida Reef, a true barrier reef, has been formed where there could not be any subsidence, as continuous increase of land is inconsistent with subsidence. According to Darwin, barriers and atolls always show a loss of land, only a small portion of which is recovered by coral and wave agencies, while on the Florida coast, according to Leconte and Agassiz, there has been a continuous growth of the peninsula by coral accretion, until a very large area has been added.[1] He attributed the formation of successive reefs to the successive formation of the depth condition necessary for coral growth, and this latter, in the absence of any evidence of elevation, to the steady building up by sedimentary deposits and extension southward of a submarine bank within the deep curve of the Gulf Stream as it bent its way round the west coast of Florida.[2] The formation of barrier reefs instead of fringing reefs on a coast which has certainly not subsided, he attributes to the shallowness and muddiness of the bottom along this coast. Only at a distance of twenty to forty miles, when the depth of twenty-five fathoms is reached, and when, therefore, the bottom is no longer changed by the waves, the conditions necessary for coral growth could be found, and here a line of reefs would be formed, limited on one side by the depth, on the other by the muddiness, of the water.

According to Leconte the building up of Florida and of the Keys was due to the co-operation of several agents: —

1. The Gulf Stream building up and extending a submarine bank within its loop, but not in the position assigned to it by Leconte.

2. Corals building successive barriers on the bank, as the latter was pushed farther and farther southward.

3. Waves beating the reefs into islands.

[1] See Smith, Hilgard, Heilprin, and Dall, for the structure of the peninsula of Florida.

[2] I can hardly see how Leconte states (Nature, October 4, 1880, p. 558) that there are barrier reefs in Florida with lagoons from ten to forty miles wide, though he subsequently (Nature, November 25, 1880) modifies this statement by indicating this to mean the space between the southern coast of Florida and the line of Keys (Old Barrier Reef) which widens from a few miles at its eastern part to more than forty miles in its western part. But this is also misleading, as it refers to the time when the Keys formed the reef, while now the channel between the line of Keys and the present reef gradually widens from a narrow lagoon near Key Biscayne to from six to ten miles wide, opposite the Marquesas, and is about one hundred and fifty miles long.

4. Débris from the reef and Keys on the one side, and the mainland already built (Keys) on the other, filling up the successive channels, and converting them first into swamps and finally into dry land, in all of which he agrees with Agassiz's explanation of the causes which have built the Florida Reef.

Neither was I able, when visiting the Alacran Reef, the reefs of the Windward Islands,[1] the elevated reefs of Barbados, of San Domingo, and of Cuba, the great barrier reef of Cuba, and becoming acquainted with the immense limestone banks so characteristic of the Caribbean region, to satisfy myself that Darwin's theory of subsidence gave an explanation of the condition of things now existing in an area of elevation, and including all the types of reefs which he considered as characteristic of an area of subsidence. If we pass to the Bermudas, Rein,[2] who carefully explored the islands, came to the same conclusion, and took a most decided stand against the theory of subsidence. Rein is of the opinion that coral reefs may grow wherever the conditions of the bottom are favorable for the development of the corals. In these he includes the temperature, the purity of the water, the supply of food by the sea, as well as a solid substructure, whether this substructure be due to the subsidence of the coast, or to an elevation of the bottom, this elevation being caused either by volcanic, organic, or other agency.

Rein also calls attention to the fact, that both Darwin and Dana have assumed a possibility as a fact, and, the theory once given, have attempted to prove the subsidence, instead of bringing the subsidence of coral reefs as a proof of the theory. Proofs of subsidence have nowhere been given except as explanations of existing phenomena, while the proofs of elevations within the regions of coral reefs are innumerable. Darwin and Dana explain the existence of deep channels between barrier reefs and the coast, as well as the formation of atolls by subsidence, and hence conclude from the existence of numerous barrier reefs and atolls that the coasts have sunk, and many islands have been buried in the sea to form atolls. It naturally follows that they calculate the vertical thickness of coral reefs as due to the same cause, and nothing but boring will settle this point.

Rein further mentions a number of coral reefs from the Tertiary to the Jurassic, none of which were more than thirty meters thick. Rein,[3]

[1] Agassiz, A., Three Cruises of the Blake, 1888, Vol. I., "The Florida Reef."

[2] Rein, J. J., Beiträge zur physikalischen Geographie der Bermuda Inseln, Bericht über die Senkenb. Naturf. Gesell., Mai, 1870, p. 140.

[3] Die Bermudas-Inseln und ihre Korallenriffe, nebst einem Nachtrage gegen die

in his excellent sketch of the Bermudas, calls attention to the discovery by Pourtalès of a conglomerate off the Florida reef, (the Pourtalès Plateau,) formed by the remnants of the calcareous remains of numerous invertebrates mixed with coral ooze and sand, which has little by little been built up from great depths. He suggests that the foundation of the Bermudas consists of a submarine bank of a similar nature, which has gradually been built up to the level at which coral reefs can flourish, the Bermuda limestone itself having had its origin upon a mountain or a terrestrial fold, which may consist of rocks having a greater or less geological age. He thus accounts in a most natural manner for the existence of the same rock which forms the surface of the Bermudas at the greatest depths which have been excavated in making the dock at that station. The limestone bank once having been built up to the level at which corals will thrive, the floating embryos carried north by the Gulf Stream found a foothold on which they began to grow, and founded the existing active coral reef. The action of the winds on the beach sand very soon formed the elevated Æolian rocks, which rise to a height of over two hundred and forty feet, and of which he, Thomson,[1] and Moseley[2] have given such excellent accounts. Jukes[3] had already, in 1845, given a similar account of such an Æolian formation at Raines Island, and Dana, in the Geology of the United States Exploring Expedition, had carefully described the formation of the sand drifts solidified into dunes and encrusting layers along the shores of Oahu.

Thomson, on page 304 of "The Atlantic," has given a graphic account of the mode of origin of the Bermudas, when once the weather edge of the reef was raised above the level of the sea, and of the manner in which the Bermudas of the present day have been built up as a bank of blown sand in various stages of consolidation, though Thomson adopts Darwin's theory, that the atoll of the Bermudas is due to the entire disappearance by subsidence of the island round which the reef was originally formed.

Thomson also gives, on page 309, excellent figures of the stratified Eolian rocks of the Bermudas, and of Æolian beds in process of formation, and on the following pages a figure of a so-called sand glacier, or a

Darwin'sche Senkungstheorie. Verhandl. d. ersten Deutschen Geographen Tage zu Berlin im Jahre 1881.

1 Thomson, Voyage of the Challenger, "The Atlantic," 1877, Vol. I., Bermudas, p. 420.

2 Moseley, N. H., Notes of a Naturalist.

3 Jukes, J. B., Voyage of the Fly.

mass of coral sand some twenty-five feet thick, progressing inland. He also describes the mode in which the free coral sand is rapidly cemented into limestone by the action of rain-water containing carbonic acid, which takes up a little of the lime and on evaporating forms the successive crust lines of demarcation between various layers of sand, forming the stratification and lamination of the Æolian rocks. The section given by Thomson, as exposed by the cutting made for the floating dock in 1870, seems to prove a slight subsidence, as there was found a bed of a kind of peat at a depth of forty-seven feet, containing stumps of cedar in a vertical position lying upon the hard bare rock. But it does not prove that this subsidence, or a greater one, which cannot be proved, has been the cause of the atoll shape of the Bermudas, any more than the slight elevations of from twenty to fifty feet, such as we so often meet with in volcanic districts, prove that the special type of coral reefs existing there have been due to their influence.

Lieutenant Nelson [1] has given an account of the geological details of the appearance of the different islands composing the Bermudas, and of the encroachments by the sea and sands, and it did not escape him that the whole of the Bermudas "may be called organic formations, as they present but one mass of animal remains in various stages of comminution and disintegration," and he also called attention to the organic composition of what he calls Bermuda chalk, which corresponds evidently to what has more recently been called coral ooze. He was among the first to notice the important action of Serpulæ in cementing together pieces of coral, and in certain localities forming even small independent reef patches. This has been fully confirmed by other observers in other districts.

Nelson has also suggested the possibility of the formation of submarine mountains by the growth of marine invertebrates round any base they may meet, the decay of their calcareous remains adding stability and bulk to the colony, while around their summits coral reefs would grow. He also says, very truly, "Zoöphytes affect a vertical growth, and in this attitude have a tendency to add to the accumulations of the exterior fence, to the prejudice of the space circumscribed."

When we pass to the very regions explored by Darwin, Mr. Henry O. Forbes,[2] who in 1879 examined the Keeling Atoll, forty-three years after Darwin's visit, — the very one which Darwin first examined, and which suggested to him his whole theory, — could not satisfy himself

[1] Trans. Geol. Soc. of London, V., Part I., 1840, p. 103.

[2] A Naturalist's Wanderings in the Eastern Archipelago, London, 1885.

that there was any proof of subsidence, or that the causes cited by the opponents of Darwin's theory were not amply sufficient to account for all the phenomena he observed there. Mr. Forbes, who spent more than a month in its study, felt inclined to believe that the Keeling Reef foundation has been formed as suggested by Murray, Agassiz, and Semper, and that the islets have been the result of the combined action of storms and the slow elevation of the volcanically upheaved ocean floor on which the reef is built.

