GEOLOGY OF GALAPAGOS, COCOS, AND EASTER ISLANDS

BY

LAWRENCE JOHN CHUBB

WITH

Petrology of Galapagos Islands

BY

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BERNICE P. BISHOP MUSEUM
BULLETIN 110

HONOLULU, HAWAII
PUBLISHED BY THE MUSEUM
1933

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INTRODUCTION

The St. George Expedition left England on April 11, 1924, passed through the Panama Canal on June 13, and twelve days later sailed from Balboa. During July and August it visited James, Indefatigable, Charles, Albemarle, and Narborough islands in the Galapagos Archipelago. A call was also paid to Cocos Island, but it was possible to spend only about twenty-four hours there, as a shortage of provisions rendered a return to Balboa necessary. Easter Island was visited in May, 1925, in the course of the return voyage from Rapa to Balboa.

Two popular records of the voyage have appeared (17, 28).* Accounts of the collections of Galapagos plants by Riley (49), Micro-lepidoptera by Meyrick (41), Brachyura by Finnegan (29), and of marine ecology by Crossland (18), have been published. A preliminary geological account (11) has also appeared.

This paper gives a full account of the geological investigations of the St. George Expedition in the more easterly volcanic islands of the Pacific, including brief accounts of the petrology of Cocos and Easter islands, from which small collections were obtained. I intended originally to include an account of the petrology of the Galapagos, based on my collections. While engaged on this work, however, I learned that Miss Constance Richardson had almost completed an investigation of Darwin's collections, which for nearly a hundred years had been preserved in the Sedgwick Museum, Cambridge. Under the circumstances it seemed best to turn over to her my collections, which, as they come from different islands, to a large extent supplement Darwin's, in order that all might be studied together. (See pages 45-64.)

My thanks are due to Mr. Percy Edmunds, manager of the sheep ranch on Easter Island, and to his assistants, who entertained several members of the Expedition at Mataveri, lent us ponies, and did everything within their power to make our stay pleasant and profitable. My work during and since the Expedition has been helped by grants from the Department of Scientific

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* Numbers in parentheses refer to Literature Cited, pages 65-67.

and Industrial Research, the British Museum of Natural History, and the Government Grants Committee of the Royal Society. M. Alexander Lacroix has very kindly had made analyses of two of my rocks from the Galapagos Islands. The new analyses published for the first time here and in Miss Richardson's paper have been carried out by Messrs. W. H. Herdsman and F. Herdsman of Glasgow, the cost having been defrayed by Bernice P. Bishop Museum. The views shown in plate 4 are reproduced from "The South Seas of Today" (28), by kind permission of Major A. J. A. Douglas, part author of that work, and of Messrs. Cassell and Company, its publishers, who generously supplied electrotypes. The other plates are from my photographs.

I owe thanks, too, to Professor W. B. R. King, who has kindly read the manuscript and made helpful suggestions.

GALAPAGOS ARCHIPELAGO

General Features

The Galapagos Archipelago, situated under the Equator and in about 90 degrees west longitude, was discovered in 1535 by Fray Tomas de Berlanga, Bishop of Panama. During the succeeding three centuries it was visited by many buccaneers, privateers, pirates, whalers, warships, and explorers. A few of the visitors noted the volcanic nature of the islands and recorded eruptions, but otherwise no observations of geological interest were made. An account of these visits has recently been given by Miss Ruth Rose (6, pp. 332-417). In 1835, when H.M.S. *Beagle* spent five weeks there, the archipelago received its first scientific investigation. An accurate chart was prepared by Fitzroy (30), and observations of great interest and importance were made by Darwin (24, 25). This expedition was followed by many others whose interests were, however, chiefly zoological and botanical; few carried geologists. Between 1875 and 1895 Theodore Wolf (67-69), state geologist of Ecuador, visited the archipelago twice. Agassiz (1, 2) called there in 1891 and again in 1905. In 1905 and 1906 an expedition organized by the California Academy of Science, devoted primarily to the investigation of the plants and animals, made some interesting geological discoveries (20). William Beebe (6, 7) visited the islands on the Noma Expedition in 1923 and again on the Arcturus Expedition in 1925. The observations of these investigators will be referred to in the course of this paper.

As shown on the map (fig. 1), the Galapagos Archipelago consists of thirteen islands and great numbers of islets and rocks, all of them of volcanic origin. The climate is exceedingly arid, and on the lower slopes at least rain is rare even during the so-called rainy season—February, March, and April. During our stay—July and August—we experienced only one light

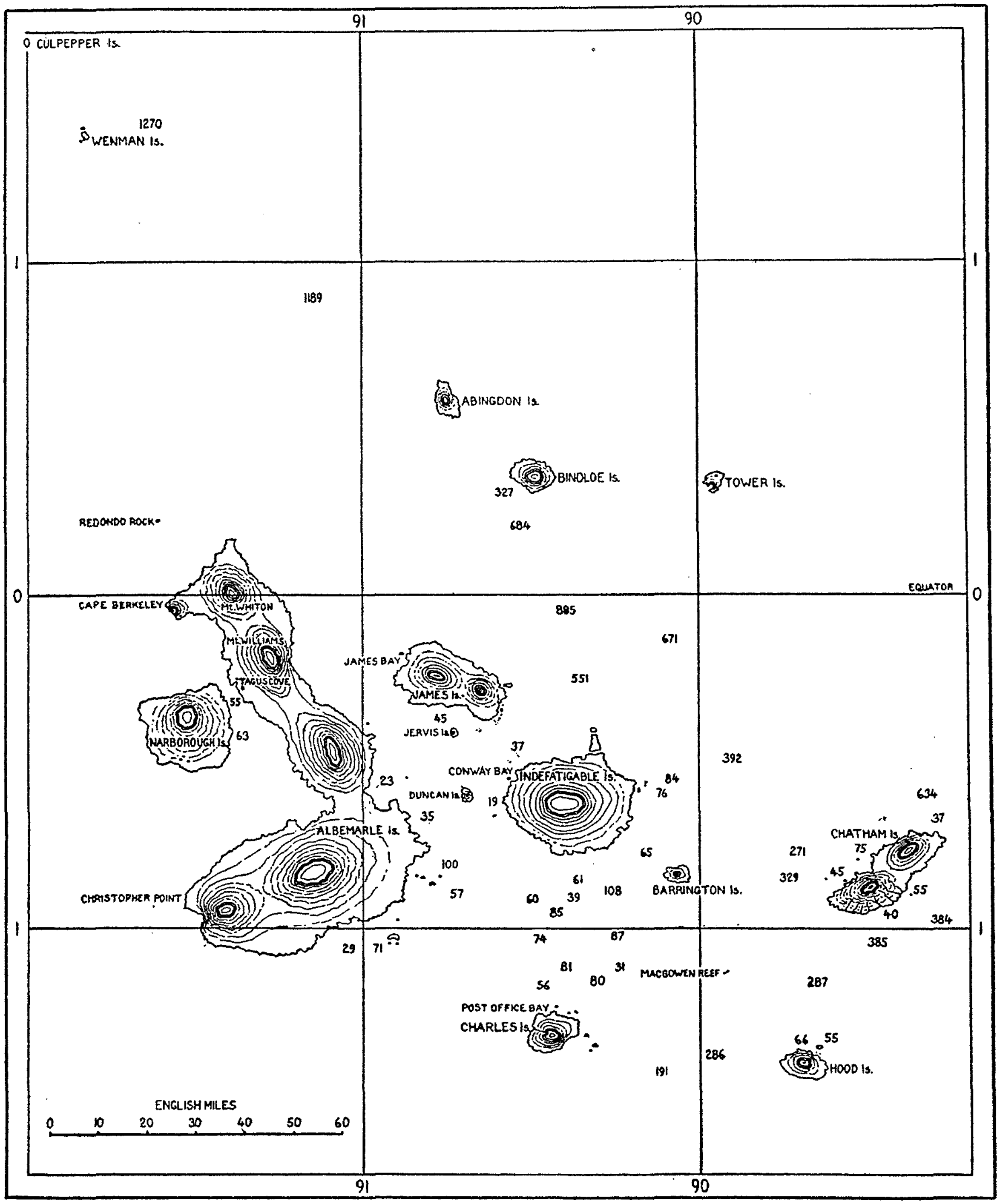


FIGURE 1.—Map of the Galapagos Archipelago, showing the positions of the major craters. (Depths in fathoms.)

shower. No fresh water was found in any part of the archipelago that we visited, though a few dry watercourses cut in the softer ashy rocks were seen. It is not improbable that these watercourses were cut rapidly in the still unconsolidated ash by temporary streams that owed their origin to the vast clouds of steam that must have been discharged during the more important eruptions. As a result of the aridity the flora of the lower ground has a "desert" character. In the higher areas of the great volcanoes, however, the soil is kept moist by clouds, and here there is more and greener vegetation, though it is nowhere luxuriant. In the more southerly islands, especially on their southern slopes which face the prevailing trade winds, the rainfall is greater and the vegetation more abundant. It is only in these parts that streams exist and permanent settlement has been attempted.

The islands have generally suffered very little subaerial erosion; the forms of the craters are clearly defined, and the rocks are remarkably fresh. This is due partly to the aridity of the climate and partly to the very recent origin of the archipelago. Darwin (25, p. 97) estimated the number of craters at more than 2,000, but of these only about 20 can be regarded as primary volcanoes. The remainder, though many are of considerable size, are secondary or parasitic craters. Most of the islands consist of single major volcanoes, but Albemarle includes six united together, and James and Chatham are each composed of two.

Albemarle and Narborough Islands

MAJOR VOLCANOES

There is no need to describe every major volcano in the Galapagos Archipelago, for they all conform to a definite type which is best exemplified in Albemarle and Narborough islands. Narborough Island consists of a single volcano, Albemarle of six, most of which are united by high saddle-shaped cols; but the northern part of Albemarle Island is united with the southern part by a low-lying flat isthmus.

The part of a typical volcano emerging above sea level is circular or oval in outline and 15 or 20 miles in diameter. In its center is a great crater, generally 3 to 5 miles across and said to be 500 or 600 feet deep. The rim of most craters stands from 3,700 to 3,800 feet above sea level, though the southernmost crater of Albemarle Island is 1,000 feet higher, and Berkeley volcano on the northwest of the island is 1,400 feet lower. From the crest of the rim the flanks slope down at an angle of about 25 degrees in their higher parts, decreasing to 15 degrees or 10 degrees at lower altitudes. From a height of 500 or 600 feet, lava fields 3 or 4 miles wide slope gently to sea level at an angle not generally exceeding 2 degrees (pl. 1).

Many visitors have commented on the abrupt change in the nature of the surface at an altitude of 500 or 600 feet. Below lie barren plains of unweathered lava; above rise comparatively fertile slopes which are said to be covered with soil. Wolf ascribed the change to the weathering of the lava at higher altitudes by the superior humidity of the atmosphere. As translated, his statement (68, p. 256) reads:

> The difference between the lower dry and the upper moist zone is so surprising, and the passage from one to the other is accomplished so abruptly, especially on the western sides of the islands, that one is at first tempted to attribute it to a change in the geological composition of the surface. But one soon becomes convinced of the untenability of this assumption on examining the rocks, and on following one of the big lava streams which take their origin in the upper region and flow down to the sea. On descending one notices how the weathered humus-rich soil, and with it the vegetation, visibly diminishes, soon the rugged lava-cinders are everywhere apparent, then the soil vanishes entirely, and finally only isolated cactuses and opuntias stand around. On one and the same lava-stream one can lay out a fruit-bearing garden in the upper part, though one had difficulty in clambering over the rough cindery crust of its lower part, which seemed as though it had only recently solidified. Thus these changes in soil and vegetation are not to be attributed to differences in the rocks or to greater age, but only to the higher humidity of the atmosphere in the upper portions.

The view thus explicitly expressed was accepted by Agassiz (1, p. 57) and other writers. Darwin (25, p. 97) had previously stated that the larger islands are composed chiefly of "solid rock," and both he and Wolf insisted on the small quantity of ejected ashes in any part of the archipelago (25, p. 112; 67, p. 561). Yet in spite of these statements, like Wolf I was "tempted to attribute the difference to a change in the geological composition of the surface," for the aspect of the higher zones, embracing the main mass of the major volcanoes, suggested that they were composed of pyroclastic material. The inclination of the slopes is the same as that of the parasitic tuff craters (see p. 13) and is too steep for basaltic lava flows. Viewed from a distance the flanks appear light fawn or grey, though radially streaked in their lower parts with bands that are nearly black. These darker bands grade into the surrounding lava fields, from which the lighter areas are separated by a sharp line of demarcation. It was thought that the lighter parts consisted of ashes and that the darker bands were lava flows, the feeding streams of the surrounding lava fields.

These views were not easy to verify, as the approach to the slopes of the major volcanoes lay over the lava fields, a difficult passage, owing to their extreme ruggedness, the intense heat, and the total absence of water. However, I succeeded in reaching the flanks of the great volcano, called Mount Williams by Beebe (7, p. 124), that lies a few miles northeast of Tagus Cove, Albemarle Island, and ascended it to a height of about 1,500 feet.

From the inner edge of the lava fields at 500 feet above sea level to the highest point reached, the slopes were found to be composed of looselycompacted friable tuff containing numerous broken fragments of lava. From fissures in the flanks, around a few of which small scoria craters have been piled up, streams of lava have flowed down, but they are entirely superficial and generally occupy dry gullies in the tuff. It is these lava streams that, by spreading out around the base of the volcano, have led to the formation of the lava fields (fig. 2).

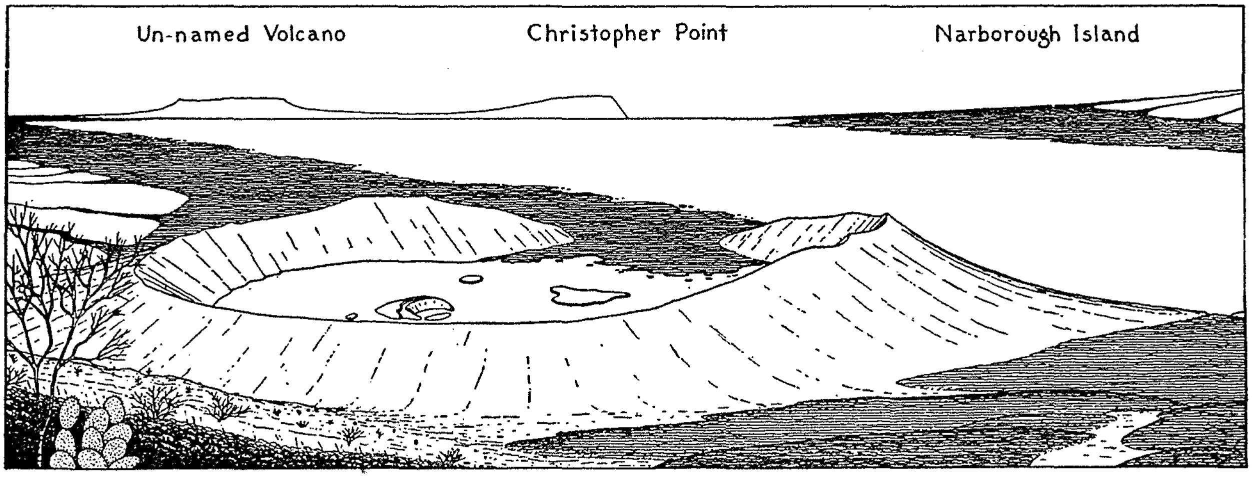


FIGURE 2.—Sketch of Beagle Crater and lava fields, from slopes of Mt. Williams, showing successive lava flows (right foreground), lava stream occupying gully in tuff slopes of Mt. Williams (left foreground), and other lava streams on more distant slopes.

The ejected lava fragments prove that there are flows interbedded with the tuff, but I have no doubt whatever that at least the higher strata of Mount Williams are mainly pyroclastic, and I think it may be confidently assumed that most if not all the major volcanoes throughout the archipelago have a similar composition.

It seems probable that Wolf contented himself with following an exceptionally broad and probably superficial lava stream down the slopes. From his account it is evident that he found not an abrupt, but a gradual change in the degree of weathering of the surface, which is what would be expected. It is even possible that he passed from an older stream at greater altitude to a newer one that had overflowed it lower down, for if the surface were somewhat weathered it would be almost impossible to distinguish one stream from another.

It is hoped that future investigators will give their attention to this question.

LAVA FIELDS

Several visitors have recorded eruptions of lava in the Galapagos, the best account being that given by Beebe (7, pp. 117-145), who actually visited one of the vents. The site of this eruption was the summit of the col connecting Mount Williams with the next major volcano to the north, Mount Whiton. There seem to have been several fisssures and a few vents around which heaps of scoria were piled up, and which merited the name of crater. The eruption is stated to have been an intrusive one. The lava is described as "flowing beneath the surface, finding actual peep-holes for the hot lava itself in scores of places, and sending forth the excess gases and steam through a thousand vents."

Such conditions are hard to understand. Surely, if such holes and vents existed, the lava would have welled up through them rather than force its way onwards below the surface against the pressure of the overlying rocks. It seems more probable that the stream was a superficial one and that a crust formed over the surface beneath which the lava flowed onwards. Such a crust might hardly be observed to move, though it would constitute an integral part of the flow. There is abundant evidence that a similar crust was formed over most of the flows and that through vents in it vapors were discharged, with the formation of fumaroles, gigantic bubbles of lava, and small piles of scoria. If this be the true interpretation, it would seem that Beebe unknowingly walked a considerable distance on the actual surface of the flow, a fact that would explain the intense discomfort that he and his companion suffered.

The eruption began on April 11, 1925, and nine weeks later, on June 14, the lava reached the sea, pouring over the 100-foot cliffs. It is stated that "the sea would answer by catching great quantities of the scarlet fluid and moulding them instantly into gigantic black bombs, whose inner gases would explode simultaneously and shoot forth a rain of half solid, half liquid boulder spray." This recalls Tempest Anderson's account (3) of the formation of pillow lava at Matavanu in Savaii, except that at Mount Williams the "pillows" did not survive the expansion of the gases within them.

Successive lava flows, apparently of the type just described, have pushed out the coastlines of most of the islands a distance of 3 or 4 miles by a process analogous to that of delta formation and due to the checking of the flows when they reached the sea. Though the average inclination of the lava fields is only 2 degrees, the offshore slopes attain angles of about 4 degrees.

On Albemarle and Narborough islands the lava fields generally completely surround the great volcanoes. It is possible to distinguish from a distance the successive flows by their color; the newest are almost black, and the older flows have weathered to a brown (fig. 2). On closer examination it would be easy to map them by direct observation of their superposition, their relative states of weathering, and the amount of vegetation growing on their surfaces. On Albemarle Island, east of the large parasitic crater, Tagus (see p. 14), five superimposed lava flows may be distinguished.

The oldest, which is still exposed only in a district situated about a mile northeast of Tagus Crater, at the foot of Mount Williams, is weathered down to a flat spread of loose cindery material, covered with vegetation. The overlying flow comes from a small breached scoria crater close to the foot of Tagus Crater. Its surface consists of large flat slabs which are slightly and irregularly tilted owing to the solidification and subsequent breaking up of a superficial crust and the partial foundering of the floating slabs in the still liquid mass below. It is considerably weathered but bears only a sparse scattering of small shrubs and cactuses. The third, fourth, and fifth flows, to judge by the direction of their feeding streams, seem to emanate from a small parasitic cone which can be seen on the skyline on the southern flanks of Mount Williams. The third flow is much weathered, is largely reduced to fine ashy material which forms flat spreads, broken and separated by projecting masses of lava, but bears no vegetation. The fourth flow is more rugged and like the fifth shows corded and festooned surfaces; neither supports any vegetation. Each of these two flows occupies a smaller area than the third, the fifth forming only a little spread around the base of its feeding stream, as though at the time of outflow the volcanic activity had been gradually declining.

North of Tagus Crater is a great lava flow remarkable for the excessive ruggedness of its surface (pl. 1). It consists of huge blocks of massive lava, many of them 8 to 10 feet across and 5 to 6 feet thick, heaped together in indescribable confusion. Between these blocks are some intervening spreads and a few mounds of scoria.

The flow next below this rugged expanse of lava is exposed near a mangrove swamp, a mile north of Tagus Crater. Its surface, in contradistinction to that of the overlying flow, is almost smooth, but its superficial layer is arched up into a series of anticlines formed by lateral pressure exerted by the still moving mass on a solidifying but still plastic crust. The crests of most of these anticlines have fallen in, but a few are still in position and form caves in which salt-water pools have collected.

Darwin (25, pp. 103-105) commented on the former high degree of fluidity possessed by a lava stream, several miles wide, near Tagus Cove. He described its surface as "almost as smooth as a lake when ruffled by a breeze," and its edges as thinning out to almost nothing. I was unable to find any lava flow which answered to this description. The very rugged flow described above is 20 or 30 feet thick at its edge, and the smaller flows to the east end in walls 8 or 10 feet high. A considerable degree of fluidity, however, is proved by the low angle of slope of the surface of the lava fields.

Other types of lava flows were found on the eastern side of Narborough Island. One is a long narrow stream that forms a ridge about 50 feet wide and 15 feet high. A deep longitudinal fissure runs down its center (pl. 1). Inside this fissure columnar structure appears. The original thin crust, 2 or 3 inches thick, has been broken up and partially reincorporated into the mass, from which pieces project at all angles. Between these the surface is generally wrinkled, corded, and festooned, but in places it is almost smooth. This flow was traced about half a mile inland, where it was found to be overlaid by a broad flow of recent appearance, the surface of which consisted entirely of large, rough, loose clinkers. Two miles farther south a flow exactly similar, and perhaps a continuation, was found overlying the beach.

In a few places the lava fields end in low cliffs a few feet high or even in higher cliffs, but generally they run into the sea as numerous little spits separated by small lagoons or bays, mangrove swamps, or beaches which in the western islands are composed chiefly of calcareous organic fragments.

PARASITIC CRATERS

An enormous number of small craters and cones, insignificant in comparison with the major volcanoes but some of them several hundreds of feet high and a mile in diameter, rise from the lava fields or form peninsulas or islets. According to Wolf (69, p. 560; 68, pp. 249-250), these craters are of two kinds and have entirely different modes of origin. He believed that there had been two periods of volcanic action, and that some of the craters were formed during the first and others during the second period.

The earlier phase is supposed to have taken place beneath the sea and to have yielded an enormous amount of palagonite and other stratified tuffs. Uplift of a few hundred feet next brought the highest points of this mass above sea level, and it is these points that constitute the first class of minor craters, which are distinguished by their crescentic form and their palagonitic composition.

Wolf believed that the submerged accumulation of tuff thus produced formed the base on which the later subaërial peaks were erected, probably burying some of the earlier tuff craters, though he offers no evidence of this. He thought, apparently mistakenly, that these great volcanoes consisted entirely of vast streams and layers of lava, almost devoid of tuffs, and he believed that during the long period while this material was solidifying, secondary outbreaks, the source of which was the still molten lava immediately below, built up on its surface hundreds of cones, not of tuff but of scoria, from small heaps and lava bubbles a few meters high, up to the 300-meter cone, from whose crater a lava stream has gushed out (68, p. 253).

