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THE SCOTTISH
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THE COCOS-KEELING ISLANDS.

By H. B. Guppy, M.B., F.R.S.E.

Part II.

COCOS-KEELING OR KEELING ATOLL.

(With a Map.)

It will be first necessary to obtain a correct conception of the true nature of an atoll. The usual description of a circular reef, bearing islands and islets and enclosing a lagoon or basin, gives an erroneous idea of the relative proportions of an atoll; and although I shall have to adopt such a method of description in this paper it will be necessary always to remember that I follow it only for purposes of convenience and clearness.

By drawing a section on a true scale across an atoll of average size it will at once become apparent that the foregoing description gives a misleading idea of the real nature of this class of reefs. A section across Keeling atoll drawn on a true scale of an inch to the mile from the ocean depths, and intended to illustrate a breadth of six miles, and its present depth in the lagoon of rather less than ten fathoms, would merely represent a flat-topped mountain, the situation of the lagoon being indicated by a very slight central depression of about $\frac{1}{100}$th of an inch, and therefore almost imperceptible to the naked eye. I have accordingly made a section representing a lagoon-depth of 30 fathoms which probably illustrates the original condition of the atoll, and may be taken as typical of most reefs of this class. It will be there seen that so trifling a proportion does the depth of an atoll bear to its breadth that such a reef can only be accurately described as *a level patch of coral reef with a slightly raised border.* It is a basin in no sense of the word, nature having disguised and exaggerated its true characters in such a manner that both the eye and the mind have been deceived.

Bearing this in mind, it follows that the characteristic feature of such a level coral patch, namely its slightly raised border, can be accounted for by an explanation much simpler and much nearer at home than one which comprises a subsiding movement of the earth's crust "immense in amount as well as in area" (Darwin). Whilst speaking of "bason-formed reefs" Mr. Darwin fully recognised that during the upheaval of such reefs above the sea, the characteristic rim would be readily removed by denudation, so that an upraised line of atolls would form a line of flat-topped mountains. This being so, it seems a little strange that he did not perceive that an atoll is merely a level patch of reef, and that its border is relatively but a little higher.[1]

We have, therefore, only to explain the origin of the slightly raised margin of a patch of coral reef in order to account for the characteristic feature of an atoll. It is, in fact, to the natural growth of corals rather than to a subsidence of the earth's crust that we must look for our explanation. Murray, following in the steps of Chamisso, the companion of Kotzebue the Russian navigator, has shown that when a coral reef nears the surface it will grow upwards more rapidly at the margins than in the centre, where the growth of coral is much retarded through the accumulation of sand and reef *débris*, and by the diminished supply of food. Hence the margins would first grow to the surface, forming a reef enclosing a lagoon. In the course of time islands and islets are thrown up on the reef by the breakers and a completed atoll is produced. Subsequently in the case of the larger atolls the islands on the reef develop a crescentic or horse-shoe shape, or may form secondary atolls or atollons, through the deposition of the sand and reef *débris* produced by the breakers. This last-named process constitutes the novel feature of this paper, and I shall have to refer to it in detail.

I will now commence my description of this atoll, which by the map accompanying this paper will be seen to be about 8 miles long, 6 miles broad, and not more than 8 or 9 fathoms deep. It exhibits itself on the map as a ring of semi-crescentic and horse-shoe islands which present their convexities seaward. The crescentic form is possessed in various degrees by different islands; some of the smaller ones are perfect horse-shoe atollons and enclose a shallow lagoonlet, others again exhibit only a semi-crescentic form, whilst the larger islands have been produced by the union of several islands of this shape. These islands are situated on a reef which constitutes the true border of the atoll and is continuous except on the north side, where there are two openings. In my description I will first refer to the reef or reef-flat, then to the islands and islets upon it, and afterwards to the lagoon it encloses.

THE REEF OR REEF-FLAT.—The islands and islets, as I have just remarked, lie on the exposed reef or reef-flat that invests the lagoon. It

[1] When we recognise the true dimensions of an atoll, and perceive how readily such a reef would lose its characteristic rim during upheaval, we can understand how in a region where atolls were numerous in some remote period of the earth's history we should now only find rounded patches of reef limestone.

is this reef, as Mr. Darwin observes, that "essentially forms the atoll," and he describes it as "a ring enclosing the lagoon on all sides except at the northern end, where there are two open spaces, through one of which ships can enter." At low-water it is possible to walk on this reef from Direction Island to West Island without encountering a greater depth than 2½ or 3 feet, thus accomplishing the greater part of the circuit of the atoll. This reef-flat varies in places between 200 and 600 yards, being widest on the southern and western sides of the atoll. At high-tide it is completely covered, but at all tides there is a constant flow of water over a great part of its surface that finds its way through the passages into the lagoon. As its characters vary somewhat in different places I will describe it in different localities.

In the first place I will refer to the reef-flat opposite the southern passage between South and West Islands, where it is very wide. Between the islets in this passage, through which runs a constant current into the lagoon, corals and sand occur on the surface, the corals being mostly a massive and a branching species of *Porites* (the last being *P. palmata* (?), which, as remarked by Mr. Darwin, changes after its removal out of the water from a yellow colour to an inky-black hue). In addition there here occurs a small branching species of *Montipora*, which, with *Porites palmata* (?), is also found in the shallow water of the lagoon. In places the sand in this passage is almost covered with reticulated balls of a delicate branching Nullipore, varying in size up to the two fists, which give the surface a peculiar appearance. On the reef-flat outside the islets corals are very abundant, a massive *Porites*, often exposed at low-water, being by far the most common, the large flat-topped masses, only alive at the margin, and frequently some feet in diameter, being in some places so closely packed that they give the flat the appearance of a tesselated pavement. Next in frequency is *Porites palmata* (?) already referred to, together with another stout-branching *Porites*, and the slender branching species of *Pocillopora* (*P. brevicornis*, Lam.) that is also found in the lagoon. As we near the wash of the breakers, these corals give place to others that prefer the broken water. A stout bossy *Madrepora* (*M. formosa* ?) is the prevailing coral in the wash of the breakers, and for a little distance inside. The actual seaward margin of the reef is of solid Nullipore, encrusting corals raised usually about 2½ feet above the level of the flat, and irregular in form, not a continuous convex mound such as Mr. Darwin observed in another part of the atoll,[1] but cut up into gullies across which plates of *Millepora verrucosa* (E. and H.)[2] stretched themselves. A peculiar-looking species of *Pocillopora* grows in the crevices and gullies of the Nullipore margin and on the flat just within it, its short compressed and blunted branches well fitting it to resist the force of the breakers. It was curious to observe how the Nullipore at the margin bridged across

