35. NOTES on the GEOLOGY of the TONGA ISLANDS. By J. J. LISTER,
Esq., M.A. (Read June 24, 1891.)

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[PLATE XXIII.]

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I. INTRODUCTION.

VERY little of a detailed character has, so far as I am aware, been published on the geology of the Tonga Islands.

Prof. Dana makes a brief mention of some of the islands in 'Coral and Coral Islands'*; and in the edition of 'Coral Reefs' published in 1874 Darwin gave a summary of what was known of the group†.

I spent several months in Tonga in 1889 and 1890, and had opportunities of visiting some of the islands in H.M.S. 'Egeria,' which was engaged, for part of the time, in making a survey. Such observations as I made on the geology of the group are embodied in the following notes.

I am indebted to Mr. Alfred Harker, M.A., F.G.S., who has examined the volcanic rocks which I obtained‡, and also to Dr. John Murray, who has looked over sections of the calcareous rocks of Eua.

II. TOPOGRAPHY OF THE GROUP.

The Tonga or Friendly Islands are situated in the Pacific Ocean between 18° and 22° 30' lat. S., and on either side of the 175th degree long. W. Tongatabu lies a little over 1000 miles to the N.N.E. of Auckland in New Zealand. The large islands of Fiji are about 400 miles to the W.N.W., and those of Samoa about 300 miles to the N.N.E.

The greater number of islands fall into three main groups. The northernmost is Vavau, which consists of one moderately large island (about 13 miles in its longest diameter), giving its name to

* 2nd ed., pp. 288 & 289.

† P. 212 and elsewhere, 3rd ed. (1889).

‡ Mr. Harker has published notes on these specimens in the Geol. Mag. for June, 1891.

the group, and a number of islets lying to the south and south-west of it. Rather more than fifty miles to the south is the Hapai group, containing the high volcanic islands of Tofua and Kao on the west; on the east a chain of low, flat, coral islets; the Kotu group in the centre; and on the south a number of isolated islands, the largest of which is Nomuka. Some fifty miles to the south and somewhat to the west of Nomuka lies Tongatabu, the largest island of the group, measuring over twenty miles in its longest diameter. A channel about ten miles broad separates Tongatabu from the small and high island of Eua to the south-east, while eighty-five miles to the south-west lies the little island called Ata by the natives, the Pylstaart of the charts, the most southerly outlier of the Tonga Islands. (See Map on p. 594 and Pl. XXIII.)

Lying far to the north of the islands mentioned are Niuafoou (= Good Hope, or Proby Island), Keppel, and Boscawen Islands, which, though politically belonging to Tonga, occupy an intermediate position between this group, Fiji, and Samoa.

III. GEOLOGICAL CHARACTERS OF THE GROUP.

According to the characters which they present, the Tonga Islands may be arranged in three divisions, viz.:—(a) purely volcanic islands; (b) islands formed of volcanic materials laid out beneath the sea, and since elevated, with or without a covering of reef-limestones; and (c) islands formed entirely of reef-limestones.

(a) *The Volcanic Islands.*

The purely volcanic islands form a line running parallel to the long axis of the group, but a little to the west of it. The direction of this line is approximately N.N.E. and S.S.W.

At the southern end is the little island of Ata or Pylstaart, which, judging from the extremely steep and rugged outline that it presents, may possibly be a member of this series. I have, however, merely seen a photograph of the island, and it can therefore only provisionally be reckoned a member of the volcanic series.

The islands of Honga-tonga and Honga-hapai, lying north of the west end of Tongatabu, are I believe the fragments of an old crater. They stand out of the sea about a mile and a half apart, and reach a height of some 300 and 200 feet respectively. Each island has a high vertical face on the side turned towards the other, and on all sides hard black layers of rock are seen alternating with softer ones, and slope away from a point situated between the two islands.

Fifteen miles to the north of these islands is the recently-formed volcanic mound named Falcon Island.

In the year 1867, H.M.S. 'Falcon' reported a shoal in the position of the present island, and ten years later smoke was seen issuing from the sea at this spot by H.M.S. 'Sappho.' In October 1885, a submarine volcano suddenly burst into activity, and built up a

mound. The volcano was still in eruption the following year. In 1887 the height was estimated as 290 feet by a French man-of-war; and from a sketch taken in that year, it appears that the summit of the island presented a rugged, uneven outline*.

The 'Egeria' visited the island in Oct. 1889. In the four years that had elapsed since its formation, a large portion had been removed by the action of the sea. Only a part (perhaps one third) of the original wide-based mound remained. This was limited for half its circumference by a cliff which was highest in the middle (153 feet), where it faced south, and subsided gradually at either end. From the summit of the cliff the surface of the mound sloped evenly downwards until it reached the level of a wide flat marked by tidal ridges, which extended round that part of the circumference of the mound not limited by the cliff. Landslips from the cliff were of frequent occurrence at high water; as many as twelve were seen in one afternoon, and the ground round the edge of the cliff was traversed by concentric cracks, showing where slices had already become loosened preparatory to their descent. Capt. Oldham erected a line of cairns at equal distances, extending from the edge of the cliff—down the slope of the mound and over the flat—as a means of measuring the rate at which the island is reduced.

The mound consisted of layers of finely-divided volcanic ash. On the face of the cliff the layers were marked by the salts which had crystallized at the surface more abundantly in some than in others, and it might be seen that each layer was thickest at the highest part of the mound, and gradually thinned out towards the periphery.

Numbers of volcanic bombs were scattered over the slope of the mound, being largest and most numerous at the highest part. These appear to have been ejected at the close of the eruption, as none appeared in the cliff-section; and the even, unscored outline of the slope negatived the idea that they had accumulated at the surface by the removal of any considerable quantities of finer materials.

The lavas presented all stages of vesicular structure, and some of the bombs displayed a distinct spiral twist in the surface ridges.

Mr. Harker† has examined the lavas and finds that they are basic augite-andesites of specific gravity 2·708.

The temperature of the interior of the mound was still high at the time of our visit. In a hole 7 feet deep a thermometer rose to 100° Fahr., while it registered 77°·5 at the surface.

To the south of the island there was an extensive shallow area with 3 fathoms of water over it. It appears that this was, in part at least, occupied by that portion of the original mound which has

* The above details are taken from an account of the island by Capt. Wharton, R.N., F.R.S., published in 'Nature' for Jan. 23, 1890 (pp. 276-278). This account is accompanied by figures and a map.

† Geol. Mag. for June, 1891, p. 250.

been removed by the action of the waves. Much of the material so removed has been thrown up on the north side of the island, forming the flat above mentioned, and an extensive shallow area beyond it.

It seems clear that unless another eruption occurs the island will in a short time be reduced again to the condition of a submarine bank formed of volcanic ashes rearranged by the action of the waves*.

It is remarkable that the depth of 1021 fathoms has been found between Falcon Island and Nomuka, the nearest of the Hapai Islands.

Next in the series come the high volcanic islands of Tofua and Kao. Tofua is a volcano in a state of intermittent activity. It is marked in the Admiralty chart as attaining a height of 1890 feet above the sea. The summit presents a fairly even outline when seen from a distance, and the sides slope steeply in all directions. The crater is situated on the northern side.

Kao is said to attain a height of over 3000 feet. It presents a singularly-perfect conical outline, from all points of view. It has not been in activity within the period of native tradition.