There can be no doubt that the numerous lava bubbles and little heaps of scoria on the lava fields originated in this way, but it seems scarcely credible that any of the larger parasitic craters, some hundreds of feet high, can have owed their origin to such a shallow source. In the districts visited I saw no craters of such a size composed entirely of scoria, though there were several that consisted partly of this material and partly of tuff. A few of the tuff craters had given forth small lava flows, and some were floored with a solidified pool of basalt.

There seems therefore to be no adequate reason for drawing such a wide distinction between the tuff and the scoria craters and for attributing either such a fundamental origin to the former or such a superficial one to the latter. The distinction seems to rest on nothing more important than that some of the craters have been cut back by the sea so as to reveal the compact palagonite within. The superficial layers are invariably of friable tuff or scoria.

It seems probable that all these craters on the plains were formed during a period subsequent to the erection of the great volcanoes on the lower flanks of which they stand but previous to the fissure eruptions of lava which everywhere overflows their bases. No doubt the main vents became blocked, and the volcanic energy, finding other minor vents, built up the small craters around them. The material seems to have been similar to that forming the major volcanoes themselves, for the tuff composing Mount Williams exactly resembles some of that of neighboring parasitic cones.

Darwin (25, pp. 99, 112) attributed the origin of the tuff forming these minor craters to the grinding together of fragments of lava within active craters communicating with the sea, but it seems more probable that it was due to the presence of a greater amount of original water in the magma that fed them.

At Narborough Island no parasitic cones touch on the coastline, but even here a considerable number of small recent craters stands a mile or two inland. On Albemarle Island there are groups of small tuff craters in the southwest at Christopher Point and in the northwest at Cape Berkeley. One of the craters at Cape Berkeley has a smaller crater standing within it, as previously noticed by Wolf (68, p. 250).

On the west coast, in the neighborhood of Tagus Cove, is a system of tuff craters of considerable interest (fig. 3). Several days were devoted to their investigation. The district has been made classic by the pioneer labors of Darwin (25, pp. 105-108), who first found here the inwardly-dipping strata now known to be characteristic of many ash and tuff craters in all parts of the world.

Tagus (Bank's) Cove, a narrow inlet about 500 yards wide, extends about three-quarters of a mile in from the main shoreline. It occupies a breach in the southern wall of a crater, here called Tagus Crater. A mile to the southeast is another crater, here called Beagle Crater (fig. 2).

Beagle Crater is nearly circular, more than a mile in diameter, and rises about 500 feet above sea level. Its floor is occupied by a shallow salt-water lake in which rise several islets. The central islet has itself the form of a small crater. The southern wall is breached, so that at one time the lake must have formed an inlet of the sea, but the lava fields on the southeast have subsequently extended around the eastern limb of the crater and closed the breach, converting the inlet into a lake.

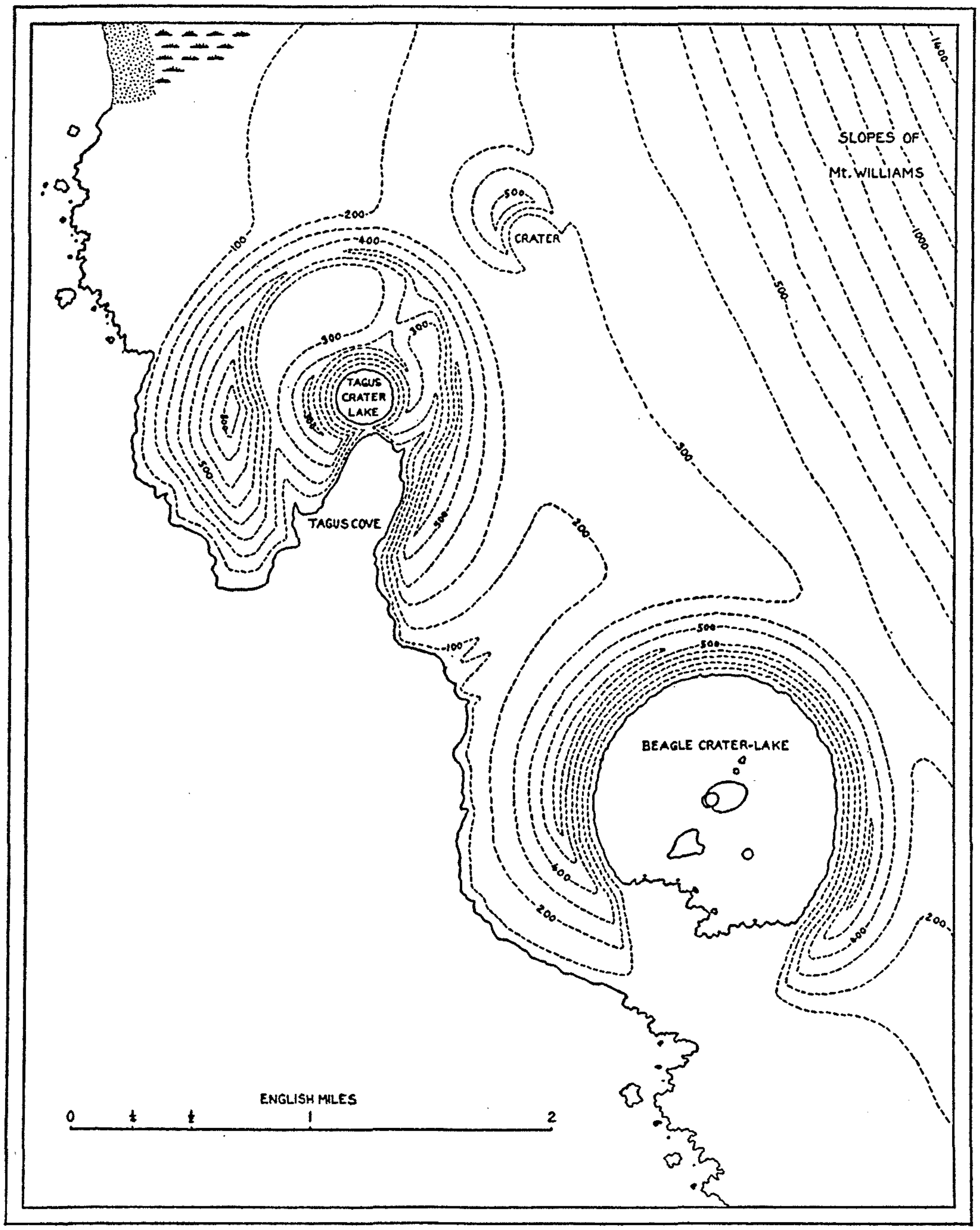


FIGURE 3.—Topographic map of Tagus and Beagle craters, Albemarle Island, with approximate contour lines at intervals of 100 feet.

The inclination of the outer slopes of Beagle Crater, about 25 degrees in the upper part, decreases to 10 degrees at lower levels; the dip of the rocks is parallel to the surface. The inner steeper slopes attain angles of 30 degrees to 40 degrees, and the inclination of the inwardly-dipping strata is the same. The inner and outer strata are confluent, so that the crest of the rim suggests an uneroded anticlinal arch. The outer slopes are scalloped with radial ridges 10 to 15 feet broad in their upper parts and widening as they descend. These are formed by an arching up of the superficial layers of the tuff. Some of them are hollow. Darwin (25, p. 106) ascribed their formation to the hardening of a superficial crust on streams of mud; as the still liquid substratum flowed down to lower levels, the solid crust would settle down, and in doing so would naturally become radially wrinkled. On the lower slopes other anticlinal ridges, some of them hollow, run parallel to the crater rim. These are no doubt the result of lateral pressure exerted by the solid crust being carried downward on the fluid material beneath.

The slopes of Beagle Crater consist of friable tuff containing numerous broken fragments of lava, some of which are 4 or 5 feet long. On its southwest side a cliff section shows alternate layers of tuff and agglomerate. The lower tuffs are compact and palagonitic, the upper ones soft and friable.

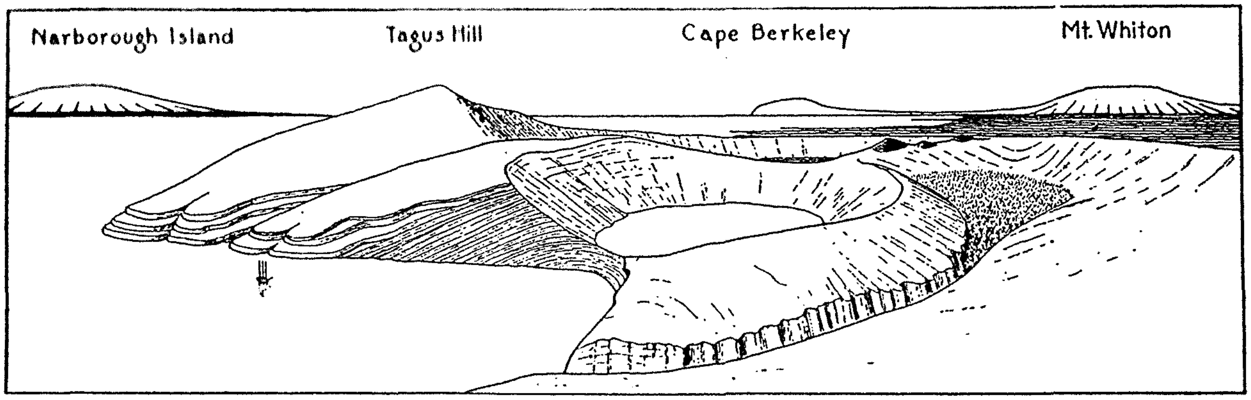


FIGURE 4.—Sketch of Tagus Cove and crater system, viewed from southeastern part of rim of outer crater; western and northern part of outer rim stretches from Tagus Hill to the right; between rim and inner crater is moat crossed at one point by ridge bearing "bubble craters."

Tagus Crater (fig. 4) is almost similar in structure to Beagle Crater. Its dimensions are about the same, except that its western wall rises more than 800 feet above sea level to form Tagus Hill, and its floor lies between 200 and 300 feet above sea level. Within this crater stands another which is much larger than the crateriform islet in the center of Beagle Crater. It measures nearly a half mile across the rim and is 400 feet high on its western side. Its floor, below sea level, is covered by a circular salt-water lake (pl. 2). It is not quite centrally situated within the older crater, part of the southern wall of which must have been shattered when it was built. Its outer slopes abut directly against the inner slopes of the older crater on the southeast and southwest. The resulting V-shaped depression has been deepened by stream action, though the gullies have apparently long been dry. The northern crescentic half of the moat between the inner and the outer crater has a level floor (pl. 2), probably representing an old lava pool, which is now covered with loose scoria. It is uncertain whether this was the original floor of the outer crater, which was pierced by the eruption that produced the inner one, or whether the lava pool owes its origin to the flooding of the moat by a still later eruption that took place within the moat itself. Evidence of such an eruption is furnished by a low broad ridge which crosses the floor and connects the inner and outer walls. It is composed of very light cindery scoria and appears to have resulted from the upwelling of lava through a fissure. On its summit and western flanks are a number of spiracles (pl. 2). These are hollow mammiform hillocks 10 to 50 feet in diameter, of red scoriaceous lava, their summits and sides fissured by irregular cracks. The tops of most of the spiracles have fallen in or have been blown off, but one was found with its roof intact and with a small opening in its side, so that it resembled a huge beehive. These gigantic bubbles must have been formed by the escape of gas through the still pasty scoriaceous lava.

North of the ridge on the outer slopes of the outer crater there is a small flow of lava. The small breached scoria crater (p. 10) stands on the lava fields just below.

On the south side, Tagus Cove completely breaches the wall of the outer crater and cuts so far into that of the inner crater that it is separated from the lake only by a narrow ridge 60 or 70 feet high (fig. 4; pl. 2). The cove is about 140 feet deep at its entrance and 30 feet deep near its head; its sides are steep both above and below sea level. It appears to have been formed not by erosion, but by an explosive outburst which has shattered the wall of the craters, for the cove shows strata of tuff dipping inwardly at about 36 degrees as the craters do. Though on the east the inwardly-dipping strata resemble talus slopes, on the west they are confluent with the uppermost outwardly-dipping beds, and they can only be ascribed to the mantling of both inner and outer slopes with the products of one eruption, the source of which must have been the cove itself.

No compact palagonite-tuff was seen anywhere in the Tagus crater system, probably because no place was found where the sea had cut in far enough to expose it. The materials of both inner and outer craters include friable tuff, with (pl. 3) or without ejected fragments, some of it pisolitic, and, on the northeastern slopes of the outer crater, scoria, as well as the lava and scoria already mentioned.

A continuous outcrop of tuff connects Tagus and Beagle craters, and the Beagle and Mount Williams craters.

The lava of the surrounding plains is more recent than the tuff and everywhere overflows its edges. Tongues of it, 40 to 50 feet wide, which have flowed down certain dry watercourses in the depression between the two craters, nearly reach the sea. The extremely rugged flow described above (p. 10) abuts against the base of sea cliffs which were cut in earlier times along the north side of Tagus Crater (pls. 1, 3). The history of the district seems to be as follows:

1. The two outer craters were built up. They formed a peninsula, as they were connected together, and Beagle Crater was connected with the main island.
2. After an interval a recurrence of volcanic activity built up smaller craters within the outer ones.
3. The old vents being now choked up, when volcanism was renewed it shattered the southern walls of both the outer craters. Sea water was thus admitted into Beagle Crater, but perhaps not into the outer Tagus Crater, whose floor may have been above sea level. It was able, however, to percolate through the comparatively thin wall of ash still separating the head of Tagus Cove from the inner crater and there to form a salt-water lake.
4. Perhaps at the same time, or perhaps later, volcanism became active beneath the northeastern part of the Tagus crater system. It was not strong enough to shatter the wall, but pasty lava welling up through a fissure across the moat formed the ridge of scoria; vapor, escaping through this, blew up the bubble-like spiracles. The fissure crossed the wall of the outer crater, allowing a flow of lava to escape, and reached the plains below where the little scoria crater was erected upon it. Later the scoria crater was breached on its southeastern side by a lava stream.
5. Successive lava streams from the flanks of Mount Williams overflowed the bases of the two craters, abutted against the base of the cliffs that had been cut around the north side of Tagus Crater, occupied little gullies cut in the tuff between the two craters, and closed the breach in Beagle Crater.

OTHER ISLANDS

James Island consists of two primary volcanoes. The larger one, 1700 feet high, forms the main mass of the island. The smaller one, 1000 feet high, forms the southeastern part. There are many small parasitic cones on the higher slopes, especially along the line between the two main craters, but they are well distributed over the island and somewhat conceal the simple original structure. A conspicuous cone on the southwestern flanks, from which activity has been reported at intervals within the last century, has extruded so many flows of lava that they form a continuous sheet over the

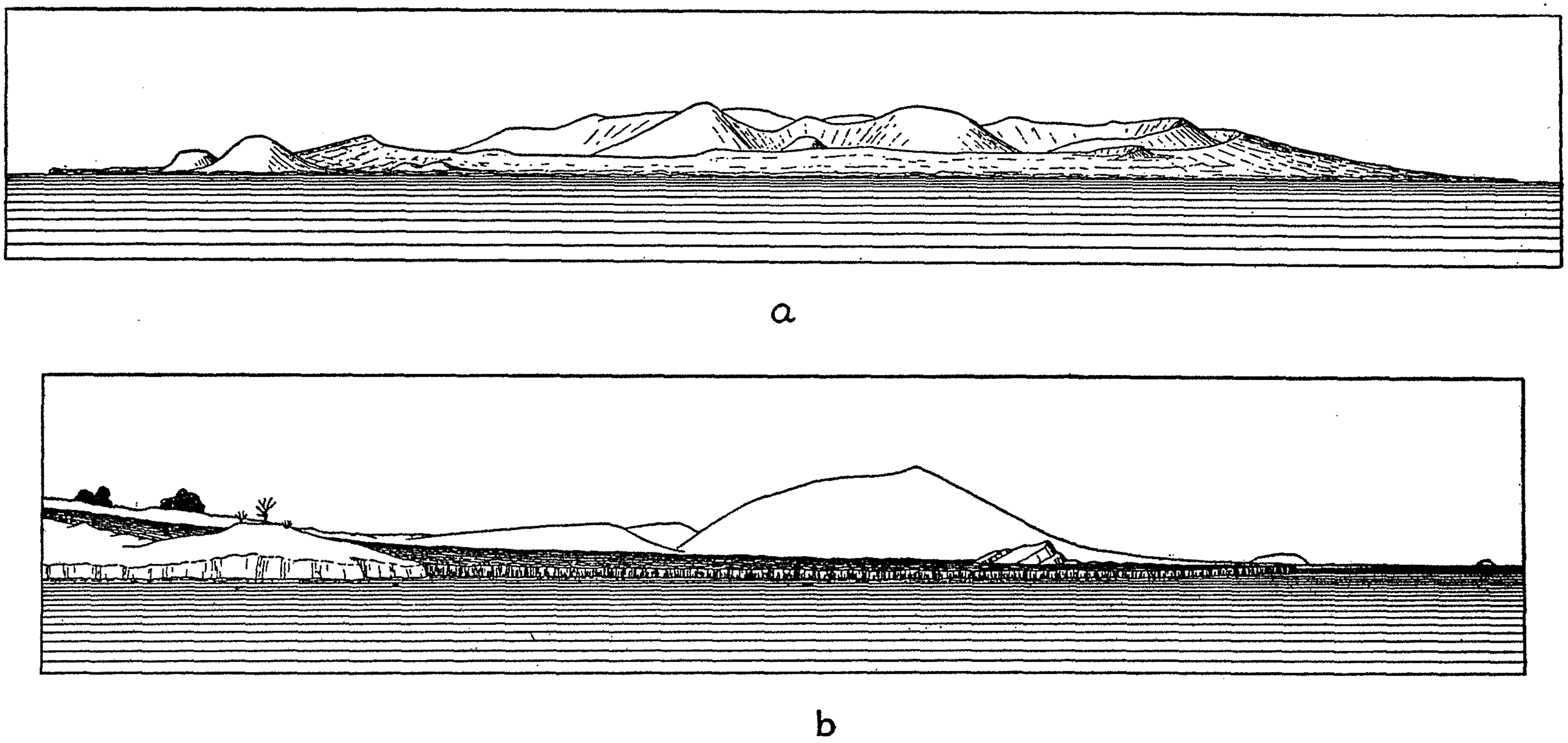


FIGURE 5.—Tuff craters: *a*, sketch of Bindloe Island from the east-northeast, showing a caldera with several tuff craters standing in and around it; *b*, sketch of southern side of James Bay, James Island, showing several tuff craters and a single lava stream that flows down the tuff slopes of the main volcano and spreads out on reaching the sea.

lower slopes. Anyone ascending the island on this side might conclude that lava constituted the whole island, whereas it actually seems to form only a crust. Lava fields surround much of the island but are absent from the western part around James Bay. Here behind a sandy beach are two salt-water pools surrounded by mangroves, and at the back a steep tuff slope, clothed with bare bushes, rises to the summit of the island. At the south end of the bay a broad glacier-like stream of black lava, almost unweathered, and showing its original corded surface, represents the first stage in the formation of lava fields (fig. 5, *b*). It can not be traced to a definite crater and seems to have originated as a fissure eruption. A number of tuff cones stand on both sides of it. The eroded remnant of one that has been surrounded rises through its surface. At the north end of the bay stands another group of tuff cones, including Albany Island. One in the adjacent mainland that has been cut back by the sea shows the radial dip clearly.

Indefatigable Island consists of a single major volcano which is essentially similar in structure and dimensions to one of the western volcanoes. It is surrounded by lava fields which bear many parasitic tuff craters, but all are somewhat weathered and overgrown, and no recent lava flows were seen. The rim of the main crater has been somewhat broken down by subaërial erosion. No volcanic activity has been reported from this island. J. H. Horneman, who accompanied the Templeton Crocker Expedition to the summit of Indefatigable in 1932, reports that the island is composed chiefly of lava, ash being found only on the highest ground. He believes that there were two generations of parasitic craters, both subsequent to the building of the major crater.

Charles Island also is similar in structure to one of the western volcanoes, though it is smaller. It measures only about 9 miles in diameter and 1780 feet in height. Its crater is broken down more than that of Indefatigable Island, having been reduced to a circle of hills surroundiing a fertile plateau, formerly the site of a settlement. Its lava fields are much weathered and thickly overgrown with vegetation. The surface behind Post Office Bay has been reduced to masses of broken scoriaceous material, including many large broken crystals of olivine and felspar, and large well-rounded grains of olivine form an important constituent of the beach sand. Some of the parasitic cones are comparatively large.

The remaining islands were not visited. Hood Island consists of one volcano and Chatham Island of two. They seem to be of a type similar to Charles Island. Some of the smaller islands, as Duncan and Jervis, were seen at close quarters. They are tuff volcanoes, similar in type to the larger ones, but without lava fields or parasitic craters. Darwin observed no crater on Tower Island, but one was found there by the Noma Expedition (6,

p. 311) and a second by Dwight Franklin on the Arcturus Expedition (7, p. 398).

Bindloe Island, passed at a distance of a few miles, differs from all the other islands seen in that it consists of a large caldera, with a number of tuff craters both within it and on its flanks (fig. 5, *a*). Abingdon Island was seen from a greater distance. It consists of a single cone. No parasitic craters were seen on it, though the chart suggests that such exist.

The archipelago includes many small islets, most of which are close to one of the larger islands and are merely parasitic cones rising from the submarine portion of the slopes of the major volcanoes. Such are Albany Island in James Bay, James Island, and Eden Island in Conway Bay, Indefatigable Island. Wenman and Culpepper Islands, situated respectively 90 and 110 miles north-northwest of Albemarle Island, are farther afield. They must represent the summits of independent volcanoes.

ABSENCE OF CORAL REEFS

No coral reefs are known to occur anywhere around the Galapagos Islands, or indeed anywhere in the Pacific east of longitude 120° W., with the very questionable exception of Clipperton "Atoll", from which rocks have been described by Wharton and Teall (55-a, 64). Although some of these had the appearance of limestone, there seems to be no evidence of the presence of any coral rock, all being highly altered trachyte. Clipperton Island is probably a crater rim which, except for one outstanding mass of trachyte, has been planed down by the sea, and has later reëmerged, perhaps owing to the recent negative movement of sea level.

Off the coasts of Panama and Colombia, Crossland (18, p. 533), marine biologist to the St. George Expedition, found that the only coral at all abundant was *Pocillopora,* which did not form reefs, and his dredging at the Galapagos did not bring to light a single coral. Agassiz (1, pp. 64, 69-70) speaks of the "coral-rock beaches so characteristic of the Galapagos," instancing those at Conway Bay, Indefatigable Island, as especially typical. He describes these beaches as being composed of "decomposed fragments of corals and other invertebrates cemented together," but my observations there and elsewhere convinced me that on most of the beaches other invertebrates preponderate greatly over the corals. No true coral rock was seen by any member of the Expedition (18, p. 539).