[1] Mr. Ross informs me that the Nullipore margin is rarely as regular as Mr. Darwin's description implies: I am able to support the opinion of Mr. Ross, who is thoroughly acquainted with the features of his own atoll.

[2] I have been mainly guided by Mr. S. Ridley's and Mr. Quelch's determinations of the corals brought from this atoll by Mr. Forbes. The *Millepora verrucosa* is referred to by Darwin as *M. complanata*.

the tops of the branches of these breaker corals so as to form a level surface, leaving the interspaces between the branches to be subsequently filled up with reef detritus.

On another occasion I walked at low-tide along the reef from Direction Island to New Selima, a distance of more than a mile. There was a strong current setting in over the reef, which was covered by from 1 to 3 feet of water, so that in the deeper places it was as much as I could do to keep on my legs. More than half the area was bare rock, often encrusted with Nullipore, whilst a little sand occurred here and there. Large mats of Alcyonarians here flourished. The most frequent of the corals was a Millepore growing in plates, the general run of its plates being across the current.[1] Next in frequency was the bossy *Madrepora* (*M. formosa* ?) already alluded to as thriving in the wash of the breakers on the south side of the atoll. Then came the stoutly branched *Pocillopora verrucosa*, a massive species of *Porites*, occasional small clumps of a long-celled branching Madrepore, and an encrusting *Montipora*. Pink Nullipore covered much of the dead coral. In fact, in the strong current flowing in over the reef pink Nullipores, Alcyonarians, the *Millepora*, above mentioned, and *Madrepora formosa* (?) appeared most to thrive.

The Nullipore is an important agent in preserving from decay the dead coral of the reef-flat. Whenever the coral clumps attain any size they die in the centre, and this calcareous alga at once attaches itself to the dead portion. This was especially noticeable with the clumps of *Millepora*, *Madrepora*, and *Pocillopora*, the central dead tops of which were thus encrusted; and it was curious to observe how this Nullipore by its lateral growth finally bridged over the spaces between the plates or branches of these corals, forming a smooth platform on their summits, and leaving the empty interspaces beneath it to be subsequently filled up with sand and reef *débris*. I often stood on a clump of Millepore which had been covered over and concealed by the Nullipore in such a fashion that I appeared to be standing on a bare rock surface. It has been already remarked that more than half the area of the reef-flat in this part of the atoll is bare rock; and I formed the opinion that this appearance had been mainly produced by the growth of the Nullipore over the corals in the manner just described. As around the whole atoll, there is here a very extensive growth of Nullipore at the breaker-margin of the reef. Washed up on the reef-flat within the broken water were great slabs of rock mainly formed of this calcareous alga, and measuring 2 feet in thickness, and as much as 10 by 5 feet in length and breadth. They had evidently been torn off from the breaker-margin, and had been piled up on the flat to a height of 3 or 4 feet above the low-water level. In appearance the fractured surface of this rock is white and chalky, exhibiting no structure to the naked eye, and resembling some chalky limestones I found associated with upraised reefs in the islands of the Solomon Group.

[1] This Millepore grows in stout plates in the centre of the clump, whilst the marginal plates are slighter, and branch at the edges. For purposes of convenience, I refer to the hydroid corals as corals.

On examining the reef in the passage south of New Selima, I found the surface to be mostly of dead rock, whilst the Millepore, and an occasional bossy Madrepore, grew in the vicinity of and within the wash of the breakers. The Nullipore grew in knobs, half-a-foot thick, at the breaker margin. On the west side of the atoll, which is somewhat protected from the direct action of the trade-swell, the aspect of the reef-flat at low-tide is somewhat quieter. Its partly bared surface is dotted with shallow pools; but as it presents few features that have not been already alluded to, I need not do more than refer to it.

I have now to consider the mode of outward growth of the reef, on the flat of which the islands have been thrown up. It is this reef that, as I have already remarked, really constitutes the atoll; and in order to understand its manner of outward growth, it will be necessary to describe certain of its other features.

The weather was rarely suitable during my visit for the examination of the outer slope of the reef. However, when sailing outside the reef on one occasion off the northern part of West Island, Mr. Ross directed my attention to two parallel submerged lines of coral banks growing up outside the breaker-margin of the reef, and separated from each other by a sandy interval, which is clearly indicated even at a distance by the difference in the colour of the water. The inner line was covered with 5 or 6 fathoms of water, and 100 or 150 yards outside it was the second line, over which there was a depth of 10 or 11 fathoms; beyond this, the submarine slope descended rapidly to great depths. Mr. Ross, whose frequent fishing excursions have made him familiar with the outer slopes of the reef, tells me that what I observed in this locality is exhibited around the greater part of the circumference of the atoll, there being sometimes even three lines of submerged banks, separated from each other by belts of sand and reef *débris*, the innermost being covered by 4 or 5 fathoms, the middle bank by from 10 to 15 fathoms, and the outermost by from 25 to 30 fathoms. These banks are situated on a kind of ledge, varying in width from 200 to 500 yards, which is to be found outside the breaker-margin of the reef around the greater part of the atoll. Here ships can anchor; in fact, Mr. Ross has sometimes anchored in his schooner even on the ledge off the weather or eastern coast. These banks are usually indicated at the surface by the successive lines of rollers outside the breaker-margin of the reef.