Semper,[1] who visited the Pelew Archipelago in 1863, was among the first to come to the conclusion that the presence of barrier reefs, atolls, and fringing reefs in one district could not be explained by the theory of subsidence, and he looked to natural and simpler causes to explain the reefs of the Pelew Islands. He was one of the first, after the general adoption of Darwin's theory of the formation of coral reefs, to visit an atoll district in the Pacific, and he was the first also to point out for that region a condition of things which seemed to him incompatible with the accepted view. He found at the Pelew Islands, within a comparatively restricted area, atolls, barrier reefs, and fringing reefs. He speaks of the channels eaten away between the coast and the barrier reef, distant three to six miles from shore, and forming a labyrinth of channels, which he considers as due to the action of currents, and in which the flow of brackish water prevents the ready growth of corals, while in the case of the barrier reefs less than half a mile or so from the shore the action of the currents is reduced to a minimum and the channels scarcely marked. He speaks of elevated coral reefs of two hundred and fifty feet in height, and comes to the conclusion that the presence of atolls, barrier reefs, and fringing reefs in an area where there had been elevation, and which had remained stationary for a long period, does not indicate that they have been formed during a period of subsidence, while their simultaneous existence would seem to preclude such a conclusion.

Semper is inclined to attribute to the action of currents mainly the great irregularities existing in reefs, which may form even closed atolls, and are in great degree dependent for their ultimate shape upon the configuration of the underlying base. On steep shores barrier reefs, according to him, could not flourish; only fringing reefs closely hugging

[1] Semper, Carl, Die Philippinen und ihre Bewohner, pp. 100–108, Würzburg, 1869. A reprint, with additions, of Semper's article in Zeits. f. Wiss. Zool., XIII. p. 558, 1868. Also, Die Natürlichen Existenzbedingungen der Thiere, Leipzig, 1880, Zweiter Theil, p. 39.

the shores, would thrive in such a position, and he lays great stress also on the difference to be traced in the conditions of the two sides of the same islands, where the one side is exposed to the action of the open sea, while on the other side the long periods of calms are most favorable to the growth of corals. Although Semper does not deny that subsidence may have accompanied in some cases the formation of atolls and of barrier reefs, yet the explanation of the existing conditions of the reefs of the Pelew Islands seems to him more plausible by the theory of currents than by that of subsidence.

Semper has more fully developed these views in his "Natürliche Existenzbedingungen der Thiere." He calls attention to the difference between the theories of Darwin and Dana, while Dana agrees with Darwin that atolls and barrier reefs can only be formed in regions of subsidence, he differs from Darwin in claiming that fringing reefs indicate a greater amount of subsidence than either of the other types of reefs. He looks upon the steep coast line of many volcanic islands as a proof that there has been great subsidence, and of course upon such steep shores, often with a vertical cliff of more than one hundred and fifty feet, there is no possibility of the formation of a fringing reef. We must admit, with Dana, that in the volcanic regions of the Pacific, for which Darwin claims a general subsidence, there have been local phenomena of elevation, and also that in regions of elevation a slight subsidence may also have taken place. But if we have to depend upon either elevation or subsidence to account for the structure of the reefs, there seems to be no possible application of a general law regulating the shape of the reefs. Darwin's map of districts of elevation and of subsidence shows that he considered a region of elevation as one where fringing reefs alone could be formed.

The basis of the whole of Semper's objections lies in the presence of barrier reefs, atolls, and fringing reefs in the same region, and he has attempted to prove that he can explain their presence and peculiar conformation by the action of currents upon growing reefs in a region which has been assumed, according to Darwin's theory, to be one of subsidence. Semper and Rein were among the first to see the importance of the discovery by Pourtalès of the formation of great limestone plateaus at considerable depth, far below that at which corals can grow, and the possibility of having thus many extensive plateaus growing gradually up to the depth at which corals can flourish. The close connection of elevated and growing reefs are strong proofs against subsidence. To establish this view, we are obliged to prove that the peculiar shape of the different types of coral reefs can be explained by the action of known forces. The moment corals have begun to grow, there is nothing to show that they are not at once subjected practically, though in a less degree, to the same conditions as exist at the surface, since a more or less extensive talus is formed in the sea just as at the sea level. The apparently simple method of continuing the slope of the land into the sea, and thus figuring out the depth of the reef, seems to me a most fallacious one. Let us look at the various sections which are known on our northern coast off the Bahamas, off the coast of Florida, off the Windward Islands, and off the coast of Georgia. These are all of different types, and in a region of coral growth would lead to very different conclusions. The Florida section, which has been given with considerable detail,[1] is perhaps one of the most interesting. The great mass of observations since the promulgation of Darwin's theory is on the side of the more recent explanation of the formation of coral reefs, while the older theory rests upon an hypothesis of which it is under most circumstances extremely difficult to obtain any proof whatever.

Doctor Guppy,[2] who spent considerable time in studying the Solomon Islands, and more particularly the geology and the formation of the calcareous limestones and reefs of the group, altogether dissents from Darwin's explanation of the formation of such a reef as he observed.

Guppy, in his memoir on the calcareous formations of the Solomon Group, has plainly shown that in that group of islands upraised reef masses, whether atoll, barrier reef, or fringing reef, have been formed in a region of elevation, and such upraised reefs are of moderate thickness, their vertical measurement not exceeding the limit of the depth of the coral reef zone, — one hundred and fifty to two hundred feet at the very outside. While this is undoubtedly the case where the reef masses rest upon a foundation of volcanic or older submerged rocks, yet the presence of coral reefs upon foundations of modern limestone, as in the West Indies, made up of fragments of the calcareous remains of all kinds of invertebrates, among which may be deep-sea corals, makes it difficult to fix very accurately the limit of demarcation between the reef limestone proper and other recent limestones when both have been modified and changed in elevated areas into the hard ringing compact limestones so characteristic of all areas of elevation. At the Solomon Islands, the

[1] A. Agassiz, The Tortugas and Florida Reefs, Mem. Am. Acad., 1883.

[2] Guppy, H. B., Suggestions as to the Mode of Formation of Barrier Reefs in Bougainville Straits, Solomon Group, Proc. Lin. Soc. of New South Wales, IX., 1884, p. 949.

presence of foraminiferal limestones of concretions of manganese, up to a height of nearly nine hundred feet, (the limit is usually, according to Guppy, five to six hundred feet,) would indicate a total elevation of more than twelve or fifteen hundred feet, and there appears to be no reason, from what we know of the formation of barrier and of fringing reefs, and of their extension seaward, why the thickness of the reef limestone should be limited to one hundred and fifty or two hundred feet even in an area of elevation.

Guppy infers that corals may begin to build at greater depths than those usually assigned, as some of the elevated reefs in the Solomon Islands "rest upon partially consolidated calcareous ooze, which is not found in depths under fifty fathoms on the outer slope of the present reef; that in the case of reefs with a gradual slope, where the lower margin of the band of detritus lies within the zone of reef-building corals, a line of barrier reefs will be ultimately formed beyond this band, with a deep channel inside; but if the band is formed on a steep slope, and reaches beyond the limit of reef-building corals, no such barrier reef will be found on account of the silt."

It is not necessary, as is supposed by Guppy,[1] in his account of the Coral Reefs of the Solomon Islands, to have an upheaval to bring corals within the constructive power of the breakers. Their natural growth is quite sufficient to raise them beyond that point. He gives for the formation of barrier reefs, and as an explanation of the existence of a lagoon inside of the reef, the same explanation as is given by Leconte, — that the outer growth of the corals is in the direction of clear water, while it is limited inland by the silt and muddy character of the water of the barrier reef channel. He is also inclined to attribute the cause of consecutive barrier reefs to elevation. This certainly has not been the cause in Florida. The reefs have grown up from the bottom wherever the platform had attained the proper level for coral growth.

Bourne, who examined the Diego Garcia atoll[2] and the coral formations of the Indian Ocean, came to the conclusion that the whole character of the Chagos group is very much opposed to the theory that atolls and barrier reefs are formed during subsidence. There are several atolls rising above the waves, that of Peros Banhos being fifty-five miles in circuit, and composed of numerous small islets placed upon a ring-shaped

[1] Guppy, Solomon Islands, Calcareous Formation of the Solomon Group, Proc. R. S. Edinb., XXXII. Part III., 1885.

[2] The Atoll of Diego Garcia and the Coral Formations of the Indian Ocean, by J. C. Bourne, Nature, March 1, 1888, p. 414; April 5, 1888, p 546.

reef, through which there are several large and deep channels. Egmont, or Six Islands, is an instance of an atoll in which the encircling reef is perfect, and unbroken by any channels. There are several submerged banks, nearly all of which have an atoll form. The great Chagos Bank is a huge submerged atoll; so are the Pitts, Ganges, and Centurion banks. Darwin considered that the Great Chagos Bank afforded particularly good evidence of the truth of the subsidence theory, yet Mr. Bourne considers that a more intimate knowledge of the Great Chagos Bank, and of the relations of it and other submerged banks of existing land, shows this view to be untenable. For as the rim of the Great Chagos Bank is on an average only six fathoms below the surface, and in the most favorable depth for growth of corals, there are actually six islets on the northwestern edge rising above high water. Bourne has also noticed the great and rapid destruction of parts of Diego Garcia, both inside and outside of the lagoon, and has called attention to the transfer of material due to storms and tides, showing that the normal action of tides and winds and waves is constantly tending to lower the sea level, and thus lay bare dry land that may have been formed by elevation or otherwise. It does not seem surprising, therefore, that the majority of atolls and barrier reefs are under such circumstances only just able to maintain their surfaces above the sea level. He gives an explanation of atollons in the centre of large lagoons, based upon the production of oceanic conditions in the interior of a large lagoon, as in Tilla-dou-Matte, where he thinks the atollons have been formed before any land reached the surface, in which the islets forming the large lagoon were few in number and distant from one another, so that the atollon would practically have an oceanic character, and be swept by currents, establishing all the conditions for a new atoll. The corals thus flourishing on the circumferential parts of the reef surrounding the islet, new atolls with shallow lagoons would be formed as long as the deep channels between the outer distant islets were swept by strong currents, becoming wider and deeper because corals could not thrive in them.