In the western islands, beaches, cemented or uncemented, composed chiefly of echinoid and molluscan fragments, are common, and in a few places these contain a considerable admixture of coral fragments. In the beaches of Indefatigable Island there is a considerable admixture of volcanic detritus, and in the Charles Island beaches this material predominates.

Dana (23, pp. 99-100) suggested that the absence of coral reefs was due to the lowering of the temperature of the surface water by the action of the cold Peruvian current, which after flowing northward up the coast of South America normally turns westward towards the Galapagos. Agassiz, however, in March and April, 1891, found the surface temperatures between the islands to be between 81 and 83 degrees, high enough to encourage luxuriant coral growth. Not unnaturally, he discredited Dana's suggestion and attributed the absence of reefs to the effect of mud brought down by the South American rivers, a factor no doubt of the greatest importance in preventing reef development near the continental shore but not operative so far afield as the Galapagos, where the water is so clear that the bottom can be distinctly seen under depths of 15 or 20 fathoms.

It happened that Agassiz's visit coincided with an unusual phenomenon. In February, 1891, the Peruvian current failed, and the warm southward-flowing current, El Nino, a branch of the equatorial counter-current, flowed far to the south. The high surface temperatures and abnormally heavy rains prevailing during Agassiz's visit were undoubtedly concomitants of the current conditions, which were maintained for a period of two or three months (43). The phenomenon was repeated thirty-four years later, in March, 1925, when the Arcturus Expedition visited the islands, and it appears to be periodic. In a discussion of the coral reefs of the Marquesas (14, p. 62), it has been shown that a failure of the Peruvian current may be expected whenever solar radiation is unusually low, as during a particularly low sunspot minimum. During an exceptionally high sunspot maximum the conditions are reversed, and the cold current probably flows out across the Pacific far enough even to influence coral growth around the Marquesas.

The surface temperatures around the Galapagos are normally far lower than those recorded by Agassiz. Near the South American coast between Panama and Gorgona Island, Crossland (18) found temperatures between 77° F. and 80° F., but these districts are almost if not quite outside the sphere of influence of the Peruvian current, and the absence of the coral reefs must be attributed to the muddy water. On crossing to the Galapagos he found a fall to 68° F. (19). The water was distinctly cold to the touch. As a temperature exceeding 71° F. is necessary to permit vigorous coral growth, there is no need to seek for any cause other than the coldness of the water to account for the absence of reefs. Dana's theory is thus shown to be correct, and the view expressed by Davis (27, p. 149) that the Galapagos lie on the outer edge of the marginal belt of the coral seas is confirmed.

STRUCTURE AND GEOLOGICAL HISTORY

Darwin (25, pp. 115-116) first called attention to the fact that the major craters of the Galapagos are not indiscriminately scattered but are arranged on the points of intersection of two sets of parallel lines which trend respectively about N. 43° W. and N. 47° E. and are therefore at right angles. (See fig. 1.) The most important line having the northwest trend runs through Culpepper, Wenman, James, Indefatigable, and Barrington islands, Macgowen Reef and Hood Island; a second line parallel to this runs through Redondo Rock, three of the craters of Albemarle Island, and Charles Island; a third extends through Narborough and one of the southern craters of Albemarle; and a fourth less regular line runs through Abingdon, Bindloe, and Chatham islands. Lines having the northeast trend run through Narborough Island, one of the Albemarle craters, and Bindloe Island; through the central Albemarle crater, and James and Tower islands; through the two southern craters of Albemarle; and through Macgowen Reef and the two craters of Chatham Island.

Darwin concluded that the principal craters lie on the points where two sets of fissures cross each other. To Wolf (69, p. 561; 68, p. 252) such attempts at grouping seem purposeless, and premature until the submerged volcanoes that must exist are discovered. The Marquesas Islands, however, show a similar arrangement on intersecting lines, and there the submerged banks and shoals fit into the scheme perfectly (14, pp. 49-51). Wolf considered the choice of lines arbitrary and suggested other lines that might be drawn, one through southern Albemarle and Indefatigable, and another through Chatham, Indefatigable, Duncan, the central Albemarle volcano, and Narborough. The former line, however, does not mark out a line of major craters. The latter may have significance, for it is parallel to the line of major and parasitic craters forming James Island, and other less distinct lines may be found parallel to it. It is arranged at an angle of approximately 45 degrees to the two sets of lines laid down by Darwin, and probably indicates a subsidiary trend such as has been found in the Marquesas. The structure and mode of origin of the two archipelagoes seem to be essentially similar.

It would appear probable that the southeastern islands, Chatham, Hood, and Charles, are the oldest. The greater amount of erosion and weathering they have suffered, though no doubt due largely to the higher rainfall in the south, is probably in part consequent upon their having had a longer existence. Indefatigable Island, which is less weathered and eroded than Charles Island but rather more so than the islands northwest and west of it, is in an intermediate state. Since the discovery of the archipelago volcanic eruptions have been recorded only from James, Albemarle, and Narborough islands, and the sole type of activity observed has consisted of outflows of lava from fissures and small craters on the flanks. Narborough has the appearance of being the most recent island. Its lavas are on the whole less weathered than those of any other island we visited. Its comparative paucity of parasitic cones also suggests that it is in an earlier stage of volcanic evolution than the other islands.

From these considerations it appears probable that volcanic activity began in the southeastern parts of the archipelago and moved gradually in a westerly or northwesterly direction. In the volcanic history of each island, three phases may be recognized:

1. A period of major eruptions, when the great volcanoes were erected. The material ejected was mainly pyroclastic, at least in the later stages.
2. A period of minor eruptions of tuff, which built up the parasitic craters. The situation of these generally at a distance of some miles from the major craters suggests that the vents of the latter were blocked to a considerable depth, and therefore that a long period of quiescence had intervened.
3. A period of upwelling of lava from fissures in the flanks of the major volcanoes. As the eruptions were no longer explosive it seems probable that most of the volatile matter in the magma had by now escaped. This phase is not yet over in the western volcanoes.

In spite of the obvious resemblances in the structure of the Marquesan and Galapagos archipelagoes, there are certain differences in their history. The craters and calderas of the first phase were found in the Marquesas to be composed mainly of lava flows, in the Galapagos chiefly of fragmentary material. This difference may be only apparent, for in the Galapagos there is little evidence of the products of the earlier eruptions. It is possible that great quantities of lava were extruded from the major craters, but that these were later masked beneath thick beds of ash. Perhaps in the Marquesas also ash once overlaid the lava, but owing to the long period during which these islands have been in existence, and to the rainy climate, the ashy covering has been eroded away.

In several of the Marquesan islands the top of the volcano has been shattered during an explosive renewal of volcanism, and within the resulting caldera a new ash cone has been built up. In the Galapagos the only major volcano that has suffered in a somewhat similar way would appear to be that of Bindloe Island. The other main vents in this archipelago were apparently more effectively blocked, so that the renewed activity expended itself in the erection of parasitic craters on the lower slopes. The last stage recognized in the history of Marquesan volcanism was a dike and sill phase. No such minor intrusions were seen in the Galapagos, probably because they have not yet been exposed by denudation; but no doubt the lava flows, which represent the latest phase here, were fed by dikes. Perhaps the dikes in the Marquesas fed similar flows which formed around the volcanoes lava fields which have since been submerged by subsidence.

In the Marquesas several of the islands have been rent by faulting, and one side has subsided beneath the sea. Only one example of similar faulting was seen in the Galapagos. The volcano at Cape Berkeley, at the northwestern corner of Albemarle Island, has been cut in half along a rift which trends N. 43° W., parallel to one of the major directions of fissuring; its southwestern side has disappeared; and it faces the sea in a line of cliffs more than 2,000 feet high. The interior of the crater is exposed to view. Its floor forms a shelf at a height of at least 1,000 feet above sea level—the "giant's armchair" noticed by Beebe. The faulting took place earlier than the later phases of volcanism, for there is a field of lava, from which rise two small tuff craters, just above sea level at the foot of the fault scarp. These must have been thrown up subsequently to the breakdown of the volcano, probably through the fault fissure itself. I saw no other evidence of faulted coasts, but according to Dall (20, p. 428) Seymour Island is separated from Indefatigable Island by recent faulting. Agassiz states (1, p. 67) that the eastern face of Wenman Island is a perpendicular cliff, and that this side seems to have been sloughed off. Perhaps this is another faulted coast.

The Marquesas have suffered uplift of 2,000 or 3,000 feet, followed by depression of 500 or 600 feet. In the Galapagos there is some evidence of elevation but very little of subsidence.

A low shelf found by Crossland (18, p. 538) around Albany and other tuff islands is no doubt the result of the recent negative movement of sea level. Darwin (25, p. 115) mentioned the occurrence of seashells, belonging to existing genera but specifically indeterminable, interbedded with the tuff of two craters on Chatham Island, and he thought that the tuff had been uplifted with the shells in mass. Wolf (68, p. 250) also claimed to have found a few molluscan remains, up to an altitude of 100 meters, in the palagonite of the smaller craters, which he regarded as a submarine deposit. Without subscribing to all of his views, it is reasonable at least provisionally to accept this suggestion, especially as the tuff commonly has a calcareous cement. It would involve an elevation of a few hundred feet after the formation of the parasitic craters. It is not, however, positive proof of uplift, as eruptions on a shallow sea floor might throw up quantities of calcareous mud and organic fragments which would become mixed with the ashes piled up above sea level, the finer calcareous material being later recrystallized by percolating water. Since the above was written I have heard from Miss Constance Richardson that she thinks sea water has been responsible for the alteration of the tuff. If so, there must have been emergence.

Ochsner found more definite evidence of elevation in the form of fossiliferous marine sediments. These have been described by Dall (20). Certain beds in the cliffs on the east coast of Indefatigable and Seymour islands were ascribed to the Pliocene, a discovery of great interest, proving that the islands have been in existence, and apparently not much smaller, since that time, though no information is given as to the amount of uplift. Other deposits, which form inliers between lava flows at a height of 40 or 50 feet above sea level in southern Albemarle, are believed to be of early Pleistocene age. Probably similar fossiliferous deposits are buried beneath the lava fields of other islands.

Perhaps evidence of elevation is furnished by the distribution of the giant tortoises. Each of the larger islands was formerly the home of its own characteristic species, but on Albemarle five species were found, and the inference is unavoidable that while specific differentiation was in progress the five principal volcanoes composing this island were separated. There is therefore a probability that elevation has occurred here, but there is no certainty of it, as the gradual piling up of ashes and the extension of the lava fields would be enough to unite the five separate islands.

The almost complete non-existence of river valleys deprives us of the best evidence of subsidence, the embayment of valley mouths. The submergence of an undulating lava field would result in an irregular coast line with numerous little spits and low offshore islets. This is exactly what is commonly found, but the same effect would be produced by lava streams flowing into the sea, without any subsidence. That no vertical movement has taken place since most of the flows reached the sea is suggested by their abrupt change of slope at sea level, though evidence of a very slight recent subsidence of northwestern Indefatigable Island is afforded by a partly submerged peat bog found by Crossland (18, p. 539) in Conway Bay.

Thus the geological evidence appears to throw no light on any pre-Pliocene movements, but it suggests that after the period of formation of the parasitic cones there was uplift of a few hundred feet, and that during the phase of lava outpourings the islands have been almost stationary, with slight local subsidences.

Certain zoologists and botanists believe that important subsidences took place in earlier times. The peculiar existing flora and fauna of the archipelago shows strong affinities with that of America, and not with that of the more westerly Pacific islands. While some naturalists, including Darwin (26) and Wallace (60), have ascribed its origin to chance arrivals brought by currents from the mainland, others have pointed out that the prevailing current comes from South America, whereas the affinities of the plants and animals, including the fossils found by Ochsner, are with those of Central America. These authors, including Baur (5) and Gunther (34), believe that the islands were connected with each other, and through Cocos Island with Central America, in Eocene times, but that they were later separated by subsidence. Beebe (6), who first accepted this view, was inclined to modify it after his second visit (7) because of the peculiar conditions then prevailing, in which the currents set from northeast to southwest and carried innumerable logs of wood apparently from the jungles of Central America.

The dimensions of the Marquesan and Galapagos archipelagoes are comparable, both being about 230 miles long from northwest to southeast, but the total land area of the Marquesas is only about 490 square miles, whereas that of the Galapagos is 2,870 square miles, nearly six times as great. It is possible that the Marquesan islands have always been the smaller, but a great part of the difference must be due to the reduction of their land area by faulting, subsidence, and erosion. A consideration of all the facts suggests that the two archipelagoes have a very similar structure, but that the Galapagos, being more recent, have not progressed as far in their evolution as have the Marquesas.

COCOS ISLAND

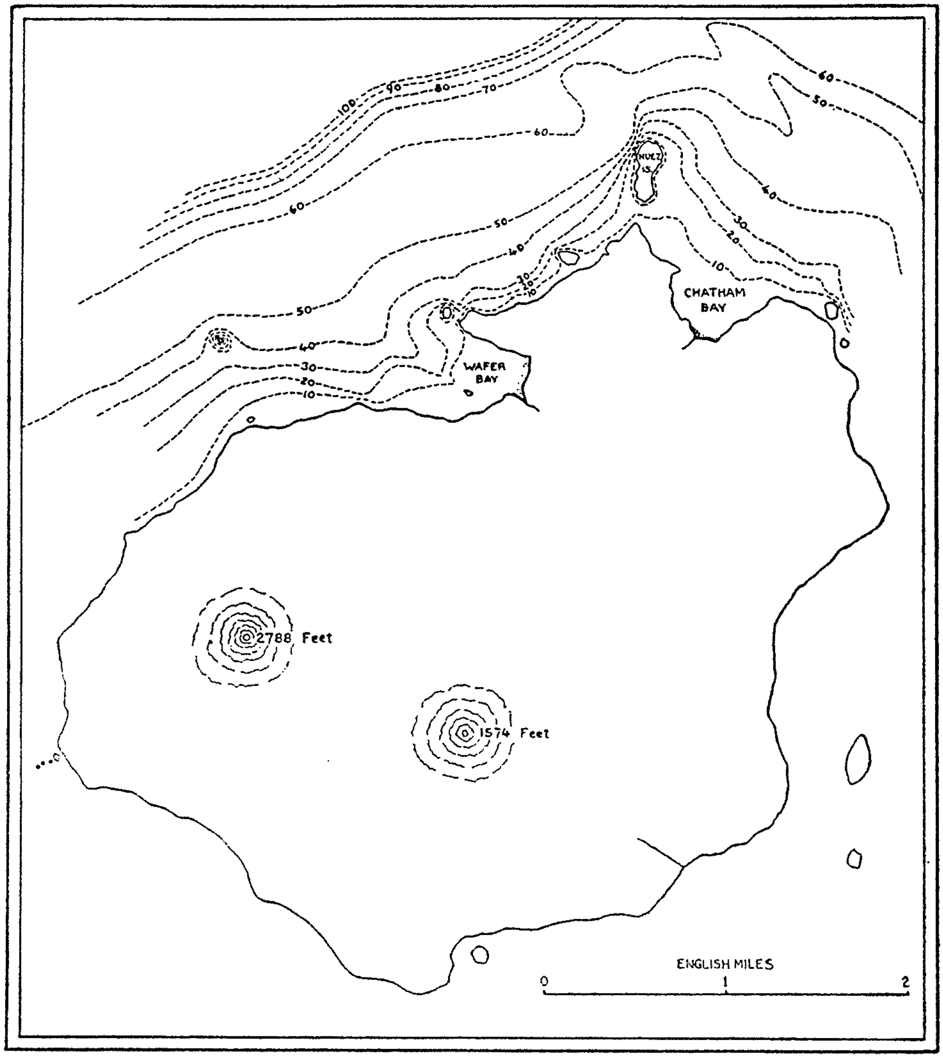
General Features

Cocos Island, in latitude 5° 32′ N. longitude 87° 2′ W., is an uninhabited island over which the state of Costa Rica claims suzerainty (fig. 6). A number of expeditions have visited it with the object of retrieving the treasure of fabulous amount which is reputed to be buried there, but up to the present it has had little attention from geologists. Agassiz (1) called there in 1891 and Beebe (7, pp. 220-281) in 1925. Agassiz included the island in the Galapagos Archipelago, but it should probably be regarded as a separate entity, for it is evidently very much older and is separated from that group by a distance of over 300 miles, with intervening depths of 1,600 fathoms, whereas the depths between the individual Galapagos islands are very much less, many of them less than 100 fathoms. The rocks of Cocos seem to be of very different types from those of the Galapagos. The contrast in appearance between Cocos and the Galapagos islands is very striking, but the differences are due largely to difference in climate. In place of waterless lava fields bearing a sparse desert vegetation, Cocos Island has vertical cliffs, innumerable waterfalls, and impassable tropical jungles (pl. 3). The rainfall is heavy, and our work was seriously hampered by torrential downpours. In aspect Cocos resembles the Marquesan islands, and its history appears to have been, in part, similar.

Topography, Structure, and History

Cocos Island is about 4 miles in diameter and rises to an altitude of 2,788 feet. From the culminating peak the ground slopes down gradually to the summit of the cliffs at a height of about 600 feet above sea level. Lionel Wafer, who visited the island in 1685, wrote (59, p. 192):

> A great many Springs of clear and sweet Water rising to the Top of the Hill are there gathered as in a deep large Bason or Pond, the Top subsiding inwards quite round.



Figurre 6.—Sketch map of Cocos Island, with depth contours at intervals of 10 fathoms.

This suggests the existence of a crater lake, but it is difficult to understand how, in such a rainy climate, it could have withstood subaërial erosion and retained its original form during the long period—to judge by the height of the cliffs—since the island first came into existence. I was unable to explore the interior sufficiently to investigate the matter.

Around three-quarters of the coastline the cliffs rise steeply to some 600 feet above sea level. They show that the island is composed chiefly of massive lava flows which weather to a pale grey and show well-marked columnar jointing (pl. 3), a structure that has facilitated marine erosion. There are many sea caves, and a tunnel one or two hundred yards long and wide enough to permit the passage of a small boat pierces the headland on the north side of Wafer Bay. In places along the base of the cliffs a shore-shelf, a few feet above the sea, gives evidence of the post-Pleistocene fall in sea level.

The offshore slopes are almost precipitous. Close to the base of the cliffs the depths are in places about 30 fathoms; indeed, near Nuez Islet off the north coast the depth is 48 fathoms within a few yards of the shore. A submerged plateau, at a depth of between 50 and 70 fathoms, has been proved to a distance of a mile and a half from the shore. From it rise many islets and rocks, commonly of sugar-loaf form.

As in the Marquesas Islands, the smaller streams of Cocos Island have been less efficient in deepening their valleys than have the waves, aided by the columnar jointing of the rocks, in cutting back cliffs, and most of them enter the sea from hanging valleys. Some of the waterfalls leap directly from the top of the cliffs into basins they have hollowed out of the shore shelf, leaving the cliff face behind them dry. Two of the rivers were much more effective, perhaps because they flow over softer rocks—the only ashy beds seen formed the bank beside one of them—or perhaps because they drain larger areas of the island's surface. This suggestion can not be verified till a survey of the interior has been carried out, but these streams seem to carry more water than do the cascades over the cliff face.

The mouths of these two streams have been embayed and form Wafer and Chatham bays on the north coast. Wafer Bay was found to be a typical embayed river valley. At the center of the entrance the depth exceeds 30 fathoms. At the head a swampy deltaic plain extends some half-mile inland. Chatham Bay was not visited.

It is clear that when the cliffs were being formed the island stood some two or three hundred feet higher above sea level than it does now, but that since then either it has subsided or the sea level has risen, with the result that the lower part of the cliffs is submerged and the lower reaches of the more mature river valleys are flooded.

There are no coral reefs around Cocos Island. The surrounding water is clear, the mean surface temperature is about 80° F., and the extreme annual range about 10° F. These conditions would seem to be very favorable to coral growths, but probably the water is occasionally chilled by extensions of the Peruvian Current.

PETROLOGY

The only published information on the petrology of Cocos Island is a description and partial analysis by Merrill (40) of a rock collected by Agassiz from near Chatham Bay (Table 1). This was described as a pale, fine-grained rock consisting chiefly of orthoclase and plagioclase, with abundant brown hornblende, granules of iron ore, minute apatites, and ferruginous decomposition products. Merrill thought that the analysis showed the rock to be andesitic rather than trachytic. Lacroix (39, p. 68) thinks that the rock may be tephritic, which would lead to the expectation of basanitoids being found among the more basic rocks.

Table 1. Partial Analyses of Rocks from Cocos Island and Rapa

	1.	2.
SiO_2	56.50	58.91
Al_2O_3	28.20	17.20
Fe_2O_3		1.99
FeO		4.86
MgO	0.98	0.44
CaO	2.83	3.33
Na_2O	6.68	7.28
K_2O	4.25	4.50
Other constituents	....	1.78
	99.44	100.29

1. "Andesite (?)," near Chatham Bay, Cocos Island, analyzed by Merrill (40).
2. Trachytoid phonolite," II.5(6).1.4., Rapa, analyzed by Mountain (55, p. 325).

It is of course impossible to calculate the norm of this rock from the data provided, but if minimum allotments of silica are made to the magnesia and lime, it is found that though no allowance has been made for the demands of the iron the residual silica is insufficient to saturate the alkalies. There can be no doubt, therefore, that the rock contains virtual felspathoids. The analysis, so far as it goes, compares closely with those of trachytoid phonolites from various places in the Pacific; as, for example, Rapa (Table 1). The Rapa rock contains sodalite, and there is 7 per cent of normative nepheline, though it could not be definitely determined if the nepheline was expressed mineralogically.

On the south side of Wafer Bay, beside a small stream, is an exposure of tuff containing angular fragments of lava up to 3 or 4 inches in diameter. The tuff [469] is a very pale buff color, harsh and friable, and very heterogeneous. Little rounded fragments of white pumiceous lava form a noticeable constituent; there is a sparse scattering of angular chips of dark lava; but there appear to be no mineral fragments separated from their groundmass. The tuff was chemically tested for felspathoids, with negative results.

Under the microscope the tuff is seen to be composed of fragments of lava, some angular and some rounded, with an average diameter of 4 or 5 millimeters. Most of these have a glassy base, either pale buff and opaque, buff with clear patches, clear and transparent, black, or yellow. Some have small phenocrysts of untwinned felspar, with a refractive index higher than that of balsam, associated with rare olivine phenocrysts; others have phenocrysts of orthoclase and hornblende. The clear transparent glasses have no phenocrysts. Many of the darker glasses are vesicular and without phenocrysts. Some, however, have phenocrysts of labradorite ($Ab_{40}An_{60}$), and some have minute felspar laths in the groundmass. There are a few fragments of trachyte, with zoned phenocrysts of felspar consisting of andesine in the center, passing into oligoclase or even albite round the margins, in a groundmass of orthoclase laths.