It would thus appear that the seaward extension of this reef is effected not so much by the outward growth of the breaker-margin, as by the formation outside it of a line of growing corals, which, when it reaches the surface, reclaims, so to speak, the space inside it, which is soon filled up with sand and reef *débris*. The evidence, in truth, goes to show that a reef grows seaward rather by jumps than by a gradual outward growth, a conclusion that does not come into conflict with Mr. Murray's view that a reef grows outward on its own talus, such a talus being the necessary foundation on which the lines of submerged coral banks are successively advanced. It is, however, apparent that if my conclusion is correct, the reef-flat ought to present on its surface some evidence of its intermittent growth in the shape of ancient reef-margins.

We have already seen that the Nullipore margin of the reef, which is composed of Nullipore thickly encrusting corals, is raised between two and three feet above the general level of the flat; and it was the difficulty of supposing that this raised border had been always worn down to the level of the flat, whilst the reef grew continuously outwards, that raised a doubt in Mr. Darwin's mind as to the seaward growth of the reef. However, with a more extended field of observation, I can now say that here and there these ancient reef-margins protrude above the flat, occurring in lines near the beach, but broken up into patches, and often extensively hollowed and worn down by the waves. They are composed of large masses of the breaker corals, and display a rough bedding with a gentle inclination seaward. These ancient reef-margins are well represented on the reef-flat of North Keeling Island, where parallel lines of rudely bedded breaker-conglomerate protrude at intervals above the flat, the Nullipore crust in some places being still preserved.

THE ISLANDS AND ISLETS.—I pass on now from the consideration of the reef-flat to the description of the islands and islets that have been subsequently thrown up on its surface. Generally speaking, these islands and islets are highest at their outer margins, where they are formed of loose coral blocks, raised from 6 to 12 feet above the reef-flat. They slope away towards the lagoon, being composed in their interiors mostly of unconsolidated sand. The loose materials of which they are formed rest on a solid foundation of a very hard conglomerate, well described by Mr. Darwin, which is often "exposed as a ledge, projecting some yards in front of the outer shore, and from two to four feet high," and has frequently "a waterworn and scooped appearance." Several bare level patches of this conglomerate rise up on the reef-flat on the weather sides of the atoll, being the foundations of islets that have long since been swept away, and I have described them below under the name of Button Islets, originally given to them in Van der Jagt's plan of 1829. This foundation of conglomerate in the outer or weather part of each island is composed of large blocks of the breaker corals, and of fragments of Nullipore, firmly cemented in a matrix of coarse calcareous sandstone, its surface often having a Nullipore crust several inches in thickness, and its mass being frequently "obscurely divided by seams, dipping at a small angle seaward" (Darwin). Such a rock now composes the raised margin of the reef in the wash of the breakers, and in this manner, I imagine, this similarly elevated foundation-rock of the islands was largely formed. However, as we approach the lagoon, we find that the conglomerate is composed of much smaller fragments of the same breaker corals, whilst in some places it is mainly made up of the coarse sandstone.

By forming an impermeable stratum beneath the loose sand and coral fragments composing the islands, this hard rock enables fresh-water wells to be sunk. It is, however, absent in those situations where ancient passages have been filled up with sand and reef *débris*, and also in those places where recent additions have been made to the land surface, and in consequence wells sunk in such localities afford only brackish water. The stratum of conglomerate exposed at the bottom of the wells is

usually one or two feet in thickness, and often overlies a bed of semi-consolidated sand of perhaps a similar thickness, underneath which another bed of conglomerate may occur.

I come now to the description of the individual islands, especially dwelling on their development of the horse-shoe or crescentic shape, and on their manner of gaining on the lagoon. A separate description is necessary, because we find that their characters vary considerably, and that each island has its lesson to guide us in the examination of the others. Afterwards I will proceed to consider the agencies at present shaping and extending these islands.

DIRECTION ISLAND.—This island, which is about three-quarters of a mile in length and some 300 yards in breadth, has a semi-crescentic form. Its general level is from 2 to 3 feet above high-water; but on its northern or seaward border coral blocks have been heaped up so as to raise its margin about 5 feet above the sea, whilst towards the eastern end the weather margin, similarly formed, is as much as 8 or 9 feet in height. The surface characters of this island tell the story of its different modes of growth. In the main it has been growing leeward or westward from its eastern portion by the formation of a succession of ridges of reef *débris*, each ridge thrown up by the waves, and marking a stage in the growth of the island. These ridges are naturally best illustrated in the western or more modern part, where the outermost or most recent of them have not yet been covered with vegetation, whilst the innermost are only scantily covered with littoral plants. The difference in age between the two parts of the island is also to be observed in the characters of the soil. In the western half the surface is usually more or less covered with loose coral masses; in the eastern or older part there is a much greater proportion of humus, and the surface is much less encumbered with loose corals. It is also noteworthy that although well-sinking has been hitherto unsuccessful in this island, fresh water has been recently obtained from a well sunk in its eastern or older part. It is true that a fortnight afterwards the water became brackish; yet this circumstance is sufficient to show that in the eastern part of the island the underlying foundation of conglomerate has had more time to consolidate than in the western portion.