Bourne emphasizes the favorable conditions under which corals flourish as occurring in localities where there is a moderate current flowing over them, not so strong as to dash them to pieces, but strong enough to prevent the deposition of sand, these conditions being found everywhere in external slopes. He lays greater stress on currents than on food supply, as he considers that to be at variance with the existence of thriving coral patches within a lagoon. While we do not deny the fact, yet the lagoon patches do not spread as vigorously as the corals growing on the exterior of the reef, or else they would soon obliterate all traces of the lagoon. Yet I can hardly see that he has made out a case, that the corals on the outside of a lagoon on the face of a reef, in full exposure to oceanic currents, laden with food, are not infinitely better off, and naturally grow more vigorously, than those which, as in a lagoon, are cut off from a great part of their food supply. They are able to grow in lagoons in spite of this, because they grow in localities which are kept clean. As I have plainly shown in the Tortugas, all corals grow remarkably well on the edge of channels, above the sand drifted by the waves and currents inland.

The following observations on the Coral Reefs of the Sandwich Islands were made in the winter of 1885, and formed the substance of a lecture delivered at Honolulu during my stay there. I have to thank Prof. W. D. Alexander for important assistance during my visit, and for the communication of valuable information from the archives of the Surveyor General's Office. Prof. James D. Dana has given an admirable account of the elevated coral reefs of Oahu, and of the extent of the distribution of reefs on the Hawaiian group. Brigham has also added many interesting observations on the coral reefs of the Sandwich Islands, and Captain Dutton in his exploration of the group noted incidentally some points bearing on the subject. Couthouy has also given a description of the elevated coral reefs of the vicinity of Honolulu, as well as of the elevated beaches of Kauai.[1] My own observations supplement those of Dana. I have gone over very much the same ground he covered in 1843, limiting myself, however, to the examination of the reef area proper, as far as it includes the living and the elevated reefs of the islands which I visited, — Oahu, Maui, and Hawaii. For my knowledge of the reefs on the other islands I am indebted to the observations of Couthouy, Dana, and of Brigham.

All investigators of coral reefs agree that corals grow in greatest perfection in the comparatively still waters of inner channels. Thus, in the Tortugas, the largest masses of Mæandrinas and Astræans are found in the old channels between formerly distinct reefs, while the great coral heads, measuring no less than twelve to fifteen feet in diameter, reach their maximum size in the so-called ship channel between the outer reef of Florida and the line of the Keys. As in Florida, so in the Sandwich Islands, the most luxurious growth of Madrepores occurs upon the face of the inner channels. There are, for instance, huge masses of

[1] Couthouy, Joseph P., Remarks upon Coral Formations in the Pacific, Journal Bost. Soc. Nat. Hist., 1842, p. 146.

a species of Porites on the inner channels opening to the sea on the fringing reef of the south shore of Oahu. In the enclosed harbor of Kaneohe there are numerous examples of hummocks, on the summits of which the corals have died on reaching the surface, while the sides are still covered with magnificent clusters of Pocillopores and Porites. Other hummocks in the same locality, not yet above the surface of the water, remain covered with this luxuriant growth, giving shelter also, wherever sand has accumulated between the single masses, to the simpler Fungiæ so characteristic of the Pacific reefs.

Dana has called attention to the manner in which parts of the surface of the inner reef of Tongatabu has become solidified by the cementing material, sand and small fragments, into a huge pavement exceeding in compactness that of the corals themselves, so that coral rock formed from the filling of the interstices of masses of branching corals may become solid enough to be used for building purposes, as is the case at Honolulu.

The entrance to the harbor of Honolulu (Plates IV., VI.) is nothing but a channel kept open by the flow of the river, which empties to the west of Honolulu from the Nuuanu valley, and has killed the corals in its path, scouring at the same time in freshets the whole harbor and the adjacent limestone walls forming the channel (Plate VII.). This and another channel farther to the westward separate the Pearl River Reef from the Honolulu Reef proper. The river forming the Honolulu harbor brings down a large amount of volcanic mud in its short course, and has deposited this in the harbor and channel, so that there appears to be nothing but dark volcanic mud for a considerable distance out towards the entrance of the channel, where the coral limestone reappears.

A similar channel, but not so well defined, exists opposite the creek forming the drainage of Manoa valley, which empties on to the reef at Waikiki (Plates IV., IX.); but this river does not bring down the amount of volcanic silt and detritus carried by the Nuuanu drainage, as it deposits a great part of its burden along the plain through which it flows before reaching the shore, whereas the river emptying from the Nuuanu has a very steep course until it reaches the harbor (Plate X.).

The Pearl River Lagoon outlet, in its turn, divides the reef again by a deep channel (Plates IV., XI.). The amount of fresh water pouring into the lagoon is much larger than that emptying into the harbor, and some of the deep ravines which drain into it extend nearly half the length of the island toward Waialua. A good part of the western slope of the

East Range also drains into the lagoon. Pearl River Lagoon is the remnant of an old entrance like that of Honolulu, when the old shore line was just inside the great plain of coral rock extending to the westward of the lagoon as far as Kalaeloa, the shore line being then its inner line.

The very characteristic bedded coral sand rock so common along the shores of the Florida Keys and of the Tortugas is not common on the southern reef of the island of Oahu. It is replaced by the formation of the massive coral sandstone pavement described above. This, however, is, as with the finer-grained sandstone, often broken into large rectangular slabs, which in their turn have been uplifted by seas unusually heavy, and thrown back on the more exposed beaches.

A very characteristic formation found only on the shores of volcanic islands fringed with corals is the peculiar pudding-stone formed of rounded and water-worn pebbles of volcanic origin, derived from adjoining basaltic rocks dipping into the sea. These pebbles are cemented together by coral limestone, sometimes only a single stone in a mass of white coral or the cementing material merely filling the interstices and barely holding the pebbles together. So that we have all possible gradations between a compact coral sandstone, with here and there a pebble enclosed, and loose friable and poorly cemented rock. There is no locality on Oahu where the process of formation of this conglomerate can be better seen than at the very eastern extremity of the Honolulu reef, at the foot of Diamond Head. This pudding-stone has already been described by Dana, who also called attention to the fact that some of the pebbles are evenly covered with a very thin incrustation of lime, looking as if they had been dipped in milk. The lime in solution is also frequently deposited in the seams of the volcanic rocks, which then resemble irregular dikes, and their cavities when filled with limestone change cellular lava into a sort of amygdaloid. Perhaps no better evidence of the amount of carbonate of lime taken up by sea-water can be given than that furnished by this constant deposition of lime from evaporation of apparently pure sea-water.

The Sandwich Islands are peculiarly placed in the track of the trade winds, so that they all present a dry and a moist side. One side is rediant with verdure, and its mountain slopes are furrowed by innumerable streams, cutting deep valleys on the weather face. The streams become powerful torrents during the rainy season, and pour an immense amount of fresh water into the sea, — so large a quantity as materially to influence the growth of coral reefs on that side. An examination of the distribution of coral reefs, and of the streams of the islands of Oahu, Maui, and Hawaii, clearly shows this interdependence (Plate I.), the coral reefs being most prominent on the lee side. Combining with this the effect of the prevailing currents in bringing pelagic food to the growing reefs, we have a most natural explanation for the absence of coral reefs to the leeward of Hawaii, while the influence of the flood of fresh water readily explains their absence along those parts of the shores of Maui, of Oahu, of Hawaii, of Molokai, where they are not indicated on the map. With the exception of a few patches of Pocillopora near Hilo, to the south of the harbor, and on the west face of the island near Kawaihae and Upolu, there are no corals to be found. In fact, we can hardly conceive of a less favorable shore for coral reefs than the east face of Hawaii, where from Hilo north there are in a length of about ninety miles over a hundred water-falls, many falling perpendicularly into the sea from great height, or pouring in rapid torrents down the steep banks and cañons of the eastern shore.[1] Just as little could we expect, and for the same reason, coral reefs to thrive on western Maui. Except at the junction of the two parts of this island, we find nowhere conditions favorable for the growth of coral reefs (Plate III.).

The coral formation of Kauai, which extends as a narrow growing reef on the eastern and windward shore, has been described by Dana. He has also given an account of the solidified beach deposits [2] similar to the drift sand rocks of Oahu, and has figured a solidified beach deposit occurring along the shores of the Koloa district, the remnant of a narrow fringing reef, which seems to run more or less continuously along the whole eastern sea face of the island.

Brigham [3] is of the opinion that the reef near Koolaii (Kauai) has been elevated. He also says [4] that ten or twelve miles west of Waimea the coral reef has been elevated on a long wide ridge transversely to the present shore line. Near Lápa he speaks of a very curious sandbank, nearly sixty feet in height, formed by the winds and currents.

1 Dana does not consider that fresh water has a great influence in the formation of harbors in coral areas, but it undoubtedly at low stages of the tide increases the volume of water which scours the harbors, while the detritus it carries must prevent corals from growing along its course, even if the fresh water was not itself a check to the growth of coral. Though corals in many instances are known to live close to fresh water, yet the fact remains that they do not thrive along coasts where large bodies of water empty into the sea.

2 Dana, U. S. Expl. Expedition, Geol. Report, pp. 275–277.

3 Brigham, W. T., On the Volcanic Phenomena of the Hawaiian Islands, p. 344, Mem. Bost. Soc. Nat. Hist., I., Part III., 1868.