Owing to the shortness of our stay and the torrential rain, I found it impossible to visit the excellent exposures of columnar lava around Wafer Bay, and I had to content myself with collecting beach pebbles. I was careful to select only rocks of types that were abundant on the beach, and as the island has always been uninhabited it can be confidently assumed that these pebbles were derived from the neighboring cliffs. The rocks are of two main types, labradorite-andesite and hornblende labradorite-andesite.

The labradorite-andesite [471A] is grey, with felspar phenocrysts up to 15 mm. long, and small phenocrysts of olivine, in an aphanitic groundmass:

Felspar phenocrysts labradorite, partly $Ad_{35}An_{65}$, but probably including less basic labradorite. They are zoned, incorporating great quantities of impurities in their central parts, but with a clear margin that has an extinction angle slightly different from that of the rest of the crystal. Many are closely twinned in two directions nearly at right angles. Olivine phenocrysts are moderately plentiful, idiomorphic, up to 1.5 mm. long, and fairly fresh. The section shows one microphenocryst of augite, enclosing small felspar phenocrysts ophitically. The groundmass, which constitutes 85 per cent of the rock, is very fine, consisting of minute plagioclase crystals, specks of magnetite, and a little glass.

A rock [470 A] that occurs as fragments in the tuff on the south side of the bay is almost identical, except that it is lighter in color owing to more felspar having crystallized out in the groundmass, and the magnetite being gathered together in microphenocrysts and not disseminated throughout the groundmass.

The hornblende labradorite-andesite [471 B] is a darker grey, with phenocrysts of hornblende 15 mm. long, and of felspar, olivine, and augite, 5 mm. long, in an aphanitic groundmass. There are enclaves of olivine.

Hornblende crystals strongly pleochroic, straw-yellow to orange-brown, and surrounded by dark brown, opaque reaction-rims. They mould themselves on the felspar phenocrysts. The latter fairly plentiful, generally idiomorphic. Many show lamellar twinning in two directions or Carlsbad twinning. They include basic labradorite, verging on bytownite ($Ab_{30}An_{70}$), and probably some less basic plagioclase. The olivine crystals idiomorphic and only slightly altered; the sparse augite crystals allotriomorphic, generally non-pleochroic, and with cleavage poorly developed. There are little phenocrysts of magnetite 2 mm. long. The groundmass, which occupies 80 per cent of the section, consists of laths of labradorite ($Ab_{48}An_{52}$), specks of magnetite, and minute needles of apatite, in a base of brown glass.

The chief mineralogical difference between the two types of rock is the presence in the second of brown hornblende, as in the rock described by Merrill. In spite of this difference the analyses (Table 2) show that chemically the two types are almost identical. The hornblende-bearing rock may be the intrusive equivalent of the other, as hornblende is rare in Pacific lavas but common in the intrusive rocks. The analyses show an alumina content higher than that of any other Pacific rock of similar basicity.

Lacroix has on petrological grounds divided the rocks of the Pacific islands into three categories, a nepheline-bearing series, an intermediate series, and a nepheline-free series (39, p. 57). There is no nepheline, virtual or actual, in the two rocks studied. Rocks of this type (II.5.4.4.) are not common in the Pacific, but they are known from the Galapagos as members of a nepheline-free suite, and in Tahiti and Rapa, where they are associated with nepheline-bearing rocks.

The Cocos Island analyses compare fairly closely with those of the Galapagos basalts, but their alumina and potash content is higher, and their lime content is lower. Except for their abnormally high alumina content they compare better with labradorite-andesites from Rapa and Tahiti. (See Table 2.)

Table 2. Analyses of rocks from Cocos Island and Rapa

	1	2	3	Norms		
					1	2
SiO_2	47.30	46.65	46.50			
Al_2O_3	19.98	20.08	17.63			
Fe_2O_3	0.27	1.94	1.19	Or	8.34	9.45
FeO	7.47	7.35	8.92	Ab	23.58	23.06
MgO	6.17	5.37	5.63	An	37.81	37.81
CaO	9.20	9.30	9.33	Di	3.40	2.29
Na_2O	2.80	2.75	3.38	Hy	3.45	4.45
K_2O	1.40	1.65	1.54	Ol	15.62	12.85
H_2O+	1.90	1.60	0.56	Mg	0.46	2.78
H_2O-	0.70	0.45	0.33	Il	3.50	3.04
TiO_2	1.80	1.60	4.62	Ap	1.34	2.02
MnO	0.35	0.26	0.18			
P_2O_5	0.60	0.88	0.52			
S	Tr.	Tr.	....			
	99.94	99.88	100.33			

1. Labradorite-andesite, II.5.4.4. Wafer Bay, St. George collection No. 471 A, analyzed by Herdsman.
2. Hornblende-labradorite-andesite, II.5.4.4. Wafer Bay, St. George collection No. 471 B, analyzed by Herdsman.
3. Labradorite-andesite, II (III).5.3″.4. Northwest of Mt. Tevaitahu, Rapa, analyzed by Mountain (55, p. 332).

The available information suggests that the Cocos rocks have affinities with those of Rapa, and in view of the presence of virtual nepheline in the rock described by Merrill, they should be included either in the nepheline-bearing or in the intermediate series of Lacroix.

EASTER ISLAND

GENERAL FEATURES

Easter Island, situated in latitude 27° 8′ S., longitude 109° 25′ W., was discovered by Admiral Roggeween on Easter Day, 1722. Since then many voyagers have visited it, but most of them were preoccupied with the gigantic statues and other monuments, and few made observations of geological interest. A summary account of the more important of these visits, with references, has been published by Voitoux (58), and there is no need to detail them here.

Two of these expeditions, however, were of real scientific importance, and though their objects were mainly ethnographic and archaeological, they have furnished almost the only knowledge of the geology of the island previously possessed. In 1886 Paymaster W. J. Thompson, in the American ship *Mohican,* spent eleven days there, and carried out an almost incredible amount of work (56). In 1914-1915 Mr. and Mrs. Scoresby Routledge visited the island on a specially built yacht, spent thirteen months there, and archieved results of outstanding ethnographic interest (52, 53). These investigators as well as Agassiz (2), who visited it in 1905, and Skottsberg (54), who called there in 1917, noted the volcanic nature of the island, and gave some account of the lithology, of the position of some of the craters, and of other topographic details.

Easter Island has many points of similarity with the type of island that constitutes the Galapagos Archipelago. The climate is less arid; indeed, according to Skottsberg (54), the average rainfall is 1218 mm. (48 inches). Yet there are no permanent streams, and the one watercourse seen was dry at the time of our visit. Most of the rainfall finds its way underground, owing to the porosity of the volcanic ashes forming much of the island, and the inhabitants depend for water on wells, springs, including submarine fresh-water springs, and crater lakes. The rainfall is sufficient to maintain a covering of coarse grass over most of the surface, but trees are rare except around Mataveri and Hanga Roa. The rocks are somewhat more weathered than are those of the Galapagos Islands, but subaërial erosion has had little effect in sculpturing the surface of the land. The forms of the craters and of the lava flows have hardly been modified since they came into existence.

TOPOGRAPHY, STRUCTURE, AND HISTORY

Easter Island measures about 14 by 7 miles. (See fig. 7.) Its triangular shape is determined by three volcanoes, of which the largest, Terevaka, forms the main mass of the island, Poike or Katiki the eastern extremity, and Rana Kao the southwestern corner. Terevaka rises more than 1,700

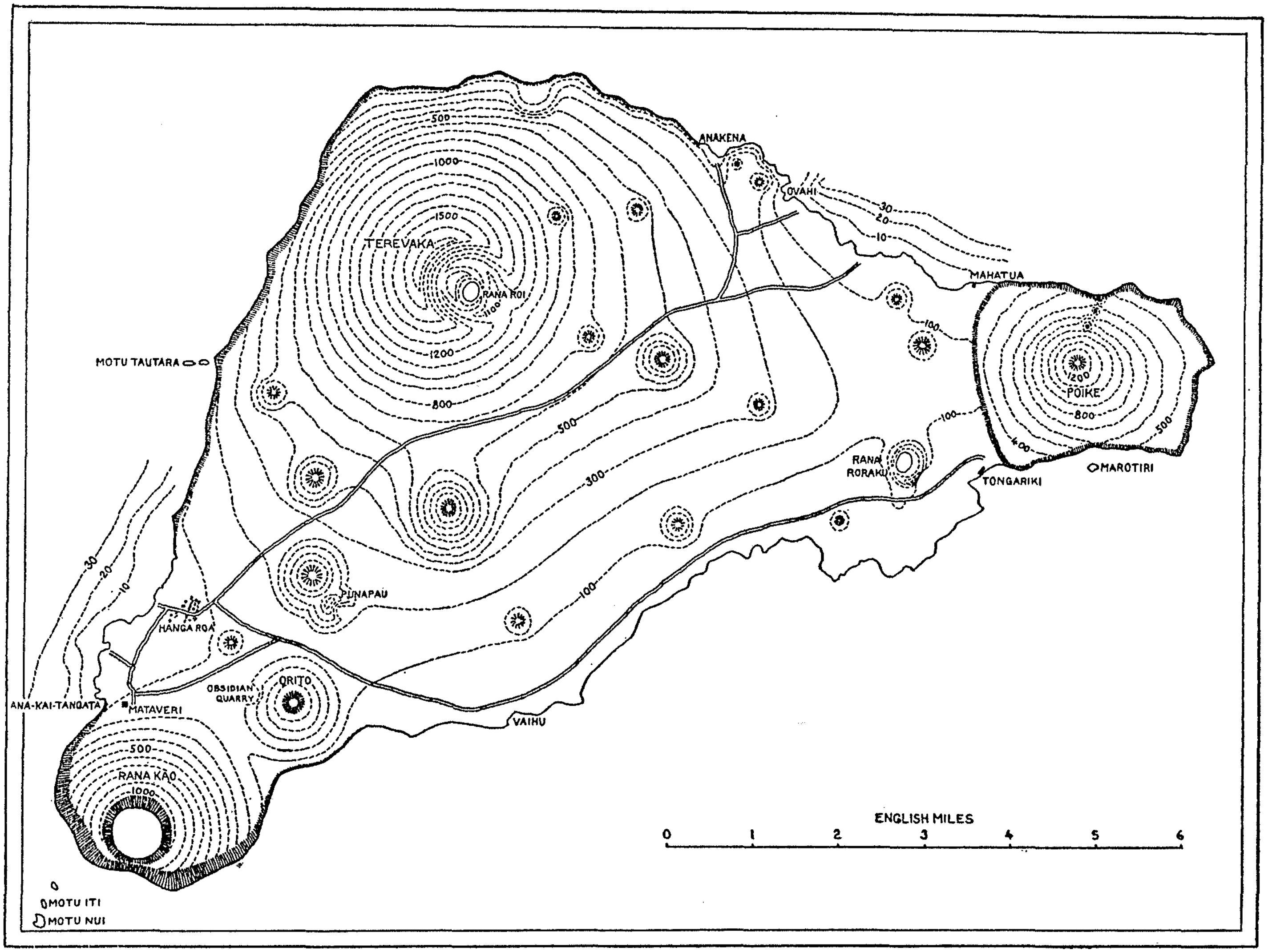


Figure 7.—Topographic map of Easter Island, with approximate contour lines at intervals of 100 feet; steeper cliffs and many of the craters represented by shading; depth contours at intervals of 10 fathoms.

feet above sea level. Its crater was not visited. It seems to be somewhat broken down by subaërial erosion or by an explosive outburst, as on a recent Chilean map an irregular crescentic rampart is suggested. The crater of Rana Kao is occupied by a large circular fresh-water lake, nearly a mile in diameter, the surface of which stands, according to Skottsberg, 390 feet above sea level. Its walls are precipitous and rise to a height of more than 1,000 feet on the northern side. Poike is 1,350 feet high, and its crater is a shallow circular basin, dry and flat-bottomed, some 20 feet deep and 250 feet in diameter.

These three volcanoes are composed chiefly of ashy material, though Rana Kao at least includes some interbedded lava flows. Their slopes are generally gentler than those of the Galapagos volcanoes, and form open grass-grown moorlands. Poike must at one time have formed a separate island, as it is cliffed on all sides, including the western inland-facing side (fig. 8, pl. 5).

From fissures in the southern and eastern flanks of Terevaka successive streams of lava have flowed down towards the southwest, south, and east, and have spread out to form lava fields which unite the three main volcanoes. These flows are more recent than the formation of the other two volcanoes, more recent even than the cliffing of Poike, for they overlap the ashes of Rana Kao immediately to the south of Mataveri and abut against the base of the cliffs of Poike between Tongariki and Mahatua. Here, at the line of junction, is a gully running from north to south across the island, with the snout of the lava flow on one side and the much higher sea-cut cliffs on the other. This feature, the "long-ear ditch," is believed by the natives to be a trench dug for defensive purposes by a long-eared race that inhabited Poike. The Routledges (53, p. 281, footnote) found ancient defensive works on its higher eastern side and ascribed the ditch itself to faulting, but it more probably originated in the way outlined above.

In contradistinction to the ash slopes, the lava fields are generally very rugged; the surface is scattered in places thickly, in others sparsely, with large blocks of lava. Most visitors have regarded these as ejected blocks and have attributed them to a final paroxysmal outburst of volcanism, but they seem to be due merely to the weathering of lava of a-a type. Individual lava flows can often be distinguished, as their sides and ends form terraces 15 to 20 feet high.

Considerable numbers of parasitic tuff craters stand on the flanks of Terevaka and rise from the lava fields around it. They are arranged on lines which radiate from a point about a mile west of the main crater. One of the most prominent of these is a line of five cones running east-southeast. The most westerly of these cones, Rana Roi, which contains a fresh-water lake in its crater, appears to stand within the main crater of Terevaka, for on the Chilean map a crescentic rampart surrounds its western side, from

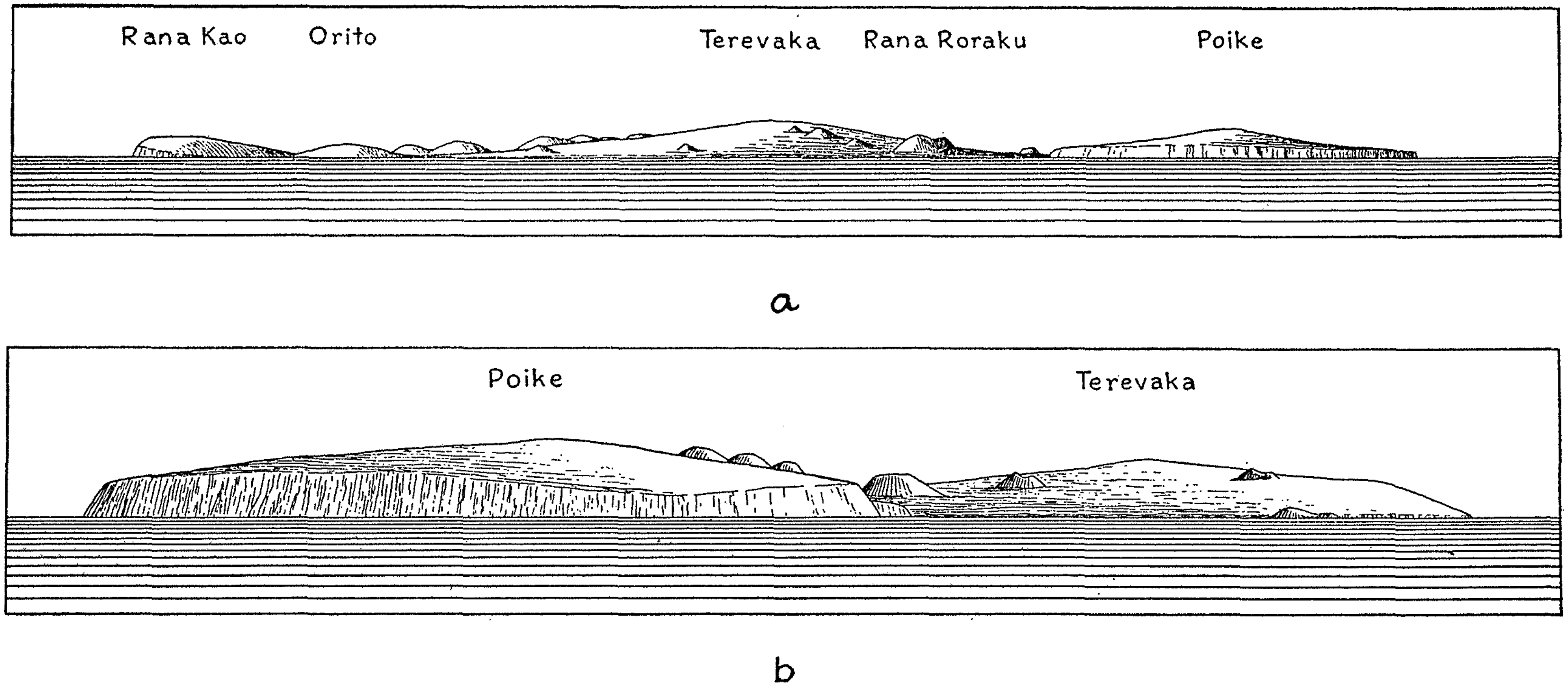


FIGURE 8.—Sketches of Easter Island: *a,* from southeast; *b,* from east-northeast.

which it is separated by a moat-like depression. According to Skottsberg (54, p. 5), there is also a depression on the east of Rana Roi, into which the lake overflows after prolonged rains, and which is probably a continuation of the moat, as has been suggested on the map (fig. 7). The most easterly cone in the line is the famous Rana Roraku, or Image Mount (pl. 4), a small tuff crater containing a fresh-water lake and the site of the quarries whence the well-known statues were carved. Another notable parasitic cone is Punapau, situated a mile to the east of Hanga Roa, composed of a red ash from which the "hats" for the statues were quarried. Orito, a mile and a half east of Mataveri, is composed not of ashes but of obsidian, a rock rare in the Pacific islands.

On Poike a line of three parasitic cones radiates north-northeastward from the main crater (fig. 8, *b*). On Rana Kao there are none; perhaps it should itself be regarded as a large parasite on Terevaka.

Where the coast is composed of lava there are cliffs generally between 50 and 100 feet high, but where it is of ashy material the cliffs attain heights of nearly 1,000 feet around Rana Kao and of 500 to 600 feet north and west of Rana Roi and around Poike. The inland cliffs on the west of Poike are about 300 feet high.

In places a shore shelf a few feet above high water level was found at the foot of the lava cliffs, but all evidence of the recent fall in sea level seems to have been obliterated by marine erosion from the cliffs of softer rock.

Easter Island is surrounded by a submerged platform of unknown extent which attains depths generally of 30 to 40 fathoms a mile from the shore. The height of the cliffs shows that it must in places be much wider than this. About 10 miles north of the island a depth of 1,145 fathoms with a bottom of volcanic sand has been recorded. At 20 miles the depth is 1,770 fathoms and the bottom globigerina ooze.

There are no coral reefs around the island. The mean ocean surface temperature is about 70° F., and the extreme annual range about 15° F. A winter temperature below 70° F. would completely inhibit coral reef development.

I was unable to find any evidence either of subsidence or elevation; indeed, several considerations suggest that the island has stood at its present level for a long time. There has been no appreciable movement since the post-Pleistocene fall in sea level. Nowhere are any considerable depths found close to shore; at a distance of 500 or 600 feet the depth is generally less than 100 feet; and the bottom apparently slopes away gradually from the base of the cliffs. Evidently there has been no uplift or subsidence since the cliffs were formed. The southeastern side of Rana Roraku has been cliffed, though the sea is now nearly a mile away. (See pl. 5.) In the absence of other evidence of elevation it is probable that the retreat of the sea was due to the extension of the land by lava which flowed from the flanks of Terevaka around the base of the crater.

There is no evidence of faulting such as is characteristic of the Marquesas, and to a lesser extent of the Galapagos. The high cliffs here are evidently due purely to marine action. Judging by the height of these cliffs, it is probable that the island is considerably older than the Galapagos Archipelago.

Table 3. Analyses and Norms of Easter Island Rocks

	1	2	3	4	5	5a	6	6a
SiO_2	71.92	59.75	50.02	49.67	45.52	51.81	40.12	50.24
Al_2O_3	13.59	15.42	15.28	14.46	14.32	16.30	13.27	16.62
Fe_2O_3	0.51	3.47	1.82	18.52	6.92	7.87	10.65	13.34
FeO	2.71	7.03	10.86		5.14	5.85		
MgO	0.07	0.93	3.31	3.74	2.98	3.40	3.32	4.16
CaO	1.08	4.50	8.08	7.23	5.88	6.69	9.47	11.86
Na_2O	5.93	4.75	4.42	2.92	2.89	3.29	2.06	2.57
K_2O	3.37	1.74	1.37	1.64	1.34	1.52	0.97	1.21
H_2O+	0.18	0.35	0.81	1.17	4.81	....	20.43	....
H_2O-	0.11	0.50	0.33		7.22	....		
TiO_2	0.28	0.70	2.42	....	2.40	2.73	....	....
MnO	0.11	0.38	0.20	....	0.20	0.23	....	....
P_2O_5	nil	0.34	0.40	....	0.27	0.31	....	....
S	....	Tr.	....	....	....	....	....	....
CO_2	....	nil	0.70	....	0.30	....	....	....
	99.86	99.86	100.02	99.35	100.19	100.00	100.29	100.00
Norms								
Q	21.42	12.18	....		8.82	10.09		
Or	20.02	10.01	8.34		7.78	8.90		
Ab	49.78	40.35	37.20		24.63	28.17		
An	0.56	15.57	17.79		21.96	25.11		
Di	4.43	3.84	12.90	Data insufficient	2.81	3.21	Data insufficient	
Hy	2.08	9.82	2.25		6.23	7.12		
Ol	....	....	10.78		....	....		
Mt	0.70	5.10	2.55		9.98	11.41		
Il	0.61	1.37	4.56		4.56	5.22		
Ap	....	0.84	1.01		0.67	0.77		

1. Rhyolitic obsidian, I″.4.1.4, Mt. Orito, analyzed by Raoult (39).
2. Andesite (α), II.4′.2(3).4., Mataveri, St. George collection No. 862, analyzed by Herdsman.
3. Andesitic basalt (β), II(III).5.′3.4.[2.′3.2(3)4.], fragment extracted from andesitic tuff, probably Rana Roraku (Mataveri according to Lacroix), analyzed by Raoult (39).
4. Sideromelane, locality not recorded, analyzed by Rosenbusch.
5. Andesitic tuff (α), II.4(5).3′.4.[3(4).1.1′.3.], probably Rana Roraku (Mataveri according to Lacroix), analyzed by Raoult (39).

5a. The same, calculated on a water-free basis.