Whilst growing westward, this island has increased its width by encroaching on the reef-flat at its seaward border. The process has been much the same. As the reef grows seaward the island also gains on the reef-flat by a succession of ridges, thrown up during heavy gales, the remains of which are still to be seen in its interior. There is yet a third mode of growth which this island illustrates. I have referred above to its semi-crescentic form; this is a more modern effect due to the curving inwards towards the lagoon of the extremities of the island through the influence of the currents, a process that tends towards the production of a horse-shoe form. The western end illustrates this process especially well. Here the incurving end is prolonged by a growing sand-bank, stretching into the lagoon, on which the vegetation of the island is rapidly encroaching. The fourth mode of growth at the lagoon margin,

well exhibited in other islands, is not well shown here. Direction Island, however, in its growth serves to illustrate, with this exception, the growth of all the islands. In a general way it may be stated that after the original or parent islet has been thrown up on the reef by the breakers, the island attains its length by extending along the trend of the reef through the accumulation of reef *débris*. After a little time it grows in width by advancing at its outer border towards the breaker edge of the reef, and by gaining on the lagoon at its inner margin through a reclaiming process to be subsequently described. In course of time the extremities of the island will grow inwards, a process which may ultimately produce a horse-shoe island. . . . In these remarks I have thought it wise to in some measure indicate in advance the methods of growth of these islands, in order to avoid unnecessary repetition whilst discussing the other islands.

WORKHOUSE ISLET, which is mostly of sand, and about 6 feet in height, bears a conspicuous coco-nut palm leaning seaward. Van der Jagt, in 1829, described it as a sand-bank 150 feet long and 100 feet broad.

PRISON ISLET, 20 feet high, is formed mostly of blown sand, which displays no arrangement, and is not consolidated. It is at present mostly covered with bushes and trees of *Scævola kœnigii* and *Tournefortia argentea*, together with coco-nut palms. It does not seem to have altered much since 1829, when Van der Jagt says that it bore twenty-five coco-nut palms, and was 20 feet high, and 250 feet in circuit.

CLUNIE ISLAND, the present burial island, is separated from the adjacent larger island of New Selima by a narrow passage, which is covered in the deepest places at the lowest tides by not more than 2 feet of water. This island is tending on its lagoon-side to assume a crescentic form by the growth of sand-banks, partly exposed at low-tide, on which the vegetation of the island is encroaching.

NEW SELIMA ISLAND is usually elevated between 2 and 4 feet above the sea, but on the outer or weather margin coral blocks have been heaped up to a height of 6 feet; whilst near the inner border, in the vicinity of the Bantam village, unconsolidated sand has accumulated until it has attained a thickness of 9 or 10 feet. In recent years the northern end of the island, on the lagoon side, extended itself about 70 yards, the new tract being partly clothed with young casuarina trees and young shrubs of *Scævola kœnigii* and *Tournefortia argentea*. At the southern end of the island, on its inner margin, there is a lagoonlet, now almost dried up, and presenting a dry tract of sand and mud, on which grow in places scattered tufts of grass, whilst patches of *Ipomœa pes caprœ* are encroaching upon its surface. Some thirty years ago, this lagoonlet, now only partially entered by the sea, was deep enough to float a boat, and it used to be a favourite resort for those who were in quest of the sea-birds that were perched on the trees around its margin.

THE "BUTTON ISLETS" OF VAN DER JAGT.[1]—This Dutch officer applied this name to three bare islets lying between the present named Prison Islet, Clunie Island, and New Selima Island. In their absence of vegetation he compared them to a sand-bank between Prison Islet and Workhouse Island. These so-called islets at present are merely patches of the reef-conglomerate, and apparently once formed the foundation of islets that have been swept away. Similar patches occur between the islands lying south from New Selima as far as the northern end of South Island. They are mostly bare, as in the case of one in the passage south of New Selima; but may sometimes be covered with bushes of *Pemphis acidula*, as in the instance of another lying close to the north end of this island. They are all made up of blocks of massive corals and stout Madrepores cemented together in various positions, some of them in the position of growth. Since they are not usually elevated more than $3\frac{1}{2}$ feet, and never more than 5 feet above the ordinary low-water level, most of them are but partially exposed at high tide. In fact, they have been often extensively eroded and hollowed into deep pits by the waves; and at the present day would merely be regarded as for the most part bare rocky patches.

SCÆVOLA ISLET, next to the bare rocky patch, off the south end of New Selima Island, is an islet not named in the Admiralty Chart; and I have named it as above for the convenience of reference. It is from 4 to 6 feet high, is composed on its outer side of loose coral blocks, and supports one or two coco-nut palms, together with bushes of *Scævola kœnigii*.

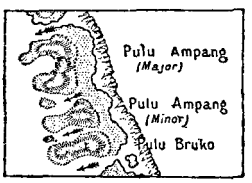
THE AMPANG ISLANDS, or STEWARD'S GROUP, include the three small islands lying to the south of Scævola Islet. The name of Steward's Group is that given to them in Van der Jagt's plan of 1829; and it correctly indicates that they form an independent group situated on the same patch of reef-conglomerate, and separated by permanent passages from the islands north and south of them, each of which has its own foundation of conglomerate. Pulu Ampang Major is an interesting example of an atollon or secondary atoll, which has assumed its horse-shoe form since the island was first thrown up by the waves, as the result of the growth of sand-banks which prolong its extremities leeward into the lagoon. In recent times the mouth of the horse-shoe has been crossed by a bank, covered with bushes of *Pemphis acidula*, and leaving only a narrow passage about a dozen paces wide leading into the lagoonlet. The lagoonlet, now 80-100 yards across, was evidently at one time much larger. At low water shallow pools half-a-foot deep dot its white chalky surface: at high tide it is covered by about $1\frac{1}{2}$ feet of water, but within the memory of Mr. Ross it had a depth of 3 feet at high water. It is evidently silting up.

Pulu Ampang Minor has no lagoonlet; but Pulu Bruko has a tiny

[1] Van der Jagt, in his map of 1829, employs names different from those now used for several islands of the atoll (See *Verhand. Batav. Genootschap der K., Deel* xiii.; 1832).

lagoonlet on its inner side, now cut off at low tide, and containing less than six inches of water. When Mr. Ross was a boy, it was deeper and larger, and was a favourite resort for catching mullet.