4 Ibid., p. 349.

He further says,[1] that the plain land of Niihau, which comprises two thirds of its surface, is composed of coral reef sand, and the detritus washed from the mountains in successive layers. He also says that the coral reef has been elevated from fifty to one hundred feet, and at the southeast end of the island is quite level. This level portion is bare and hard; the coral structure is not evident, its fracture is conchoidal, and it has a metallic ring. Opposite Kaula the reef is covered with sand in round hills, which have a thin crust of earth.

Brigham has noticed that the limits of the coral reefs could readily be traced by the marked change in color of the water of the fringing reefs, which extend to a considerable distance from shore, usually remaining quite level as far as the outer edge, when they drop into deeper water.[2] No detached coral reefs are known in any of the channels between this island. This is very noticeable off Molokai, where there is a fringing reef on the lee side, which can be plainly seen while steaming along its shore. But whether the coral said to have been obtained there by Rev. Mr. Andrew at a height of three or four hundred feet above the level of the sea is drift coral sand, or indicates a corresponding elevation of the island, I am unable to state.

Nowhere do the drift coral sands seem to play such an important part as on the windward side of some of the Sandwich Islands. This is due to their position in the belt of the trade winds, and to the immediate proximity of the fringing reef to the shore. In some cases the sands merely drift with the wind, forming irregular banks, which become cemented together by the action of the rains into a more or less friable sand rock. The sand rock consists of thin distinct layers, indicating the successive duration of the winds which have driven the sand in a given direction; the successive layers are frequently separated by a thin smooth crust, formed by the action of water on the exposed surface. On the weather side of Oahu, all the way from Kahuku Point to Diamond Head, we meet with such sand drifts (Plate II.). Where the hillsides are more exposed to the full force of the trade winds in the range of an old elevated reef which is pounding to pieces, as at Laie, the sands are carried far inland towards Kahuku Point (Plate II.), where they form well weathered pointed pinnacles of disintegrated sand rock, and assume most fantastic shapes, reaching to a height of over two hundred feet above the level of the sea, the material having been furnished by the drift from the disintegration of the old reef; the loose sand is first swept inland by the trades, and banked up in layers, which are subsequently

[1] Ibid., p. 351. [2] Ibid., p. 352.

furrowed and torn by the rain waters, and either cemented or disintegrated into the shape they now present.

Dana has given a figure[1] of one of the best examples of such drift sand rock, which is found near Kahuku Point, at an elevation of about seventy-five feet above the level of the sea. As he states, the island of Oahu has undergone an elevation of somewhat more than twenty feet, since these sandstone bluffs were formed, and this bluff before its elevation undoubtedly occupied the same relation to the fringing reef which now forms the elevated plain back of Kahuku Point as the sandstone rocky bluff of Laie Point holds to the present edge of the shore. Organic remains are very rarely found in these coral sandstones, although an occasional shell left by a hermit crab, or a thin fragment of coral or of a Lamellibranch may sometimes be rolled up into the sand drift and cemented in it. A walk on the long steep coral sea-beach extending from Kahuku Point to Laie shows at once where the material for these coral sandstone bluffs must have come from.

On Maui we also have a long coral sand beach stretching from Kahului Bay to Paia (Plate III.), from which drifts have been blown, forming extensive coral limestone deposits on the base of the eastern slope of Western Maui, near Wailuku. The drifts have in some cases formed large heaps of considerable height, which have accumulated on the mountain sides for nearly the whole length of the line of separation between Eastern and Western Maui. These accumulations of limestone vary in thickness from a few thin layers, scarcely concealing the undulations of the ground beneath and forming a thin veneer, to drifts of considerable magnitude, with rounded tops, more or less disintegrated, and showing plainly in section the successive layers which have formed them. Through the thinner layers frequently crop out the grasses and plants which have been partially covered by the drifting coral sand, while in the thicker deposits the vegetable matter is found in all possible stages of decomposition, finally leaving tubular spaces, which have been attributed to annelids by some observers, and supposed thus to prove a very considerable elevation of certain parts of the Sandwich Islands, as at Wailuku, where Captain Dutton[2] mentions this drift coral sandstone as fragments of an elevated coral reef.

The low plain which separates Eastern and Western Maui (Plate III.), extending from the landing at Maalaea to Kahului Bay, the harbor of Wailuku, on the north, is the top of an old coral reef, which flourished

[1] Geology of U. S. Exploring Expedition, p. 46.

[2] Report of Director of U. S. Geological Survey, 1883, p. 201.

when the inlet still gave free entrance for the sea-water driven through it by the trade winds. The reef finally choked up this passage, flourishing thereafter only at the northern edge, where it is still active. Little by little the old reef has been completely hidden by the mass of drift sand derived from the beach of coral limestone sand to the east of Spreckelsville, which at one time may have been much farther inland. The coral sand on the beach is finely triturated, and the finer fragments form regular dunes of all possible sizes, from small horseshoe-shaped heaps, driven slowly along by the trades and growing constantly, so that we find some of these dunes of no less than twenty feet in height, which have travelled two to three miles towards the foot of the Western Maui slope, where they are comparatively sheltered and become cemented together by the rain. The Spreckelsville beach thus supplies the drifting coral sand, afterward hardened into the rock mentioned above, as well as the remarkable sand dunes which travel inland, obstructing the roads and the trails. They resemble the huge travelling sand dunes found on the desert back of Mollendo, which frequently cross the railroad tracks leading to Arequipa, and impede the progress of trains as much as snow drifts do in a northern region.

In estimating the thickness of coral reefs,[1] it has been usual to take the declivity of the land, and to calculate from the estimated slope and distance from shore the thickness at any given point. This must be a very defective method, at least in volcanic countries, where the fringing coral reefs have frequently been entirely covered over by volcanic outbursts, such as ashes, lava, or perhaps torrential rains, bringing down from the mountain-sides an unusual amount of detrital matter. The drilling for artesian wells near Honolulu has most plainly shown this alternation of growth of reef corals and of either lava outflows or water-

[1] Darwin and Dana both argue that the subsidence of the land is the only possible cause for the thickness of a fringing or barrier reef, which may be as much as one or two thousand feet. The evidence brought forward by Mr. W. O. Crosby (On the Elevated Coral Reefs of Cuba, Proc. Bost. Soc. Nat. Hist., 1882, p. 124) does not throw any additional light on Darwin's theory of subsidence; it is of the same character as all the statements which prove the subsidence by the existence of coral reefs, and while there may have been coral reefs formed during subsidence, it does not prove that their growth is due to subsidence any more than the presence of elevated reefs proves them to be due to elevation. They grow and must have flourished continuously in periods of both elevation and subsidence, as long as neither the elevation nor the subsidence was more rapid than the rate of growth of corals, and as long as the area in which they were found as elevated reefs was inside of the limits of depth within which we know corals to grow.

washed material. On the other hand, we may have the coral reef forming merely a shell of very moderate thickness, covering the underlying lava rocks. Such is probably the case with the inner reef of the harbor of Kaneohe (Plate V.), where it is easy in the inner harbor to trace all the transitions from lava islets rising high above high-water mark (Mokolii, Plate V.), and surrounded at the base with a thin layer of coral, or to similar islands scarcely reaching above the water level (Ahuo Laka Mokuo Loe, Plate V.), where the lava rock can be seen in the centre of the Pocilloporæ surrounding it, and again from these to numerous similar islands (Plate V.), which, judging from analogy, have a nucleus of lava, but, not reaching to the water level, have become entirely coated with coral. Finally, there are larger islets which are covered by dead corals in the centre, and fringed only by a circle of living corals, while outside of the harbor we have a reef of greater thickness, probably forming a regular fringing reef on the outside of the entrance to Kaneohe Harbor (Plate V.). The flat plain underlying the northern edge of the harbor, having been built up to reach the water level for nearly its whole width, is covered only with occasional patches of living coral in the deeper parts, and with a flourishing growth of corals on the edges adjoining the inner harbor. Near Kahuku Point there are several most interesting cases, showing the thin veneer of coral which must in some instances cover the underlying lava. It is not uncommon to find at a few rods from the shore what may be called coral tables. They are parts of the elevated coral reef, left as pinnacles on the top of a projecting mass of lava, the coral table being at the same level as the adjoining disconnected elevated coral reefs. These coral tables can hardly have been left cemented where they were unless the intervening coral reef has been all washed away, and they should not be confounded with similar unattached blocks upthrown and not necessarily cemented in their natural attitude, such as have been described by Dana. A very fine specimen of such a large unattached coral rock block is seen lying on the reef across the entrance of Kaneohe Harbor.

In estimating the thickness of a fringing coral reef, the following indications, taken from sections of artesian wells bored in the vicinity of Honolulu, will be of interest.

With the exception of Mr. James Campbell's well and the well near Pearl River Lagoon, the artesian wells are at Honolulu or to the eastward and near Diamond Head. To Messrs. Lewes and Cooke I am indebted for data regarding the character of many of the wells. Water was reached at depths ranging from three hundred to six hundred and twenty feet, and none of the wells were started at a greater height than forty-two feet above high-water mark.

Palace yard artesian well: —

72 ft. of coral rock.
6 ft. of lava.
Then 260 ft. lava to coral, thickness not given.
Then clay.
Then lava to 706 ft.

A second well half a mile inland from the above: —

30 ft. of boulders.
Coral was reached at 200 ft., of a thickness of 30 ft.
Then 250 ft. of clay.

At Waimea, Oahu, 900 ft. was drilled through hard ringing coral rock; then sand and lava were encountered.

Near Pearl River Lagoon, close to the road running above the elevated coral rock plateau to the southeast of the Pearl Lochs, a well passed through 300 to 400 ft. of coral rock.