6. Palagonite, locality not recorded, analyzed by Rosenbusch.

6a. The same, calculated on a water-free basis.

PETROLOGY

Although several of the earlier writers gave some account of the field characters of the rocks of Easter Island, only Velain (57) attempted a petrological description, based on a fragment of a statue preserved in Paris. Rosenbusch (51, p. 333) published analyses of two rocks. Unfortunately these are of less value than they might be, as the ferrous and ferric iron were not differentiated, and some of the minor constitutents (as TiO_2, P_2O_5, MnO) were not determined. Speight (8, pp. 66-67) has given a brief account of rocks collected by Macmillan Brown (see p. 43). Recently Lacroix (39, pp. 47-49) has published a description with analyses of three rocks. He describes the tuff forming the Paris statue, previously studied by Velain, and its included fragments, as coming from Mataveri, but though this was the place where the statue was found by the expedition that brought it to Paris, there can be no doubt that it was originally quarried at Rana Roraku, the source of every statue on the island, except for one of basalt, now in the British Museum. Lacroix expresses the opinion that the rock forming Rana Roraku is probably the lithoidal equivalent of the obsidian of Mount Orito, but his own description of the statue rock proves that this is not so. The tuffs of Rana Kao, however, appear to correspond with the obsidian.

The five analyses already published, together with one new one, are given in Table 3. In Lacroix's original paper the analyses of the tuff and the basalt were interchanged by a printer's error which is here corrected with the authority of the author.

OBSIDIAN

As obsidian [853, 857, 861] has always been used by the natives for the manufacture of implements, fragments of it are to be found scattered over the surface of the whole island, but the source of all this material is Mount Orito, which is composed of it. Fragments of exactly similar rock are included in the tuffs of Rana Kao. It is an ordinary black obsidian, with an irregular conchoidal fracture, showing flow structure, and with pumiceous streaks.

Under the microscope it is seen to have a sparse scattering of laths of orthoclase, 1.5 mm. long, with Carlsbad twinning. There are still fewer little crystals of green augite, 0.5 mm. long. The groundmass is an almost colorless glass, with a refractive index less than that of orthoclase, with streaks of tiny vesicles, and minute needles of indeterminable minerals, which, however, react to polarized light.

The obsidian of Mount Orito, a description and analysis of which (Table 3) have been published by Lacroix (39, pp. 48-49) is very similar. It contains 21 per cent of virtual free silica. It is an unusual type in the Pacific, but a similar rock occurs at Tutuila (39, p. 53).

RHYOLITIC TUFF

On the western side of Rana Kao is a rhyolitic tuff [859] containing fragments of obsidian and of andesitic lavas. The tuff is composed of fragments, generally between 2 and 20 mm. in diameter, of a pale yellow lava which is as soft and friable as chalk, and so light that it will float on water. An exceptionally large fragment of this lava, more than 60 mm. in diameter, was found. It is streaked with innumerable much-elongated vesicles, and with a few threads of ordinary black obsidian.

In thin section it is seen to be composed of a pale transparent glass, with a refractive index lower than that of balsam, very closely striated, and almost devoid of crystalline matter, except for a very few minute felspars, apparently orthoclase, and one triangular crystal of quartz.

It is apparently a special form of the obsidian and owes its lightness to its intensely vesicular structure. It differs markedly, however, from the pumiceous bands in the obsidian of Mount Orito and even from those in the obsidian fragments incorporated in the tuff. These bands are not yellow, but grey, and they are hard and harsh instead of being soft and friable.

ANDESITE

A fragment of andesite [862] was collected south of Mataveri from a lava flow emanating from the north and overflowing the tuffs of Rana Kao.

The rock is aphanitic, light grey weathering brown, with hackly fracture, and flow structure.

In thin section the rock shows very few small felspar phenocrysts, 1.5 mm. long, which are generally untwinned or have Carlsbad twinning only. Their refractive index is slightly greater than that of Canada balsam, and they appear to be oligoclase. There are a very few irregular crystals of magnetite, 0.5 mm. in diameter. The groundmass consists of a scattering of minute laths of felspar and specks of magnetite in a patchy base of brownish glass.

As the rock seemed to be intermediate in type between the obsidian and the andesitic rocks, it was analyzed (Table 3). It was found that the silica, percentage 59.75, lies almost exactly halfway between those of the other two types, and the percentages of the other constituents serve to bridge the gap. The rock contains 12.18 per cent of virtual free silica. The normative plagioclase is oligoclase $Ab_{72}An_{28}$. The analysis compares closely with those of the circum-Pacific andesites.

ANDESITIC BASALT

Andesitic basalt (β) seems to be the predominant type of rock on Easter Island. It occurs as flows in many parts, and the fact that it is the only type known to occur as ejected fragments in the tuffs of Rana Roraku suggests that it is present in bulk below the surface.

Lacroix (39, p. 48) has described these fragments as compact or slightly vesicular rocks, with small phenocrysts of olivine and augite, large microlites of andesine ($Ab_{55}An_{45}$), with smaller microlites of a more acid felspar, of augite, and of magnetite, and a little brownish glass.

Some of the fragments from Rana Roraku that I have examined differ in that they contain no recognizable olivine, and in a few some of the felspar appears as small phenocrysts. On the whole, however, all seem to be of the same type.

A lava [858] from near Orongo, on Rana Kao, is typical of the flows of this type of rock. It is light grey, with patches of orange-brown decomposition products, showing phenocrysts of felspar up to 6 mm. long and smaller ones of augite, in an aphanitic groundmass.

The felspar phenocrysts are andesine, $Ab_{53}An_{47}$. Many are untwinned, or with Carlsbad twinning only. The larger crystals are crowded with impurities which tend to form a network over the surface, but their margins are usually clear. They generally show optical zoning too, the outer zone having a refractive index slightly lower than that of the inner, but still higher than that of Canada balsam. The augite crystals are small and elongated and contain a network of impurities similar to that in the felspar. There is a scattering of small crystals of magnetite up to 0.25 mm. in diameter. The groundmass is brown glass, with many incipient felspar microlites. No olivine is recognizable.

The rock differs from those previously described in that it contains no free silica but more than 10 per cent of virtual olivine. (See Table 3.)

Rosenbusch's sideromelane is probably a glassy form of the same rock. The analysis (Table 3) differs little except for its much higher percentage of iron, but perhaps other constituents are included in this figure.

ANDESITIC TUFF

Specimens of andesitic tuff [855] from the statue-quarries on Rana Roraku confirm the opinion that this is really the source of the rock described by Lacroix as being derived from Mataveri.

The tuff is a harsh friable yellowish rock composed of angular fragments of an average diameter of 2 or 3 mm., the majority of which are of brown palagonite, though a few are of black glass. Most are closely and finely vesicular. They contain a few microphenocrysts of felspar commonly showing simple, and rarely, multiple twinning, consisting chiefly of basic andesine ($Ab_{52}An_{48}$), but including also some labradorite ($Ab_{44}An_{56}$). There are a few microphenocrysts of augite.

Raoult's analysis (Table 3) shows that the rock is considerably hydrated. As recalculated (Table 3) on a water-free basis it closely resembles that of the andesitic basalt, but it differs in that the norm shows 10 per cent of virtual free silica. Except for the statement that it contained some sideromelane and zeolites, Rosenbusch gave no description of the palagonite. The rock is the most basic recorded from Easter Island. If the analysis be recalculated with omission of the water (Table 3), it compares closely with that of the andesitic tuff similarly recalculated, except that it shows a considerably higher percentage of lime. Probably it is the same rock, and the extra lime is due to the presence of zeolites.

Evidently the rocks of Easter Island differ very considerably from those of Cocos Island. If the analyses of the andesitic types are recalculated on a water-free basis, they show higher percentages of silica, iron, and the alkalies, and lower percentages of alumina and magnesia than those of the Cocos andesites. None of the Easter Island rocks contain felspathoids, virtual or actual; indeed, of the four completely analyzed, three contain a considerable percentage of virtual free silica. These rocks show affinities with those of Pitcairn and Mangareva (39, pp. 43-46), and to some extent with those of the Galapagos and of the Marquesas (14, pp. 23-48).

Theories of Origin

It is evident from the foregoing description that every geological consideration leads to the conclusion that Easter Island is a typical oceanic island, a volcano rising from great depths, formed by a series of eruptions that probably originated on the floor of the ocean.

Certain ethnographic and popular writers have put forward opinions that are at variance with these conclusions. Barclay, who commanded H. M. S. *Topaz* at the time of her visit in 1868 (4), propounded the theory that at the time the monuments were erected Easter Island formed part of a much larger island, of an archipelago, or of a continent which was united with South America, but which has since subsided beneath the sea. These theories are based on the belief that the construction of the monuments would require a larger population than the island could support, and have found other advocates.

It is possible, even probable, that in ages geologically remote large areas of the Pacific, including the site of Easter Island, were occupied by continental land which was united with South America, but it is highly improbable that such conditions existed within the very recent period of human occupation. The intervening depths are great, considerably exceeding 2,000 fathoms eastward and northeastward from Easter Island, and sinking to 3,500 or 4,000 fathoms as the continental coast is approached. Southeastward the ocean is somewhat shallower, but even here the depths are of the order of 1,500 or 1,800 fathoms.

Although nearly all visitors have recognized the volcanic nature of the island, some of them, including even such conscientious and unbiased investigators as Thomson and Routledge, have reported or suggested the occurrence there of rocks of continental types. Thomson (56, p. 450) expressly states that the formation is of a purely volcanic nature and gives details of the field characters of the rocks which fully confirm the statement, yet in a vocabulary he gives native names for slates, granite, and flinty beach pebbles. According to Routledge (53, p. 175), the ashes of Rana Roraku contain numerous lapilli of metamorphic rock. On the strength of these statements, Daly (21) included Easter Island in his list of islands containing continental rocks. I hoped therefore to find among the ejected fragments definite evidence of a submerged continental platform below the island, but my hopes were not realized. A close study was made of the rock fragments included in the tuffs of Rana Roraku, Rana Kao, and other craters, but so far as my observations went all were of volcanic rocks, of types similar to those forming the surface flows.

Thomson's "slate" is probably a lava showing platy jointing. This type is not uncommon. It forms, for example, the roof of the sea cave Ana-kai-tangata near Mataveri, a cave that owes its origin to lava overflowing a mound of tuff. Owing to its rapid cooling, the lower part of the flow has developed a platy jointing parallel to its floor. Subsequently the sea has eroded away most of the tuff to form the cave. The "granite" is perhaps a coarsely porphyritic basalt or dolerite, the "flinty" rock a fine-grained lava. The "metamorphic rocks" of the Routledges are fragments of lava, some of which may have been more or less glazed on the surface by the heat of the eruption that shattered them; but this can hardly be called metamorphism. They certainly show no sign of having been affected by metamorphism on a regional scale.

The occurrence of rocks of continental types has been recorded from other mid-Pacific islands, but when specimens have been collected and subjected to petrological examination the record has generally been found to be erroneous. For example, Lacroix has proved the "granite" of Borabora to be an olivine-gabbro which was no doubt intrusive in the basalts (39, p. 27), and the "leptynite" of Nukuhiva to be a trachyte of a type not uncommon on the island (39, p. 40).

It is unlikely that the investigators who made these and similar records would desire or expect that far-reaching geological conclusions should be based on their casual use of terms which seemed to them to be descriptive of the rocks they saw, but which they did not intend to be interpreted in a strict petrological sense. If continental rocks do indeed occur below any of these islands, they must be at such a depth, probably 2 or 3 miles, that any fragments of them that were carried up were completely assimilated by the ascending lava before they reached the surface.

There is abundant evidence that at the time when the monuments were built the coastline of Easter Island was substantially the same as it is now.

The monuments are erected close to the shore, in some places only a few feet above sea level, in others on the summits of sea cliffs several hundreds of feet high. The sites were obviously selected for their proximity to the sea. If the island formed part of a larger island or continent, the cliffs would not have been in existence and the inhabitants would have had no means of knowing how the coastline would run at the present epoch, and no object in using this knowledge, if they had it, in the selection of sites for their monuments. No perceptible movement of emergence or submergence has taken place since the post-Pleistocene fall in sea level, that is, according to Daly, during the last 3,500 years. Evidently the theory that the island is a relic of a much larger land mass that has subsided within the human period must be abandoned.

The theory that Easter Island is the last remaining fragment of a large vanished archipelago has recently found an ardent advocate in Professor J. Macmillan Brown, who spent five months there in 1921-1922 (8). Part of Brown's evidence is drawn from reported discoveries of early voyagers. For example, Juan Fernandez claimed to have found in 1576, after a month's sail southwest from Callao, a large inhabited land which he took to be a great southern continent. John Davis reported that in 1687 he saw, about 500 leagues from the Chile coast, in latitude 27° S., a small sandy island, and to the west of it a long tract of high ground. Brown believes that these travelers saw some of the islands of the hypothetical archipelago, and scornfully dismisses Routledge's suggestion that what Davis saw was the Mangareva (Gambier) Islands, which correspond well with his description. The distance of Mangareva from the Chilean coast is nearer 1,500 than 500 leagues, but as he had no better method of determining longitude than that of dead reckoning, Davis may well have been 1,000 leagues out in his calculations. Errors of this order were not uncommon. Mendaña, for example, when he first sighted the Marquesas Islands in 1595, believed that he had rediscovered the Solomon Islands, which actually lie about 1,200 leagues farther west. Fernandez's account is obviously exaggerated, and there is nothing to indicate in what part of the Pacific lies the land he discovered.

Brown has pressed geological arguments into service in the attempt to prove the former existence of extensive land. He states (8, pp. 18-19, 51):

> The material [composing Rana Roraku] is puddingstone or conglomerate; the original dust has been perhaps laid in shallow water and sprayed with angular fragments of shattered rock, some volcanic, others that look like altered slate or fire-clay, and others that may be granite. The strata have been hardened by pressure and then forced from the horizontal to the vertical position by the volcanic thrust of the lava below. . . .
>
> In the great statues and the strata from which they have been cut there is indication of a different condition of land in so landless a region. . . . The strata [of Rana Roraku] have been laid in a shallow inland sea with its bottom rising through the ages; the volcanic dust showered into it from high mountains has been allowed to settle without disturbance.

Rana Roraku is a perfectly normal little crater composed of bedded ashes which were obviously derived from the crater itself and which have the usual quaquaversal dip. They have not been subjected to any later disturbance. The field evidence is entirely in favor of the crater having been formed on dry land, and the included fragments show no sign of water action. Speight (8, pp. 66-67) described Brown's own specimens of the statue material as a basic volcanic agglomerate consisting of fine-grained matter including palagonite and broken shreds of basic felspar, in which were angular fragments of basalt and augite-andesite. He found no calcite or other evidence that the material was laid down on the sea bottom. He made no mention of granite, slate, or fire clay. Lacroix states definitely (39, p. 48) that the tuff composing the Easter Island statue now in Paris is of subaërial origin.

It is certainly extraordinary, if such enormous subsidences have taken place both east and west of it, as Brown believes, that Easter Island itself has not subsided a yard.

According to Skottsberg (54, p. 8), the flora and fauna of the island are very poor, apparently just such as might be expected on a remote oceanic island which had always been small and isolated and which had been peopled only by occasional chance arrivals.

Brown's theory is based largely on highly speculative ethnographic arguments which involve putting entirely new interpretations on most of the native legends, comparable to those put upon the geological evidence. They can not be discussed here, but it is strange, if such a stupendous catastrophe has taken place within the last 250 years, that there should be no more definite record of it in native tradition.

There seems to be little doubt that the population of the island was between 2,000 and 3,000, a number amply sufficient to carry out the construction and erection of the monuments if the work were continued over a period of several centuries, as native traditions suggest. Thus the only real argument for supposing the island to be a relic of a larger land mass or of an archipelago that has existed within the period of human occupation falls to the ground.

REGIONAL RELATIONS

In previous papers (12, 13, 14) certain views have been expressed on the regional relations of the islands of the central and southern Pacific, and these may now be extended to embrace other islands including those described in this paper.

Under the east central Pacific there lies a vast area, the Albatross Plateau, under depths of less than 2,000 fathoms, though on all sides the depths exceed this figure. No islands rise from the central part of this plateau, but at each end is an archipelago that appears to have been built up on a set of intersecting fissures, the Marquesas at the western end, and the Galapagos at the eastern. On or near its southern margin too there are several volcanic islands, including the Mangareva (Gambier) Archipelago, Pitcairn, Easter, Sala-y-Gomez, and the Juan Fernandez islands.

It is suggested that the plateau constitutes a resistant block which has withstood lateral pressure that has been brought to bear on it from all sides, that around its margin it has become cracked and fissured, and that on the fissures volcanic islands have been erected. That these islands owe their origin to a common cause is suggested by the similarity of their structure and geological history, so far as it is known. In this paper attention has been called to these similarities so far as the Galapagos, the Marquesas, and Easter Island are concerned. Pitcairn appears to be a volcano resembling that at Cape Berkeley, Albemarle Island, in that it has been rent by faulting.

Petrographically, too, these islands resemble each other and differ from most of the other Pacific islands. The most striking characteristics of their rocks are the almost complete absence of nepheline-bearing types and the presence of virtual free silica in many.

Cocos, St. Felix, and St. Ambrose islands are constituted in part of nepheline rocks, and for this reason they are regarded as lying, not on the resistant block, but beyond its eastern margin. Petrographically they resemble the Society Islands and Austral Islands which lie to the west of the plateau.

It is thought that beyond the margins of the block the crust is more pliable and has yielded to pressure, with the formation of anticlines and synclines. Volcanoes that have produced nepheline-bearing rocks have been erected on the anticlines. The folds have tended in the western area to migrate from southwest to northeast with a wave-like motion proved by the history of their coral reefs. There is not sufficient evidence, however, to determine whether the folds which probably underlie Cocos, St. Felix, and St. Ambrose islands have suffered a similar movement.

Petrology of the Galapagos Islands

By

CONSTANCE RICHARDSON

INTRODUCTION

Petrological descriptions of rocks from the Galapagos Islands are given in papers by Rosenbusch (50)*, Gooch (33), Merrill (40), Lacroix (39), and Washington and Keyes (62), and some old analyses of palagonite tuffs are presented by Bunsen (9). Rosenbusch (50) describes a palagonite tuff from James Island, but this paper is really concerned with rocks from the Kaiserstuhl. Merrill (40) describes a basalt from Chatham Island and other rocks from the neighboring Malepelo and Cocos islands collected by the Albatross Expedition. The paper by Gooch (33), entirely devoted to the Galapagos Islands, describes basaltic lavas and scoriae, pumice with orthoclase crystals from Indefatigable and Abingdon islands, and an olivine bronzite bomb from Charles Island. Lacroix (39, pp. 67-69) summarizes all that was at the time known about the constitution of the Galapagos Islands and adds two short descriptions with analyses of a felspar-rich and an olivine-rich basalt sent him by Chubb as representing the two dominant types of lava developed in the archipelago. Washington and Keyes (62) describe and give analyses of an andesine basalt and a palagonite tuff brought back by Beebe from Eden Islet.

The rocks described in this paper were collected by Darwin during the voyage of the *Beagle* in 1835 and by Chubb during the St. George Expedition in 1924. They include lavas, gabbroic xenoliths, tuffs, and ejected fragments from tuffs and agglomerates. Between the two collections, the main islands are fairly well represented. The bulk of Darwin's specimens are in the Beagle Collection, now in the Sedwick Museum, Cambridge. A few are in the Geological Survey Museum, London. In the petrological descriptions which follow, Nos. 3220-3289 refer to specimens from the Beagle Collection in the Sedgwick Museum, Cambridge; Nos. 323-467 refer to specimens collected by Chubb, a set of which will be deposited in the British Museum, London, and another in Bernice P. Bishop Museum, Honolulu; Nos. F3146-F3154 refer to slides of specimens belonging to the Geological Survey Museum, London.

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* Numbers in parentheses refer to Literature Cited, pp. 65-67.

As many of the specimens from different islands of the Galapagos Archipelago are very similar, it will be most convenient to describe them according to rock types and afterwards to give a summary showing where these are developed.

LAVAS

The lavas of the Galapagos Islands are almost all basaltic, but they include a trachyte, an oligoclase andesite, and a spilite [F 3153]. This is, as far as the writer is aware, the only recorded spilite from an island in the Pacific; but as the specimen was collected nearly a century ago, it may easily have been incorrectly labeled.

TRACHYTE

The soda trachyte [3268] from James Island is compact, greenish-grey, with a few small crystals of felspar visible to the naked eye. A thin section shows abundant phenocrysts of felspar, a few of augite, and also occasionally hornblende, olivine and magnetite set in a trachytic groundmass.

The felspar phenocrysts form about 8 per cent of the rock and generally contain inclusions of augite and have rounded outlines, but a few are lath-like in section. They often show patchy extinction, zoning, and also twinning according to Carlsbad, Albite, and sometimes other laws. The twinning tends to be irregularly developed, but symmetrical extinction angles of about 4 and 7 degrees were obtained in one example of combined Carlsbad and Albite twinning. Most of the crystals are negative with a fairly large 2V, but a few have a large positive 2V. Determination of refractive indices by immersion method gave 1.545 for the highest and 1.523 for the lowest. The highest index is greater than $\gamma = 1.541$ for a potash-oligoclase ($Or_{18}Ab_{64}An_{18}$) from Erebus, and the lowest rather below $\alpha = 1.526$ for an anorthoclase ($Or_{27}Ab_{63}An_{10}$) from Kenya recorded by Mountain (42, p. 336). As there is no evidence that two separate felspars are present, these data are taken to indicate a felspar whose composition has changed during crystallization from potash-oligoclase to anorthoclase. The approximate average composition of the total felspar present in the rock as calculated from the norm is $Or_{23}Ab_{72}An_5$. Since the lowest refractive index of the groundmass felspar is the same as that of the phenocrysts, the average composition of the phenocrysts must be more calcic than $Or_{23}Ab_{72}An_5$, and is probably potash-oligoclase rather than anorthoclase.

The augite phenocrysts are smaller, rounded, and pale green with a strong dispersion and an extinction angle of 45 degrees. They have a narrow darker border where $Z \wedge C$ rises to 52 degrees, and are not therefore appreciably alkaline.

The rare hornblende phenocrysts are of two distinct varieties. The most abundant has an extinction angle $Z \wedge C = 15°$, and shows very strong dispersion and unusual pleochroism with X = brownish-yellow, Y = violet, Z = deep blue-green, $Z > Y > X$; and has the following approximate refractive indices $\alpha = 1.664$, $\beta = 1.685$, $\gamma = 1.688$. It appears to be allied to hastingsite, but the pleochroism is somewhat different. There are only a few fragments of the other hornblende which are deep brown and translucent and show some pleochroism. They are identical with identifiable cossyrite occurring in the groundmass.

The olivine phenocrysts are yellowish and markedly negative with high double refraction and are evidently near fayalite in composition.

