CONTENTS

ILLUSTRATIONS

Fringing and Fossil Coral Reefs of Oahu

By James B. Pollock

INTRODUCTION

ACKNOWLEDGMENTS

The observations which form the basis of this study were made during a residence of two years in Hawaii from the summer of 1922 to the summer of 1924.

It is a pleasure to acknowledge here the numerous acts of courtesy and kindness which I received from various residents of Honolulu during my stay in the islands. While it is impossible to mention them all by name, gratitude demands that the mention of some names be not omitted.

To A. L. Dean, then President of the University of Hawaii, to Professor H. F. Bergman, botanist, and Professor C. H. Edmondson, zoologist, thanks are due for the free use of University laboratories and apparatus. Professor Harold S. Palmer, geologist, first pointed out to me the location of some of the fossil reefs, later presented me with a pocket level for taking elevations, and extended numerous other courtesies. Dr. Harold L. Lyon, placed at my disposal the excellent botanical library belonging to the Hawaii Sugar Planters' Experiment Station. The resources of Bernice P. Bishop Museum, including its library and herbarium, were at my disposal through the kindness of Herbert E. Gregory, Director; Miss Elizabeth B. Higgins, Librarian; and Dr. Forest B. H. Brown, botanist. Dr. Harry L. Arnold, a physician of Honolulu who continues a great interest in natural history, has aided me in many ways. To these and many others unnamed I render my most grateful acknowledgment. Finally, due thanks are here expressed to the administrative officers and the Regents of the University of Michigan for the privilege of spending my sabbatical leave of absence in Hawaii, following a year of exchange with the Professor of Botany in the University of Hawaii, thus giving me two years in the islands, the last of which could be devoted wholly to the problems selected for study.

---

[1] Papers from the Department of Botany of the University of Michigan no. 225. A synopsis was read by Professor H. H. Bartlett, University of Michigan, at the Third Pan-Pacific Science Congress, Tokyo, Japan, November 10, 1926.

LOCALITIES STUDIED

The island of Oahu is surrounded by a fringing coral reef. Along the southwest coast the rim of this reef, exposed at low tide, varies in distance from the shore from about 300 feet (90 meters) to 1200 feet (365 meters). In addition to having the living, growing reef offshore, the island has areas of raised, fossil reefs in many localities, in which the structure of reefs of an older time may be observed.

Living and fossil reefs were studied at Honolulu harbor and at points eastward from Honolulu to Koko Head and westward to Kaena Point. (See map, fig. 1.) The harbor of Honolulu was originally a natural passage through the reef. Like many such harbors in the coral regions of the world, it is believed to be due to the presence of large quantities of fresh water at the mouths of the rivers, together with the silt that the streams transport. The silt in large quantities is fatal to coral, and fresh water so dilutes the sea water as to prevent growth of the coral, which would otherwise fill up the harbor and make a continuous reef. The natural entrance to the harbor has been widened and deepened by dredging, and part of the material removed in the process has been used to fill up adjacent low or submerged

