On Coral Reefs Present and Past.

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Modern Coral Reefs.

Introduction.—The remarks made by our President, incident to the recent visit of the Cotteswold Club to the fine old Coral reef at Brown's Hill, near Stroud, suggested the following communication,* in which I shall endeavour to bring within the compass of a short paper the observations I have from time to time made to our members, by way of explanation, when the different Coral beds met with in our rambles over the Cotteswolds have formed the subject of conversation. In doing so, however, it will be necessary to introduce my remarks upon the Coral reefs of the past with a brief *resumé* of some of the leading facts connected with the natural history of the Coral formations of the present period, in order that the physical conditions under which such structures are produced, and the laws which appear to regulate the Polyp life of their builders, may be better understood.

That there are masses of rock many leagues in extent, founded in the recesses of the ocean, and built up into gigantic structures, from a hundred to two thousand feet in thickness, by the secretions of Polyps, is a fact of deep interest to the naturalist, and of great significance to the geologist, the study of which affords him important data for reasoning on the operations of these animals in former periods of the earth's history. It has

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* The substance of this paper was communicated to the Members of the Club at the May-Hill Meeting, 13th June, 1866.

now been ascertained by the investigations of Quoy, Gaimard, Beechey, Fitzroy, Nelson, Darwin, Dana, Couthouy, Jukes, and Agassiz, that the vital operations of reef-building Polyps are limited within a certain Bathymetrical range; that beyond that depth they cannot live; and that the forms which reefs assume depend upon the elevation or subsidence of the ocean's bed on which their foundations are laid. When we compare the stupendous results obtained by the operations of a community of Polyps with the boasted monuments of man, the latter sink into insignificance. The great wall of China, or the pyramids on Egypt's plains, are as nothing when contrasted with the Atolls that stud the Coral Sea, and the Barrier reefs that stretch along the shore of New Caledonia to the length of four hundred, or those which extend along the north-east coast of Australia for upwards of twelve hundred miles. How marvellous the fact, that these masses of calcareous rock have been secreted, through successive ages, by generations of tiny architects, amidst the waters of the ocean, and in defiance of the violence of its ever-restless waves! The study of such phenomena prepares the mind of the geologist for the investigation of operations of a similar character, that have taken place in the seas of former periods of the earth's history; for many palæozoic and secondary rocks may be said to be ancient Coral reefs, which appear to have been formed under conditions analogous to those now in operation in the waters of the Pacific Ocean.

Coral reefs are masses of limestone accumulated through long periods of time, under certain physical conditions, by the living energies of reef-building Actinozoa: they assume various forms, in accordance with the outline of the coast, or the contour of the submarine rock or bottom on which they commence to build; such structures, however, are not entirely composed of dead and living Coral, for as these islands are the favourite abodes of many Mollusca, Crustacea, Echinodermata, and other Radiata, their skeletons after death largely contribute to augment the growth of the reef.

The principal reef-building Actinozoa belong to the groups *Poritidæ*, *Astræidæ*, and *Meandrinidæ;* these form the large solid

masses of Coral Polyps which occupy the outer margin of the reef, and are there exposed to the wild fury of waves, rolling in an endless surge over their structures; whilst the branching Actinozoa, the *Madreporidæ*, and *Gorgonidæ*, and the cup-like *Explanariæ*, nestle in the still waters of the lagoon and channels within the reef, protected from the violence of the waves by the natural breakwater formed by their Astræan associates. It is only the external outer film of the Coral that contains in its myriads of cells the tiny living architects: the great mass of the structure is made up of the Coral masses, or of the branching forms of the skeletons growing on the reef; the intermediate spaces being filled in with fine light-coloured mud derived from the debris of other parts of the reef, or with triturated portions of the more delicate structure torn from the living margin, and embedded in the mud and sand accumulating in the still water of the lagoon; sometimes a true Oolitic or Pisolitic structure is produced by the motion given to the Coral grains; from these combined causes, and many others which may be unknown to us, we find the Coral rock consisting of a coarse grayish solid limestone, which is sometimes granular, or compact, earthy, or crystalline, according to the agencies that were in operation during the formation of the reef of which it formed a part.

Life Depth.—It was long supposed that the reef-building Polyps lived in very deep waters, as the remains of Coral structures were sometimes brought up by the sounding-line, or indicated by impressions made on its armed lead, at depths of many hundreds or even thousands of feet; and it was taken for granted that the Polyps lived and flourished in these profound recesses of the ocean. The careful observations, however, made by Ehrenberg, on the reef-building Actinozoa of the Red Sea, those of Darwin, Dana, and Jukes, in the Pacific, and of Agassiz, in the Gulf of Mexico, have proved that no reef-building Polyp can thrive at a depth of more than about fifteen fathoms, although other forms of Actinozoa live in much deeper water; the true reef-builders live and flourish only within this Bathymetrical position, many of them preferring much shallower

water, but none of them working beyond one hundred feet of the surface. When reef structure is found beyond this depth, it has been caused by the subsidence of the ocean bottom on which such formations were originally laid. Should the reef region be slowly sinking, at a rate not faster than that at which the Polyps can make the reef rise, then almost any thickness may be obtained through long periods of operation. The observations made by Professor DANA about the Coral regions of the Pacific, have led to the conclusion "that some of the reefs have a thickness of two or three thousand feet, or more, and which has been acquired during such a slow subsidence." [1] DARWIN[2] says that thick beds of Coral are formed only at small depths beneath the surface of the sea, and that Captain MORESBY,—whose opportunities for observation during his survey of the Maldiva and Chagos Archipelagoes have been unrivalled,—informed him that the upper part or zone of the steep-sided reefs, on the inner and outer coasts of the Atolls in both groups, invariably consists of Coral, and the lower parts of sand. At seven or eight fathoms depth, the bottom is formed, as could be seen through the clear water, of great living masses of Coral, which at about ten fathoms generally stand some way apart from each other, with patches of white sand between them, and at a little greater depth these patches become united into a smooth steep slope without any Coral; and when we know that the reefs round these islands do not differ from other Coral formations in their form and structure, we may conclude that in ordinary cases reef-building Polypifers do not flourish at greater depths than between twenty and thirty fathoms. EHRENBERG[3] says of the Coral reefs of the Red Sea, which he carefully studied:—"The living Corals do not descend there into great depths. On the edges of islets and near reefs, where the depth was small, very many lived; but we found no more, even at six fathoms. The pearl-fishers at Yemen and Massaua asserted that there was no Coral near the pearl-banks at nine fathoms depth, but only sand."

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[1] DANA, Text Book of Geology, p. 268.

[2] DARWIN, Structure and Distribution of Coral Reefs, pp. 82-83.

[3] EHRENBERG, Über die Natur und Bildung der Coralleninseln im Rothen-Meere, p. 56.