Continuing the line are Metis Island, which appeared a few years before Falcon Island, and is stated in the Admiralty chart to have been still in activity in 1886; and the volcano Lette, which is figured in the chart of the group (No. 2421). In 1866, when this island was visited by Lieut. Creak, R.N., in H.M.S. 'Esk,' vapour was seen issuing from the crater†.

To the north of Vavau is the volcano of Amargura. An explosion occurred in 1847, when the island was in part "destroyed by the eruption of its crater" and "ashes were thrown in large quantities on passing ships 500-600 miles to the N.E."‡.

Northwards the line passes through Boscawen and Keppel Islands, which lie close together, halfway between Amargura and Samoa.

Boscawen Island (= Niua-tabu-tabu) is described in Findlay's Directory as one entire mountain about 2000 feet in height "resembling the Moluccas;" it is therefore probably a volcanic island.

Niua-fou (or Good Hope Island), lying considerably to the westward of these islands, is probably a member of the same series. It is described as a volcanic island with black lava rocks all round the shores, and with a crater in the middle containing a brackish-water lake. An eruption occurred in 1853, when a village was destroyed and many lives were lost. Another eruption occurred in 1867§.

In the continuation of the direct line northward is the large volcanic island of Savaii, the most westerly of the Samoan islands. The Samoan volcanoes, however, form a series having a direction approximately W.N.W. and E.S.E., which crosses that of which the

* For a fuller account (with figs.) of the present condition of the island, see a paper by the present writer in Proc. Roy. Geograph. Soc. vol. xii. (1890) p. 157.

† Findlay, 'South Pacific Directory,' 3rd ed. p. 456.

‡ Findlay, *op. cit.* p. 456.

§ Findlay, *op. cit.* p. 558.

Tongan volcanoes are members at right angles. It is significant that Savaii is the largest of either series, and is situated at the point where they intersect. Savaii ends the series in a northerly direction.

The soundings which have been taken in this part of the Pacific show that the Tonga Islands are situated on a ridge, which rises to within 1000 fathoms of the surface and is prolonged in a south-westerly direction for half the distance between this group and New Zealand. To the south of the Tonga Islands the top of the ridge reaches the surface of the sea, or comes close to it, at the Minerva Reef and three shoal patches indicated in the chart.

On the eastern side, where soundings have been taken, the slope descends to depths of over 2000 fathoms, and at two points, one to the north-east of Vavau, the other to the east of the southern extension of the ridge, the very great depths of 4530 and 4428 fathoms have been sounded.

On the west the slope appears to be less steep, but a depression (with a depth where it has been measured of over 1500 fathoms) lies between this ridge and the Fiji group.

The Kermadec Islands, lying between the southern part of the ridge and New Zealand, are the highest points of a large area which is also within the 1000-fathom line. It is, however, separated from the Tonga ridge to the north and New Zealand to the south by depths of over 1500 fathoms.

Both elevations are traversed by a line of volcanoes, which, as Mr. S. Percy Smith * has pointed out, continues the direction of that of the Taupo Zone of New Zealand. Mr. Smith suggests that the volcanoes are situated in the course of a great fissure which extends from Ruapehu, at the southern end of the Taupo Zone, through the Kermadec and Tonga groups to Samoa. This view receives some support from the fact that the eruption of Falcon Island, beginning in Oct. 1885, was contemporaneous with the increased activity (in November) of the geyser of the white terrace of Lake Rotomahana, which preceded the great explosion of Tarawera in June of the following year.

[In the map facing this page the dotted areas between New Zealand and the Tonga Islands indicate depths of less than 1000 fathoms. (The eastern limit of the Kermadec area is undetermined.)

The thick circles indicate active or extinct volcanoes, the broken circles islands whose volcanic nature is doubtful.]

(b) *Islands formed of Sedimentary Volcanic Material.*

Belonging to this division are several islands in the Hapai Group, and the island of Eua.

The Nomuka Group, which forms the southern division of the Hapai Islands, consists of a number of small islands which are the highest points of an extensive plateau. Over a large area the top of this plateau is within 50 fathoms of the surface of the sea.

* 'Geological Notes on the Kermadec Group,' Trans. N. Z. Inst. vol. xx. p. 333.

Nomuka itself is a limestone island, and will be described later; but Mango, Tonua, Nomuka-iki, Tonumeia, and probably Kelefasia are formed of volcanic tuffs.

The island of Mango lies about six miles E.S.E. of Nomuka. The main part of the island is some two miles in length, and of an oval shape, with the long axis running east and west. Projecting to the south of the west end of the island there is a small peninsula connected with the main mass by a narrow neck. At the eastern and western ends of the island there are rounded hills attaining a height of about 150 feet above sea-level.

This island is composed for the most part of layers of volcanic tuffs which vary widely in character. The summit of the eastern hill is formed of thick and approximately horizontal layers of fine white material which is largely calcareous, but contains a fine scoriaceous residue. The western hill is composed of layers of a coarse sandstone dipping at an angle of about 2° or 3° towards the W.S.W., and consisting of rounded fragments of lava embedded in a calcareous matrix. Fragments of coral, some of them 6 inches in diameter, are mixed with the volcanic fragments. Between the two hills layers of the two kinds of rock alternate with one another.

The southern peninsula is formed of a mass of breccia traversed in various directions by cracks, but presenting no regular stratification. The fragments are embedded in a calcareous matrix and vary greatly in size. Lying on the surface are some large boulders, some of coral, some of volcanic rock, which appear to have been isolated by the gradual removal of the finer material in which they were embedded. The largest of these was a rounded mass of coral which measured 10 feet in length, 7 feet in breadth, and $3\frac{1}{2}$ feet in height. In the cliff which surrounds this part of the island, fragments of coral were thickly scattered among the volcanic constituents. I counted 43 pieces exposed in one square yard. Though Mango is surrounded by a broad fringing reef, I failed to find any raised coral-rock upon it.

The island appears to have been originally formed as a submarine bank, probably of volcanic origin, on which corals grew. On a return of volcanic activity the coral-reef was broken up, and the fragments of it mixed with the volcanic materials have formed the breccias of which the island is composed.

It appears that the southern promontory was the nearest point of the present island to the centre of the eruption, for there the constituents of the breccia are largest and mixed indiscriminately without stratification. The nearly horizontally stratified rocks on the eastern and western hills were laid out now in finer, now in coarser layers by the action of the water. The island has subsequently been elevated to its present height, the rounded outline of the hills being due to subaerial denudation.

It is remarkable that while the island is now surrounded by flourishing coral-reefs, there should be no old raised reef upon it. The most probable explanation appears to be that elevation took place too rapidly to allow of the growth of reefs of any considerable extent.

Some miles to the westward of Mango is the small island of Nomuka-iki (=little Nomuka), to the south of Nomuka, and separated from it by a narrow channel. This island is about 60 feet high, and one mile in its longest diameter; it also is formed in part of a hill of volcanic tuff, the remainder consisting of a flat of calcareous sand. The layers are horizontal and are made up of finer and coarser beds of brown and grey ashes alternating with one another. Here there are no fragments of coral mixed with the ashes. A fossil univalve of the genus *Pyrula* occurred in these beds, and some of the finer ones contained vertical burrows (of an annelid?) which were filled in with the coarser material of the overlying layer.

As at Mango, there are no raised coral-rocks overlying the volcanic beds, although broad fringing reefs surround the shores.