At low water these three islands, as indicated in the small accompanying plan, are connected together on the outside by the dry reef rock; but towards high tide the sea overflows the reef, and there is a continuous rush of water through the temporary passages. By the encroachment of the vegetation on either side the gaps between the islands are rapidly closing in, so that in the course of time these three islands will unite towards their outer borders. This is especially the case with Pulu Ampang Minor and Pulu Bruko, bushes of *Pemphis acidula* nearly joining them together. It has long been surmised that the largest islands of this atoll had originally a compound origin; and here we have an illustration of the process of union. At the lagoon end of each of the two passages, so called, that separate these three islands, a sand-bank or shoal has been formed, and the shoal between the two northern islands now bears a pretty coco-nut islet. These shoals are extending laterally, so that at no distant date the islands will be united at their inner margins as well as at their outer borders, and two lagoonlets will represent the original gaps between the islands. Here we have, as I shall subsequently explain, the key to the origin of North Keeling Island, and I may here remark that I was originally indebted to Mr. Ross for directing my notice to this unusual mode of formation of a lagoon, and for the suggestion that it would remove my difficulties in connection with this island. (The bearing of these facts will be referred to when I come to sum up my remarks.)



THE AMPANG ISLANDS
(Keeling Atoll.)
The arrows indicate the direction of the currents running through the passages into the lagoon.

PULU KUMBANG has no lagoonlet, and needs no special reference.

GOOSEBERRY ISLAND, the Armstrong Island of Van der Jagt's map, originally consisted of two or three smaller islands, and thus represents the future condition of the adjacent Ampang group, above described. In one place, where the island is only 50 yards across, the line of junction between its northern and southern portions may still be traced. Here there is little or no soil, the surface being strewn either with loose coral blocks or with blown sand. The inner border of this island is deeply indented along its whole length by a series of more or less perfect lagoonlets open to the lagoon, which are especially well shown in the southern half, where they are mostly dry at low water, and are crossed at their mouths, as in the case of the lagoonlet of Pulu Ampang Major, by sand-banks, clothed with *Pemphis acidula*, that tend to shut them off from the great lagoon. This reclaiming agency by the closure of the mouth of the lagoonlets of the various islands is in progress all around

the lagoon shores of the atoll; and it is the principal method by which the islands are gradually gaining on the lagoon.

PANDAN ISLAND is an example of a horse-shoe atollon, one-third of a mile across, and exhibiting the mode of origin of these horse-shoe islands in a very unmistakable manner. The lagoonlet is partly dry at low tide, the water then remaining being less than a foot deep, whilst the turtle-grass growing on the bottom is just exposed. The surface of the lagoonlet is formed of sand and mud. The two arms of the horse-shoe are rapidly extending into the great lagoon, especially the southern arm, which is continued as a shoal of sand, curving to the north-west, the surface of which is being occupied by the gradually advancing littoral vegetation. It is evident that the mouth of the lagoonlet will soon be closed, and that this will be followed by the obliteration of the lagoonlet, the area of which will in course of time be occupied by the vegetation of the island, or, perhaps, before this occurs, the surface will be planted with coco-nut palms by the proprietor.

There is nothing in the small islands intervening between Pandan Island and South Island that calls for special notice, so I will proceed to the description of the large South Island.

SOUTH ISLAND, or SOUTH-EAST ISLAND, which has a sweep of some 5 miles, and a breadth varying between 150 and 1000 yards, has had its origin in the union of several smaller islands. We know from Van der Jagt's plan of 1829, and from Fitzroy's plan of 1836, that these passages must have closed up before the occupation of the atoll sixty years ago. In truth they must have been obliterated at a much earlier date, seeing that they are not indicated in an old plan of the atoll, which was published in Van Keulen's Atlas in 1753, a plan that may have been made even in the seventeenth century, since it bears neither the author's name nor the date.[1] Mr. Leisk informed Mr. Darwin in 1836 that he had seen an old map in which this island was divided up into several islets: Mr. Leisk, as Mr. Forbes points out,[2] was not always accurate; and I prefer, therefore, the testimony of the early map in Van Keulen's Atlas to uncorroborated second-hand information. However, these ancient passages are even now traceable by the narrow necks occurring in different parts of the island, by the absence of soil on the surface, which is formed of loose coral blocks, by the open character of the wood growing upon it, and by the absence of the underlying reef-conglomerate that forms the foundation of the original islands. In wells sunk in such ancient passages Mr. Ross is unable to obtain fresh water, owing to the absence of the impermeable foundation of reef-conglomerate. This can be readily understood if we imagine the passage between two small islands, each having their own foundation of reef-conglomerate, such as Pulu Bruko and Pulu Kumbang, to become filled up with sand and reef *débris*. Vegetation would soon spread over the newly-formed neck, but for a long time the

[1] This map will be given in the next part of this paper.

[2] *Eastern Archipelago*, p. 15.

surface would be formed mainly of loose coral fragments and sand, and, owing to the absence of the foundation of reef-conglomerate, a well sunk there would yield only brackish water.