Distribution.—The influence of physical agents on living beings determines the geographical distribution of the species: thus light, heat, and temperature, latitude and longitude, atmospheric pressure and water pressure, individually and collectively, affect the life, growth, and development, as well as the decadence and destruction, of all organised bodies. The Actinozoa, it would appear, are remarkably sensitive to the influence of these agents; for although numerous genera of this class inhabit the waters of every region of the globe, still it has been ascertained that the true reef-building Polyps are limited to the seas of the tropics. Most of the high islands between the parallels of 28° north and south of the Equator, and also the borders of the continents within the same limits, are fringed with Coral reefs, provided the other conditions necessary to their development are present. Should the slope of the rocks below the water be steep, the Polyps cannot grow far from the shore; but if the slope is gentle, they make a wide fringing reef around the coast, the outer limit of which is determined by the depth of the water. Where the bottom is muddy, and rivers pour fresh water in any great abundance into the sea, there the reef-building Polyps are absent. According to Dana's observations, wherever cold oceanic currents invade tropical seas, and lower the mean temperature of the water in the coldest winter month below 68° Fahrenheit, there likewise reef-building Polyps cannot live. For this reason, and others perhaps not fully explained,—there are no Coral reefs on the West Coast of South America, or round the Galapagos Islands, in consequence of the cooling influence of that branch of the Great Antarctic or Humboldt's current, which sweeps along the western shores of that continent.

The Bermuda Islands, in 32° 15′ N., are the most northern limits of Coral reefs at present known; their distance from the Equator is, however, entirely compensated by the increased temperature of the ocean, derived from the Gulf-stream which flows around their western shores. In the Red Sea there are Coral reefs in lat. 30°. In the Pacific Ocean, the Loo-Choo Islands, in latitude 27° N., at the north-east of the Isle of Formosa, have reefs on their shores, and there is an Atoll at the north-west of the Archipelago of the Sandwich Islands, in 28° 30′.

In the Southern Hemisphere the reef-building Actinozoa do not extend so far from the Equator. In the Southern Pacific there are only a few reefs beyond the line of the tropic. Houtman's Abrolhos, on the western shores of Australia, in latitude 28° S., are of Coral formation.

In the middle of the Pacific Ocean the distribution of the reef-building Polyps extends over a zone of 56° of latitude in width, which on the western coast of America is reduced to 16°, and on that of Africa to 12°, whilst on the shores of Asia and Australia it extends over a diameter of 64°.

This irregularity in the width of the Coral zone in different parts of the ocean probably depends on the direction, force, and temperature of the extra-tropical currents, like those of the Galapagos Islands, which flow along the western shores of both continents at the north, and at the south of the Equator, and the inter-tropical currents found on their eastern shores; the Coral zone appears to be contracted on the west shore, and enlarged on the east. This irregular distribution of Coral reefs may at first sight appear to form an exception to the general law enunciated by Dana; but were all the physical conditions fully understood under which the exceptions occur, it would perhaps appear that the disposition of the warm and cold currents of the ocean is the real cause of their distribution, and that the exceptions, instead of breaking, in reality proved the rule.

Whilst the reef-building Actinozoa — *Poritidæ*, *Astræidæ*, *Gemmiporidæ*, *Madreporidæ*, *Meandrinidæ*—are limited to the Coral seas, and are not found living at more than 100 feet below the surface, other families of this class have a much wider range. The *Caryophyllidæ* extend from the Equator to the Arctic seas, and live at various depths, some species having been found at more than 200 fathoms; the *Alcyonaria*, in like manner, seem to prefer deep seas, *Corallium* having been found at 120, and *Gorgonia* at nearly 200 fathoms; and M. Sars dredged at Oxfjord *Virgularia Finmarchica* at a depth of 240 fathoms. Although depths equal to, or even exceeding these, have yielded many species of *Zoantharia*, still in general the members of this order are most abundant in seas of not more

than from 50 to 100 fathoms deep. The shallow vertical range of the reef-building Polyps has been already explained. Certain species are, however, chiefly found in particular parts of the reef itself, *Astræidæ* and *Seriatoporidæ* choosing its more submerged portions below the outer exposed edge, upon which *Porites* and its allies flourish. On the surface of the reef, *Astræidæ* and *Fungidæ* may readily be distinguished, and among these the globular masses of the Brainstone Coral, *Meandrina*, are often conspicuous.

The reef-building Actinozoa have likewise a limited range in space, and certain specific forms appear to characterise the various shores and oceanic regions in which they are found. The existence of natural barriers, whether of land or deep water, of thermal or frigid currents, exercise a marked influence on their distribution; hence we find that the species living in the West Indies, and in the seas of the Antilles, are special to those regions, and none of them are identical with the forms existing in the East Indies and in the Pacific, the central region of that ocean having likewise been found to possess its own species. Although these oceans appear to possess similar physical conditions of depth and temperature, still we find specific Polyp forms limited to certain areal regions of the same, and obeying the great law of their being—"hitherto shalt thou come, but no farther." For of 306 species collected in the East Indies and Pacific, 27 only are common to the two oceans, and there are none between the Great Ocean and the Atlantic.

The proximity of volcanic land, owing to the lime generally evolved from it, has been thought to be favourable to the growth of Coral reefs; but Darwin * has well remarked, "there is not much foundation for this view, for nowhere are Coral reefs more extensive than on the shores of New Caledonia, and of North-eastern Australia, which consist of primary formations; and in the largest group of Atolls, namely Moldiva, Chagos, Marshall, Gilbert, and the Low Archipelagoes, there is no volcanic or other kind of rock, excepting that formed of Coral."

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* On Coral Reefs, p. 61.

Classification.—Mr. Darwin has divided Coral reefs into

I. Atolls, or Lagoon Islands,
II. Barrier, or Encircling Reefs,
III. Fringing, or Shore Reefs.

I. *Atolls*, so named by their inhabitants, consist of a wall of Coral rock rising in the ocean from a considerable depth, and returning into itself, so as to form a calcareous ring, more or less complete, having a sheet of shallow water, or lagoon, within the circle. The wall is breached in general, in one or more places, and when sufficiently wide and deep to admit a vessel, it may form a convenient harbour. The outer side of the reef slopes away at an angle of 45° or more, to a depth of from two to five hundred fathoms, whilst the inner side inclines gently towards the middle of the lagoon, forming a saucer-shaped cavity, having a depth of water from one to fifty fathoms. The annexed sketch of Whitsunday Island, in the South Pacific, taken from Admiral Beechey's work, affords a faint idea of the general aspect of one of these Atolls, or lagoon islands.