The beds have evidently been laid out by water, but under quieter conditions than those of the neighbouring island, and the mound has since been elevated to its present height.

A little to the south of Mango are the two islands Tonumeia and Kelefasia. Capt. Oldham visited Tonumeia when engaged in the survey of the group in 1890. He found it to consist of volcanic tuffs forming a cliff 80 feet high, and dipping at an angle of 3° to the south*. Mr. Harker finds that a specimen of these beds consists of "fine volcanic ash compacted by a calcareous and ferruginous cement into a yellow-brown rock."

Capt. Oldham also obtained some black nodules two inches in diameter, with portions of a calcareous matrix still adherent, and which had presumably weathered out of the layers of tuff. Mr. Harker describes these as consisting of oxide of manganese having "the general characters of psilomelane, but soft and of a low specific gravity, and therefore perhaps altered."

The presence of these nodules, supposing them to have occurred naturally in the beds of which Tonumeia is composed, is very remarkable. They are generally supposed to be formed only in deep water; but the situation of the island on the same shallow plateau as Mango and Nomuka-iki, and the general correspondence of its formation with theirs, point strongly to the conclusion that these islands were all formed under similar conditions. The presence of coral and other organic remains amongst the volcanic constituents of these islands shows that they were formed in shallow water.

Judging by its appearance as seen from the sea, I have little doubt that Kelefasia belongs to the same class of islands.

The island Tonua, to the north-east of Mango, was also examined by Capt. Oldham. It is composed of yellowish-white rocks which form a cliff twenty feet high, and consist of volcanic ashes with little calcareous matrix, though shells of pteropods and the cast of a gasteropod (*Murex*?) were found among the volcanic fragments†.

In the central part of the Hapai group there are two islands,

* The substance of Capt. Oldham's report on this island and Tonua is given in Mr. Harker's paper in the *Geol. Mag.* for June, 1891.

† Harker, *op. cit.*

Kotu and Matuku, which, as seen from the sea, appeared to me to be of the same nature as those above described in the Nomuka group. The only confirmatory evidence that I can offer is a remark on the island of "Kotoo" in the narrative of Capt. Cook's Voyage to the Northern Hemisphere (vol. i. p. 271), where it is stated that this island "terminates in reddish clayey cliffs."

Leaving the Hapai Group, I will now attempt to describe the island of Eua, lying to the south-east of Tongatabu. (For the map of this island, see Pl. XXIII.) Eua is somewhat oval in shape, but pointed at the two ends; the long axis is directed almost exactly north and south. It is about $12\frac{1}{4}$ miles long, rather more than 4 miles broad, and attains a height of 1078 feet. The island is formed of a basis of volcanic rock, in great part covered by limestone. A ridge of high ground traverses the island from north to south, attaining a height of over 1000 feet at two points, one near the middle of the ridge, the other about four miles to the south. Between these two points the general level of the ridge is from 800 to 1000 feet. The volcanic formation comes to the surface over a great part of this high ground, and where it is bare of vegetation is readily recognized by its bright red colour; but patches of limestone occur in many places, sometimes in large projecting masses, like that which forms the south summit, sometimes weathered down into groups of isolated pinnacles standing on the volcanic basis.

Northward the ridge descends gradually to an elevation of about 500 feet and extends at this level, as a long flat-topped plateau or terrace, to the north end of the island. This will be referred to as terrace *b*. The volcanic basis appears in irregular patches along the centre, but its eastern and western sides are bordered by cliffs of limestone, some 200 feet in height, whose base evidently marks an old shore-line at a previous stage of elevation of the island.

The whole eastern side, presented to the trade wind, is very abrupt, and rises in range above range of limestone-cliffs, the steep slopes between them being covered with dense wind-swept forest. The descent is interrupted along the greater part of this aspect by a narrow terrace, from which on the one hand perpendicular cliffs descend to the sea, and on the other a slope of debris leads to the foot of the range of cliffs which limit the central ridge along its whole length. This terrace is, however, absent opposite the middle of the eastern aspect, and here a steep slope extends directly from the foot of the higher range of cliffs to the sea. The volcanic basis is exposed on this slope, and at the shore are projecting dykes of intrusive rock. Farther to the south the terrace is again interrupted by a break occupied by a small terrace at a lower level. At this point also a dyke appears on the shore at the foot of the cliffs.

Along its western aspect the central ridge is well-defined at the northern and southern ends, being bordered by limestone cliffs. The middle part of this aspect is broken up by small valleys which

take their origin in the highest part of the island, and here the volcanic basis is largely exposed. A wide terrace of limestone standing at a level of 250 to 350 feet extends along the whole of the western side of the island, spreading out from the lower slopes of the central ridge. This will be referred to as terrace *a*. It is widest opposite the middle of the island, becoming narrower to north and south, and forms nearly half the total area of Eua. From its western border the land slopes more or less steeply to the sea.

The western aspect of the island offers a marked contrast to the eastern. Instead of the dense wind-swept forest, there are wide open stretches of grass-covered country, intersected here and there with belts of luxuriant bush. The streams which have scored the western slopes of the central ridge dip underground on reaching the limestone terraces and pursue a subterranean course to the sea. There are, however, continuing some of the stream channels, deep gorges cut in the western terrace, whose sides descend abruptly from the general level; these are overflow channels, in which water runs only after heavy rains.

There is one stream, possibly there are others, in the higher part of the island, which pursues a different course. At an elevation of about 620 feet there is a funnel-shaped depression in the volcanic deposits; and at the bottom of this funnel a vertical shaft descends several hundred feet into the interior of the island. Its mouth measures about 100 feet in one diameter and 30 feet in the other. After flowing down the side of the depression the stream falls into the shaft, pouring over the layers of hardened tuff at one end of the long axis of the opening. The mouth of the shaft is surrounded by trees, festooned with creepers which hang down into it, and a mist rises, carried upwards by the return currents of air. The native name of the place is "Ana-ahu" (=Smoky hole). It would appear that a crack was formed during the upheaval of the island, which has been gradually enlarged at this spot by the action of the stream.

The volcanic basis of Eua appears to consist very largely of fragmentary accumulations arranged in strata. At the mouth of the "Ana-ahu" (about 620 feet above the sea) the layers are horizontal, and composed of moderately coarse fragments. Between layers of a purely volcanic nature there occur others which are hardened by a cement of calcite, in which, besides the volcanic fragments, foraminifera and other organic remains are embedded*.

Dr. John Murray finds among the organic remains "many pelagic foraminifera, and pelagic molluscs such as pteropoda and heteropoda; also a few ostracoda and fragments of bottom-living molluscs. Among the foraminifera *Globigerina rubra* and *bulloides* and other *Globigerinæ* are most abundant." Dr. Murray concludes that "these rocks were evidently laid down in deeper water" than the limestones investing the volcanic basis.

* Slide No. 1268 in the collection at the Woodwardian Museum, Cambridge.

Among the volcanic fragments Mr. Harker has detected red garnet and tourmaline, whose presence indicates the existence of metamorphic rocks somewhere in the vicinity.

A similar partly calcareous rock occurs at the northern end of terrace *b*, where the volcanic basis is exposed*.

The uppermost part of the volcanic formation consists of red, yellow, and brown beds of ashes, which are very much decomposed by weathering. Some are nearly horizontal, others a good deal contorted, but they are never, so far as I observed, regularly inclined at an angle, as though they had formed part of a volcanic cone.