Another well passed through

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|---|---|
| 100 ft. of soil and boulders. | 30 ft. of coral. |
| 100 ft. of coral. | 90 ft. of clay. |
| 12 ft. of clay. | 28 ft. of sand and boulders. |

A well in Thomas Square: —

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|---|---|
| 6 ft. of soil. | 60 ft. of clay. |
| 10 ft. of sand. | 50 ft. of coral. |
| 200 ft. of coral. | 80 ft. of clay. |
| 44 ft. of clay. | 50 ft. hard pan. |
| 10 ft. of coral. | |

Another well, after a few feet of surface soil, came upon a bed of

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|---|---|
| 38 ft. of coral. | 5 ft. of clay. |
| Then 22 ft. of white sand. | 45 ft. of coral. |
| 43 ft. of yellow sand. | 30 ft. of clay. |
| 47 ft. of lava. | 100 ft. of coral. |
| 110 ft. of coral. | 78 ft. of clay and coral mixed. |
| 100 ft. of lava. | 28 ft. of clay. |
| 70 ft. of coral. | 120 ft. of lava. |

The "coral" in these wells was so ground up that it could only be recognized as such from the larger fragments, and the so-called clay was mainly lava detritus finely pulverized.

The well of Mr. James Campbell is thirty feet above high-water mark.

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|---|---|
| 50 ft. of gravel and beach sand. | 20 ft. of soapstone. |
| 270 ft. of tufa. | 110 ft. of brown clay. |
| 505 ft. of hard coral. | 48 ft. blue lava. |
| 75 ft. of brown clay. | 10 ft. of black clay. |
| 25 ft. of washed gravel. | 18 ft. of clay. |
| 95 ft. of red clay. | 249 ft. hard brown rock (lava). |
| 28 ft. of white coral. | |

The well of Mr. A. Marques is at the mouth of Manoa Valley, 36.67 feet above high-water mark : —

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|---|---|
| 10 ft. of earth. | 30 ft. of clay. |
| 20 ft. of coral. | 150 ft. of lava. |
| 40 ft. of lava. | 268 ft. of clay, rock, and lava. |

That of Mr. Dillingham is 38.72 feet above high water : —

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|---|---|
| 90 ft. of loam. | 25 ft. of coral. |
| 40 ft. of coral. | 40 ft. of clay. |
| 60 ft. of clay. | 300 ft. of lava. |

That of Mr. Ward is 13.36 feet above high-water mark : —

| | |
|---|---|
| 15 ft. of loam. | 23 ft. of coral. |
| 180 ft. of hard coral. | 107 ft. of sand. |
| 4 ft. of clay. | 4 ft. of sand. |
| 24 ft. of coral and shells. | 4 ft. of lava. |
| 41 ft. of clay. | 18 ft. of lava rock. |
| 10 ft. of hard coral. | 35 ft. of rock. |
| 109 ft. of clay. | |

There are in the Museum at Honolulu pieces of wood, charred or decomposed, brought up from a depth of two hundred and fifty feet from one of the artesian wells. This would merely indicate that the pieces had been washed down from the mountain sides on the then existing slope, and would not necessarily indicate a subsidence. The alternating of so many successive layers of clay and coral and lava indicates, in my opinion, merely the gradual extension seaward of the shore line as fast as lava detritus was washed down or flowed over from successive eruptions, while the growth of the layers of coral indicates the period of rest during which the coral beds were deposited, each in its turn being overwhelmed by a layer of lava or laval detritus, until we reach the existing condition of things. That such a succession of coral growth and lava beds actually took place in the past can safely be inferred from the borings of the artesian wells, as well as from what we see going on in the harbor of Kaneohe along its shore line, along the shore line at Diamond Head and other parts of the fringing reefs east and west of Honolulu, as well as in certain portions of the islands where coral sand rock is intercalated between beds of lava of greater or less thickness.

The great thickness of the coral rock can be accounted for by the extension seaward of a growing reef, active only within narrow limits near the surface, which is constantly pushing its way seaward upon the talus formed below the living edge. This talus may be of any thickness, and the older the reef, the greater its height would be, as nothing indicates that in the Hawaiian district there has been any subsidence to account for such a thickness of coral rock in its fringing reef.

Dana thinks that the western coral islands beyond Bird Island, in the Hawaiian range, indicate participation in the general subsidence, which he traces over a large part of the Pacific Ocean, as indicated by atolls and barrier reefs. Yet he himself describes the fringing reefs of Kaui and Oahu, and mentions their width as being considerable.

There appears to be no evidence that there has been any considerable elevation in the Hawaiian Islands, twenty to twenty-five feet being probably the extreme ; while the existence of cinder cones with their base close to the present sea level would indicate also that there had been no special subsidence. There is, however, some evidence of subsidence on the southern shore of Hawaii. At Kalapanu is a sunken plain about a mile wide and two miles long, where there has evidently been a subsidence of about fifty feet ; and the raised coral reef extending along a part of the shore would indicate another change of level in former times. Brigham has given a sketch plan of the plain in Fig. 27, on page 373 of his " Notes on the Volcanoes of the Hawaiian Islands." [1] Plate XIII. shows the position of the sunken beach at Kaimu.

From the recent examination of the islands of the Hawaiian group, and the explanations given by Dutton of the causes determining their present physiognomy, it would be more natural to suppose that the gradual building up of the various islands by overflows and eruptions had overwhelmed such reefs as existed (if any did exist) during the period of great volcanic activity of the islands. There have been as yet no sunken reefs discovered in any of the channels between the islands, and as far as we know the reefs are all littoral formations of the present shore lines.

The greatest depth in the channel between Oahu and Molokai is 317

[1] Mem. Bost. Nat. Hist. Soc., Vol. I. Part III.

fathoms; between Molokai and Maui, 137 fathoms; and between East Maui and Kahoolawe, only 40 to 50 fathoms; while between Maui and Hawaii there is a depth of 1107 fathoms, and over 1890 fathoms close to Kaui between Kaui and Oahu. These soundings were kindly given me by Hon. H. A. Wiedemann, and were taken by a vessel sounding for a submarine cable to communicate between the islands.

It is interesting to note the structure of the reef as we pass over it at high tide from the shore to the sea face. The slope of the channel forming the harbor entrance is made by a steep bank of muddy whitish ooze. The reef-flat itself, varying from half a mile in width to less, is also covered nearer shore with coral ooze, and interrupted by small rounded knobs of decomposed algæ, Nullipores, and stalks of dead Sargassum. These cover irregular patches of greater or less size, separated by bare spaces of ooze. A little farther out, in depths varying from five to six or even ten feet of water, we come across numerous rounded patches, covered by clusters of Millepora, with here and there a group of Pocillopora, and in the intervening bare patches the coral limestone is frequently pitted by numerous Echinometradæ and Diadematidæ. Some of the rounded knolls rise close to the surface, and sometimes even are bare, leaving deep pools between them, in which the characteristic reef fauna flourishes. Such knolls, when farther out to sea, and arranged, as they often are, in regular lines of considerable length parallel in a general way to the trend of the shore, form successive concentric lines of breakers, diminishing towards the shore. Upon these the sea beats, breaking up, pounding to pieces, and triturating the corals growing upon the sides of the knolls, until they are changed into the ooze which gradually cements the shore portions of the reef into a solid limestone mass (see Plate VIII.), and freely supplies the fine material for the coral sand beaches close to the land. On Plate VI. the lines of breakers on the sea face of the reef are faintly indicated. On smooth days I could follow beyond the outer line of the breakers the occasional patches of large Millepores, or of Pocillopora, or Porites, or Astræa, together with the few Gorgoniæ which run out on the somewhat steeper outer slope of the reef. These gradually diminish, and as far as could be seen with the sea glass disappeared completely in about ten fathoms. It was very easy to examine the Honolulu portion of the reef by accompanying the fishermen, who are in the habit of going out daily in their canoes just outside of the breakers, and whose skill in crossing the swell in their outriggered canoes it is very interesting to watch. The small amount of animal life on the Honolulu reef (on the lee side of the island of Oahu) is surprising, as compared with that on the weather side on the reefs of Kaneohe Bay. This difference is due to the fact that much of the pelagic life brought by the trade winds against the weather side of Oahu is swept past the lee side without bringing any great quantity of food to the coral reef. This is plainly shown by the comparative scarcity of pelagic life, even on the most favorable days, on the lee side along the sea face of the Honolulu reef, as contrasted with that of Kaneohe Bay. On such days little could be seen off Honolulu beyond a few Salpæ, a huge species of Appendicularia in its house, a few Diphyes and Praya, and a few pelagic crustacea, even when the wind had been blowing from the south, and was driving the pelagic fauna towards the lee shores again. The Honolulu reef contrasts also with the Florida Reef in the scarcity of Sponges. The very gradual sea slope of the Honolulu reef is one of its marked characteristics.

The in-shore flat of the reef, left bare at low tide, as well as all the low land extending to the base of the hill slopes to a height of nearly twenty feet above the level of the sea, is made up of coral reef sand. This is the character of the whole reef, whether west of Honolulu or east, all the way from the outskirts of the city to Waikiki, and to the base of Diamond Head. At Diamond Head the coral reef sand is mixed with the volcanic material washed down from its slopes, and where it is washed directly into the sea we find the lava sand as well as the coral sand remodelled by the action of the water, forming either layers of clear lava sand overlaid by coral sand, or all possible gradations between a mixture of fine sands of the two and a modern conglomerate or breccia of the larger fragments cemented together by the lime carbonate held in suspension, or by the finer or coarser sands. Pot-holes, gullies, and corrugations, due to the wearing action of the sea-worn lava gravel rolling up and down the lava beds, characterized them wherever exposed to the action of the breakers or of the sea ; while, if subsequently protected, these or similar holes and corrugated surfaces are gradually filled by a deposit of finer or coarser washed material, which, becoming cemented, produces very striking effects. Some of the larger pot-holes in the lava beds in the adjoining elevated portions of the reef often contain masses of Porites and of Mæandria of considerable size, more or less washed, as well as numerous fragments of mollusks, the whole cemented together in a solid calcareous mass, as we find it on the exposed part of the shore edge of the reef. Towards Diamond Head the outer slope of the reef approaches the shore. (Plate IV.) The reef there is narrow, and, owing to the greater depth off shore and the narrowness of the reef, there are only one or two lines of breakers acting directly upon the shore portion of the reef.