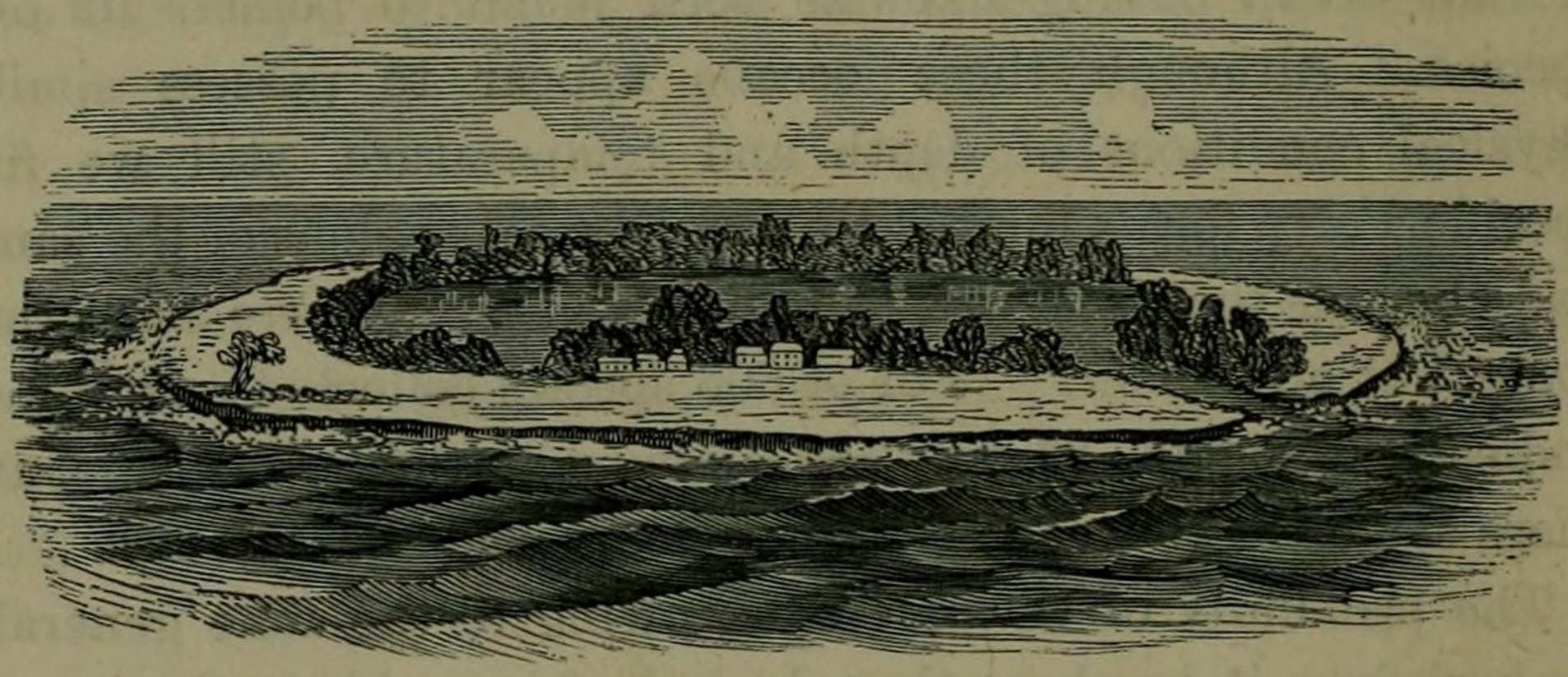

Fig. 1.—Whitsunday Island.

M. Darwin remarks, * that "this island is one of the smallest in size, one mile and a half long, and has its narrow islets united together in a ring of land, which is comparatively rare, so that it does not represent the singular aspect of one of these islands. The immensity of the ocean, the fury of the breakers, contrasted with the lowness of the land and the smoothness of the bright green water within the lagoon, can hardly be imagined without having been seen."

* Naturalists' Voyage, p. 466.

The summit of the outer wall of an Atoll is entirely composed of masses of living Actinozoa; numerous species of *Porites*, *Milleporæ*, *Astreæ*, and *Meandrinæ*, flourish there in luxuriance, forming mounds of Coral from four to eight feet wide, and as many thick, and separated from each other by narrow winding channels, six feet deep, which intersect the entire line of reef at right angles. The cells in the upper tier of the rock are empty, as the Polyps cannot endure exposure to the sun's rays at low water; hence this check to their upward development occasions their lateral expansion into masses having broad flat summits; all below low water-mark, the Coral wall teems with life; and the dead portions of Coral are covered over with layers Nullipore, one of the calcareous Algæ, which can bear any amount of exposure; this marine plant envelopes the exposed Coral like Lichens coating an old tree. The reef-forming Polyps thrive best in the surf occasioned by the breakers, and hence, where the surge rages most furiously, there these tiny architects work with the greatest activity. The violence of the waves frequently breaches the reef, and detached portions are driven inwards towards the lagoon, where they form, with other masses of similar origin, an inner reef; thus the ring of rock is enlarged along its inner circle, and the active development of the *Porites* living on the outer wall soon repairs the damage done by the storm. So rapidly does the wall of Keeling Atoll shelve downward, that Admiral Fitzroy, at a distance of 2200 yards from the breakers, found no bottom with a line 7200 feet in length; hence the submarine slope of this Atoll is steeper than that of any volcanic cone.

The lagoon, it would appear, has a fauna of its own; distinct species of Actinozoa with delicate branching stems, multitudes of Radiata and Mollusca indigenous to it nestle among the shallow waters, and fishes breed abundantly in the winding channels and crooked crannies of the Coral rock.

II. *Barrier Reefs* are similar to Atolls in structure, but differ in physical arrangement. They run parallel with the shores of some continent, or larger island, separated from the

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* Naturalists' Voyage, p. 466.

land by a broad and deep channel of smooth water; the outer side of the encircling reef plunges into very deep water, whilst the intervening channel represents the lagoon of an Atoll.