The seaward or outer border of the northern part of this island is, for the most part, composed of large coral blocks heaped up usually 7 or 8 feet above high water, but attaining a height of 11 or 12 feet at the South-East Bend, which is the most exposed part of the whole coast. This angle of the atoll receives the first brunt of the Trade-swell, with only the reef-flat to lessen its fury. Here the conglomerate, forming the foundation of the island, has been extensively exposed, and worn back into faces 3 feet in height. Over all is a massive-looking slope of large blocks of coral, forming a kind of glacis, which has itself in places been worn back by the breakers. Stunted pandans, and similarly stunted bushes of *Scævola kœnigii* and *Tournefortia argentea* crown the summit of the slope, affording in their appearance mute testimony of the frequent violence of the Trade-blast. The outermost pandans, which bear the full force of the wind, are only 5 or 6 feet high, and have a very sorry appearance; but their protection enables the pandans immediately inside to grow a little higher, and these in their turn perform the same service for those still further in, until by this process of mutual protection the innermost pandans attain a fair height, and the gently rising plane of their summits offers but little resistance to the gales. I have sat for an hour on this South-East Bend, admiring the manner in which this weathermost angle of the atoll braved the elements. Its natural glacis of loose coral blocks, and its crown of stunted pandans at once explained how the land was able to resist the fury of the breakers in the heaviest gales, and the manner in which the vegetation combined to face the storm. The remainder of the seaward margin of the island, to the southward and westward of the South-East Bend, is for the most part composed of blown sand, and rises usually from 12 to 15 feet, but in some places as high as 20 feet. The old trees of *Tournefortia argentea*, that border this part of the coast, are often partially buried in the sand, and some have been in this manner killed.

The inner or lagoon border of South Island may be described as consisting of a number of semi-circular bays, varying in width from 100 or 200 yards to half-a-mile or more, and surrounding bare white chalky mud-flats which are exposed at low tide. The smaller bays are converted into crescentic lagoonlets by long banks of sand that nearly cross their mouths; on these banks *Pemphis acidula* finds its home, and occasionally young coco-nut palms have been planted upon them by Mr. Ross. Similar banks, clad with the Pemphis bushes, tend often to close in the larger bays to a greater or less degree at low water; all along the lagoon margin of this large island, we observe the broad expanses of chalky mud-flats, their glaring whiteness being partially relieved by the lines of Pemphis-covered banks that stretch across them. At high tide the lines of Pemphis bushes alone are seen, and then we perceive the extent and character of this reclaiming process which is in operation all around the lagoon shores of the atoll. The small and larger bays, or the lagoonlets, as they may be more aptly termed, are being gradually filled in by the

reclaiming influence of the bush-covered banks or bars that more or less cross their mouths; and here and there we can see how the bordering vegetation, led on by such plants as *Ipomœa pes capræ* and *Triumphetta procumbens*, is gradually invading the enclosed chalky flats, the surface of which, in not a few instances, may be already dotted with patches of the Pemphis bushes. Into the origin of these lagoonlets or semi-circular bays, and of their outlying sand-bars, I shall enter later on; it will be sufficient here to point out the manner in which this island, like all the other islands, is gaining on the lagoon, a circumstance which the proprietor sees with no displeasure, since Nature unassisted increases the number of his acres. Often, however, Mr. Ross hastens the process by planting on the newly gained land almost before the sea has finally relinquished its hold, and coco-nut palms now flourish in many places that were occupied by the waters of the lagoon in his youth.

I should add that the west end of this island is rapidly extending lagoonwards, thus exhibiting in a marked degree the peculiar incurving of the extremities of Direction Island, Gooseberry Island, and the smaller islands already described.

THE ISLETS OF THE SOUTH PASSAGE.—These four islets are founded on patches of reef-conglomerate which is composed mostly of small coral fragments and coarse sand, Burial Islet and East Cay lying on the same patch. East Cay has a crescentic form on its inner side, and was evidently at one time a more characteristic horse-shoe islet than it is at present, the original lagoonlet being nearly silted up, whilst vegetation has greatly encroached on its surface.

WEST ISLAND, or ROSS ISLAND, which is the most extensive island of the atoll, has a sweep of about 6 miles, and a width varying from 100 yards to rather over half-a-mile. Like South Island, it has had a compound origin, and the narrowest portions or necks often mark the situations of the ancient passages. As in the case of South Island also, there is evidence to show that the passages have not been recently closed. We find no indication of them in Fitzroy's plan of 1836, or in that of Van der Jagt made seven years before, and when we refer to the plan, published without any clue to its origin or date, in Van Keulen's Atlas of 1753, we perceive that West Island was one large island when that early plan was made.

The scene on the outer or seaward margin of this island is generally very different from that which one witnesses on the weather-beaten coasts of South Island. Being for the most part sheltered from the south-east Trade, the water on the reef-flat is less disturbed, and outside the reef the sea is comparatively quiet; but every quarter of an hour a succession of huge rollers from the SW. or SSW. roll quietly in and break on the edge of the reef. The sloping mass of large loose coral blocks, that the breakers have thrown up to protect the South-East Bend against their fury, is here replaced by a white sandy beach nearly free from coral boulders. The heat of the sun is more oppressive from the absence of the cool blast of the Trade; and the trees and shrubs

bordering the beach, chiefly *Scævola kœnigii* and *Tournefortia argentea*, grow under these more favourable conditions to a greater height, and make a greater display of flowers and foliage.

Coming to the more detailed description of this island, I will refer first to its incurving southern extremity, which illustrates in a remarkable manner the action of the currents through the passages in shaping and extending the two ends of an island by the distribution of the sand and reef *débris* transported by them into the lagoon. The southern end of West Island has been curved lagoonwards, and has attained considerable breadth through the formation of a series of parallel incurving banks of sand, five or six in number, each of which marks a stage in the inward growth of this extremity of the island. The present Turtle Islet[1] has been formed on the principal of these banks; and in the early days of the occupation of the island, some sixty years ago, it formed the prolongation of this end of the island. But in more recent times two similar, though smaller, parallel banks have been thrown up outside it. The space reclaimed by them, which has been planted with coco-nut palms, represents an encroachment on the lagoon to the extent of about 200 yards. Even within the last few years, two other banks have been formed outside these banks. They are about 20 paces apart, and bear each of them a scanty line of bushes and young trees of *Scævola kœnigii* and *Tournefortia argentea*, the highest in September 1888 being about 8 feet. In a short time, as in the former case, Mr. Ross will plant coco-nuts on the ground they have regained. It is from the sand and reef *débris* brought into the lagoon by the rapid current through West Cay Passage, especially during gales, that all these banks have been mainly formed. Each bank is marked by a point, and thus the inner border of this end of the island has the appearance of a saw.