As mentioned above, dykes of intrusive rock project on the eastern shore. They are composed of augite- and hypersthene-andesites. Large rounded boulders of this rock, mixed with boulders of coral, form the shore, and the natives obtain here the hard rounded stones which are used for pounding the root of the kava plant, in the preparation of the beverage of that name. The dykes penetrate the beds of tuff and form well-marked projections at the surface; they do not, however, penetrate the overlying limestone.

Besides the intrusive rocks there is a crystalline, plutonic rock in this part of the island, of which I obtained a specimen from a boulder on the shore. Mr. Harker describes it as "uralitized gabbro." Although I did not find this rock *in situ*, I have no doubt that it exists as a natural constituent of the island. It is highly improbable that a boulder should be brought here by artificial means, for there is no possible landing-place for vessels along the whole of this eastern coast, and the only access to it from the anchorage on the western side is by steep hill-paths. A reef about 100 yards wide stretches out from the shore, and on the edge of this reef a vessel would strike, supposing one to be wrecked. I think therefore it may be concluded that the rock occurs naturally on the island.

The volcanic basis of Eua appears to have been produced by an extensive submarine eruption which formed a mound of considerable extent, and into which lava was injected.

The eruption seems to have occurred at some depth, for the organisms found mingled with the volcanic materials are, according to Dr. Murray, pelagic and not shallow-water forms. Subsequent to its formation and the cessation of the volcanic forces, but prior to the deposition of the overlying limestones, the mound was elevated to at least its present height and considerably denuded. The evidence for this denudation is afforded by the elongated shape, and the steepness of the eastern slope of the volcanic basis which underlies the limestone; these imply the removal of a considerable part of the original mound, which is built up in the main of horizontal layers. After its denudation the island subsided again, before the deposition of the limestone formation.

The limestones invest nearly the whole of the lower part of Eua up to a level of about 500 feet, and above this level they occur, though less continuously, as high as the summit.

* Slide No. 1273.

Diagenetic Sections across Eua (Tonga Islands).

Fig. 1.

EXPLANATION.

Fig. 1. Section passing E. and W. through the summit. At the S.E. end the country lying to the N. of the section is indicated, to show the position of the Pinnacle from whose base specimens Nos. 1269 and 1270 were taken.

Fig. 2. Section E. and W. through the island, to the north of the summit. The position of terrace b, 'Grey Boulder Hill,' is shown.

Fig. 2.

The most striking feature of the formation is the existence of well marked terraces on the lower slopes.

The terrace α , as above stated, extends along the whole length of the western side of the island, at an elevation of about 250 to 365 feet above sea-level.

The outer, western border of the terrace is for a great part of its length higher than the interior. Beginning at the northern end, we find the terrace forming a narrow band, so narrow that it makes only a slight interruption in the sloping side of the island. To the south it gradually widens out, being at first level from side to side, but soon the interior becomes depressed below the margin. The depression is greatest at one-third of the length of the island from north to south. Here the margin is about 65 feet higher than the interior. As we advance southward the depression of the interior becomes less marked, until at the junction of the middle and southern thirds of the length of the island the terrace is again level, and remains so to the southern end. Passing across the terrace from east to west, in the region of the depression we descend a very gradual slope to near the outer border. From the lowest part the ground rises to the margin of the terrace, in most places by a gradual ascent, but at one point the rise is abrupt. Opposite the town of Ohunua there is a gap in the high margin, the bottom of which is at the same level as the depressed inner part of the terrace. Through the gap there runs a steep-sided ravine, cut in the limestone rock; it is formed by the junction of two of the overflow channels of the streams of the upper part of the island, and there is water in it only after heavy rains. Having passed the gap the ravine pursues a straight course down the sloping side of the island to the sea, and at its mouth there is a break in the reef and an anchorage for small vessels.

On the margin of the terrace to the south of the gap the limestone rock forms projecting masses, and in some of these definite *Astræa*-like coral structure is to be seen. Other specimens present a homogeneous structure to the naked eye. Dr. Murray has examined sections of these*, and finds that they are "chiefly made up of calcareous algæ, together with fragments of coral, molluscs, echinoderms, and foraminifera"†. He concludes from the character of the organisms that the deposit was "formed in quite shallow water."

With regard to the peculiar conformation of the terrace, it appears that the depression in the interior must either have existed at the time that the terrace was elevated above sea-level, or have been excavated since by the denuding action of rain or streams.

Slide No. 1271.

Among the foraminifera the following kinds were recognized:—

<i>Miliolina</i> , sp.	<i>Planorbulina larvata</i> (P. & J.).
<i>Orbitolites duplex</i> (?).	<i>Carpenteria monticularis</i> (Carter).
<i>Textularia trochus</i> (d'Orb.).	<i>Polytrema miniaceum</i> (Linn.).
<i>Globigerina bulloides</i> and <i>G. rubra</i> (?).	<i>Calcarina hispida</i> (Brady).

In ordinary weather the streams flow beneath the limestone rock, and it is only after heavy rains that running water is found in the ravines which traverse the terrace. Moreover, the sides of these slope abruptly down from the level of the terrace, and their course is for the most part quite independent of the direction of the depression. Finally, it may be asked, Why should the drainage from a flat area excavate the interior and leave the margin comparatively untouched along almost the entire length of the terrace? It appears, then, that the terrace had much the same general conformation which it now presents when it was upraised from the sea; in other words, that the elevated border constituted a small barrier-reef lying nearly a mile from the shore of the island as it then existed, with a break in it at one point, and enclosing a lagoon with a depth of 6 fathoms over a considerable area. At its northern and southern ends the reef joined the shore and became fringing. A similar relation of reef to shore occurs in the reefs now forming the harbour of Suva in Viti Levu, the capital of Fiji, where the barrier which protects the anchorage is continued into a fringing reef along the southern shore of the island.

As above described, there is a narrow limestone-terrace running along the eastern side of the island at about the same level as terrace *a* on the western, and interrupted in the middle by a deep gap, the head of which is formed by the cliffs of nearly the highest part of the island. On the north of the gap the terrace ends abruptly in a cliff, facing south, and standing out beyond the cliff is an isolated pinnacle of limestone rock, which I estimated as measuring about 300 feet from top to bottom. The rock of the base of the pinnacle presents to the naked eye a compact homogeneous structure, except that in one specimen there is a cavity which was occupied by a univalve of the genus *Cerithium*. Dr. Murray has examined sections of the rock * and finds that it is made up principally of calcareous algæ, together with fragments of echinoderms, molluscs, and a number of foraminifera †.

The limestones of terrace *b*, which stands at an elevation of about 500 feet, are also for the most part homogeneous compact rocks. A section from the edge of the terrace ‡ is found by Dr. Murray to be "chiefly made up of calcareous organisms. Fragments of molluscs, echinoderms, polyzoa, and calcareous algæ, together

* Slides 1269 and 1270.

† Viz. :—

Spiroloculina, sp.
Bulimina (cf. *compressa*).
Bolivina textilarionides (Reuss).
Textularia trochus (d'Orb.).
Cristellaria, sp.
Globigerina (*rubra*?).
Truncatulina, sp.
Planorbulina (cf. *larvata*).