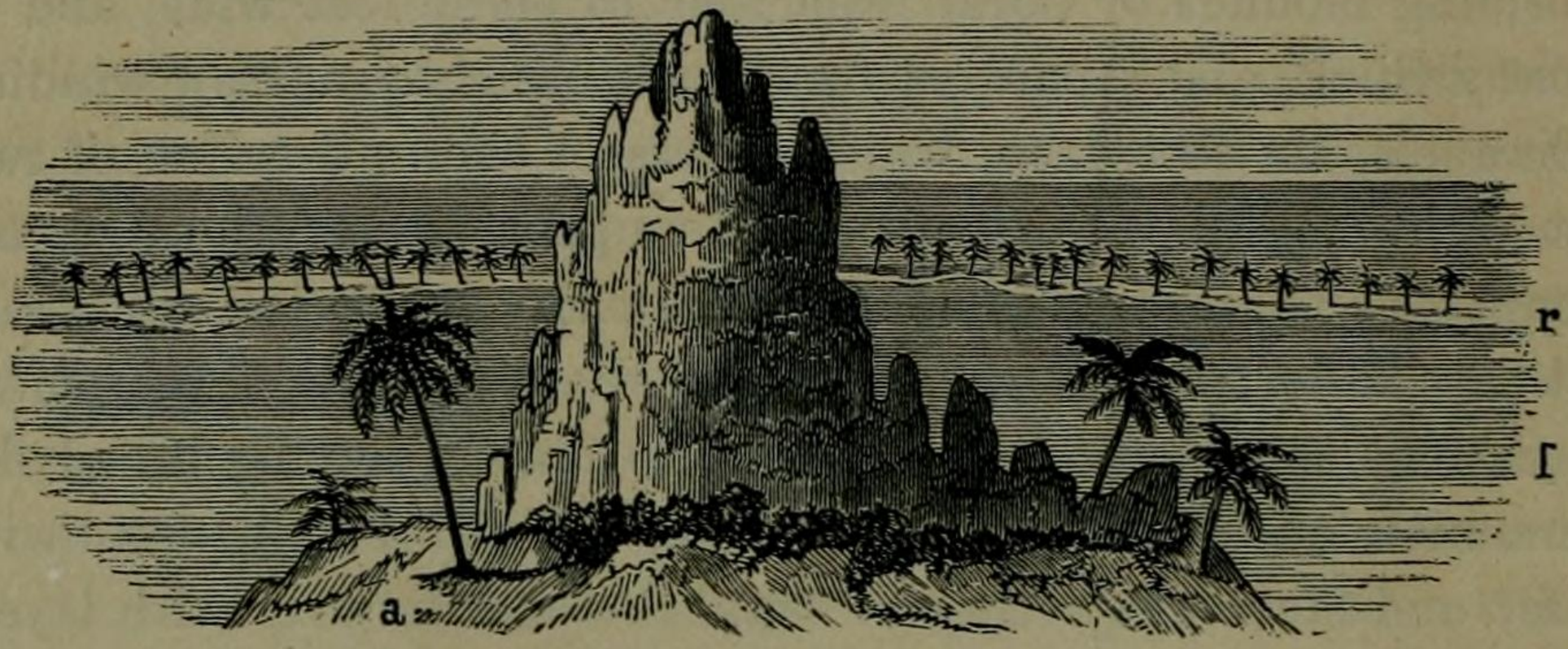

Fig. 2.—Bolabola Island.

The accompanying sketch (Fig. 2) taken from the voyage of the *Coquille*, representing the Barrier reef seen from within, from one of the high peaks of the Island of Bolabola, gives a good idea of this form of encircling reef, which imparts a most singular and picturesque character to the scenery of the islands they surround. As in Whitsunday Island, the whole of that part of the reef which is above water is converted into land: this is a circumstance of rare occurrence; more usually a snow-white line of great breakers, with here and there an islet crowned by cocoa-nut trees, separates the smooth waters of the lagoon channel from the waves of the open sea.

Balbi called Barrier reefs, Atolls "with high land rising from within their central expanse," and Darwin has shewn that they are Atolls in one phase of their growth. Ellis, in his "Polynesian Researches," states that these reefs lie in general at a distance of from one to one-and-a-half miles, or even three miles, from the shore. The central mountains are generally bordered by a fringe of flat, marshy land, from one to four miles in width, consisting of Coral sand, and other *detritus*, derived from the lagoon channel, or soil washed down from the hills; this silting-up process is only the slow conversion of the lagoon channel into dry land, by the gradual sinking of the island and the upward growth of the Coral forming the Barrier reef out at sea.

Lagoon channels of Barrier reefs represent in every respect the true lagoons of Atolls; they have a shallow level bottom of fine sand, and are filled with a fauna analogous to those living in lagoons; they have a depth of water of from 30 to 50 fathoms. The lagoon channel round the Society Islands varies from 3 to 30 fathoms; at Vanikoro, from 30 to 56½; at Gambier Islands, from 23 to 29. Some Barrier reefs have only a few islets on them, whilst that which encircles Bolabola is converted into a strip of land.

The heights of the islands encircled by Barrier reefs vary: Tahiti, according to BEECHEY, is 7000 feet; Bolabola, (LESSON,) 4026 feet; Maurua, (BENNETT,) 800 feet; Aitutaki, (FITZROY,) 360 feet; and Manouai, (WILLIAMS,) 50 feet. Some of these islands, like New Caledonia, are formed of primary strata; others, like Tahiti, of madreporic Limestone; and many are composed of volcanic rocks. The central land consists either of one island, or of several, encircled by a Barrier reef. There is no essential difference between Barrier reefs and Atolls: the latter enclose a lagoon in a circle of Coral rock, the former surround an island, or group of islands, at some distance from the shore, with a reef having a lagoon channel separating it from the island. Were the central land being removed by subsidence, as in the case of Bolabola, there would remain a circular Atoll, formed of numerous Coral islets, clothed with cocoa-nut trees, having in the centre a deep lagoon.

The Barrier reefs of Australia and of New Caledonia, from their immense extent, are marvellous structures. The reef on the West Coast of New Caledonia is 400 miles in length, and for many leagues is distant eight miles from the shore, and near the southern end of the island it is about sixteen miles in width. The great Australian Barrier reef extends, with few interruptions, for nearly one thousand miles, and its average distance from the land is from twenty to thirty miles, and in some parts from fifty to seventy. The lagoon channel in this case becomes a great arm of the sea, having an average depth of from ten to twenty-five fathoms where the reef is near the island, but where it is most distant the depth is from fifty

to sixty fathoms. The sea close outside the reef is profoundly deep, but soundings may sometimes be obtained from some of the breaches.

III. *Fringing Reefs* skirt the shores, from which they are not far removed; they have much shallower water on their oceanic side, and a narrower lagoon channel between the reef and mainland, of which they in general form a sloping portion. The reefs fringing the Island of Mauritius afford a good type of this class. Many of these reefs are found in the Red Sea, on the East Coast of Africa, Madagascar, and the adjacent islands on the North, in the Indian Archipelago, between the Bay of Bengal and New Guinea, and as far as the Salomons Isles; they may be traced at intervals to the south of the Society Isles, in longitude 150°W., and northwards through the Phillipines; they also occur in the West Indies, and the Peninsula of Florida, forming the keys and reefs that jut out from the mainland into the Gulf of Mexico. As some important observations have of late years been made on the Fringing reefs of this region, I purpose giving in detail the facts related by Professor Agassiz,[1] as they throw much additional light on the natural history of Coral formations. The Florida Keys are a line of small islands a few miles from the southern extremity of the main land, at different distances from the shore, stretching gradually seaward, in the form of an open crescent, from Virginia Key, and Key Biscayne, to Key West, at a distance of twelve miles from the coast, which does not, however, terminate the series, for sixty miles farther west stands the group of Tortugas, isolated in the Gulf of Mexico. Although disconnected, these islands are so many parts of a submerged Coral reef, parallel with the shore of the peninsula, and continuous beneath the water, the parts visible above the surface being portions of the reef that have completed their growth, and been elevated above low water-mark:—

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[1] Proceedings of the American Association for the Advancement of Science, p. 81: Fifth Meeting, Washington, 1851; and in more detail in his Methods of Study in Natural History.

"Several of the Florida Keys, such as Key West and Indian Key, are already large, inhabited islands, several miles in extent. The interval between them and the mainland is gradually filling up, by a process similar to that by which the islands themselves were formed.

"The gentle landward slope of the reef, and the channel between it and the shore, are covered with a growth of the more branching lighter Corals, such as Sea-Fans, Corallines, &c., answering the same purpose as the intricate roots of the Mangrove tree. All the *débris* of the reef, as well as the sand and mud washed from the shore, collect in this net-work of Coral growth within the channel, and soon transform it into a continuous mass, with a certain degree of consistence and solidity. This forms the foundation of the mud-flats which are now rapidly filling the channel, and must eventually connect the Keys of Florida with the present shore of the peninsula.