By the successive formation of these parallel incurving sand-banks, of which Turtle Islet marks by far the largest, the great southern lagoonlet of West Island has been formed. This lagoonlet presents at low tide a large bare expanse of chalky mud. Within the memory of those living on the atoll, it has shoaled to such an extent that large boats formerly accustomed to enter it cannot enter now. Here the process of reclaiming is in operation on a large scale; and, in truth, Turtle Islet is extending itself at its west end in such a manner, that it will in the course of time close the entrance to this large lagoonlet.

Near the middle of the inner margin of West Island there is the entrance to another large lagoonlet, the surface of which is formed like the other of chalky mud, which is partly covered at high water, but is completely dry at low tide. We learn from Van der Jagt's map that in 1829 this lagoonlet was dry at low tide, but covered by 4 feet at high water. It has evidently been gradually silting up, and its extent, as I learn from Mr. Ross, has undergone considerable diminution by the advance of the marginal vegetation on the chalky mud-flats. In one place an acre or more was permanently reclaimed by the obliteration of an inlet through the collection of Krakatoa pumice.

[1] This islet is at present separated at low water from the adjacent point by a narrow passage nearly dry, except in its centre, where there is a depth of 1½ feet.

At the head of this northern lagoonlet there was originally a passage cutting through West Island; and I am inclined to think that the long arm mainly shutting in this lagoonlet commenced its existence as a sand-bank before this ancient passage was closed, just as similar banks have been formed, as already described, at the inner ends of the present passages between the Ampang Islands. The situation of this ancient passage is here indicated by the narrow width of the island (90 or 100 yards); by the loose coral blocks, with but scanty soil, on the surface; by the scattered arrangement of the trees growing there; and by the sudden contraction of the width of the reef on the seaward side of the island, where the conglomerate foundation of the island is exposed on the beach. It would in truth appear that in the early history of the island there was not only a wide passage here, but a deep channel caused by a gap in the reef mass. Other passages, in more modern times probably, also cut through the island; but none of them have been shown in any of the early plans of this atoll. One, as indicated by a double line in the map attached, cut off the south extremity of the island, and, probably before its closure, the bank on which Turtle Island is placed had already begun to form. Here the belt of land is only 60 yards across, and the outer entrance of the old passage is marked on the beach by the extensive exposure of the foundation conglomerate which was then worn back by the waves into low water-worn faces that still remain.

The northern portion of West Island has within the memory of the residents been increasing in two ways. Banks of mud and sand, derived from materials brought in through the adjacent passage, and washed off the neighbouring point, have been formed along its inner margin, enclosing lagoonlets that are now filled up. In this manner, as Mr. Ross informs me, some 300 or 400 yards have been added in recent times to the width of the island. In places where there were shallow lagoonlets half-a-century ago, we now find tracts, somewhat marshy from the collection of rain-water, on which coco-nut palms have been established. Then again it is evident that, although the northern point of this island has suffered some loss in times past, it is now working northward and lagoonward again, as indicated by the shoal that prolongs it, and by the young plants, only 1 to 2 feet high, of *Scævola kœnigii* and *Tournefortia argentea*, that occupy this extremity of the island.

HORSBURGH ISLAND.—This island is nearly a mile in length, and about 800 or 850 yards in width. It was originally an atollon, or secondary atoll, open to the north. At present, however, the lagoonlet is nearly filled up, and is represented by a salt-water lakelet about 200 yards in length, and 2 or 3 feet deep at low tide. Though now separated from the north coast by a narrow barrier formed of loose blocks of coral, it has an indirect communication with the sea by percolation. On this intervening barrier are still standing, in good preservation, the stumps of huge ironwood trees (*Cordia subcordata*), that were burnt half-a-century ago. As already remarked, these trees grow very slowly, and, judging from the rate of growth observed by the residents, the trees originally

growing on this barrier must have taken centuries to attain their great size, a circumstance which goes to show that this salt-water lakelet has long been cut off from direct communication with the sea, though sufficient time has not since elapsed for the growth of a protecting reef-flat on the north side of the island. Horsburgh Island, in fact, represents the last condition of an atollon, the earlier stages being illustrated by Pandan Island and Pulu Ampang Major. In recent years the principal changes in this island have occurred at its inner or southern margin, which has grown lagoonward. About fifteen years ago, Mr. Ross made a small boat-harbour of large coral blocks on this shore; but it has become silted up with sand and is now useless, whilst the adjacent beach and vegetated surface has advanced twenty paces or more on the lagoon.

THE AGENCIES AT PRESENT SHAPING AND EXTENDING THE ISLANDS AND ISLETS.—When in the Solomon Islands I formed the opinion that small atolls and horse-shoe islands, such as are often situated, as in the case of Keeling atoll, on the borders of large atolls, owed their characteristic shape to the guiding influence of the prevailing surface-current (*Proc. Roy. Soc. Edin.* 1885-86, p. 900); but I had no clear conception of their mode of development, and it was not until I visited Keeling atoll and there saw the process in actual operation that I was enabled to perceive how these secondary atolls are really formed. Strangely enough I found that Mr. Ross, as the result of his life-long observations of the changes in the atoll, had arrived at a similar explanation, and it has very lately come to my notice that Dr. Bassett-Smith of H.M.S. *Rambler*, after his recent examination of the islands and islets of the Tizard Reef, formed a similar opinion of the origin of the horse-shoe islands and atollons that are sometimes situated on the circumference of large atolls.[1]

In my description of the several islands and islets, I have frequently referred to the circumstance that their extremities, curving inward towards the lagoon, are merely banks of sand which have been formed from the materials brought in by the currents through the passages between the islands, and heaped up in such a manner as to prolong the extremities of each island lagoonward in the form of two horns. In the case of the larger islands, a crescentic form is thus developed, and in the case of the smaller islands a more perfect horse-shoe shape is attained; but it is only when the two horns of sand are vegetated that the island exhibits this characteristic outline. In several cases the vegetation has but just begun to occupy the banks, and there is then merely an island prolonged by two bare sand-banks into the lagoon. All the stages in truth are exhibited, from the islet recently thrown up on the reef to the perfect horse-shoe atollon.