Polytrema miniacum (Linn.).
Rotalia, sp.
Tinoporus bacculatus.
Cymbalopora Poeyi (d'Orb.).
Gypsina inhaerens (Schultze).
Cycloclipeus Carpenteri (Brady).
Heterostegina depressa (d'Orb.).
Nummulites Cumingii (Carpt.).

‡ Slide No. 1272.

with a large number of foraminifera"*. True coral does, however, exist on this terrace, as I found one large mass clearly exhibiting a structure like that of a *Porites*.

The limestones from the higher part of the island present for the most part a compact structure. Some of them are crowded with foraminifera, but large masses of coral appear to be absent.

With regard to the nature of the limestone formations as a whole, as indicated by the sections above described, Dr. Murray writes to me that they "may all have been formed in or about reefs, and true coral-reefs may have been living quite close to them when they were laid down;" but from the scarcity of examples of the larger corals he concludes that "it is more likely that they were laid down in depths of from 30 to 100 fathoms, and that they formed the base of true coral-reefs."

The conformation of the surface of terrace *a* points to its having formed a true reef, and having been elevated without much denudation; but in the case of terrace *b* and the higher limestone rocks, the extent to which they have evidently been denuded and their nearness to the volcanic basis bear out Dr. Murray's view, founded on the nature of the organisms they contain.

Some features of interest are presented by the shores of the island.

On its western side, in the neighbourhood of the village of Ohunua, the island is bordered by a narrow fringing reef some 50 to 100 yards in width. There are clear traces here of recent elevation. To the south of the village there is a low shore-cliff undermined by the action of the sea, but separated from the present shore by a strip of sand some 50 to 60 yards wide, covered with cocoanut palms and other trees.

From a little to the north of the village the island is bordered by a cliff some thirty feet high, which extends to the northern end. The foot of this cliff is washed at high tide by the sea, and is deeply undermined, the upper limit reached by the action of the sea being sharply defined. Above this present line of undermining, and separated from it by a projecting ledge of rock, there is another and older one, the upper limit of which is sharply defined and separated from that of the present line of wave-action by a distance of seven feet. When looking at the cliff from the sea, I thought I detected a third line of wave-action at a still higher level.

From the foot of the cliff the shore-platform extends some fifty to a hundred yards, and is bordered by growing coral. Over the greater part of its extent this platform is flat, and at high tide is

* *Miliolina*, sp.
Orbitolites complanata (?).
Textularia trochus (d'Orb.).
Polymorphina, sp.
Globigerina (bulloides?).
Truncatulina, sp.
Planorbulina larvata (P. & J.).
Carpenteria monticularis (Carter).

Polytrema miniatum (Linn.).
Gypsina inherens (Schultze).
Rotalia, sp.
Calcarina hispida (Brady).
Cycloclypeus Carpenteri (Brady).
Heterostegina depressa (d'Orb.).
Nummulites Cumingii (Carpt.).

covered by about two feet of water. In some places, however, there are the remains of the shore-platform which was formed when the island stood at a lower level, and corresponds with the higher line of undermining seen in the cliffs above. Its upper surface is above the level of high water, and is worn into irregular shapes. It is overgrown in some places by a small shrub (*Pemphis acidula*).

These features point clearly to recent elevation, and the distance between the two lines of undermining seen on the cliff shows that the extent of this was 7 feet. Further, it is clear that the elevation took place rapidly, at least as measured by the rate at which the sea is wearing back the cliffs, for if it had been accomplished slowly, in comparison with that measure, the rock which forms a projecting ledge between the two levels of excavation would have been worn back during the elevation.

It is interesting also to note that if the island were to remain at the level it occupies at present, all traces of the recent elevation would in time be obliterated, for as the cliff was worn back the rock bearing the impress of the action of the waves when the island was at the lower level would be removed, while the remnants of the older reef-platform would be worn away to the level of the present one.

It may further be observed that a reef-platform such as this consists of two distinct parts—an outer formed by the growth outwards of the existing reef, and an inner formed of the base of the older and elevated reefs, whose higher portions have been removed by the action of the sea.

At the south end of the island there is no reef; deep water extends to the foot of the cliffs.

A narrow fringing reef, some hundred yards wide, extends along the eastern side of Eua. Its upper surface is above the level of high water and partly worn away by the sea, offering evidence of the recent elevation of the island, corresponding to that found on the western shore. The margin of the reef is exposed to the full force of the rollers coming up before the trade wind, and presents a remarkable basin-like growth of corallines similar to that found on the southern side of Tongatabu, to be described later.

At the south end of the eastern shore of Eua there is a remarkable instance of the different manner in which the volcanic and limestone rocks are excavated by the action of the waves.

A narrow terrace, perhaps a quarter of a mile broad, runs round this end of the island, standing at a level of some 240 feet above the sea. It is bordered by cliffs which go sheer down into deep water. Limiting it on the land side there is a steep ascent to a higher terrace above.

The limestone rock here lies on the steeply sloping surface of the volcanic basis of the island. The outer or sea border of the terrace and nearly the whole face of the cliff are formed of limestone; but at the inner border of the terrace, and here and there in the lower part of the cliffs, the volcanic basis is exposed. At one point there is a large circular chasm excavated in the terrace which descends to sea-level and communicates with the sea by a

wide opening, overarched by a natural bridge of the limestone rock, the under surface of which is festooned with stalactites. The sea entering beneath the arch washes the bases of the nearly vertical sides of the chasm. The place is called by the natives *Matalanga Maui* (or the hole made by the implement for planting yams belonging to the god Maui). The manner in which the chasm has been excavated appears obvious. At the foot of the cliffs there are several caves in different stages of excavation, which are formed by the sea wearing back the volcanic rock where it is exposed beneath the limestone. The *Matalanga Maui* has been formed by the removal of the volcanic rock to such an extent that the cave has approached the surface of the terrace and the roof has fallen in.

I may here recapitulate the main features which seem to be indicated by the structure of Eua.

The presence of the plutonic rock points to the existence of an ancient and much denuded mass of such a character in the vicinity.

In the neighbourhood of this mass, and at a considerable depth below the surface of the sea, a volcanic eruption occurred, forming a mound, some of whose upper layers were mingled with pelagic organisms as they were laid out.

It appears that the mound was elevated above the surface, considerably denuded, and afterwards depressed to such a depth, at least, as to submerge its summit.

A covering of calcareous organisms was deposited on the volcanic basis while it was submerged; but so far as the evidence goes the formation is a shallow-water one. The island has since been again elevated by stages to the present height.

During periods when the elevatory forces were in abeyance, the sea wore back the already emerged limestone-deposits, forming terraces bounded by lines of cliff, but in one case at least (namely, the western terrace *a*) it appears that a true coral-reef was formed in the neighbourhood of the shore.

Dr. Murray finds that it is impossible to assign the organic deposits of the island to a definite geological epoch. Though he is of opinion that they are old, there is no satisfactory evidence to refer them to the Tertiary period.

(c) *Islands formed entirely of Limestone.*

The islands forming the remarkable group of Vavau differ widely in their shape and arrangement from coral islands in general.

Vavau consists of one large island which gives its name to the group, and of a number of smaller islets (see Pl. XXIII.). Vavau Island presents a high and fairly even coast-line to the north and north-east, bordered by limestone cliffs from 300 to 500 feet in height. On the south and south-west the general lie of the land is lower than that on the northern coast. Long promontories stretch out from the main mass of the island, separated by narrow and deep

arms of the sea. The islets are grouped about this coast, in some cases continuing the lines of the promontories. The beautiful and secluded harbour of Neiafu is bounded in part by two of these promontories, and protected from the sea by one of the larger islets situated between them. It forms a long basin more than 20 fathoms deep over the greater part, and almost entirely surrounded by land over 100 feet in height.