Dana has described the so-called modern chalk of Oahu, which is found at a single locality near Diamond Head, in a part of the elevated coral reef. It is at the foot of a tufa cone rising from the water's edge, and, as Dana has already stated, coral must have been thriving on the shores when the eruption took place, as there are fragments imbedded in the tufa, although the chalk itself is of later origin. There is nothing to be observed throwing any light on the causes which have produced this chalk at this particular part of the elevated reef, except that it must have been deposited in a confined area, subject to special conditions. Yet this chalk is not more similar to the modern chalk than the modern chalk dredged off Nuevitas, which was deposited under most dissimilar circumstances. The Oahu chalk appears to differ very slightly from such deposits of fine coral sand as are deposited in sheltered localities on the shores of coral beaches. It does not contain any organic remains, but has in addition the peculiar fracture of chalk, and, as is stated by Dana, is used on the blackboard in some of the schools of the islands.

At Makapuu the reef has been raised about twenty feet, and farther north the whole coast is fringed with a growing reef, extending in some places over three quarters of a mile in width. There are extensive sand dunes, also, mentioned by Dana and Brigham, a short distance back of the shore reef at the foot of Konahuanui.

The elevated reefs of the Sandwich Islands, although not elevated more than twenty to twenty-five feet, are extensively quarried as limestone for building purposes, especially those parts of the reef which evidently formed its inner portion, and in which the corals and mollusks living on the surface of the reef have been admirably preserved.

On the southern edge of the Aliapaakai basin, six miles west of Honolulu and three quarters of a mile from the sea, there is a raised coral reef which has been much displaced; it has been fully described by Dana. Living corals are comparatively rare upon the reef-flat. Large specimens of Porites[1] flourish in pits and hollows of the reef, and a scanty marine fauna, with occasional masses of Nullipores and Sargassum. The top of the edge of the reef is barren, and is deeply furrowed; it is only somewhat farther down the slope that the reef fauna flourishes actively again.

[1] Dana speaks of the huge size of individual masses of Porites in the rock of the inner reef of Tongatabu, which were twenty-five feet in diameter. Geology of U. S. Exploring Expedition, 1849, p 39.

One cannot fail to be struck with the hardiness of the large masses of Porites still found living, half exposed to the air at low tide, in the impurer water of the reef near to the shore, which seem to die more from the effect of sediment than from the effect of the exposure to the sun, or from the impurity of the water. In fact, Porites both at the Sandwich Islands and at the Tortugas are among the hardiest of reef corals. As Jukes, Guppy, and others have noticed, in many species of corals exposure to air is not always fatal, although in Florida the Madrepores, which hold to the Atlantic reefs the same relation the Pocilloporæ hold to the Pacific, are frequently killed over extensive tracts when exposed to air by low tides or winds. As far as I could judge from an examination of the sea face of the Sandwich Island reefs, the Pocilloporæ do not extend to a depth of more than fifteen fathoms, and then gradually disappear, though the sea face of the reef was swept by a constant current running westerly, due to the trade winds, and during the season of trade winds but little sediment found its way there to prevent their active growth.

Dana has called attention to the great extent of the elevated reef of Oahu, which occurs at the foot of the mountain slopes along the whole southern face, at heights ranging from five to twenty feet above the level of the sea, forming the large flats of the Pearl River Lagoon. It is nearly continuous from Makapuu to Kahuku Point, extending from there to a small river emptying at Waimea, where it abruptly ceases, but flourishes again on both sides of Waialua, and along the greater part of the northwestern coast near Waianae. The elevated reef attains its greatest width near Kahuku Point, where it is nearly a mile wide, and we can trace this elevated reef as a fringing reef before the elevation of Oahu just as plainly as we now trace the present fringing reef of the south shore of Oahu, and that in Kaneohe Bay.

Near Kahuku the drift sand-hills are of great size and height, and resemble an elevated beach. The elevated reef near Kahuku and that along the northwest end of Oahu are quite distinct from the solidified sand-dune deposits.

At Laie[1] the drift sand has formed hills of sandstone hard enough for building purposes. These hills are thirty to forty feet high, much broken and worn by the action of rain and wind into grotesque honeycombed masses and ragged pinnacles, which, as Brigham says, have often been mistaken for elevated coral reef rock.

The mouth of the stream at Waimea is often completely closed by a

[1] Brigham, Mem. Bost. Soc. Nat. Hist., Vol. I. p. 358.

dam of sand at low stages of water, which is in its turn broken through again whenever sufficient head of water has accumulated behind it.

Some extensive ancient dunes, from one hundred to one hundred and twenty feet in height, indicate an effect of the trade winds now no longer acting. It may be that some of these more ancient inland dunes, which have become solidified near Diamond Head, were formed under the influence of the trades before their full force on the eastern edge of the reef was destroyed by the elevation of the long hill forming Diamond Head. It may be that we owe to the presence of these dunes most of the coral sand and calcareous material which we find up to a considerable elevation between Diamond Head and Honolulu in the Manoa Valley.

Although the Honolulu reef has a far less rich fauna than the reef of Kahului Bay, yet the limestone which it forms, not having been exposed to the action of the trade-wind surf, presents the reef much as we see it, flourishing and gradually dying out in proportion to its proximity to the shore. The corals, Serpulæ, Nullipores, echinoderms, mollusks, and even crustacea, are not ground to pieces, as in reefs open to the violent action of the sea, where all traces of their identity are destroyed in the process of formation of the coral limestones characteristic of such exposed reef shores. On the contrary, the coral heads themselves, as well as all the animals flourishing upon such a protected reef as that of Honolulu, are rapidly fossilified and imbedded in limestone, being gradually covered with the floating lime held in suspension or in solution in the water; so that, whenever we get a good section of the shore coral limestone, we invariably find, either on the reef-flat itself, or on the immediate shore line, or on those portions of the reef which have been slightly elevated, a limestone representing the reef as it grew and flourished, in which we can plainly distinguish the different species of coral, as well as the invertebrates which once lived in their shelter.

In the section to be seen on King Street, near the Prison Point, beyond the bridge, a face of about six feet in height was being quarried, the highest point perhaps three feet above high-water mark, the Prison Knoll, which is the continuation of this limestone ridge, being about ten feet above high-water mark. This and another limestone knoll facing the opening of the Nuuanu Valley are formed of a close white limestone mass of decomposed reef rock, in which the individual heads are more or less distinct, and which contains a large number of shells and echinoderms imbedded in the mass cementing the corals together. The western and eastern extensions of this old shore line of the reef, which must have been elevated about twenty feet above the sea level, has been preserved; but in the continuation of the dividing ridge between the valleys of Nuuanu and of the Manoa, they have been denuded on each side of that ridge and appear again on the eastward at a few points on Diamond Head and towards it on the west. But the lower levels of the same reef can be traced continuously along the present southern shore line all the way from Diamond Head. The salt ponds and flats, which extend inland in the Manoa Valley between Honolulu and Waikiki seem to indicate an inner lagoon much like that of Pearl River, which has gradually been filled up by the silt swept down by the river.

The comparative poverty of the fauna of the Honolulu reef is undoubtedly due to its being on the lee side of the island of Oahu, the outer face of the reef alone obtaining a fair supply of food, brought by the westerly current due to the trades, which runs along the south coast of Oahu.

Mr. Rose was kind enough to take me out in a canoe to examine the corals in Kaneohe Bay. We found the bottom of the bay covered in many places by numerous more or less circular patches of living corals (Plate V.) in all stages of growth, from domes a few feet below the level of the sea covered by flourishing corals to small fringing reefs round the shores of the islets and rocks which occur in the bay, and to elliptical reefs, awash when the corals were living only on the outer slopes. The bases of all these islands are undoubtedly summits of volcanic rocks projecting above the general level of the bay, which have been coated or surrounded by corals. To the southward of Kaneohe Head, on the plain of Kailua, are extensive dunes similar to those already described.

The edge of the bay is itself entirely surrounded by a fringing reef (Plate V.) of corals, mainly of species of Porites, which have gradually died out near the shore, and thrive only near the deeper water on the edge of the channel. The opening of the bay is barred between Kapapa and Ahuo Laka by a barrier reef (Plate V.) of very moderate thickness, extending towards Kekepa and Mokolii, resting upon a lava bottom, which is exposed in places. There are two entrances into the inner lagoon of the bay. The breakers pound heavily upon this barrier, and from it huge coral blocks are constantly thrown up and ground to pieces, the sand being carried in towards the bay and forming the bar of the harbor. Dana looks upon these huge blocks, as well as the islands off Kaneohe Bay, as having been elevated from six to eight feet above high tide.[1] Kaneohe Bay is to a certain extent sheltered from the full force of the trade winds by the small peninsula of elevated coral reef which stretches to the eastward of the bay. On the barrier reef, as well as on

[1] Dana, J. D., Geology of U. S. Exploring Expedition, p. 253.

the isolated patches in the bay, we find mainly Pocilloporæ, and sheltered by them in the interior circle of the coral patches solitary Fungiæ with a few Gorgoniæ, which seem to be much less numerous than upon the reef near Honolulu, and there are also comparatively few algæ and corallines. The large masses of Porites growing near the shore have little by little been choked by the silt coming down from the Pali, and a volcanic sand flat, with a band of living corals on the outer edge, is thus formed near the fringing reef, in marked contrast to the coral sand flats formed by the action of the breakers.