Mr. Ross and I explained in the following manner the origin of the crescentic and horse-shoe shapes of the islands and islets on the margin of Keeling atoll. We both likened the process to the formation of a V-shaped ridge of sand when a stake or some other obstacle, such as a stone, has been placed in a river-bed. Whilst the stone represented the

[1] *Report of an Examination of the Tizard and Macclesfield Banks* (Hydrographic Department, 1888).

original small island thrown up on the reef by the breakers, the V-shaped ridge of sand represented the arms of the horse-shoe island, which are similarly formed of sand; and just as the extremities of the V would in the course of time converge behind the obstacle, so in the case of a horse-shoe island the horns would tend to approach each other. It would thus appear that three conditions are necessary, the obstacle, the constant current, and the supply of sand.

In order, however, to satisfy myself that this view was correct, I had to ascertain the reality of the three conditions in Keeling atoll. It was essential to learn how and to what extent the surface-currents acted, and to discover the source of the sand. The Westerly Drift, or, in other words, the surface-current produced by the Trade, which blows usually from ESE. or SE. during the greater part of the year, strikes the south-eastern shores of the atoll. Being there divided, it sweeps around the coasts, the two branches meeting and forming an eddy off the north-west angle of the atoll opposite Horsburgh Island, where driftwood and wreckage usually collect. Mr. Ross takes advantage of this current in transporting any valuable timber that has been thrown up on the weather coasts. In the course of time, he tells me, these timbers, if launched again beyond the breakers, are invariably to be found off Horsburgh Island, or stranded on its shores. This current finds its way over the reef into the lagoon through the several passages between the islands, its rate varying usually from half a knot to two knots, according to the state of the tide, the size of the breakers, and other conditions. Only rarely is there any check to the inflow of water, as, for instance, during north-west gales.

It was the accidental circumstance of finding a quantity of fine calcareous sand in my tow-net whilst using it in one of the passages for collecting minute surface animals that first directed my attention to the transportal of sand into the lagoon. By carrying a line across one of the narrower passages, to the middle of which I fastened the net so as to keep it a foot above the bottom, I soon satisfied myself that a large amount of fine sand was brought in through the passages. No other precautions were necessary except careful watching, as the constant set of the current kept the net in position. Subsequently I made a considerable number of observations in different passages at various states of the tide, at different depths, and during the varying conditions of the breakers, arriving at last at the conclusion that the minimum amount of sand daily carried into the lagoon was about ten tons.[1] My method of estimation consisted in estimating the average sectional areas of all the passages and the receiving area of the net. The net was usually kept in position for an hour at a time, when the sand thus collected was carefully incinerated and weighed.

The water always seemed perfectly clear, even when there was most sand. The quantity of sand increased with the depth, being greatest at

[1] I assumed the average depth of the passages to be two feet at all states of the tides. The passages must not be confused with the deep and wide openings or gaps in the reef on the north side of the atoll.

the bottom, and of course increased with the force of the current. The size of the particles also varied with the depth of water and with the force of the current. Usually the average size of the larger calcareous particles, when the net was kept a foot off the bottom, was from $\frac{1}{70}$ to $\frac{1}{100}$ of an inch; but along the bottom and a foot above it, especially when the current was rapid, much larger particles were carried in, and I sometimes observed in my net calcareous joints of *Halimeda opuntia*, $\frac{1}{5}$ of an inch across, together with large tests of macroscopic foraminifera and large Alcyonarian spicules. When the sand thus collected in a tow-net is allowed to settle in a glass of water it gets a slight fluffy covering composed of soft-tissued minute surface animals, crustaceans, confervæ, and marine vegetable matter. On removing these materials by gentle incineration, the sand will be found to be in the main made up of amorphous calcareous grains with a small proportion of other matter consisting of Alcyonarian and sponge spicules, and of the tests of foraminifera and diatoms.

I have taken the minimum daily amount of sand transported into the lagoon at ten tons. However, Mr. Ross, who followed my experiments with interest, tells me that this can only apply to ordinary weather, and that during and just after heavy gales the passages are swept clean by bore-like rollers that rush in through them every quarter of an hour or so. On one occasion two children were in this manner carried off their feet and drowned. Probably, therefore, I should not be far wrong in placing the annual amount at 5000 tons. The source of this sand is to be found mostly in the unceasing action of the breakers on the weather-edge of the reef. Nearly all of it is deposited at and near the margin of the lagoon. The current through the passage becomes checked and often imperceptible as it enters the deeper water of the lagoon, but the passage itself is usually kept patent, and the sand is heaped up on either side of the inner end of the passage in the form of two sand-banks stretching away into the lagoon. Or, to state the matter in other words, the current over the reef, on striking the island, is divided, and, passing into the lagoon on either side, deposits its sand on getting into the deeper water in the form of two sand-banks prolonging the extremities of the island lagoonward. Thus arises the horse-shoe or crescentic form of the island. During a limited portion of the year a westerly swell sets across the lagoon from the exposed north-west opening of the atoll, and then there is a tendency to the formation of a bank or bar of sand across the mouth of the horse-shoe or the crescent. Thus we explain the origin of the bars that have been thrown across the mouths of the numerous lagoonlets, which I have already described. I have before referred to the exceptional instances when owing to the same westerly swell a bar of sand has been thrown across the inner mouths of the passages between the Ampang Islands, giving the appearance, as in the case of North Keeling Island, of a lagoonlet, open on the weather side instead of on its lee side.

(*To be continued.*)