The surface rock all over the group consists, so far as I am aware, of limestone. I was unable to find the underlying basis at any point. Even at the foot of the high cliffs on the northern shore the rock, at the two points at which I saw it, was of this nature, and I found no fragments of volcanic or any other formation than limestone on the beaches. Although I saw no vertical cliff at this part of the island, extending from the top to the shore, the coast-line is in many places so steep that I have no doubt that the formation attains a thickness of at least 300 feet. It consisted for the most part of a hard homogeneous material, but at one point, in the lower part of the cliff, numbers of large bivalve shells were embedded.

The main mass of the island presents an undulating surface, gradually sloping from the high northern border towards the south. Though there are valley-like depressions in several places, I came upon none which contained streams or even ravines. Springs of fresh water issue from the rock at many points on the shore.

The outlying islands to the south of the group, as may be seen by the Admiralty chart (No. 2357), are surrounded by coral-reefs, which in many cases extend as broad expanses far from the island with which they are connected. As the inlets penetrate among the islands and promontories, and their shores are cut off from the open ocean, the reefs become narrower or disappear; though in some cases (as in the inlet to the north of the promontory in which Neiafu is situated) there are coral reefs of considerable extent growing far up in the sheltered channels.

There is one feature which at once strikes a visitor approaching the group by the usual steamboat course from the south-west and passing up to the harbour of Neiafu, namely, that the off-lying islands and projecting points of the main island, on either hand, are flat-topped when seen in profile, and that the majority of them stand approximately at one of three levels of elevation above the sea. Corresponding in level with the tops of the lower islands there are, moreover, terraces on the sides of the intermediate and highest ones; and in the same way there are, on the sides of the highest points of land, terraces whose level corresponds with the tops of the islands of an intermediate height.

The islands and promontories may thus be described as being one-, two-, or three-storied (see fig. 3).

On first entering the group, the flat one-storied islands Hunga and Nuipapa lie on either hand: their sides drop vertically into the sea and are deeply undermined below by the action of the waves. Right ahead stands up the mass of Mo'unga Lafa (= Flat Mountain), whose densely wooded sides present two well-marked terraces in

Fig. 3.—*View among the Islands to the South of Vavau.*

their descent to the sea. Opposite it, on the right of the passage is the island of Falevai (called "Kopa" in the Admiralty chart), which consists in part of a two-storied mass, in part of a one-storied tongue of land which extends out towards Mo'unga Lafa, while a terrace at the same level interrupts the slope on the side of the higher part of the island. Small islands are dotted over the sheltered expanse of water, two of which, A'a (called "Koto" in the chart) and Langito'o, present features of interest which will be alluded to below. As we advance, the hill Talau comes into view, exactly repeating the shape of Mo'unga Lafa, in the level outline of the summit and the two lines of terraces on its sides.

The rough aneroid measurements that I obtained give about 140 feet as the upper limit of the first "story," 260 to 350 feet as that of the second, and 420 and 520 for the summits of Talau and Mo'unga Lafa, the two highest points of land in this part of the group. Although these numbers show that the levels of the terraces at different points do not agree accurately, the conclusion was strongly impressed upon me on the spot, that the terraces and islands at each level do in fact correspond, that is, that at successive stages in the elevation of the group, the summit of each "story" has stood at sea-level. The differences in their level may be in part accounted for by the unequal action of the elevatory forces at different points of the area acted on. Thus, on the hills Talau and Mo'unga Lafa, which are between three and four miles apart, while the summit of the lowest story is at about the same level in each (140-150 feet), the two upper ones stand at about 270 and 420 feet in Talau as against 360 and 520 feet in Mo'unga Lafa. From this it appears that the second elevation was of greater extent in the neighbourhood of Mo'unga Lafa than to the eastward near Talau.

One remarkable feature in the contour of the land is the fact that in some cases the summits of the islands, though level in profile, are excavated by well-marked depressions.

The most perfect example of this structure is presented by the little island of A'a (the Koto of the chart) above mentioned. The island is of an oval shape, being about three quarters of a mile long and half a mile broad. It rises out of deep water, and is not surrounded by a reef. In the chart a sounding of over 40 fathoms is shown close to the southern shore, and except for a small shallow area at the eastern end the other soundings in the neighbourhood indicate nearly as great or greater depths.

The sides slope steeply up to a height of from 85 to 95 feet (an elevation considerably less than that of the top of the first "story" in the surrounding islands), but the interior of the island is depressed 50 or 60 feet below the level of the margin, being occupied by a flat which stands at a height of some 36 feet above the sea. The margin is of a nearly uniform height and forms a complete unbroken ring. On its summit rough masses of limestone rock stand up, but the flat interior is formed of brown earth. It seems clear that when the rock forming the edge of the island stood at sea-level a small lagoon some 10 fathoms deep occupied the centre.

I was led to visit A'a by seeing its depressed interior from the top of Mo'unga Lafa. From that position the neighbouring island Langito'o, to the west of A'a, which rises to about the same height, appeared to have a similar depression in it. Unfortunately I had no opportunity of visiting this island.

Fig. 4.—*Sketch of the contour of the island of A'a (Vavau Group).*

The numbers indicate heights, in feet, above the sea.

The summit of the three-storied hill Talau, near Neiafu, presents similar features. Here, too, a high margin surrounds a central depression, but the margin is complete for only three quarters of a ring. For the other quarter the level of the margin descends to that of the interior.

The accompanying rough map of the summit of the hill shows

Fig. 5.—*Sketch of the contour of the summit of Talau (Vavau Group), Tonga Islands.*

The numbers indicate heights, in feet, above the sea.

the contour. From this it is seen that the bottom of the depression lies some 40 to 50 feet below the higher part of the margin.

The summit of the other three-storied hill, Mo'unga Lafa, is, I believe, as the name implies, flat. The uniform covering of bush obstructs any general view of it; but in traversing it I was unable to find any depression corresponding to that in the summit of Talau.

In the short visits that I paid to the Vavau Group, I landed on a few only of the islands, and had not the means of making satisfactory observations of contour. I have drawn attention to the features above described, with the hope that when the survey of the Tonga Islands which was begun by H.M.S. 'Egeria' is continued, the heights and contours of the islands and terraces occurring at different levels in this remarkable group may receive special attention.

The peculiar shape of the group, penetrated by long, narrow, and deep inlets of the sea, may perhaps be accounted for by supposing a much-denuded basis, probably of volcanic nature, whose surface was deeply scored by valleys previous to its subsidence. While the island was submerged the deposits which formed the limestone rock were laid down, and the lower layers would have already begun to accumulate during the downward movement. But, though the base of the limestone deposit may very probably have been formed during subsidence, the upper part and the contour of the land must be chiefly referred to the succeeding period, which has, in the main at least, been one of elevation.

During intervals in the elevation, the terraces and plateaus which constitute so marked a feature have been formed, first on the highest and later on the lower peaks and ridges, while the intervening valleys still penetrate far among the islands and promontories.

It is interesting that, both at Vavau and at Eua, the reefs which have been formed during intervals in the elevation of the islands have in some cases acquired atoll- or barrier-like contours.