The groundmass has a trachytic texture, and is composed largely of laths of anorthoclase which show faint Albite and Carlsbad twinning. Green, pleochroic, strongly-zoned, aegirine-augite ($X \wedge C = 35^\circ$–5°), and both types of hornblende found as phenocrysts occur in raggy interstitial patches. The brown hornblende is intensely pleochroic with X = pale brown, Y = golden brown, Z = deep purplish brown, opaque except in very thin flakes, $Z>Y>X$, and $Z \wedge C$ about 35°. It is, therefore, referred to cossyrite. There is in addition a very small quantity of magnetite sprinkled through the slice. Neither nepheline nor quartz was detected, but the latter is present in the norm to the extent of 1.69 per cent.

An analysis of this trachyte (Table 4, no. 1) shows an unusually high percentage of alkalies with rather more than twice as much soda as potash. Analyses of similar rocks that contain about the same percentages of alkalies show rather more Al_2O_3 and less total iron, with the result that they contain a much smaller proportion of femic minerals. The mode of the trachyte does not show much relation to the norm owing to the presence of alkaline hornblendes and aegirine augite.

Table 4. Analyses of Trachytes

	1	2	3	4	5	Norm of 1		Mode of 1	
SiO_2	61.90	61.69	63.43	63.84	62.17	Q	1.69	Phenocrysts	
Al_2O_3	16.75	17.33	18.64	18.46	18.58	Or	19.24	Felspar	8.3
Fe_2O_3	2.27	5.30	2.78	1.54	2.15	Ab	58.94	Augite	1.0
FeO	4.83	0.07	1.02	1.79	1.05	An	4.14	Hornblende	0.2
MgO	0.57	0.16	1.38	0.78	0.73	Di	5.93	Olivine	0.1
CaO	2.30	1.05	1.68	2.45	1.57	Hy	5.31	Groundmass	
Na_2O	7.20	7.47	6.77	7.25	7.56	Mt	3.29	Felspar	67.4
K_2O	3.25	3.47	3.82	3.08	3.88	Il	0.47	Aegirine Augite	8.6
H_2O+	0.20	1.93	0.24	0.39	1.63	Pyr	0.14	Cossyrite	9.0
H_2O-	0.10	0.42		0.10	0.07	Ap	1.64	"Green" hornblende	5.5
TiO_2	0.25	0.67	0.28	none	tr.				100.1
ZrO_2	n.d.	0.16	n.d.	n.d.	n.d.				
P_2O_5	0.07	0.05	0.18	0.24	0.11				
Cl	n.d.	n.d.	0.04	n.d.	n.d.				
S	0.08	n.d.	0.01	n.d.	n.d.				
MnO	0.30	0.21	0.09	none	tr.				
BaO	n.d.	0.07	n.d.	n.d.	n.d.				
	100.07	100.10	100.36	99.92	99.50				

1. Soda trachyte [3268] James Island, Galapagos, analyzed by Herdsman.
2. Anorthoclase trachyte, Launiupoko Hill, Kukui, Maui, analyzed by Steiger (17a).
3. Trachyte, Mas-a-fuera, Juan Fernandez, analyzed by Sahlbom (47, p. 283).
4. Biotite-bearing alkali trachyte, Gough Island, analyzed by Herdsman (54a).
5. Acmite trachyte, North Crazy Mountains, Montana, analyzed by Melville (70).

OLIGOCLASE ANDESITE

The oligoclase andesite [3267] from James Island is a fine-grained, bluish-grey, occasionally slightly scoriaceous lava containing a few fragmentary phenocrysts of felspar which are probably labradorite. It appears to be very similar to oligoclase andesites from the island of Hawaii (61) and from Maui (63).

The rock contains also abundant microphenocrysts of oligoclase (about $Ab_{72}An_{28}$), less plentiful prisms of pale green augite ($Z \wedge C = 47°$), a few of dark golden-brown hornblende ($Z \wedge C = 15°$), and rare negative olivine which does not appear to be rich in the fayalite molecule. The groundmass is trachytic, and varies in grain-size as though a first-formed fine-grained crust had been reincorporated in the lava. It consists mainly of oligoclase laths (about $Ab_{75}An_{25}$), abundant magnetite granules, short needles of augite, and sometimes a few stumpy prisms of brown hornblende. A slightly brownish glassy residuum with a refractive index near that of Canada balsam can be recognized in places.

BASALTS

The basaltic lavas of the Galapagos Islands include a few rocks classed as andesites on account of their felspar composition which are in other respects very similar to the basalts. They are almost all porphyritic, and tend to be rich in either felspar or olivine phenocrysts, though the olivines are never sufficiently abundant for the rock to be termed an oceanite. None of them show true alkalinity; but analcime occurs occasionally as interstitial material where there has been considerable alteration of the olivine present, and is sometimes accompanied by the development of a yellow pyroxene and hematite.

BASALTS WITH OLIVINE PHENOCRYSTS ONLY

Porphyritic olivine basalt forms a large flow entering James Bay, James Island. A specimen [346] taken from 12 feet below the surface of the flow is grey, rather porous, and friable with small pale green olivine phenocrysts which form about 20 per cent of the rock. In thin section these are colorless, rounded, and somewhat shattered, and contain abundant inclusions of small brown picotite octahedra. They are enclosed in a groundmass of labradorite laths ($Ab_{35}An_{65}$-$Ab_{39}An_{61}$), smaller olivine granules, ophitic plates of purplish augite, and interstitial iron ore. The doleritic basalt described by Lacroix (39, p. 68) comes from the same part of the flow and shows the same features. The analysis of this rock and of two closely similar Hawaiian basalts is quoted in Table 5. A rock [3280] collected by

Darwin from James Island is so similar to No. 346 that it probably comes from the same flow, and another [415] from Charles Island is almost identical.

Table 5. Analyses of Olivine Basalt

	1	2	3	Norms	1	2	3
SiO_2	46.72	46.76	47.72	Or	1.78	3.89	3.89
Al_2O_3	14.10	13.78	15.44	Ab	15.46	15.72	19.39
Fe_2O_3	2.14	1.26	0.23	An	28.00	19.46	29.75
FeO	9.63	10.43	9.52	Ne	....	7.95	....
MgO	11.64	11.07	11.31	Di	18.28	25.00	16.19
CaO	10.92	10.54	10.23	Hy	11.58	....	2.72
Na_2O	1.83	3.59	2.31	Ol	15.88	22.02	22.37
K_2O	0.30	0.64	0.63	Mt	3.11	1.86	0.23
H_2O+	0.20	0.10	0.46	Il	3.72	3.95	3.50
H_2O-	0.21	0.10	0.05	Ap	0.81	0.67	0.34
TiO_2	1.96	2.12	1.81				
P_2O_5	0.34	0.32	0.15				
MnO	0.14	0.08	0.16				
	100.13	100.79	100.02				

1. Doleritic basalt [346] James Island, Galapagos, analyzed by Raoult (39, p. 69).
2. Olivine basalt, block from pit crater summit of Hualalai, Hawaii, analyzed by Washington (61, p. 102).
3. Olivine basalt, Iao valley, Kukui volcano, Maui, analyzed by Keyes (63, p. 203).

A specimen [323] from the actual surface of the same flow from which No. 346 was taken differs in having a groundmass that contains abundant dark-brown opaque glass enclosing small olivine granules and laths of labradorite which show great variation in size. The smaller laths are thinner than the section, and are surrounded by crystallites, giving them a tufted appearance. At the actual surface the glassy base is pale yellow, transparent, and contains bundles of dark-brown crystallites. It passes rapidly into the more normal opaque glass by increase in the brown crystallite material. Similar basalts with olivine phenocrysts and vitreous bases are found on Indefatigable Island [375, 387, 410], James Island [3281] and Chatham Island [F 3146]. With the exception of No. 387 they all have a smaller proportion of glass and contain a more thoroughly crystalline residuum in which augite crystallites and magnetite granules can be identified as well as felspar and olivine. This type of groundmass is also found in a basalt from Chatham [3234] which contains phenocrysts of labradorite in addition to olivine, an aphanitic basalt scoria from Bindloes [3286], and a microporphyritic olivine basalt lapilli [377] from a small crater on Indefatigable Island whose olivine is largely replaced by orange-brown iddingsite.

There is a rather larger proportion of olivine phenocrysts (20-25 per cent) in No. 425 from Charles Island than in No. 346, but the actual crystals are generally smaller. They show evidence of magmatic resorption, and some alteration resulting in the formation of a narrow dense marginal zone of magnetite, and a reddish pleochroic interior due to the presence of parallel-orientated dustlike inclusions which may be iddingsite. The groundmass consists of labradorite laths ($Ab_{30}An_{70}$-$Ab_{38}An_{62}$), prisms of colorless augite ($Z \wedge C = 48°$), locally altered to a pale yellow variety with $Z \wedge C = 60°$ around some of the vesicles. Another specimen [F 3150] from Charles Island is identical with the altered portions of No. 425, and may easily have come from another part of the same flow.

A similar yellow augite, which is generally more strongly colored, but still has an extinction angle $Z \wedge C$ of about 60 degrees is common in specimens showing alteration, but is only an important mineral in a few specimens, for example No. 3287 (Tower Island) and No. 3278 (James Island). In the Tower Island specimen it occurs in granules almost to the exclusion of the common pale green augite. It is markedly positive, has strong double refraction, dispersion, and a mean refractive index about 1.71. Similar alteration of augite in basaltic rocks is recorded from Rapa by Smith and Chubb (55, p. 328), and was found to be identical by comparison of slides; and also from Tahiti by Lacroix (38) and from Vesuvius by Lacroix (37) and by Cesaro (10). Lacroix (37, p. 194) quotes two analyses given by Freundenberg (31, p. 264) of a grey-green augite and a yellow variety replacing it which show clearly that the change in color is largely due to the complete oxidation of the iron, stating that the extinction angle changes from 30 to 70 degrees. He has probably taken this value from a zoned aegirine-augite described earlier in the same paper (31, p. 249), as Freundenberg says quite clearly that there is no accompanying change in optical properties. Hence no conclusion can be reached regarding the composition of this yellow pyroxene, but it is certainly not an aegirine-augite.

Olivine phenocrysts are much less plentiful in the remaining basalts in which olivine phenocrysts are dominant, and they generally show some alteration which may be pneumatolytic, as the rest of the minerals are perfectly fresh.

In two light-grey and compact basalts from Chatham Island [F 3149, F 3152] which contain a few spherical vesicles, lined with transparent minerals in No. F 3152, the olivine phenocrysts appear brownish and dull in hand specimens. Thin sections show that this is due to a narrow margin of yellow iddingsite replacing the olivine which contains unusually large picotite inclusions. There are also occasional relics of bytownite phenocrysts, especially in No. F 3152. The groundmass contains labradorite laths (about $Ab_{34}An_{66}$), granules of faintly greenish augite, some olivine almost entirely replaced by iddingsite, magnetite, a little residual brown glass in No. F 3149, and calcite and analcime as interstitial material and vesicle linings in No. F 3152. The same type of alteration is shown by olivine with a prismatic habit in a microporphyritic basalt also from Chatham Island [F 3151].

Another porphyritic basalt [3235] from Chatham Island contains abundant small red olivine phenocrysts, whose color is the result of partial alteration to an iddingsite which is deep orange-red in thin section. There are in addition some microphenocrysts of medium labradorite. These are enclosed in a groundmass of more acid labradorite, slightly green-brown granular or prismatic augite, smaller grains of almost completely altered olivine, magnetite, and in places calcite and dirty isotropic material.

A somewhat similar, but less highly porphyritic rock [317] is found on Charles Island. The olivine is marginally altered to a dusty red iddingsite or hematite and forms phenocrysts which are generally too small to be visible in the hand-specimen. There are also a few microphenocrysts of colorless augite, some picotite, and in one section a green, partially resorbed fragment of hercynite. The groundmass contains abundant hematite, probably formed from original magnetite, which gives the rock a red color.

BASALTS WITH DOMINANT FELSPAR PHENOCRYSTS

The scoriaceous basal lavas from the Tagus Cove area on Albemarle Island have abundant phenocrysts of bytownite ($Ab_{10}An_{90}$–$Ab_{15}An_{85}$). These are generally much shattered and contain inclusions of brown opaque glass along their cleavage planes. In No. 458 they are about 5 mm. long, form nearly 30 per cent of the rock, and are associated with rare smaller phenocrysts of augite and olivine. They are enclosed in a groundmass of felspar laths ($Ab_{42}An_{58}$–$Ab_{53}An_{47}$), granules of colorless augite, rare olivine, much magnetite, and a little residual brown glass. The specimen described by Lacroix (12, p. 68) as a "basalte porphyritique à plagioclase" comes from the same locality and differs only in a slight and unimportant manner from No. 458. The analysis (Table 6, no. 1) shows a high percentage of CaO and Al_2O_3 owing to the abundance of bytownite phenocrysts, and the norm a little quartz. There are very few analyzed basalts which contain as much CaO and Al_2O_3. The nearest is from Reunion and is also given in Table 6.

Table 6. Basalts with Felspar Phenocrysts

	1	2	3	4	5	6	7	8
Sio_2	47.80	48.65	46.27	45.55	48.24	48.04	48.10	48.68
Al_2O_3	18.31	17.50	18.43	18.25	15.82	15.35	15.90	15.70
Fe_2O_3	1.47	0.25	3.98	7.28	0.78	5.72	1.93	1.81
FeO	8.20	9.75	8.22	5.01	9.84	7.67	10.28	9.75
MgO	4.89	6.61	3.75	6.00	5.84	5.77	6.28	6.08
CaO	13.00	11.85	12.33	10.20	9.84	10.13	11.60	11.64
Na_2O	2.48	2.15	2.58	3.18	3.63	3.26	2.68	2.32
K_2O	0.57	0.38	0.96	0.85	0.64	0.79	0.30	0.88
H_2O+	0.31	tr.	n.d.	0.95	0.72	0.27	0.40	0.10
H_2O-	0.11	0.10	n.d.	0.25	0.11	0.04	0.10	
TiO_2	2.40	2.10	2.98	1.80	3.88	3.13	1.90	2.68
P_2O_5	0.41	0.21	0.33	0.23	0.16	0.33	0.23	0.46
S	n.d.	tr.	n.d.	tr.	n.d.	n.d.	tr.	n.d.
MnO	0.14	0.25	n.d.	0.30	0.20	0.10	0.29	n.d.
	100.09	99.80	99.83	99.85	99.70	100.62	99.99	100.10
Norms								
Q	3.75	....	....	....	....	....	....	....
Or	3.39	2.22	5.56	5.00	3.89	4.45	1.67	5.00
Ab	20.96	17.81	22.01	25.64	29.87	27.77	23.06	19.39
An	37.09	40.03	35.86	32.52	25.02	24.74	30.30	30.02
Ne	....	....	....	0.85	0.28	....	....	....
Di	20.35	14.87	19.10	13.45	18.67	18.65	20.02	20.56
Hy	11.46	13.44	0.43	....	....	8.91	5.44	13.97
Ol	....	7.66	4.73	6.50	11.98	0.76	10.28	2.28
Mt	2.14	0.23	5.80	10.68	1.16	8.35	2.78	2.55
Il	4.56	3.96	5.62	3.50	7.45	5.93	3.65	5.17
Ap	0.97	0.34	0.67	0.34	0.34	0.67	0.34	1.01

1. Plagioclase basalt [458], Tagus Cove, Albemarle Island, analyzed by Raoult (39, p. 69).
2. Porphyritic olivine basalt [463], Narborough Island, analyzed by Herdsman.
3. Plagioclase basalt, Etang Salé, Reunion Island, analyzed by Boiteau, (39a, p. 544).
4. Olivine andesite [3239], Chatham Island, analyzed by Herdsman.
5. Andesine basalt, Eden Islet, Galapagos Islands, analyzed by Keyes (62, p. 539).
6. Andesine basalt, Hualalai, Hawaii, analyzed by Washington (61, p. 104).
7. Olivine andesite [433-B], ejected fragment, Albemarle Island, analyzed by Herdsman.
8. Basalt, Reunion Island, analyzed by Boiteau (39 b, p. 253).

Darwin's specimens Nos. 3247 and 3248 are macroscopically identical with No. 458 described above, and may come from the same flow. The groundmass in No. 3247 is coarser, probably as the result of slower cooling. A specimen [443] from a very rugged flow on the other side of Tagus crater is less scoriaceous. The individual crystals are larger and bytownite phenocrysts more abundant (35 per cent). It overlies a smooth flow [442] containing smaller but much more plentiful phenocrysts (50 per cent) than any of the other bytownite-bearing basalts, and an appreciable proportion of these are augite and olivine. No. 3289 from Abingdon Island is superficially somewhat similar to No. 443, but contains about 50 per cent of felspar phenocrysts which are less basic ($Ab_{18}An_{82}$–$Ab_{25}An_{75}$), and it has a coarser groundmass with a good deal of olivine largely altered to a yellow serpentinous mineral.

The felspar phenocrysts in a basalt [3265] from James Island are basic labradorite ($Ab_{21}An_{79}$–$Ab_{40}An_{60}$) and much smaller than those in any of the above basalts. They show the usual shattering and invasion by the magma and also marked zoning, especially in the outer portions of the crystals, which is often parallel to their present irregular margins. There are also a few rounded phenocrysts of pale-greenish augite and colorless olivine, generally partially replaced by an orange-yellow iddingsite; and a second generation of microphenocrysts of felspar, olivine, and augite which in places form aggregates and grade into a groundmass of the same minerals with magnetite and interstitial brown glass. Another specimen [3266] from James Island differs from the foregoing chiefly in containing only a few phenocrysts of the first generation and having none of augite, but a larger proportion of olivine.

A basalt [463] from Narborough Island is only slightly porphyritic. The felspar phenocrysts ($Ab_{14}An_{86}$–$Ab_{30}An_{70}$) are small, strongly zoned, especially near their margins, and some of them occur in aggregates with olivine. The groundmass is moderately coarse and consists of felspar laths ($Ab_{40}An_{60}$), pale-greenish granular augite, some rather larger colorless olivine granules, iron ore, which is mainly magnetite, and a little residual brown glass. This specimen contains fewer bytownite phenocrysts and more olivine than No. 458, and these differences are reflected in the analysis (Table 6, no. 2). Another basalt [467] from Narborough Island is very similar but contains additional augite phenocrysts. The groundmass felspar is more acid ($Ab_{45}An_{55}$) than in No. 463, and the olivine shows considerable alteration. A few yellow augites replace the normal greenish variety.

The remaining basalts with dominant felspar phenocrysts come from James Island. They contain phenocrysts of olivine and augite in addition to felspar, much of which is strongly zoned, and show more or less extensive alteration of the olivine and replacement of the normal augite by a yellow variety. In No. 3278 the felspar phenocrysts are basic labradorite ($Ab_{28}An_{72}$–$Ab_{35}An_{65}$) and show great variation in size and marked resorption by the magma. The olivine phenocrysts are entirely replaced by magnetite with a little hematite and iddingsite. In the early stages of replacement the alteration products are concentrated along possible cleavage directions. The augite phenocrysts are colorless with a narrow rim of yellow pyroxene which is also devloped as small prisms throughout the groundmass, where it is greatly in excess of the normal augite. It is there associated with labradorite laths and hematite which appears to be derived from original magnetite and olivine. The alteration has been less extensive in No. 370, where iddingsite is a more abundant alteration product of the olivine, and hematite and yellow pyroxene are confined to definite areas in the groundmass, which is finer grained and somewhat obscured by brown glass. No. 3269 is less altered and shows practically no yellow pyroxene.

NON-PORPHYRITIC BASALTIC ROCKS

An olivine basalt or dolerite [F 3154] from Dalrymple rock, Chatham Island is a very coarse-grained rock, and may represent a volcanic neck filling a tuff cone which has since been denuded away.

It is composed of labradorite laths ($Ab_{30}An_{70}$-$Ab_{45}An_{55}$) about 0.8 mm. long, grains of olivine showing slight alteration, smaller colorless granular prisms of augite which often form aggregates around the olivine, irregular patches of magnetite, abundant needles of apatite, rare interstitial analcime and much yellow powdery material which is visible in the hand specimen. This is made up of minute greenish-yellow or brown scales which sometimes form darker fringes around the other minerals and occasionally surround cavities which may be filled with chabazite. It is probably crystalline chlorophaeite, and its mode of occurrence suggests that it represents an original interstitial glassy residue.

An olivine andesite [3239] from Chatham Island is not as coarse-grained as No. F 3154.

It is formed largely of felspar laths ($Ab_{54}An_{46}$-$Ab_{62}An_{48}$) which show considerable variation in size, granular prisms of pale greenish-brown augite and colorless olivine showing slight marginal alteration, much magnetite, and in places apatite and very occasionally a little analcime. The analysis of this specimen (Table 6, no. 4) shows high Al_2O_3 and CaO, and also Fe_2O_3, which is probably the result of partial alteration of the olivine. The normal felspar is much more calcic than the modal, suggesting that the augite is aluminous.

The andesine basalt from Eden islet described by Washington and Keyes (62, p. 539) has felspar of about the same composition as that in No. 3239, and would according to the terminology adopted in this paper be classed as an andesite. It differs, however, in containing a titaniferous augite, and the analysis consequently shows a higher percentage of TiO_2 than No. 3239 (Table 6).

A porphyritic olivine andesite [3279] from James Island also contains felspar laths of about the same composition as No. 3239, but differs in the presence of a few large, slightly altered olivine phenocrysts, and in having ophitic augite which is strongly zoned and passes locally into a yellow variety.

GABBROIC XENOLITHS

Gabbroic xenoliths were collected by Darwin from the lavas and scoriae of a small cone at Freshwater Bay, James Island, and described by him in some detail (25, p. 110-112). He refers to the felspar as albite because of the cleavage angle.

The specimens have a burned appearance and tend to be very friable. They all consist of much-shattered glassy felspar, black iridescent augite, duller reddish olivine, and in places interstitial red earthy material, but show some variation in grain-size and proportion of the different minerals.

No. 3273 contains zoned felspar laths ($Ab_{29}An_{71}$-$Ab_{39}An_{61}$) about 7 mm. long which made up about half the bulk of the rock, pale brownish-green ophitic augite, colorless olivine granules containing about 29 per cent of fayalite and showing much alteration to a red-brown pleochroic, fibrous or dusty material which is probably iddingsite, and a little deep red interstitial glass with occasional crystallites. The composition of the felspar and the olivine is about the same in the other xenoliths. No. 3270 contains more and olivine. This is especially true of No. 3271, which is a eucrite rather than a gabbro. augite and less felspar than No. 3273, whereas No. 3271 and No. 3272 have more felspar

Darwin (25, pp. 111-112) suggests that the xenolithic material is responsible for the phenocrysts in the lava flows from this small crater, but determination of the composition of the felspar ($Ab_{40}An_{60}$–$Ab_{60}An_{40}$) and the olivine (18 per cent fayalite) phenocrysts in the basalt matrix does not bear this out.