The whole bay before corals began to flourish upon it must have contained a number of small volcanic islands, and a large number of sunken volcanic rocks and ledges, which have become capped with coral or surrounded by diminutive fringing reefs. What is now going on in the Bay of Kaneohe on a diminutive scale, we may apply to groups of volcanic islands in the Pacific. If we add to this the powerful agency of accumulations of limestone on the deeper summits or banks, until these surfaces are built up to a height at which corals can begin to grow, we have all the various elements needed for the formation of fringing reefs, barrier reefs, or atolls within a comparatively limited area, as is the case in those archipelagoes of the Pacific where these various kinds of reefs have been observed to occur together. The base upon which the barrier reef of Kaneohe has been built up has probably been formed by the washing down and disintegrating of a lava crest of considerable height, if we may judge of it from Mokolii.

According to Dana and Darwin the line of barrier reefs and of atolls indicates the former extent of the area of land before the reefs began to form, which in some cases was three or four times that now above the level of the sea, and in the whole Pacific reef district the atolls and reefs are the monuments of islands which have long ceased to exist.

The formation of a barrier reef upon a foundation denuded to the depth at which corals can flourish has not been observed before. Captain Wharton[1] gives a very interesting account of "the preparation of a suitable foundation for coral builders by a process directly the reverse of that of building up by marine organisms on mounds that have failed to reach the surface," from which it appears probable "that the cinders and ashes which formed, and still form, the summit of the volcanic mound originally thrown up, are being by wave action gradually swept away, and will continue to be so removed until the top of the bank is reduced below the limit of such action, or the solid rock is laid bare."

[1] W. J. L. Wharton, "Foundation of Coral Reefs," Nature, October 11. 1888.

Dana argues against the possibility of coral reefs being planted upon submarine banks of the requisite depths for corals to thrive, yet this is actually what we see going on in Florida, and we can there trace all the steps from the barrier reef to the keys, and to the incipient reef or coral bank making a beginning upon the limestone bank which has been raised by accretion to the depth requisite for the growth of corals. It seems to me that a wide flat reef cannot be formed by a slow subsidence, but must have grown, during a period of rest or slow elevation, simply by the dying out of the coral next to the land, as has been observed on the shore edge of Kaneohe Bay.

Captain Wharton[1] has also given, in a recent number of "Nature," a number of instances of the growth of corals on banks, or on the edge of banks, illustrating the formation of barrier reefs and of atolls without the introduction of subsidence. He instances many cases in which reefs now growing will when awash form perfect atolls of large size, enclosing deep lagoons, without any further deepening by solution. He also calls attention to the great width of many of the existing fringing reefs, which should show more signs of solution than they do if Murray's theory is sufficient to account for the formation of the whole intervening lagoon. The rotten state of the surface of all coral reefs, especially fringing reefs, shows that there is considerable solution as well as removal of material going on ; but the very fact that the majority of these reefs are of great width goes to show also that solution alone is not active enough to remove great masses and form lagoons. The case of Rodriguez is cited by Captain Wharton, where, although there is a rise of tide of nearly six feet, with every facility for a scouring action and rapid change of water, yet there is a fringing reef of a width of nearly four miles and three quarters, intersected only by narrow shallow channels. In the case of the Florida Reef there is nothing to show that the outside reef has not arisen on the southern edge of the Florida Reef plateau, when it attained a depth at which corals can grow. The lagoon between the reef and the keys was certainly never filled by corals which have been carried away by solution, though it has been occasionally obstructed by the growth of patches of corals, which are of the same date or of a later growth than the coral reef proper.

Dr. Coppinger[2] describes Amirante Bank as a submerged atoll, which,

[1] "Coral Formations," Nature, February 23, 1888, p. 393.

[2] Cruise of the Alert, by R. W. Coppinger, London, 1882, p. 225. In Florida there is nothing to show that detached barrier reefs cannot grow up to reach the constructive power of breakers, as Guppy seems to argue from the existence of sunken barrier reefs.

if raised fourteen feet, would become a true atoll. According to Guppy,[1] elevation is necessary to form an atoll and bring it within the destructive range of the sea, and a fringing reef, according to him, could not be formed near shore or grow outwards. No such elevating action exists along the whole line of the Florida Keys, yet the reef has grown up to the action of the breakers. The same is the case with Kaneohe Bay.

Neither fringing reefs, nor barrier reefs, nor atolls, grow exclusively outward. I am inclined to consider the islets on the inner side of a lagoon as remnants of islands formed by coral heads and coral sand flats, rather than to suppose that the intervening channel has been eaten away solely by the solvent action of sea-water. Leconte, as I have stated, ascribes the limitation of corals towards the shore, and their growth seaward, on the one hand to the muddiness of the inner waters of the lagoon, and on the other to the purity of the water due to its depth. It really seems doubtful whether the islands in the lagoon channel at Tahiti, mentioned by Murray,[2] are portions of the original reef still left standing, and not, as is the case with the coral heads in the ship channel of the Florida Reef, independent coral patches, which have not been overwhelmed by the action of sediment from the outer reef, or as in the Tortugas, where we find active coral growth in the inner line of the open channels. He further says, when coral reefs are much broken up the coral growths in the lagoon are relatively abundant, while there are but few coral patches and heads in the lagoons and lagoon channels when the reefs rise to the surface, or are nearly continuous. This is certainly the case at Kaneohe Bay.

Geikie[3] also calls attention, in the examination of maps of coral regions, to the difficulty of the theory of subsidence, as in the case of the Fiji Islands, where fringing and barrier reefs and atolls all occur in close proximity, and where all evidence seems to point to elevation, or at least to a long period of rest.

The fringing reef of Kaneohe Bay forms a scalloped outline, with an occasional white coral sand beach where the wind has a wider sweep than in the eastern and more protected parts of the bay. But these

[1] Guppy, H. B., Notes on the Characters and Mode of Formation of the Coral Reefs of the Solomon Islands, being the Results of Observations made in 1882–84, during the Surveying Cruise of H. M. S. Lark. Proc. Royal Soc. Edinb., 1885–86, p. 857.

[2] Murray, Proc. Royal Soc. Edinb., 1879–80, p. 515, April 5, 1880, Vol. X. No. 107.

[3] Geikie, The Origin of Coral Reefs. An Address read before the Royal Physical Society of Edinburgh. Proceedings, Vol. VIII. p. 1, 1884.

coral beaches alternate with darker lava silt brought down from the neighboring mountains, often forming very extensive shore flats, of which the Chinamen, by damming out the sea, have taken advantage for cultivation ; along part of Kaneohe Bay there is quite an extensive flat thoroughly cultivated, where cattle are turned out. This flat is formed of coral sand, extending far out to Mokolii Island from the adjoining headland, from which diverge coral patches. On rounding the northern end of the bay we see that the reef north of Mokolii comes close to the shore, and assumes the character of a narrow fringing reef, following the shore line more or less regularly. At Kahana a small harbor has been formed by the extension northward of the reef from Makuua. Westward the road along the edge of the island runs behind the shore sand dunes or the beach shelf, or on its summit. There is no trace of elevation from the point to the south of Kaneohe Bay to the great Kohuku reef-flat, extending south to Laie.

At Kohuku there is a fine bluff of consolidated drift sand, of which Dana has given an excellent figure. Similar drift rocks extend all round the base of the slope of the foot-hills, marking the old shore line of the Kohuku reef, which extends from this point as a flat coral plain, slightly elevated (twenty to twenty-five feet) above the level of the sea, from half a mile to a mile in width, to the present coral sand beach of Kohuku, which is exposed to the full action of the trade-wind breakers, and has thrown up a high sand-bank built up from the elevated reef. This elevated reef extends all the way from Laie to Kohuku, the small outlying islands being the remnants of sand drift rocks which are gradually being eroded by the sea, and which have in former times, when the reef was active, supplied the material for the innumerable sand drifts of the foot-hills. These sand drifts have become gradually eroded into the most fantastic shapes, covering the hillsides with innumerable small points resembling Gothic spires. This elevated reef does not seem to be active on its sea face. No soundings are available for that part of the shore, and the heavy rollers break directly on the present sand beach, so that the sea face is probably quite steep.

Near Waimea the fringing coral reef crops out here and there behind the high sand beach formed from the disintegration of the underlying elevated reef. There, as at Kohuku, the reef seems to stop abruptly near the line of beach breakers, and the slope appears steep, there being no trace of recent reef corals beyond the line of shore breakers. The coral sand at the back of the beach was thrown up to a height of from ten to twenty feet. The breakers form a small lake across a gulch, of which they dam the outlet by throwing up a high sand dam; this breaks through when the water has accumulated a sufficient head. Half a mile beyond Waimea the coral caps the lava beds at a height of nearly ten feet above the high-water mark.

At one other point two miles beyond Waimea, towards Waialua, we find numerous coral tables capping lava bases. Many of these coral tables are blocks ten by twenty feet, one of them as much as fifty by one hundred feet. The height of the lava supports is usually five or six feet. This elevated coral reef, all the way from Kohuku to Waialua, is cut by lava spits, which project beyond its surface and extend seaward. At Waialua there is a very fine patch of the elevated coral reef, from five to six feet above the level of the sea. Traces of this reef can be seen for five or six miles to the southward of Waialua, along the beach, made up of coral sand mixed with more or less lava sand, which reaches towards Kaena Point.

As will be seen on examining Plate I., the reefs of Hawaii consist only of isolated patches of limited extent near Hilo. On the sides of Upolu Point, both east and west, isolated patches have been observed, near Kawaihae, and at the southernmost point of Hawaii somewhat larger stretches of coral exist.