"Outside the Keys, but not separated from them by so great a distance as that which intervenes between them and the mainland, there stretches beneath the water another reef, abrupt, like the first, on its seaward side, but sloping gently toward the inner reef, and divided from it by a channel. This outer reef and channel are, however, in a much less advanced state than the preceding ones. Only here and there a sand-flat large enough to afford a foundation for a beacon, or a light-house, shows that this reef also is gradually coming to the surface, and that a series of islands corresponding to the Keys must eventually be formed upon its summit.

"What is now the rate of growth of these Coral reefs? We cannot, perhaps, estimate it with absolute accuracy, since they are now so nearly completed; but Coral growth is constantly springing up wherever it can find a foot-hold, and it is not difficult to ascertain approximately the rate of growth of the different kinds. Even this, however, would give us far too high a standard; for the rise of the Coral reef is not in proportion to the height of the living Corals but to their solid parts, which never decompose. Add to this, that there are many brittle, delicate kinds that have a considerable height when alive, but contribute to the increase of the reef only so much additional thickness as their branches would have if broken and crushed down upon its surface. A forest in its decay does not add to the soil of the earth a thickness corresponding to the height of its trees, but only such a thin layer as would be left by the decomposition of its whole vegetation. In the Coral reef also we must allow not only for the deduction of the soft parts, but also for the comminution of all these little branches, which would be broken and crushed by the action of the storms and tides, and add, therefore, but little to the reef, in proportion to their size when alive.

"The foundations of Fort Jefferson, which is built entirely of Coral rock, were laid on the Tortugas Islands in the year 1846. A very intelligent head-workman watched the growth of certain Corals that established

themselves on these foundations, and recorded their rate of increase. He has shown me the rocks on which Corals had been growing for some dozen years, during which they had increased at the rate of about half-an-inch in ten years. I have collected facts from a variety of sources and localities that confirm this testimony. A brick placed under water, in the year 1850, by Captain WOODBURY, of Tortugas, with the view of determining the rate of growth of Corals, when taken up, in 1858, had a crust of Mæandrina upon it a little more than half-an-inch in thickness. Mr. ALLEN also sent me from Key West a number of fragments of Mæandrina from the breakwater at Fort Taylor; they had been growing from twelve to fifteen years, and have an average thickness of about an inch. The specimens vary in this respect, some of them being a little more than an inch in thickness, others not more than half-an-inch. Fragments of Oculina gathered at the same place, and of the same age, are from one to three inches in height and width; but these belong to the lighter, more branching kinds of Corals, which, as we have seen, cannot, from their brittle character, be supposed to add their whole height to the solid mass of the Coral wall. Millepore gives a similar result.

"Estimating the growth of the Coral reef according to these and other data of the same character, it should be about half-a-foot in a century; and a careful comparison which I have made of the condition of the reef, as recorded in an English survey made about a century ago, with its present state, would justify this conclusion. But allowing a wide margin for inaccuracy of observation, or for any circumstances that might accelerate the growth, and leaving out of consideration the decay of the soft parts and the comminution of the brittle ones, which would subtract so largely from the actual rate of growth, let us double this estimate, and call the average increase a foot for every century. In so doing, we are no doubt greatly over-rating the rapidity of the progress, and our calculation of the period that must have elapsed in the formation of the reef will be far within the truth. The outer reef, still incomplete, as I have stated, and therefore, of course, somewhat lower than the inner one, measures about 70 feet in height. Allowing a foot of growth for every century, not less than seven thousand years must have elapsed since this reef began to grow. Some miles nearer the mainland are the Keys, or the inner reef; and though this must have been longer in the process of formation than the outer one, since its growth is completed, and nearly the whole extent of its surface is transformed into islands, with here and there a narrow break separating them, yet, in order to keep fully within the evidence of the facts, I will allow only seven thousand years for the formation of this reef also, making fourteen thousand for the two.

"This brings us to the Shore-bluffs, consisting simply of another reef exactly like those already described, except that in course of time it has

been united to the mainland by the complete filling up and consolidation of the channel which once divided it from the extremity of the peninsula, as a channel now separates the Keys from the Shore-bluffs, and the outer reef again from the Keys. These three concentric reefs, then,—the outer reef, the Keys, and the Shore-bluffs,—if we measure the growth of the two latter on the same low estimate by which I have calculated the rate of progress of the former, cannot have reached their present condition in less than twenty thousand years.

"But this is not the end of the story. Travelling inland from the Shore-bluffs, we cross a low, flat expanse of land, the Indian hunting-ground, which brings us to a row of elevations called the Hummocks. This hunting-ground, or Ever-glade, as it is also called, is an old channel changed first to mud-flats and then to dry land, by the same kind of accumulation that is filling up the present channels, and the row of Hummocks is but an old Coral reef with the Keys, or islands, of past days upon its summit. Seven such reefs and channels of former times have already been traced between the Shore-bluffs and Lake Okee-cho-bee, adding some fifty thousand years to our previous estimate. Indeed, upon the lowest calculation, based upon the facts thus far ascertained as to their growth, we cannot suppose that less than seventy thousand years have elapsed since the Coral reefs already known to exist in Florida began to grow. So much for the duration of the reefs themselves. What, now, do they tell us of the permanence of the species by which they were formed? In these seventy thousand years has there been any change in the Corals living in the Gulf of Mexico? I answer most emphatically, *No.* Astræans, Porites, Mæandrinas, and Madrepores, were represented by exactly the same species seventy thousand years ago as they are now. Were we to classify the Florida Corals from the reefs of the interior, the result would correspond exactly to a classification founded upon the living Corals of the outer reef to-day. There would be among the Astræans the different species of Astræa proper, forming the close roundheads,—the *Mussa*, growing in smaller stocks, where the mouths coalesce and run into each other, as in the Brain-Corals, but in which the depressions formed by the mouths are deeper,—and the Caryophyllians, in which the single individuals stand out more distinctly from the stock; among Porites, the *P. Astræoides*, with pits resembling those of the Astræans in form, though smaller in size, and growing also in solid heads, though these masses are covered with club-shaped protrusions, instead of presenting a smooth, even surface, like the Astræans,—and the *P. Clavaria*, in which the stocks are divided in short stumpy branches, with club-shaped ends, instead of growing in close compact heads; among the Mæandrinas we should have the round-heads we know as Brain-Corals, with their wavy lines over the surface; and the *Manicina*, differing again from the preceding by certain details of

structure; among the Madrepores we should have the *Madrepora prolifera*, with its small, short branches, broken up by very frequent ramifications; the *M. cervicornis*, with longer and stouter branches, and less frequent ramifications, and the cup-like *M. palmata*, resembling an open sponge in form. Every species, in short, that lives upon the present reef is found in the more ancient ones. They all belong to our own geological period, and we cannot, upon the evidence before us, estimate its duration at less than seventy thousand years, during which time we have no evidence of any change in species, but, on the contrary, the strongest proof of the absolute permanence of those species, whose past history we have been able to trace."*

Theory of the Formation of Coral Reefs.—M. Darwin, during his voyage as Naturalist to H.M.S. *Beagle*, between the years 1835 and 1840, was the first to explain the manner by which Barrier and Atoll reefs had been formed from ordinary Fringing reefs, on the principle of the depression of the land; and from that time to the present nearly all geologists have admitted this to be the true explanation of the phenomena, and of which the following account is a brief *resumé*.