FRAGMENTS FROM TUFFS AND AGGLOMERATES

The tuffs and agglomerates from craters in the neighborhood of Tagus Cove, Albemarle Island, include many fragments most of which are angular, dark grey and aphanitic, though some are slightly vesicular, and a few porphyritic. In addition there are a few coarse-grained ultrabasic nodules.

The aphanitic fragments (border-line andesites and basalts) show in thin sections considerable range in grain size, but close similarity in composition and in the proportions of the various minerals present. They consist of basic andesine or acid labradorite felspar laths, pale green or greenish-brown granular augite, iron ore (largely magnetite) a small quantity of brown interstitial glass, and olivine which is only distinguishable from the augite in the coarser specimens.

A typical example [433B] of the fine-grained fragments contains andesine laths ($Ab_{52}An_{48}$), greenish brown augite, a little olivine, magnetite, and some interstitial glass. As shown by the analysis (Table 6, no. 7), its chemical composition is nearer that of the basalt from Narborough Island (Table 6, no. 2) than any of the other analyzed Galapagos specimens. But calculations show that it could not be derived from the porphyritic varieties (Table 6, nos. 1 and 2) by the removal of bytownite phenocrysts. An analysis of a basalt (Table 6, no. 3) from Reunion Island is given for comparison.

The porphyritic fragments have groundmasses similar to the aphanitic fragments, but owing to the prsence of phenocrysts of bytownite are all basalts. They range from very slightly porphyritic with occasional phenocrysts of bytownite (about $Ab_{10}An_{90}$–$Ab_{15}An_{85}$) to highly porphyritic with phenocrysts of olivine and augite in addition but subordinate to bytownite.

The ultrabasic fragments consist of crystals of basic bytownite (about $Ab_{10}An_{90}$–$An_{15}An_{85}$), faintly brownish-green augite which is generally ophitic, colorless olivine, and interstitial pale brown glass in varying proportions.

Bytownite is most abundant in No. 461 A, where it forms about 85 per cent of the bulk of the rock and occurs as slightly rounded crystals about 5 mm. or 10 mm. long containing inclusions of brown glass identical with that occurring interstitially except for the presence in the latter of darker crystallite aggregates. The refractive index (1.608) of this glass is equal to that of the sideromelan in some of the tuffs which are of about the same age. Augite and olivine are present in addition, but neither is important. There is sufficient glass in this specimen for it to resemble a highly porphyritic pitchstone. Both bytownite and glass are much less abundant in the other ultrabasic fragments, which therefore have a granular gabbroic appearance. Also the felspar crystals are smaller and show great variation in size, especially in No. 450 C; and the augite forms large ophitic plates, one occupying the whole of a slide of No. 451 B.

The same minerals are present in No. 434 B, which is comparatively fine-grained and has a different appearance in thin section. The bytownite forms well-defined laths, whereas the augite and olivine are both granular and tend to occur in aggregates. The small quantity of residual glass shows streaky variations in color, and has a refractive index which ranges between about 1.590 and 1.630.

The identity of the included and interstitial glass in these ultrabasic fragments suggests that they represent aggregates formed by crystal sinking near the bottom of the magma-reservoir which were occasionally brought up at explosions with the more abundant non-porphyritic and porphyritic fragments from higher levels which had crystallized completely prior to ejection.

TUFFS

The tuff specimens from Chatham, James Island, Tagus Cove, Albemarle Island, and from Eden Islet are all basic. They are composed largely of sideromelan fragments showing all degrees of palagonitization and are in many respects very similar to tuffs from Iceland described by Peacock (44). It will convenient to adopt Peacock's classification, with a slight modification, and divide the tuffs into unaltered sideromelan tuffs, slightly altered palagonite tuffs, and highly altered palagonite tuffs, including specimens which would be called "palagonite rocks" by Peacock (44, p. 54) because they differ from the other highly palagonitized tuffs only in size and proximity of the fragments.

All tuffs from one island show, however, certain common features regardless of palagonitzation. The tuffs from Eden Islet and Chatham Island have fragments of olivine with picotite inclusions, and also a few basalt fragments which are generally trachylitic. The Albemarle Island tuffs on the other hand are characterized by abundant crystal fragments of bytownite ($Ab_{10}An_{90}$–$Ab_{15}An_{85}$), olivine, and augite in this order of abundance, and also a large variety of basalt fragments. The tuffs from James Island occupy an intermediate position.

SIDEROMELAN TUFFS

Sideromelan tuffs are recorded from James and Albemarle islands. They are green or yellowish-brown in color, and tend to be friable. Some [3276, 372, James Island] are completely unconsolidated; others [453, Albemarle Island] are held together by fine volcanic dust which gives a comparatively strong cement when it is altered as the result of weathering or incipient palagonitization [3277, James Island].

Specimen No. 453 (Albemarle Island) is a typical fine-grained, greenish-brown, fairly compact tuff consisting principally of sideromelan fragments which are pale greenish-brown in thin section and have a refractive index of 1.606. The majority are small (0.5 mm. in diameter) and show ash structure, but a few are larger and vesicular, containing in places crystallite aggregates which give the glass a mottled appearance. There are also many small fragments of felspar, most of them partially embedded in the sideromelan, and a few of olivine, augite, and basalt, which is generally tachylitic. Interstitially there is a much darker brown material which is probably fine volcanic dust.

The other sideromelan tuffs show some difference in the proportion of the various constituents and some very slight marginal alteration of the sideromelan fragments. For example, No. 3277 (James Island) contains fewer crystals but more plentiful basalt fragments, some of which are holocrystalline. It consists principally of large, highly vesicular sideromelan fragments which have a very narrow marginal zone of fine black banding, in places associated with a yellow coloration as noted by Peacock (44, p. 59). The interstitial dust is yellowish. No. 445 (Albemarle Island) differs from Nos. 453 and 3277 in being composed largely of crystal fragments, and is a crystal-vitric tuff whose composition suggests that it is the explosive equivalent of a basalt with bytownite and olivine phenocrysts such as No. 442 (Albemarle Island).

Nos. 3249, 3250, and 435 (Albemarle Island) are less consolidated and coarser-grained than No. 453. They also contain more abundant and much more varied basalt fragments and pisolitic nodules which are almost all spherical and about 5 to 10 mm. in diameter. These have a thin compact outer shell, composed of the smallest sideromelan fragments and dust, which gives a superior resistance to weathering and surrounds an interior differing from the tuff matrix only in the absence of the largest fragments. As in No. 3277 there is incipient marginal alteration of the fragments, especially of those forming the outer coats of the pisolites in No. 435.

Such pisolites are formed either by the condensation of water in an ash cloud giving balls of mud (32), as took place during the 1906 eruption of Vesuvius (45), or by gentle rain falling on heated ash, as was observed by Lacroix (36) at Mt. Pelée after the main eruption in 1902. They are also recorded from the Philippine Islands by Pratt (46), from Hawaii by Frielaender (32), from the Brisbane tuff by Richards and Bryan (48), and from the Pentlands by Johnston-Lavis (35). These authors regard the pisolites as mud-balls which formed from ash clouds, but in the absence of any evidence that mud fell on Albemarle Island, the pisolites there were probably formed as at Mt. Pelée.

SLIGHTLY ALTERED PALAGONITE TUFFS

Some palagonite tuffs from Chatham, Albemarle, and Eden islands are slightly compacted and show a good deal of variation in appearance, though all are brownish in color and similar in thin section, with the exception of Nos. 447 and 449 (Albemarle Island) which are crystal-vitric tuffs and differ from No. 445 only in the marginal palagonitization of the sideromelan fragments.

The fresh sideromelan shows exactly the same features as in the unaltered tuffs, but in the Chatham Island specimens its refractive index is only about 1.590 and it often encloses olivine crystals which may show fantastic resorption and are in places associated with picolite octahedra and small labradorite laths.

The palagonite is bright yellow in thin section and forms borders about 0.02-0.04 mm. wide replacing the sideromelan with a well-defined undulose inner margin and in places stringers pushing out into the unaltered glass. In No. 3224 (Chatham Island) the palagonite is traversed by fine black bands parallel to the original outline of the fragment and concentrated against the unaltered sideromelan. Apart from the absence of change in color, this is closely similar to the palagonite described by Peacock (44, p. 60). Black bands are more marked in No. 3223 (Chatham Island), where they are concentrated in definite zones separating palagonite of slightly different shades of yellow; but they are hardly developed in the Eden islet specimens [406, 407, 409].

In all the specimens described above the palagonite has a variable refractive index which lies between 1.480 and 1.535. It is isotropic, except at the extreme outer margin, where it may show faint double refraction, and in most specimens is followed by a thin band of zeolitic material.

True cement is generally lacking, the smallest completely altered fragments playing an important part in holding the rock together. A little interstitial granular zeolite is sometimes present, and calcite which is locally important in No. 406 (Eden Islet). The areas where the calcite is developed are grey in color and stand out on weathering. In No. 407 (Eden Islet) a colorless chlorite occurs interstitially with calcite, and the sideromelan fragments are fairly far apart, so that the rock has a speckled brown and white appearance.

HIGHLY ALTERED PALAGONITE TUFFS

The highly altered palagonite tuffs from Chatham, Eden, James, and Albemarle islands are even more varied in appearance than the slightly altered tuffs, and only some of the specimens from Chatham Island [3220-3222] and Eden Islet [393] agree superficially with Von Waltershausen's "Palagonitfels" (44, p. 54). They are brown, compact, and have a resinous luster and conchoidal fracture. In the hand specimen a few olivine fragments and vitreous particles are visible.

The palagonite in No. 3222 (Chatham Island) is bright yellow, transparent, and isotropic in thin section, and has a refractive index of about 1.530. It has replaced all but the cores of the largest sideromelan fragments, the included crystals of olivine, felspar, and spinel, and the few brown crystallite bands. The outlines of the original sideromelan fragments are perfectly preserved, and the interstitial spaces and vesicles are filled with chlorite and zeolites. There is generally a very narrow fringe of indeterminable fibrous zeolite around the palagonitized fragments. In places this fringe is followed by a wider fringe of pale green chlorite, and the residual space is occupied by squarish granules which are probably phillipsite.

The palagonite in the Eden islet specimen [393] has a higher average refractive index (1.580) and is a deeper but more variable yellow color. It is turbid in places, and may then show faint double refraction.

The palagonite tuff described by Washington and Keyes (62, p. 540) is almost identical, though the term "glass" is used instead of "palagonite" in the description. Its analysis (Table 7, no. 9), when calculated on a water-free basis, is, apart from the oxidation of the iron, closely similar to analyses of basalts from Albemarle and Narborough islands (Table 7, nos. 2 and 3).

The lowest portions of Eden Islet are formed principally of brown palagonite rock similar to that described above, but in places a rather different type is developed [403]. This also has a resinous luster, but it is less pronounced. The rock is red in color and the individual fragments larger and not as closely packed as in No. 393, so that white interstitial material is visible in places.

The palagonite is orange in thin section and some of it shows slight zonal variations in color. Its refractive index may be as high as 1.630, though that of the unaltered brownish sideromelan is only 1.603. This is probably due to the absorption of ferric oxide from extraneous solutions. The larger fragments contain more unaltered sideromelan than in No. 393; and, when crystallites are present, show very clearly their resistance to palagonitization. Chlorite again forms fringes to the vesicles and margins of the fragments, and there is interstitial calcite and finely granular zeolitic material.

Orange palagonite which also has a high refractive index lying partially above that of the unaltered sideromelan is found in some tuffs from James Island. The specimens studied [3282, 3283] show complete palagonitization of all but the largest sideromelan fragments, but have neither a resinous luster nor conchoidal fracture. This is partly due to the greater abundance of interstitial material, and also probably in No. 3283 to slight crystallization of the palagonite.

A light drab-colored compact tuff [459] from Albemarle Island has a very slight resinous luster. It contains abundant basalt and crystal fragments, especially in one band, and also dark spherical bodies.

In thin section these are seen to be pisolites whose interiors have not been palagonitized, except when their fine-grained outer shells have been fractured. The palagonite is very pale in color, but has a high average refractive index (1.585). The tuff agrees closely in original composition with the pisolitic sideromelan tuffs [3249, 453], but owing to palagonitization the matrix is as hard as the pisolites, and fractures pass through these without interruption.

In a group of tuffs from Chatham Island [3226, 3236-3238] the specimens are compact and pale brown and tend to have a platy fracture, but no resinous luster.

Under a lens the coarser-grained specimens, for example, No. 3226, appear to consist of pale yellowish fragments, some of which are cellular and surrounded by darker brown borders with white interstitial crystalline material. A few of the yellow areas enclose black vesicular sideromelan. Thin sections show that the yellow and brown substances are both palagonite, and the interstitial crystalline material zeolites, calcite, and pale green chlorite. The yellow palagonite is generally clear and transparent, but some of it is traversed by faint black zonary lines which form a marked band against the unaltered sideromelan. The darker palagonite completely replaces the smallest fragments and is sharply separated from the yellow in the larger. It is orange brown in thin section. Some of it is crowded with black zonary bands, and some is turbid and may show double refraction.

The palagonite shows extensive crystallization in only one specimen [3225, Chatham Island]. In thin section it varies in color from yellowish-green to bright orange, and is generally turbid and doubly refracting with spherulitic or fibrous crystallization between crossed nichols, though the fibers are too small to be identified in ordinary light.

The tuffs from the Galapagos Islands differ from the Iceland tuffs in the absence of palagonite cement and the greater rarity of fibro-palagonite. The chlorite and zeolites have clearly been deposited from traveling solutions and have not been formed at the expense of the neighboring palagonite, as in some of the Iceland rocks.

Peacock (44, pp. 67-69) has shown that palagonite is a hydration-oxidation product of transparent basalt glass formed by the action of glacial, marine, or magmatic waters. The low elevation of the tuff craters in the Galapagos suggests that sea water was the main agent of palagonitization, but the only evidence in favor of uplift is the presence of a few marine shells noted by Darwin (25, p. 115) and by Wolf (68, p. 250).

SUMMARY OF ROCK TYPES AND ANALYSES

The following list records the types of rocks so far reported from the different islands of the Galapagos Archipelago. Those not represented in Darwin's or Chubb's collections are credited to the author who described them. All the available analyses except that of the palagonite by Bunsen (9) are grouped in Table 7.

Abingdon:	Basalt with abundant felspar phenocrysts
	Vitreous basalt scoriae (Gooch)
	Pumice with orthoclase (Gooch)
Albemarle:	Basalt with abundant bytownite phenocrysts
	Ejected basaltic and ultrabasic fragments
	Sideromelan and palagonite tuffs, some with pisolites
Bindloes:	Vitreous basalt scoriae
	Basalt with felspar phenocrysts (Gooch)
	Basalt scoriae (Gooch)
Charles:	Basalt with olivine only phenocryst
	Amygdaloidal basalt (Gooch)
	Basalt scoriae (Gooch)
	Olivine bronzite lapilli (Gooch)
Chatham:	Basalts with dominant felspar phenocrysts
	Basalts with olivine only phenocryst
	Olivine basalt or dolerite
	Olivine andesite
	? Spilite
	Olivine basalt (Merrill)
	Palagonite tuffs and palagonite rock
Hood:	Basalts (Gooch)
Indefatigable: (including) Eden)	Basalt with olivine only phenocryst
	Andesine basalt (Washington and Keyes)
	Pumice with orthoclase (Gooch)
	Palagonite tuffs with palagonite rock
James:	Basalts with olivine only phenocryst
	Basalts with felspar dominant phenocryst
	Aphanitic basalt
	Porphyritic olivine andesite
	Oligoclase andesite
	Soda trachyte
	Gabbroic xenoliths
	Sideromelan and palagonite tuffs
Narborough:	Basalts with few felspar phenocrysts
Tower:	Basalts (Gooch)

Table 7. Analyses of Rocks from Galapagos Islands

	1	2	3	4	5	6	7	8	9
SiO_2	61.90	46.72	47.80	48.65	45.55	48.10	48.24	38.13	47.75
Al_2O_3	16.75	14.10	18.31	17.50	18.25	15.90	15.82	14.64	18.34
Fe_2O_3	2.27	2.14	1.47	0.25	7.28	1.93	0.78	7.93	9.94
FeO	4.83	9.63	8.20	9.75	5.01	10.28	9.84	0.87	1.09
MgO	0.57	11.64	4.89	6.61	6.00	6.28	5.84	3.84	4.78
CaO	2.30	10.92	13.00	11.85	10.20	11.60	9.84	8.97	11.25
Na_2O	7.20	1.83	2.48	2.15	3.18	2.68	3.63	2.67	3.34
K_2O	3.25	0.30	0.57	0.38	0.85	0.30	0.64	0.15	0.19
H_2O+	0.20	0.20	0.31	tr.	0.95	0.40	0.72	12.34	....
H_2O-	0.10	0.21	0.11	0.10	0.25	0.10	0.11	8.41	....
TiO_2	0.25	1.96	2.40	2.10	1.80	1.90	3.88	2.50	3.12
P_2O_5	0.07	0.34	0.41	0.21	0.23	0.23	0.16	0.01	0.01
S	0.08	n.d.	n.d.	tr.	tr.	tr.	n.d.	n.d.	....
MnO	0.30	0.14	0.14	0.25	0.30	0.29	0.20	0.15	0.19
	100.07	100.13	100.09	99.80	99.85	99.99	99.70	100.61	100.00

1. Soda trachyte [3268], James Island, analyzed by Herdsman.
2. Doleritic basalt [346], James Island, analyzed by Raoult (39, p. 69).
3. Plagioclase basalt [458], Tagus Cove, Albemarle Island, analyzed by Raoult (39, p. 69).
4. Porphyritic olivine basalt [463], Narborough Island, analyzed by Herdsman.
5. Olivine andesite [3239], Chatham Island, analyzed by Herdsman.
6. Andesite [433 B], ejected fragment, Albemarle Island, analyzed by Herdsman.
7. Andesine basalt, Eden Islet, analyzed by Keyes (62, p. 538).
8. Palagonite tuff, Eden Islet, analyzed by Keyes (62, p. 541).
9. The same as No. 8, but calculated to 100.00 as free from H_2O.

AGE RELATIONS

In an attempt to determine the age relations of the Galapagos rocks, the compositions of the felspar and olivine phenocrysts in the porphyritic rocks, deduced from refractive index tables given by Winchell (66), were plotted against each other (see fig. 9). In rocks where the only phenocrysts are olivine, the composition of the groundmass felspar was plotted against that of the total olivine. Data from non-porphyritic rocks and tuffs, which contain both olivine and felspar, were also used. In the graph the average compositions are plotted, except for rocks in which the felspar shows a range of more than 12 per cent anorthite or the olivine 5 per cent fayalite, when the range is shown by a dotted line. In order to avoid confusion, the tuffs from James and Albemarle islands are each represented by a single point, which is the average of several closely similar determinations.

The points indicate one main line of differentiation (Series I) and a definite subsidiary line where the olivine is enriched in fayalite (Series II).

As a basalt magma cools and crystallizes, the felspar crystals which it contains become more acid and the olivine richer in fayalite. Thus the composition of felspar phenocrysts in lavas erupted at intervals from a cooling and partially crystalline basalt magma will become increasingly acid as the process continues. Hence the right-hand ends of the two curves (fig. 9) represent the oldest lavas. Xenoliths from the acid end of Series II are inclosed in basalt containing felspar phenocrysts showing a long range in composition from near the acid end of Curve I. Thus the basalts of Series II must be older than some of the lavas of Series I, but may in part be contemporaneous.

The sequence of events therefore appears to be the ejection of tuffs at Albemarle, James, and probably other islands which cannot be represented on the graph, followed by basalts with abundant bytownite phenocrysts at Albemarle (which agrees with field evidence) and Abingdon islands. Most of the succeeding basalts (central portion of Curve I) contain only olivine phenocrysts. It is possible that these really belong to another line of differentiation and that the points representing them lie on Curve I by accident, as there are some basalts with felspar phenocrysts which give nearly coincident points. These were followed by basalts at James Island (long range in composition of felspar phenocrysts) containing xenoliths, and finally andesites.

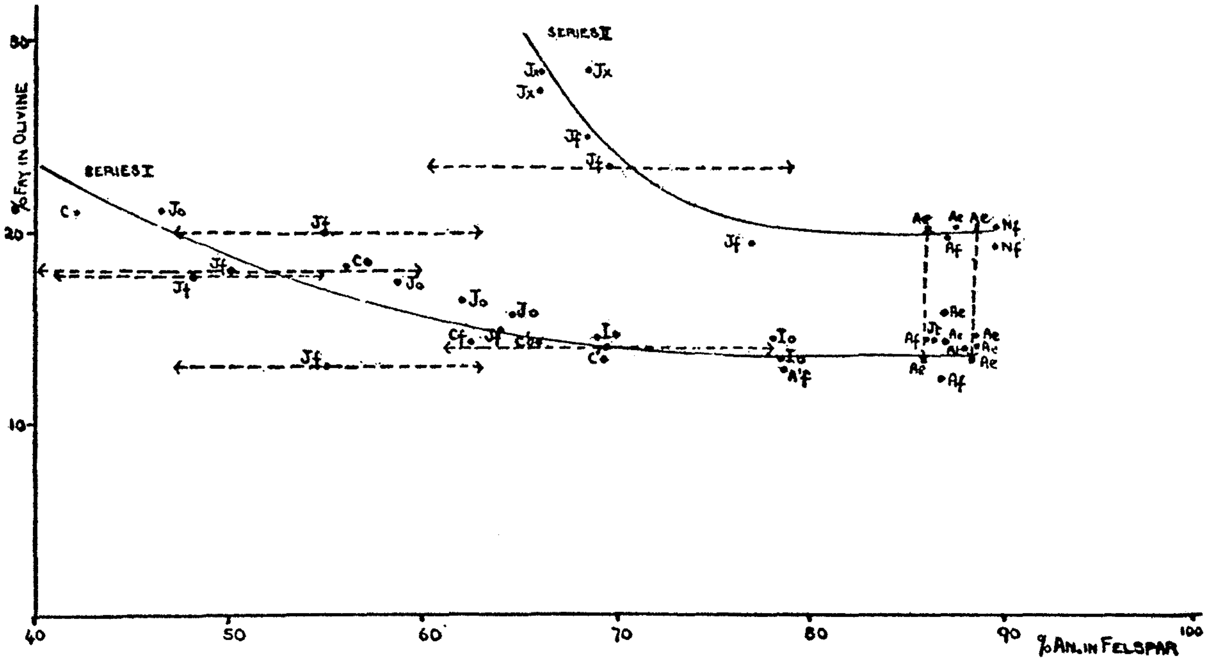

Figure 9.—Graph showing relationships of the rocks of the Galapagos Islands, symbols to be interpreted as follows: *A'*, Abingdon Island; *A*, Albemarle Island; *C'*, Charles Island; *C*, Chatham Island; *I*, Indefatigable Island; *J*, James Island; *N*, Narborough Island; *f*, lavas with dominant felspar phenocrysts; *o*, lavas with dominant olivine phenocrysts; *e*, ejected fragments; *t*, crystals from tuffs; *x*, xenoliths.