The larger islands of the Hapai Group lie in a line extending from Haano in the north to Uiha and Alefa in the south. They are indeed the elevated parts of a long reef, which, after extending in a south-westerly direction for some 30 geographical miles, sweeps round in an even curve to the west and north-west, and is finally lost among the reefs and islands of the Kotu Group. At two points in the northern part of the reef, gaps are indicated in the chart. The northern of these is bordered by reefs which are continued for a considerable distance in a westerly direction. To the south of the southern part of this reef there is an outer and more interrupted line of reef concentric with it. On the convex or weather side the margin of the reef is even, but on the opposite side the coral grows in irregular patches and the margin is ill-defined.

The island of Lefuka may be taken as a type of the islands situated on the reef. It is about three quarters of a mile in breadth, and some three or four miles in length. From the beach on the western side there is a very gradual slope towards the eastern side of the island, which is about 20 feet above high water. Near the

eastern side there is a rather rapid descent, terminating in a little cliff some 10 feet high, whose base is much excavated by the waves. The rock of which the cliff is made consists of masses of coral of various sizes, cemented together into a conglomerate. Its structure, in fact, resembles that of a shore-platform. Extending from the foot of the cliff some 300 yards to seaward is the present shore-platform, on which, at low tide, there is about a foot of water near the shore, while the outer part lies bare. The cliff of raised rock extends along the whole of the eastern shore of the island.

Some distance from the concave side of the long Hapai reef there are numerous shoals and small islands. The island of Fotuha, north of the Kotu Group, displays the abrupt undermined cliffs of a raised coral-island, and stands at an elevation of about 100 feet above the sea.

The few soundings that are given in the chart show depths of 10 to 24 fathoms along the greater part of the western boundary of the reef, though 30 fathoms is marked opposite the northern break in the reef above alluded to, and 56 fathoms within its northern border.

The Kotu Group consists of a number of small islands, from whose shores considerable tracts of reef extend at sea-level.

The only island of this group on which I landed was Hafeva. I found no raised coral-rock, but a loose sandy formation which attained a height of some 12 feet at the shore. The interior of the island is depressed and occupied by a marsh. There is a wide gap among the reefs on the western side, with a depth of some 8 fathoms, forming an anchorage which was at one time used by whalers. Of the other islands of the Kotu Group, three show the deeply undermined cliffs characteristic of raised coral-islands; but two of them, Kotu and Matuku, as already stated, recall, in their reddish-brown cliffs and peculiar outline, the tuff islands of Mango and Nomuka-iki of the southern part of the Hapai Group (see p. 598).

It seems clear that the long reef of the Hapai Group must be regarded as a barrier-reef or an imperfect atoll. The shoals and islands situated within the concavity of the reef, both the northern ones and those of the Kotu Group, probably either rest on or are parts of the mass on whose eastern and southern slopes the reef has grown, and the volcanic character which I thought I recognized in two of the latter offers some evidence as to the kind of formation of which the basis is composed.

The outer line of reefs, lying some four miles to the south of the main one, and concentric with it, is a very remarkable feature. Its relation to that reef seems to imply that it is of an older date, and accords very well with the view that the reefs are slowly growing outwards on the slopes of a submerged mound. It must be observed, however, that in the northern part of the great reef, in the neighbourhood of the larger islands, there appears no reason for supposing that the reef is moving away from the centre of the group, for it is bordered by flourishing coral-reefs on the western as well as on the eastern side.

The raised reef-platform of which the islands to the north are formed, as well as the raised coral-island Fotuha, and those of the Kotu Group, show that elevation has taken place, though only to a comparatively small extent, in the northern and western parts of the group. On the other hand, the absence of islands of any considerable size from the southern parts of the reefs appears to indicate that this region was not affected by the elevation.

The island of Nomuka in the southern part of the Hapai Group is triangular in shape, the sides, which are about equal, measuring some 2 miles in length. To the south lies the little island Nomuka-iki, separated by a channel a mile and a half wide, and 15 fathoms deep.

A large shallow lagoon occupies a great part of the larger island; it is less than a fathom deep, and its level does not rise and fall with the tide, while the water it contains is much denser than sea-water *. At the bottom of the lagoon there is a thick layer of black mud, which gives out a strong smell of decomposing matter when it is stirred. The land border is broad on the west and north-west of the lagoon, but narrow on the other sides. A ridge on the western side attains a height of over 160 feet at two points. On the east the land is much lower, varying from 15 to 96 feet above the sea, and on the south-west it is often hardly higher than the top of the beach. The formation consists of coral rock.

Nomuka and Nomuka-iki are surrounded by fringing reefs, which in the case of the latter stretch out a considerable distance (in one part over a mile) from the shore. The twenty-fathom line encloses both islands; on the eastern and north-western sides of Nomuka it is about half a mile from the edge of the reef, while on the west and south-west of Nomuka-iki it is a mile away and encloses some outlying coral patches. Outside the twenty-fathom line the slope is very gradual. Eight miles from land on the west and south-west (the only directions in which distant soundings have been taken) the depth is not greater than 50 fathoms †.

Nomuka is evidently an atoll which has been formed in shallow water, though it is only in the last stage of its elevation that the ring has been completed; and here the shallowness of the surrounding sea appears to exclude subsidence as a factor in its formation: for the summit of the elevation on which, on that hypothesis, the limestone formation rests would lie beneath the lagoon; but the floor of the lagoon is only some 9 fathoms higher than the bottom of the surrounding sea outside the reef.

To the east of the Nomuka Group, a reef dotted with islands is

* On comparing the density of the lagoon-water with that of sea-water and distilled water by means of a hydrometer, the readings were:—

Distilled water	— 2
Sea-water	+25
Lagoon-water	+39

† Opposite the western end of the channel between the islands I obtained a branch of a living madrepora at a depth of 31 fathoms, and a living fragment of one of the *Poritidæ* came up on the 'Egeria's' sounding-lead from the same depth.

marked on the chart, resembling on a small scale the great Hapai barrier to the north.

Tongatabu is the largest island of the group. It is some 22 miles in greatest length, and of an irregular crescent shape, with its convexity presented to the south. Considerable tracts along the northern shore are not above the reach of the highest tides ; but the level gradually rises towards the convex border, and the highest part is at the south-east, opposite Eua.

An extensive shallow area lies to the north of the island. Opposite the middle of the northern shore, and extending for about a third of the whole of its length, there is a large basin, which forms the harbour of Nukualofa. It has an average depth of 15 fathoms, and communicates with the outer water by a deep channel on the eastern side.

A wide shallow area, having a depth of from 6 to 9 fathoms, extends from the western point of the island eastward, bounding the basin and eastern channel on the north. Along the outer or seaward margin of this area coral reefs grow up to the surface, forming a more or less continuous barrier on the east and north-west. To the north, however, the line of reefs is interrupted, and here shallow banks (though apparently without reefs) extend for some 15 miles in the direction of the Nomuka Group. Several islands, some of sand, some of coral rock elevated about 15 feet, are dotted along the reefs on the north of the harbour and eastern channel.

The interior of Tongatabu is partly occupied by an irregular and shallow lagoon, which communicates with the sea on the north.

Regarding the island and the shallow tract to the north as a whole, we find an area whose circumference, represented by the convex border of the island on the south, and the shallow 9-fathom area, on which reefs have grown, to the north, stands at a higher level than the central part, represented by the lagoon and the 15-fathom basin.