Assuming that the outer edge of a Barrier reef marks the position, or nearly so, of a Fringing reef that was constructed along the shore when the island around which it formed stood at a higher level out of the water than it does now, we should have a condition of things which would be represented by Fig. 3, where (a, a, b) represents the section of an island surrounded by a Fringing reef, (r, r,) rising to the surface of the sea.

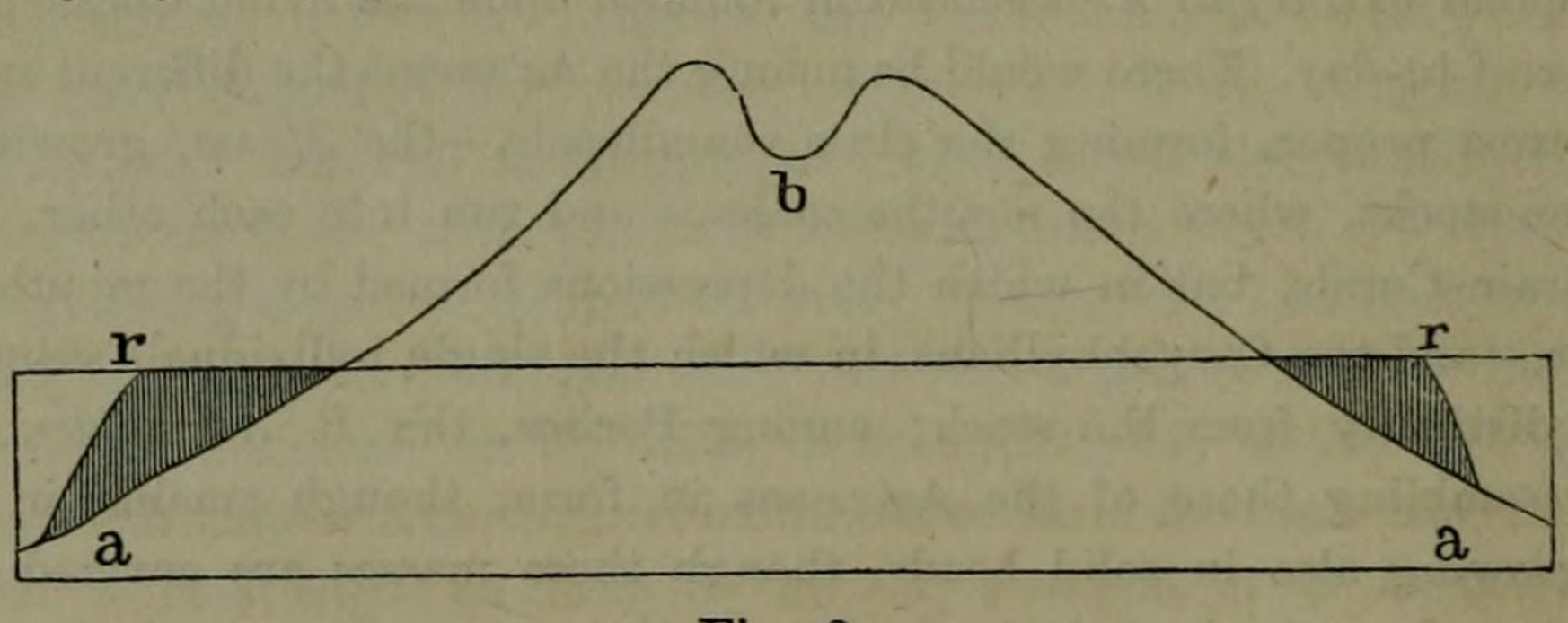

Fig. 3.

As the sloping shore slowly subsides by the depression of the land, the sea necessarily flows farther over it, and in course of ages the outer margin of the reef (Fig. 3, r) would

* L. Agassiz, Methods of Study in Natural History, pp. 185-192.

recede farther and farther from its former relation to the island. The Polyps, however, ever most active where most exposed to the play of the waves, have grown vertically upwards at the outer edge of the reef, and build here energetically, to regain the position most favourable for their development; but this subsiding island is becoming lower and smaller, and the space between the edge of the reef (r, r,) and the beach, proportionately broader. This is filled with a channel of shallow water, into which masses of Coral, torn from the outer margin, are hurled by the fury of the stormy waves. These become thickly coated with *Nulliporæ*, to a thickness of 2 or 3 feet. The lagoon channel is filled likewise by other *débris*, and crowded with other species of Polypifera that luxuriate in shallow water. A section of the island, after a subsidence of several hundred feet, is given in Fig. 4. The former living margin of the reef (r) is now dead

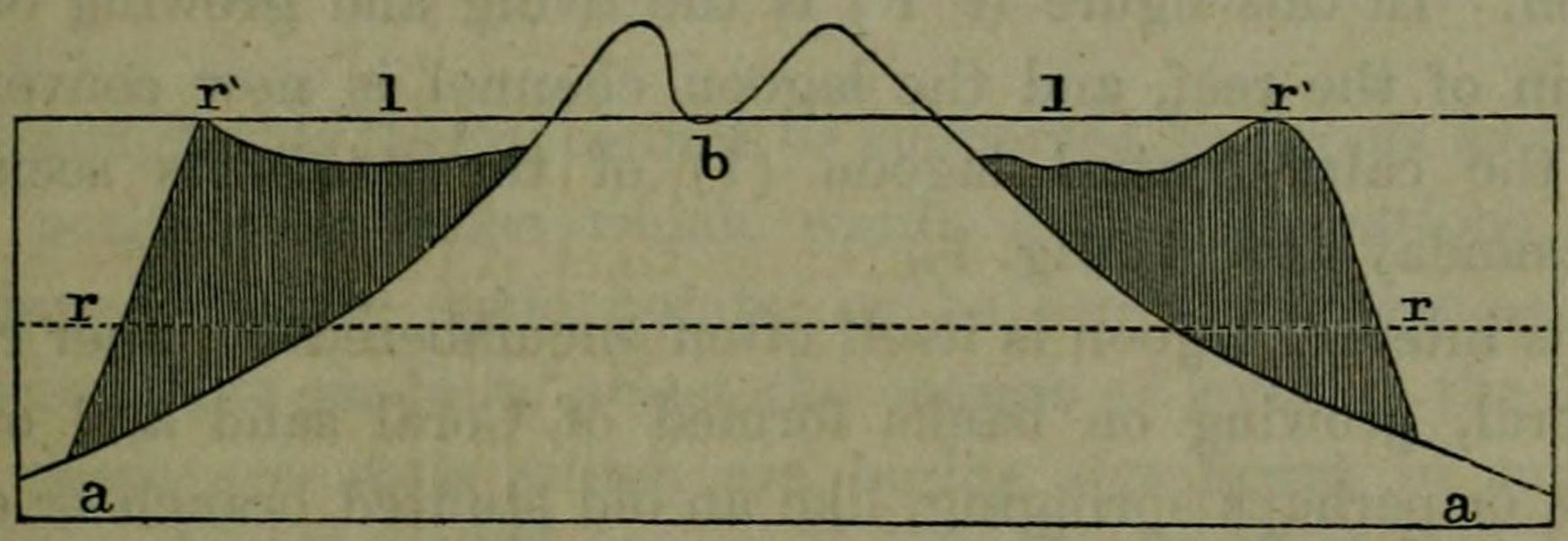

Fig. 4.