The so-called coral reef to the south of Hilo (Plate I.), near Keokea Point, consists mainly of detached patches of corals (Pocillopora). They are very much like the patches of corals to be found on the west coast of Mexico, and do not constitute a regular reef, although a good deal of coral grows in this way, judging from the amount of coral sand and fragments thrown upon the small beaches to the south of Hilo. The patches are mainly the same species of Porites and Pocillopora which form the reef of Honolulu. There is comparatively little animal life on these coral patches, and the lava rocks off Hilo do not appear to support a rich fauna. Although small algæ grow thickly on the rocks, no Sargassum was found attached, as near Waikiki on the Honolulu reef, and on the coral conglomerate of the Spreckelsville beach on the north shore of Maui.

Near the northern extremity of Hawaii, near Honoipu, there is a patch of coral and another patch to the eastward of Mahukona, clearly seen from the railroad running round the northern point of Hawaii. On the lee side of Hawaii there is, near the village of Kawaihae, a stretch of coral reef, which protects a bay once a great resort of whalers. The village itself is prettily situated at the northern end of a long coral sand beach. To the south extend, as far as the eye can reach, the various ancient flows of lava which have come down the slopes of Hualalai and of Mauna Loa ; while to the eastward of Kawaihae are seen the older flows of Mauna Kea and the deeply furrowed cañons extending from the shore nearly to the summits of the Kohala mountains. An interesting patch of elevated coral is also found on the edge of the sunken plain of Kalapana, similar to the restricted patches now growing on some points of Hawaii.

The coral reefs of Maui see (Plate III.) are found on the long beach of the windward side of the island, on Maalaea Bay, and along the lee side of Western Maui from Maalaea Bay to a short distance north of Lahaina. The evidence I have been able to collect on the coral plain between Maalaea Bay and Kahului indicates that Eastern and Western Maui have been united by a coral reef, which flourished in the shallow passage once existing between these two parts of Maui. The great coral plain lying at the foot of Western Maui, and extending to meet the slopes of Haleakala on the opposite side, is only the surface of the old coral reefs which once flourished there. The plain which divides the two parts of Maui is in some places scarcely above the level of the sea ; it abuts somewhat abruptly on the steep slopes of West Maui, while it passes imperceptibly into the slopes of East Maui at Haleakala.

The corals mentioned by the Rev. Mr. Andrews, as found at elevations of from five hundred to eight hundred feet even on the eastern slopes of West Maui, are, as I have satisfied myself, all Æolian formations such as I have described.

The large reservoir for the Hawaiian Commercial Company, below Wailuku, from one hundred and twenty-five to one hundred and seventy-five feet above the level of the sea, is built in natural depressions left between the sand dunes which have been formed in former times on the old beaches extending all the way across to Maalaea Bay from Kahului Bay. The highest of these sand dunes must be from two hundred to two hundred and fifty feet above the level of the sea, and they have become solidified into sandstones by the action of the rain. Coral sand dunes can now be seen travelling across the road leading from Spreckelsville to Wailuku, some of which are from twenty-five to seventy feet high. But a great many have become fixed at a distance from the beach from which they originated, having become overgrown by a species of Bermuda grass.

Brigham says that on the windward shore of Maui [1] the coral sand is piled up in ridges nearly one hundred feet above the sea, shifting with

[1] Mem. Bost. Soc. Nat. Hist., Vol. I. p 367.

the wind, which sometimes drives columns of sand miles along the beach. This is the material which forms the fine coral sand beach reaching from Wailuku to Paia.

The stratified coral sand rock seen by Captain Dutton[1] at Diamond Head, and to the east of the village of Wailuku on Maui, which he takes as evidence of a recent upheaval of two hundred feet, and perhaps more, are only consolidated sand drifts, such as I have described above. There certainly is nothing in the character of this æolian coral limestone to compare with the consolidated reef rock at the level of the sea. The shells he mentioned as imbedded in it have either been blown up by the violent winter gales, or are the shells of gastropods carried up by hermit crabs, which I have often met with more than a mile from the coast in their wanderings.

I have not seen on the shores of Maui coral ledges indicating any elevation. The highest masses of coral rock are fully within the reach of the action of moderate, or even very heavy seas. The observations of Rev. Mr. Andrews, quoted by Dana, in regard to the possible elevation of Molokai and Maui, do not appear to me to indicate anything beyond coral sand dunes.

The existence of coral sandstone on the east slope of West Maui at a considerable height, over extensive tracts, does not indicate any elevation, but is due merely to the æolian deposits which have found their way to certain favorably situated places under the action of the prevailing trade winds. Nowhere in the district I have examined on Maui have I succeeded in finding any trace of corals beyond the height to which fragments might be carried by the action of the waves or wind and tides of unusually severe storms. The bedding of the sandstones at considerable heights was evidently entirely due, as has been shown by Dana, to the successive deposits of sand cemented together by interrupted rain fall, forming the delicate crusts which separate the various thin layers of coral sandstone which have accumulated at certain points.

I was greatly interested, on visiting the long coral sand beach which extends from Kahului to Hamakuapoko, to find very much the same action going on in the formation of coral conglomerate, breccia, and oölite, which I had so often watched at Loggerhead Key, and on the island of Key West on the beach north of Fort Taylor. This action was, however, modified by the fact that a much heavier sea, due to the trade winds, was driving upon the surface of the reef off the beach, and was still pow-

[1] Hawaiian Volcanoes, by Capt. Clarence Edward Dutton. Fourth Annual Report of U. S. Geological Survey, 1882–83. Washington, 1884, p. 81.

erful enough on the beach itself to throw up huge masses of Porites, of Pocillopora, and of Astræans, and with them a large number of shells living on the reef. The whole is pounded by the process into a sort of coquina, which is cemented on the beach, much like coral breccia. Owing to the steady action of the trades, the finer sands accumulated on the beach would be blown up the slope and carried off to form the travelling dunes, or the masses of drifting coral sand carried inland to form the coral sand drifts, while quite heavy fragments were also blown up bodily to the upper level of the beach.

Kahului Bay is sheltered by a wide, flat, active coral reef, the harbor being an inlet of the western and widest end of the reef. The reef extends easterly, gradually becoming narrower toward Paia, where it ends. Only occasional patches of corals are found to the eastward of this point. It is this extensive coral flat, covered with huge masses of Porites and Pocillopores, upon which the full force of the trade-wind sea is pounding, which furnish many of the larger blocks of the Maui coral coquina which were left as formed in sheltered places, and were covered by a luxuriant growth of a species of Sargassum ; the surface of many of these blocks was protected by masses of Nullipores and other calcareous algæ. The Kahului beach is broken by numerous spits extending out on the reef. These spits are remains of lava flows which have become covered with huge rounded masses of lava, and in part by fragments of broken coral and by coral sand, sometimes one to two feet in thickness. In this breccia and conglomerate, as well as in the stratified coral coquina formed in its proximity, numerous rounded and waterworn pebbles of lava have become imbedded. The coral lava conglomerate thus formed has a most striking appearance. I had been greatly puzzled by finding similar deposits inland near Maalaea Bay, on the low plain extending towards Kahului, and on some of the sugar plantations at a distance to the east from the road connecting the above-named places.

The recent British Admiralty Chart, No. 1520, shows very well the distribution of the coral reefs of the Sandwich Islands. The only islands which I examined for reefs myself are Oahu, Maui, and Hawaii, and in passing close to the south shore of Molokai I could readily see from the color of the water that there was an extensive fringing coral reef.

CAMBRIDGE, November, 1888.

## EXPLANATION OF THE PLATES.

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### PLATE I.

The Hawaiian Islands. From British Admiralty Chart. Soundings in fathoms. The shaded shore plateaus show the position of coral reefs.

### PLATE II.

Oahu. From Hawaiian Government Survey, W. D. Alexander, Surveyor-General. The shaded shore plateau indicates the recent and ancient coral reefs.

### PLATE III.

Maui. From Hawaiian Government Survey, W. D. Alexander, Surveyor-General. The shaded shore plateau indicates the position of coral reefs.

### PLATE IV.

The south side of Oahu. The shaded portions indicate the position of the active reefs, extending along the south side of Oahu from Barber's Point towards Makapuu Point, and in Kaneohe Bay. From British Admiralty Chart.

### PLATE V.

Kaneohe Bay. From Hawaiian Government Survey, W. D. Alexander, Surveyor-General. The lined and colored parts indicate the extent of the active reefs of Kaneohe Bay. Soundings in fathoms at low-water mark.

### PLATE VI.

Honolulu and its Fringing Reef. The line of breakers indicates the position of the outer slope of the reef. From a photograph.

### PLATE VII.

The eastern side of the entrance of Honolulu harbor. From a photograph. Diamond Head in the distance.

## PLATE VIII.

The shore edge of the Fringing Reef, extending to the east of Honolulu harbor, towards Waikiki, with Diamond Head in the distance. From a photograph.

## PLATE IX.

The rotten shore edge of the Fringing Reef east of Honolulu, near Waikiki. From a photograph.

## PLATE X.

Passage cut through the shore edge of the Fringing Reef by the river coming down the Nuuanu Valley to the westward of Honolulu, seen from Smith Bridge. From a photograph.

## PLATE XI.

Pearl River Lagoon, the inshore arms of the Pearl Lochs. From a photograph.

## PLATE XII.

Coral Sand Beach at Kahana formed from the triturated blocks of an ancient coral reef which once flourished between Kahana Bay and Kahuku Point. From a photograph.

## PLATE XIII.

Sunken Coral Sand Beach at Kaimu, Hawaii. From a photograph.