Neither the oligoclase andesite nor the trachyte could be represented on the graph, but the presence in the andesite of olivine which does not appear to be very rich in fayalite suggests that it may be a late member of Series I. The trachyte with its occasional fayalite crystals might be an offshoot of Series II.

SUMMARY AND COMPARISON

The chief petrological characters of the Galapagos Archipelago are the predominance of basaltic material (both lavas and tuffs) on all the islands, the absence of nepheline-bearing rocks, and the rarity of trachyte.

The basaltic rocks are almost all prophyritic with dominant phenocrysts of olivine or basic plagioclase, and they are distinguished by a very low content of K_2O and also high Al_2O_3 and CaO in the felspar-rich varieties (Table 7). These two types of basalt are found together on many Pacific islands (39) and at Ascension Island (22), but only those from Mangareva (Gambier Islands) (39, p. 43-45) and Juan Fernandez Islands (39, p. 65; 47) are also similar as regards chemical composition. Actually some of the Hawaiian basalts have analyses which are nearer to that of the porphyritic olivine basalt from James Island (Table 5), and certain basalts from Reunion Island are chemically closer to the felspathic types (Table 6) than are those of Mangareva and Juan Fernandez.

The analyzed trachyte and andesine basalt as well as the porphyritic olivine basalt can be matched much closer in Hawaii than elsewhere (see Tables 4, 5, 6), but the dominant lavas of Hawaii are olivine basalts, and none resembling the bytownite-bearing basalts of Albemarle Island are developed.

The Juan Fernandez are the only islands on which both types of basalt are found in addition to soda trachyte similar to that occurring in the Galapagos Archipelago (Table 4). Although oceanites and basanitic lavas are also present, the Juan Fernandez Islands are petrologically closer to the Galapagos than are any other islands. Both are situated comparatively near the American coast of the Pacific, but their similarity is not shared by San Felix and San Ambrasio islands (65), or any of the other islands on that side of the Pacific where the lavas are throughout richer in K_2O.

The author desires to thank Professor C. E. Tilley for help given during the progress of the work, Mr. L. J. Chubb for providing specimens for study in connection with those in the Beagle Collection, the Director of the Geological Survey for lending slides for examination and description, and Bernice P. Bishop Museum for a grant toward the cost of analyses.

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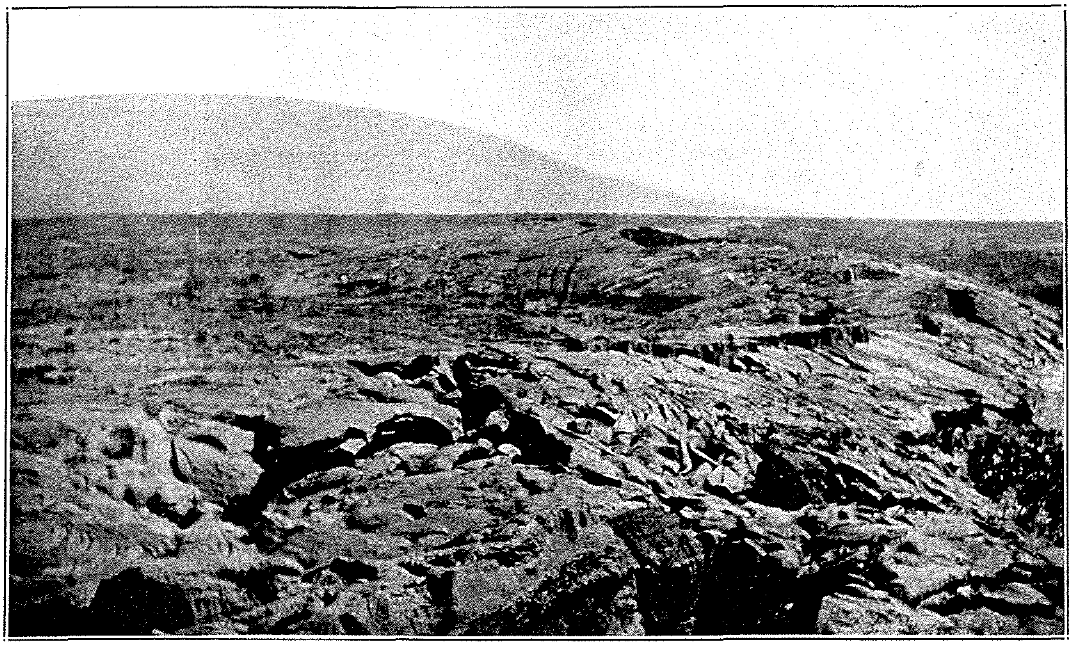

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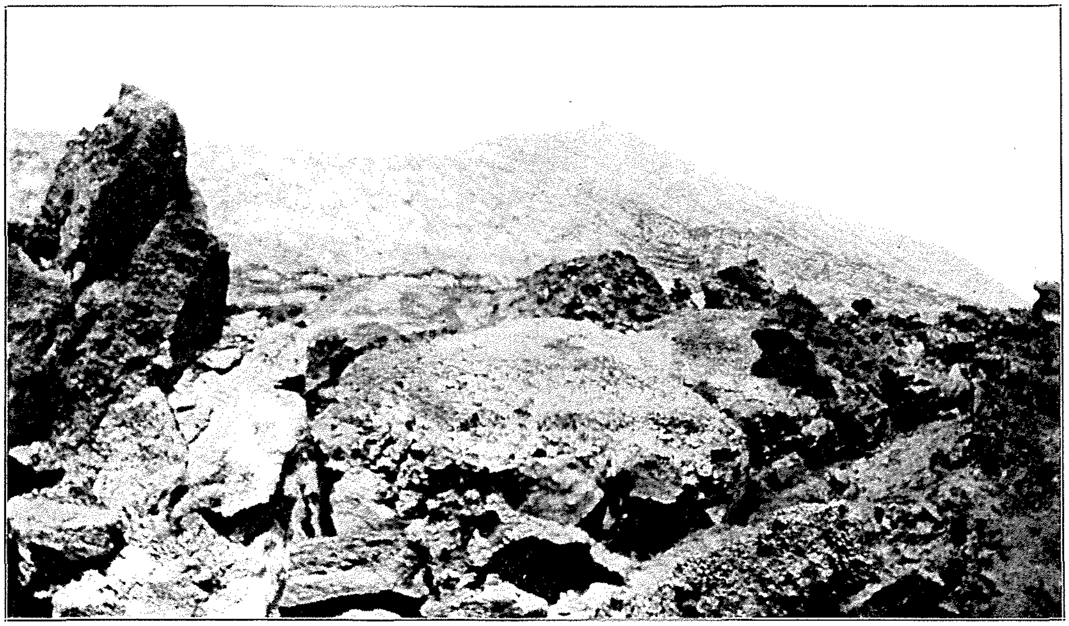
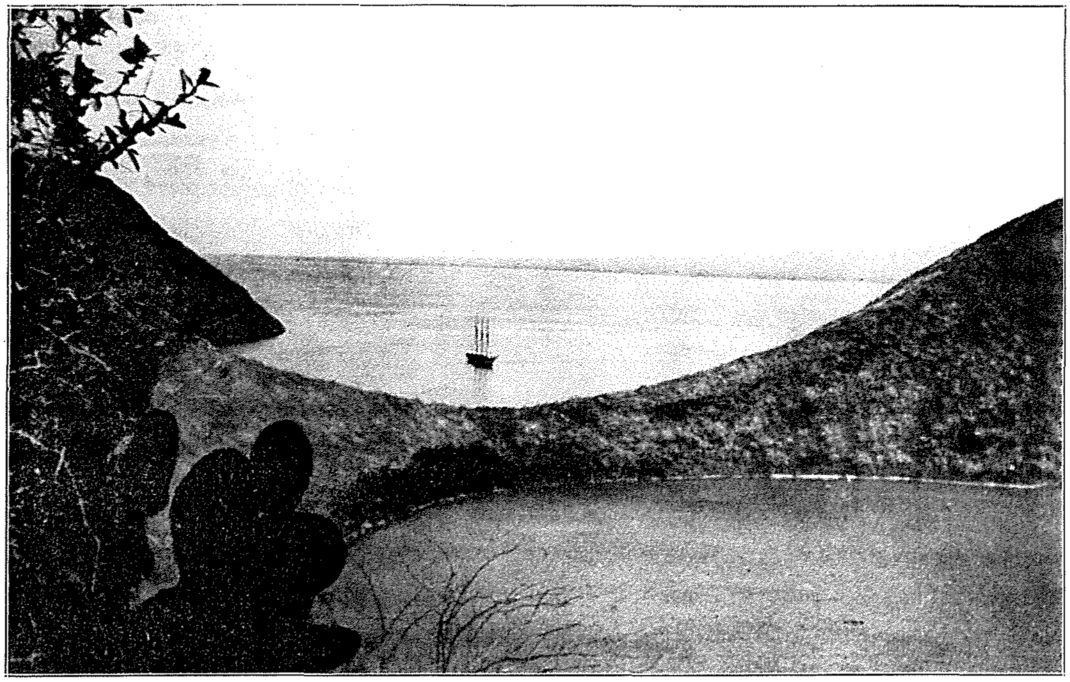


B

LAVA FIELDS, GALAPAGOS ISLANDS: *A*, LAVA FIELDS AND MAIN CRATER OF NARBOROUGH ISLAND, IN THE FOREGROUND A NARROW SINUOUS LAVA STREAM WITH A LONGITUDINAL MEDIAN FISSURE AND CORDED SURFACE, IN THE DISTANCE THIS NARROW STREAM OVERFLOWED BY A BROAD RUGGED STREAM; *B*, TAGUS HILL, ALBEMARLE ISLAND, FROM THE NORTH, SHOWING A RUGGED LAVA FLOW WHICH ABUTS AGAINST BASE OF CLIFFS.



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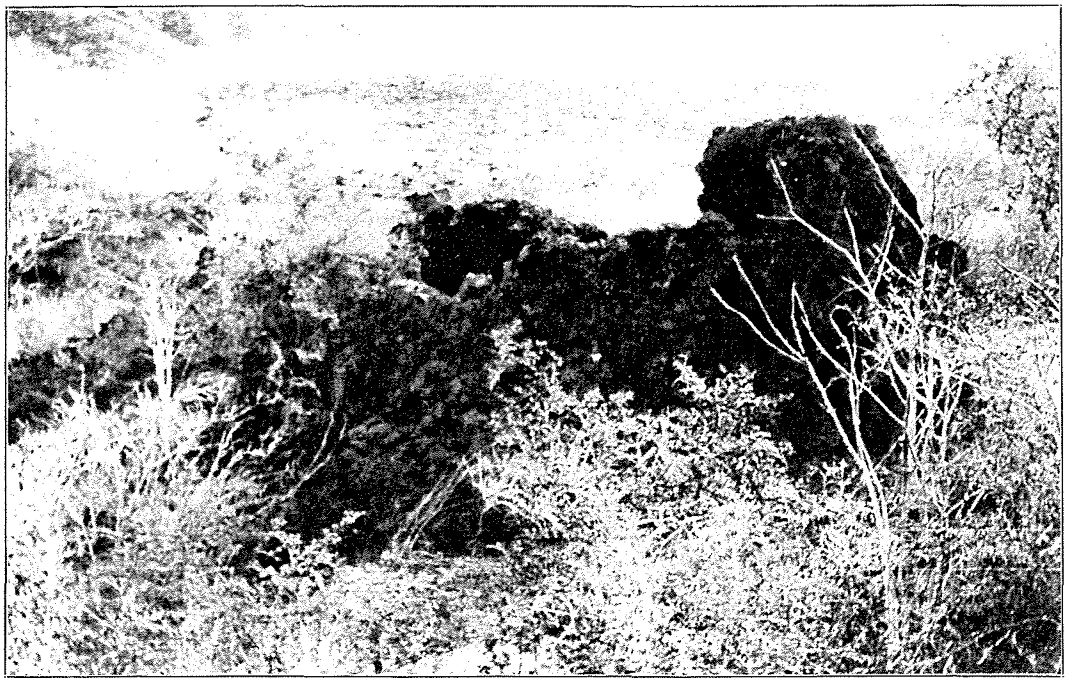
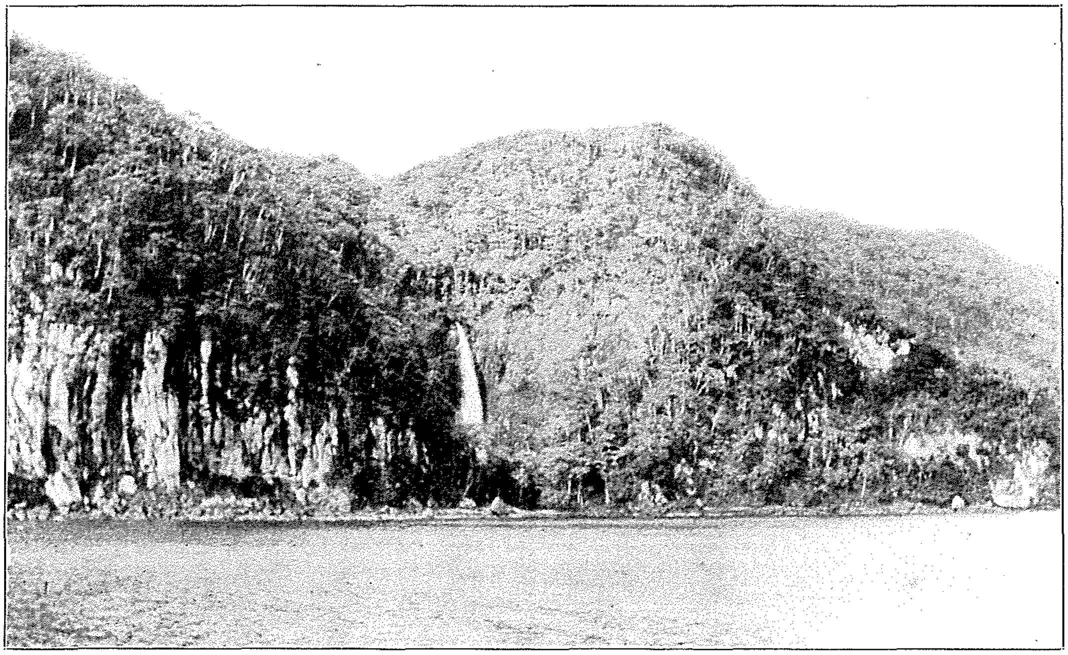


B

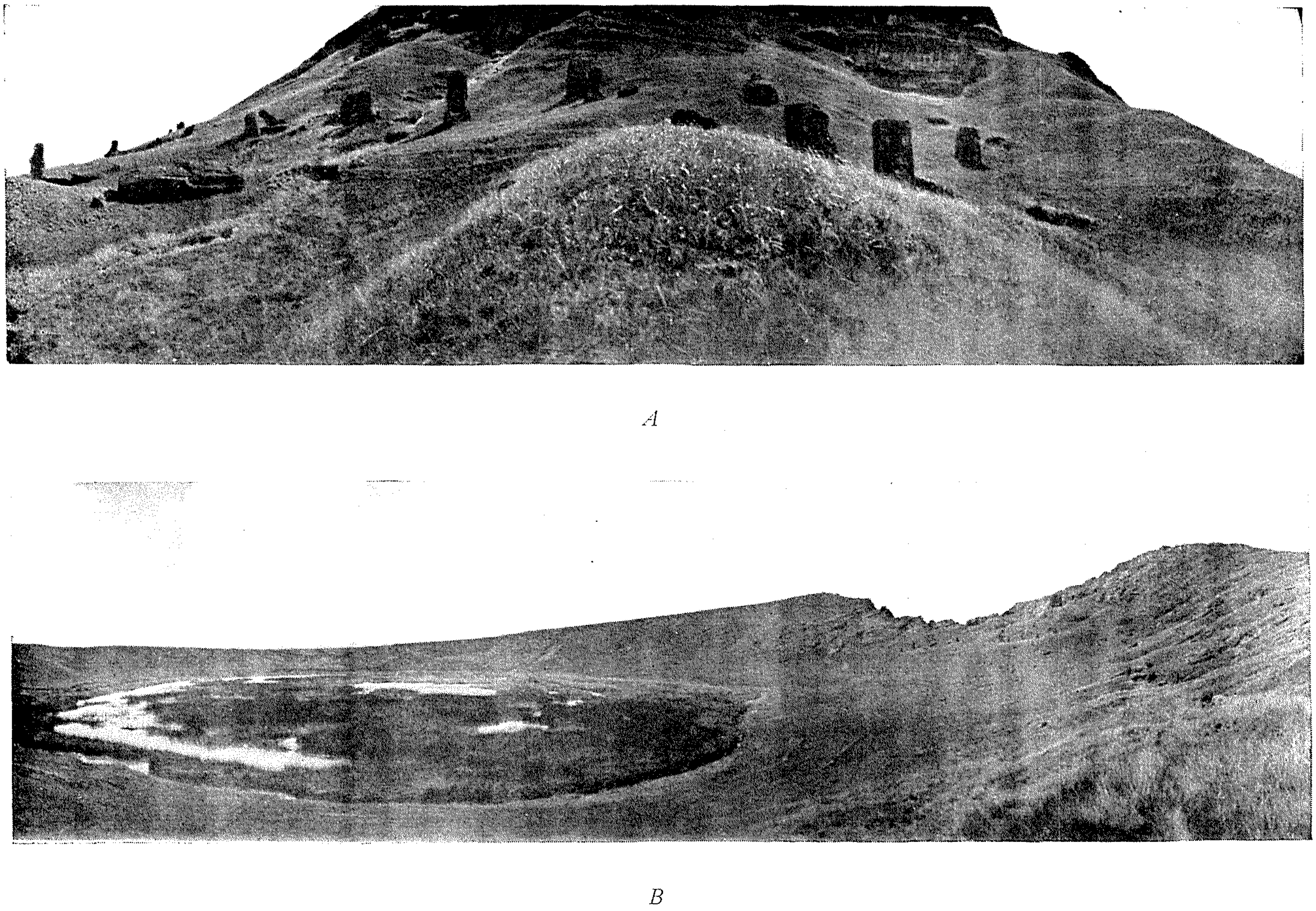
TAGUS CRATER, ALBEMARLE ISLAND: *A*, TAGUS CRATER LAKE, SHOWING SALT-ENCRUSTATIONS AROUND ITS MARGIN, LOW KNIFE-EDGED RIDGE SEPARATING THE LAKE FROM TAGUS COVE, SLOPES OF NARBOROUGH ISLAND IN THE DISTANCE; *B*, "BUBBLE CRATER" ABOUT 12 FEET HIGH ON SIDE OF RIDGE THAT CONNECTS INNER AND OUTER CRATERS OF TAGUS, TOP COLLAPSED, BEYOND IS FLAT-BOTTOMED MOAT.

A



B

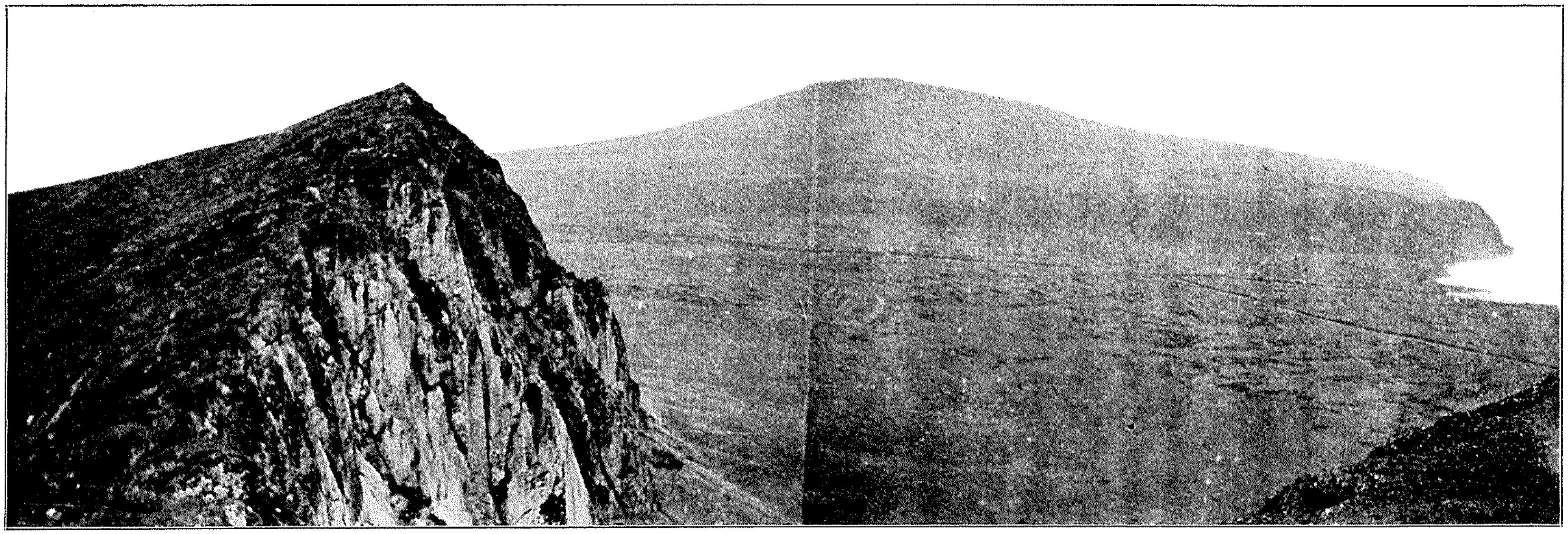
CLIFFS ON ALBEMARLE AND COCOS ISLANDS: *A*, INLAND CLIFFS OF FRIABLE TUFF CONTAINING LARGE FRAGMENTS OF LAVA, NORTHWESTERN SIDE OF TAGUS HILL, ALBEMARLE ISLAND; *B*, CLIFFS OF COLUMNAR LAVA, WEST OF WAFER BAY, COCOS ISLAND. HANGING VALLEY, LUXURIANT VEGETATION.



A

B

RANA RORAKU, EASTER ISLAND: *A*, SOUTHERN SLOPES SHOWING STATUES OF ANDESITIC PALAGONITE-TUFF WHICH HAVE BEEN REMOVED FROM THE QUARRIES IMMEDIATELY ABOVE; *B*, RANA RORAKU FRESH-WATER CRATER LAKE.



POIKE VOLCANO, SEEN FROM SOUTHERN RIM OF RANA RORAKU, EASTER ISLAND, SHOWING INLAND CLIFFS WITH LAVA FIELDS ABUTTING AGAINST BASE; ON LEFT IS PART OF RIM OF RANA RORAKU, SHOWING INNER SLOPES AND OUTER CLIFFS; ON RIGHT IS TONGARIKI BAY.