Coral, dragged down to a depth at which the Polyps could not live; but their progeny, working onwards and upwards in proportion as the land was subsiding, have maintained their position, and now form the margin of the outer Coral circle surrounding the land, where they form a Barrier reef, (r` r) separated by the lagoon channel (l, l) from the remnant of the land, (a, a, b) as already described in the case of the island of Bolabola, (Fig. 2) where the Barrier reef is seen from within, from one of the high peaks of the island.

If the land continues to subside, and the Coral reef continues to grow upwards on its old foundations, whilst the water gains on the land until the highest peak is submerged, there will remain only a perfect Atoll, of which Fig. 5 represents a vertical

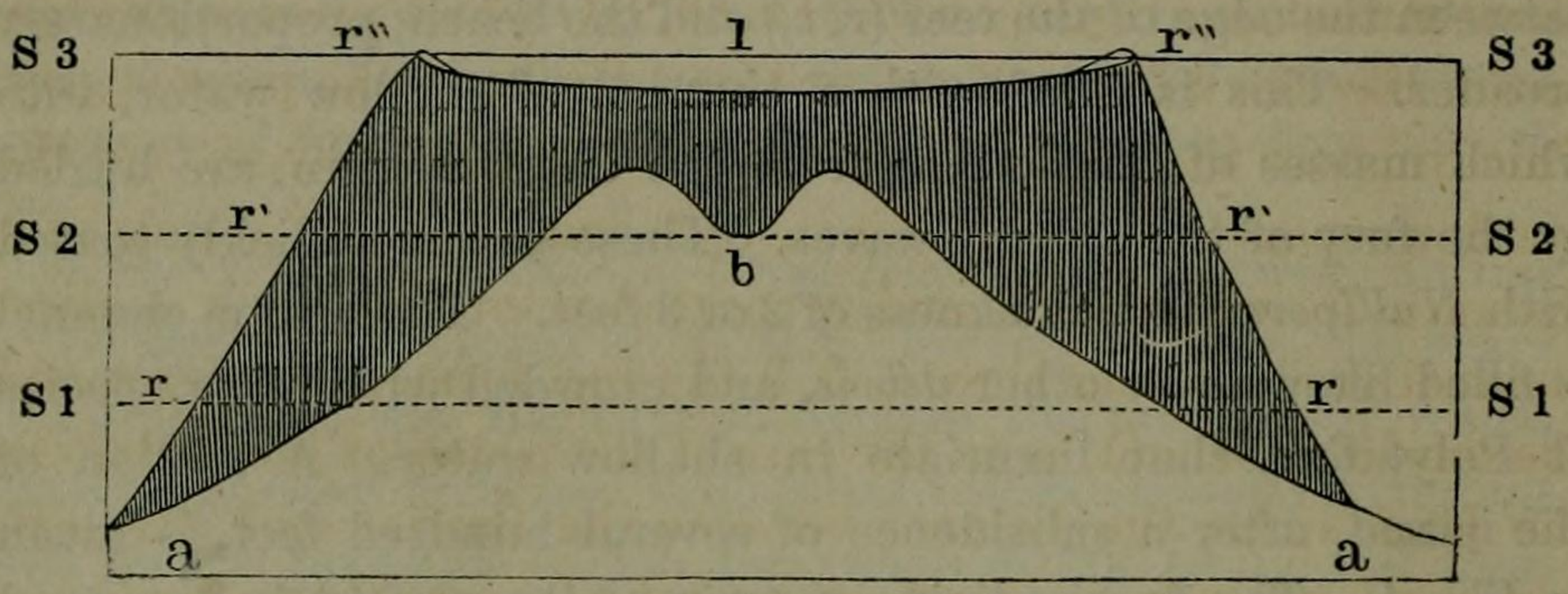

Fig. 5.

section. In this figure (r‴ r‴) is the living and growing outer margin of the reef, and the lagoon channel is now converted into the calm central lagoon (l) of the Atoll, as seen in Whitsunday Island (Fig. 1.)

This internal lagoon is itself often encumbered by inner reefs of Coral, growing on banks formed of Coral sand and other *débris*, or perhaps springing, like an old stunted branch or crag of rock, from one of the peaks of the Coral strand. In Fig. 6 an

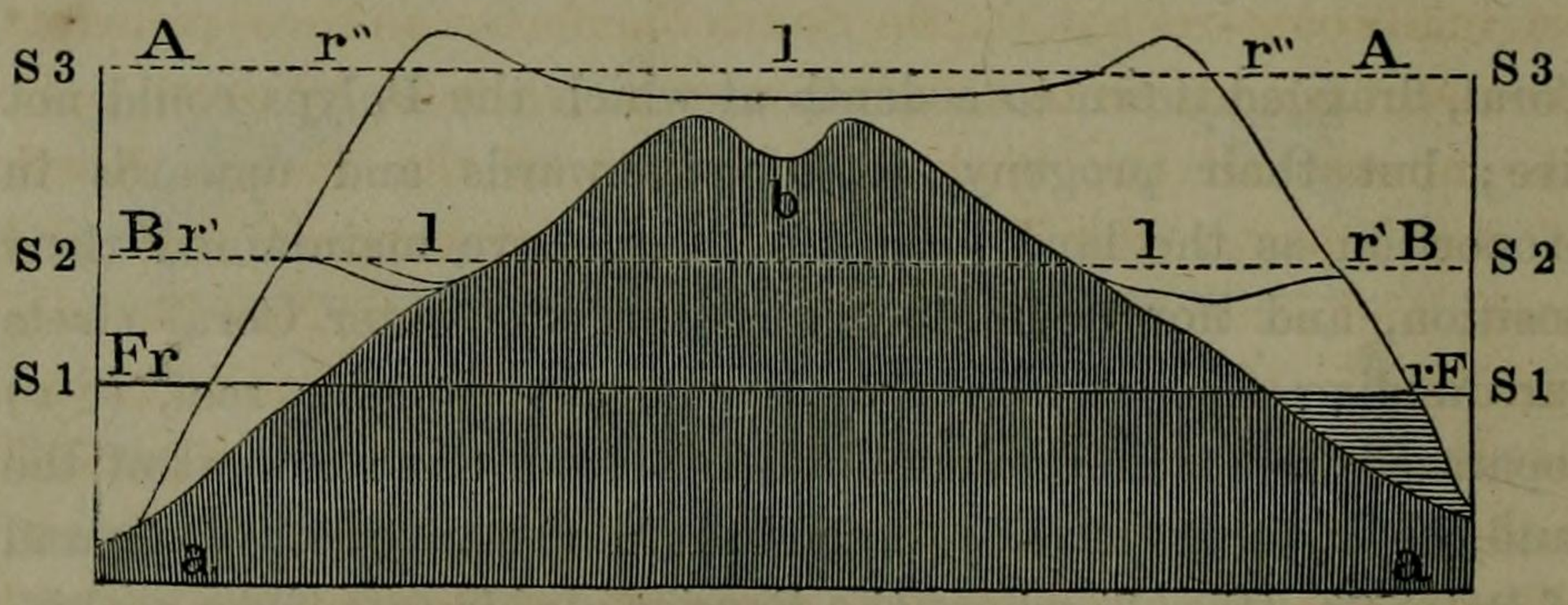

Fig. 6.

attempt is made to illustrate these changes of land level, in relation to the unchanging sea level, by drawing three successive lines S 1, S 2, S 3, to represent the surface of the sea at three different periods of time, as if the sea had risen, instead of the land forming the sea bottom having been depressed.