In mentioning this island, Darwin pointed out* that "it resembles either an up-raised atoll, with one half originally imperfect, or one unequally elevated." The gaps in the line of reef along the northern margin show that the atoll was imperfect ; but the gradual rise of the land towards the convex side, and the fact that it attains its highest point where it most nearly approaches the greatly elevated island of Eua, appear to point strongly to the conclusion that it has also been unequally elevated.

The island is formed of coral limestone throughout, and in many places this rock lies at the surface. In the grassy roads of the town of Nukualofa one often meets with flat patches of coral, many feet in diameter, on which the lines of astreids or madrepores are seen radiating from a common centre. Elsewhere the rock is covered with a layer of reddish-brown clay, which in some cases attains many feet in thickness†.

The contour of Tongatabu is flat or presents gentle undulations,

* 'Coral Reefs,' 3rd ed. p. 177.

† A similar clay overlies the limestone formation of Vavau.

but there are no streams or stream-channels on the surface. The rain soaks through the porous rock, and finds its way to the sea by underground channels excavated in the limestone. The caverns and subterranean galleries which have been thus hollowed out by the water are in some places very extensive, and in walking about the island one is often reminded of their presence by the hollow sound of one's footsteps.

Some remarkable features are presented by the narrow reef fringing the southern and eastern shores of Tongatabu. The land gradually slopes towards the ocean, and ends abruptly in a low cliff of coral rock. From the foot of the cliff there extends towards the sea a narrow reef-platform, whose outer edge is raised, forming a barrier* several feet in height. This barrier is in the position of the mound formed of nullipores which is commonly found near the seaward edge of a reef-platform†. It presents a steep surface towards the platform, and a vertical one towards the sea. In many places there is on the platform a depth of five feet or more of water, whose level is above that of the sea, and which is prevented from flowing away by the barrier on the seaward side. The upper surface of the barrier is formed of a number of shallow basins—the upper ones several feet in width—whose rims are perfectly level and which stand at different heights, the lower basins surrounding the upper, stage below stage, strongly recalling the structure which was presented by the well-known pink and white terraces of Lake Rotomahana in New Zealand. The outer part of the barrier is penetrated by fissures which open above by rounded apertures left between the margins of the basins.

The rollers, coming up from the open ocean, break against the steep face presented to them by the reef, and are thrown aloft in clouds of spray, while great jets and spouts of water are forced up through the fissures. The water falls into the basins on the barrier, streaming over their level edges along the whole of their circumference, to be caught by the basins beneath, and so down from basin to basin.

The edges and outer sides of the basins are covered with living nullipores, which grow in encrusting laminæ, and flourish in the freshly aerated water which streams over them. Wherever the water flows, the nullipores grow; and thus the edges of the basins are kept level, and are constantly growing upwards and outwards.

It appears probable that such a barrier is a form of the nullipore mound. Its unusual height and the remarkable basin-like formation may be due to the steepness of the outer slope of the reef, causing the waves which break against it to be thrown upwards, and thus the water in which the nullipores flourish always falls on them from above.

The reef on the eastern shore of Eua presents similar features.

The little island of Eua-iki lying opposite the mouth of the eastern

* This term is used without any reference to a barrier-reef.

† The nullipore mound at Keeling Island is described in Darwin's 'Coral Reefs,' 3rd ed. pp. 13, 14.

channel is composed of a higher central area, separated by a rapid descent from the lower peripheral part. It has evidently been elevated in two stages.

IV. CONCLUSION.

The view of the mode of formation of the Tonga atolls suggested in Darwin's 'Coral Reefs,' is that they grew during a period of subsidence, when the volcanoes of the group were inactive, and that elevation has occurred simultaneously with a recent volcanic outbreak *. Dana also considers that the islands were formed during subsidence, and regards the elevation which has taken place as merely a local phenomenon †. The additional information on the group which we now possess appears to make a different view of the formation of these islands more probable. It is clear that elevation has been in progress for a long period, and has been renewed again and again after intervals during which reefs of considerable extent have grown; it has to a greater or less extent affected all the larger divisions of the group, while at Vavau and Eua reef-structures have been raised to heights of over 500 and 1000 feet.

Such an elevatory movement is quite in keeping with the presence of the line of volcanoes which traverses the group, and I am not aware that there is any evidence that these have, as a whole, passed through a quiescent stage previous to their activity in recent times.

With regard to atolls in general, one reason for considering them to have been formed during subsidence is the improbability of there being any other basis than a subsided island on which the reefs could have grown. In the Tonga Islands, however, the soundings of H.M.S. 'Egeria' show that Tongatabu and Nomuka rest on shallow banks, and where the underlying basis of the islands is exposed, as in the Nomuka group and at Eua, it is seen that they consist of layers of volcanic materials laid out under water. The process now going on at Falcon Island illustrates the way in which a volcanic mound, composed of soft material and originally standing above the sea, may be reduced to a submarine bank, and so form a basis for coral growth.

In consideration of these facts it appears probable that the atoll-shaped islands of the southern part of the Tonga Group have grown on banks of volcanic material laid out in shallow water, and that there is no necessity to call in the hypothesis of subsidence to account for their formation.

EXPLANATION OF PLATE XXIII.

Map of the Tonga Islands. The map of Eua is prepared partly from the survey of H.M.S. 'Egeria' (1888). The outlines of the patches of volcanic formation in the central part of the island are not accurately drawn.

* 'Coral Reefs,' 3rd ed. pp. 177, 186, 188.

† 'Origin of Coral Reefs and Islands,' *Ann. Journ. Sci.* ser. 3, vol. xxx. (1885) p. 99.

DISCUSSION.

Mr. HICKSON said that Mr. Lister's researches on the coral reefs of the Friendly Islands were of great interest and importance, as they supported the view that atolls and barriers may be formed in regions of elevation, and that the "subsidence theory" is not sufficient to account for all the phenomena that occur in volcanic regions. The Tonga and Kermadec groups of islands are very similar to the chain of islands that stretches from the northern peninsula of Celebes to the southern promontory of Mindanao. Here we find a chain of volcanoes, many of them active at the present day, represented by the Ruang, the Siau, and the Awa, with broad barrier-reefs and ring-shaped atolls in their immediate vicinity. The researches of Sluiter in the Java seas prove that coral islands and reefs are frequently formed on a substratum of soft clay and mud.

Mr. J. W. GREGORY remarked on the great value of Mr. Lister's paper, and the interest attaching to the discovery of a plutonic rock on the islands. Taken in conjunction with the discovery of similar rocks in the Marquesas, and the presence there of genera otherwise restricted to South America and Malaysia, it helped to afford an explanation of some difficult problems of distribution. Manganese nodules seem characteristic of deep-sea conditions, not only at present, but in earlier periods; thus in the Maltese Miocenes they are associated with a fauna of about 1000 fathoms. Their occurrence, therefore, proves considerable elevation, and it is not surprising that the coral limestone occurs as thin crusts; the Tongas thus afford only another case of coral formation in shallow or rising areas, for which, as Darwin has so emphatically insisted, his theory was not proposed.

Mr. GOODCHILD enquired whether the boulder of gabbro referred to might not have reached its present level as an ejected block; this view might serve to explain the occurrence of plutonic rocks in an oceanic island.