The island (a, a, b) represented in section, is surrounded by a Coral strand or Fringing reef, (Fr, rF, S1) which grew in shallow water, like the Florida Keys, or Coral banks of the present day. Then suppose the island to sink slowly and gradually, so that the sea flows more and more over it, (S2) until the reef stands at a distance from the land, and separated therefrom by a shallow channel or encircling lagoon, (l, l) the reef forms a Barrier round the subsiding island, as in the case of the island of Bolabola. As the land sinks, the distance between the Barrier reef (Br`, r`B) and the land (a, a, b) increases, and the lagoon channel widens. When the highest peak of the land disappears, (S 3) and the Barrier reef becomes an Atoll (Ar``) or ring reef, without a central island, then the lagoon channels unite and form a central lake (l.)

Although this theory cannot be supported by proofs as direct and positive as those which result from observations long continued on the same points, or be proved by geometrical measurements made to attest the change of level on the land, still there are facts which are highly significant in support of the explanation. For example, we remark that the Atolls show, in their general distribution, the form or the direction of the land around which the base of the reefs had been originally constructed. In the South Pacific Ocean three principal groups of islands lie in a direction of north-west by south-east, like almost all the land in this part of the globe. North of the Equator the Caroline Archipelago extends east and west; and south of the line, the islands of Ceram, New Britain, and New Ireland, have a similar direction. In the Indian Ocean the Laccadives and the Maldivas Atolls extend in a line parallel with the chain of the Ghauts on the adjoining Asiatic continent. There is likewise a considerable resemblance between the general form and disposition of the Atolls and that of ordinary islands.

All are elongated in the direction of the group of which they form a part; and thus a series of Atolls, forming an Archipelago, would be but the translation to the surface, so to speak, of the submarine land which support the Atolls themselves.

If Barrier reefs and Atolls indicate great areas of subsidence, Fringing reefs, bordering the shores of emerged lands, are often stationary, or give evidence of a slow and gradual elevation of the continent they fringe. In the islands of Mauritius, Bourbon, Timor, and New Guinea; in the Mariana Isles, the Sandwich Archipelago, and other Fringing regions, there has been a modern elevation of the land, as proved by beds of recent shells in raised beaches, which the highest tides do not now attain. The shores of the Red Sea have experienced similar elevatory movements, followed by a movement of depression; and many of the Friendly Isles are but ancient Atolls, that have been submitted to oscillations of the same kind. The Keys of Florida, and the Great Reef itself, attest the slow growth of the Coral formation in this part of the peninsula; and the gradual rise of the same to form new land in this region has been already fully explained. Fringing reefs, therefore, shew that the shores which they skirt are stationary or rising; whilst Atolls and Barrier reefs attest that subsidence has taken place.

If we examine attentively the map coloured by Mr. Charles Darwin, shewing the geographical distribution of the different kinds of Coral reefs, we become impressed with the vastness of the areas occupied by reefs and islands of Coral formation, none of which rise to a greater height above the level of the ocean than that attained by matter thrown up by the winds and waves of an open sea. In the Pacific Ocean there is a band of groups of Atolls, which, measuring from the south end of the Low Archipelago to the northern termination of the Marshall islands, is 4500 statute miles long, and varying from 200 to 600 miles broad: to this may be added the Caroline and Pelew Archipelagoes, stretching more than another 1000 miles to the westward. The great Barrier reefs on the north-east coast of Australia are 1250 statute miles in length, and from 10 to 90 miles in width. The Laccadive, Maldiva, and Chagos groups,

in the Indian Ocean, stretch along a line 1500 miles in length, the Maldivas themselves being 470 miles long by 60 miles in breadth.

The lowness of the islands of Coral formation, over all this vast area, depends upon the fact that Coral-Polyps are powerless to raise their structures higher than the line of low water-mark. To elevate them higher than this, various agencies are at work, but chiefly those of the winds and waves, the force of which detaches masses from the reefs, and piles these up in shallow water, where the interstices become silted up by Coral sand, fine mud, and other *débris*, of the reef. The general theory of elevation and subsidence of the sea-bottom within the area of the Corallian sea, the conversion of the irregular surface of the reef into one continuous level, and the alterations which its dead and deeply-submerged portions become exposed to in the lapse of time,—are subjects that belong to the consideration of the philosophic geologist, and which have received the most ample illustration and most satisfactory explanation by Mr. C. Darwin's admirable researches on this most interesting subject.*

As monuments of past changes, Coral reefs form the basis of some of the most important inductions that have been made in this branch of dynamical geology, and they open up a field of investigation, which has recently yielded some valuable facts regarding the long duration of the life of species in time, and to which I have given full prominence in the section on Fringing reefs. The palæontologist studies in these modern reefs all the slow processes by which the multiplication of the same specific forms through long lapses of time produce changes in the earth's surface, and he is prepared thereby for the investigation of those ancient reefs which existed in the seas of all past ages. Having ascertained that an island occupied each region where now the calm waters of the lagoon lave the Coral strand, he sees in every Atoll a living monument of land that

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* Geological observations on Coral reefs and volcanic islands must be consulted by all who wish to understand the numerous details connected with this subject.

has now sunk beneath the waves; and the inference becomes conclusive, that tropical seas must have rolled over those existing continents, amid whose mountain-chains the remains of ancient Coral reefs are found.

Ancient Coral Reefs.

A. *Structure and Classification of Fossil Corals.*

As the study of all the known facts connected with the Natural History of modern Coral reefs is necessary to a correct appreciation of the probable conditions under which those of past time were formed, I have devoted a greater space to the consideration of this part of the subject than it was my intention to have done when I commenced this paper; however, these observations are so numerous and important, and so interesting and instructive at the same time, that I have ventured to introduce them here even at the risk of being thought tedious. The careful investigation of the *modus operandi* of modern agents is indispensable to the right comprehension of those which prevailed in ancient time; for every thing concurs to show that the past resembled the present, as the present is but a continuation of the past: and the student who most cautiously proceeds from the investigation of the known, to the study of the unknown, is pursuing the only true method by which he can hope to arrive at a sound induction respecting the conditions under which phenomena of an analogous or identical nature were produced in former periods of the earth's history.

All the great epochs into which Geologists have divided the fossiliferous rocks contain, in greater or less abundance, the remains of the fossil skeletons of Actinozoa. Sometimes their accumulation is so considerable, that strata of great thickness and vast extent may be said to be composed of the extinct forms of Corals; whilst the name commonly given to some formations, as Coral beds, or Coralline Limestone, is sufficient