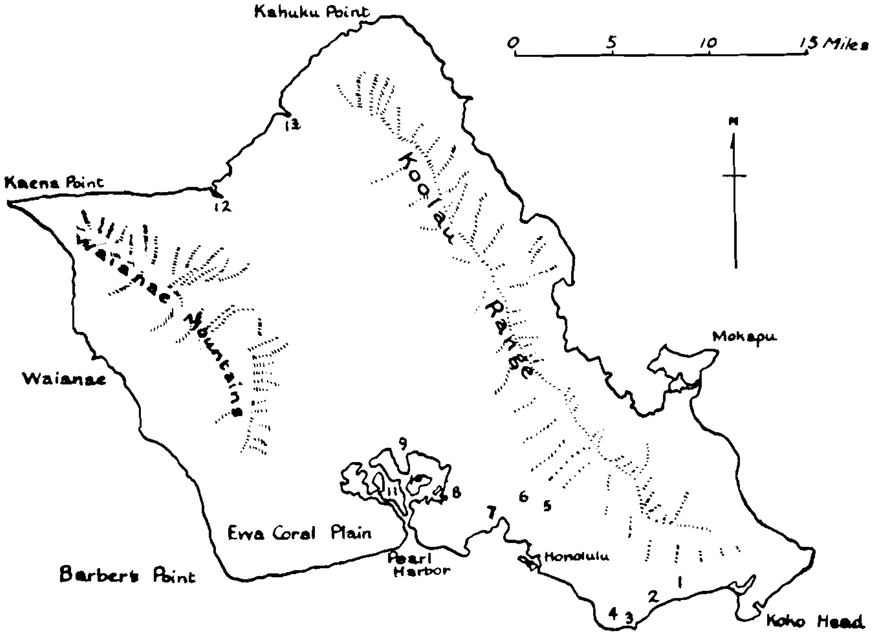


FIGURE 1.—Map of Oahu showing localities at which fringing and fossil reefs were studied: 1, Wailupe Valley; 2, Kahala; 3, Black Point (Kupikipikio); 4, Diamond Head; 5, Kalihi Valley; 6, Moanalua Valley; 7, Salt Lake crater; 8, Makalapa crater; 9, Pearl City; 10, Ford Island; 11, Waipio Peninsula; 12, Waialua; 13, Waimea.

areas. The surface of Sand Island, just west of the harbor entrance, is largely made up of material which lay at the bottom of the harbor and its entrance. Similar material has resulted from recent dredging at Kalihi basin adjoining the harbor and by a fill at Kewalo, about 1 mile east of the harbor. At Waikiki, 3 miles east of Honolulu harbor, in a region of flat land bordering the sea a drainage canal, called the Alawai, and sewer ditches, in places dug more than 10 feet below sea level, have brought to view along a stretch of several miles materials that were deposited in the sea beneath the land upon which the city of Honolulu is rapidly building.

From the small promontory of Black Point (Kupikipikio), and extending through the residential district of Kahala to the volcanic craters at Koko Head, the reef was studied in considerable detail. On the side of Black Point facing Diamond Head (Pl. I, *C*) are raised coral reefs which antedate the eruption that produced the promontory. Some of the best specimens of fossil nodular algae were collected there.

Between Kahala and Koko Head, several sharply cut valleys, separated by steep volcanic ridges, descend from the mountains to near the shore. Near the mouth of one of these, Wailupe Valley, an interesting fossil reef partly eroded by the ocean at its present level is exposed 5 to 8 feet above low tide. This will be referred to as the Wailupe Fossil Reef. In the western part of Honolulu in Kalihi, part of the land is composed of coral reef rock which rises gradually from sea level to an altitude of nearly 20 feet, the knobs of the rock being exposed along the streets and in vacant lots. At Moanalua, about 3 miles west of Honolulu, reefs are exposed at the shore line, and others at a higher elevation. Still farther west, about 3 miles, is the famous Pearl Harbor, into which flow several of the larger streams on this side of Oahu. It is a natural harbor, separated from the sea by coral reef material and some volcanic tuff, but its entrance and some of its bays have been deepened by dredging to adapt it better to the use of the Navy. Two peninsulas, Pearl City and Waipio, project into Pearl Harbor from the mainland. Within the harbor are several islands, the most important being Ford Island and Kuahua Island. These peninsulas and islands divide Pearl Harbor into several bays or expansions known as lochs. The east side of Pearl Harbor is largely composed of volcanic tuff, overlain around the shore by calcareous deposits formed when the sea stood about 20 feet higher than at present. Ford Island and Waipio Peninsula, as well as the channels that form the outlet of Pearl Harbor, show good exposures of coral reef around their shores, while Kuahua Island seems to be composed of volcanic tuff only.

In the vicinity of Pearl Harbor excavation for the foundations of a score or more of large oil tanks and some thousands of feet of ditches in which the pipe lines were laid to connect the tanks with the pumping station gave unusual opportunity to see what was below the land surface. Dredgings from the harbor were also exposed for study. These various activities made the time auspicious for observations of the kind here recorded.

Between Pearl Harbor and Kaena Point studies were made of the living and fossil reefs, especially those of the Ewa Coral Plain in the region where it is traversed by the Oahu Railway, and the fossil reefs at the village of Waianae. In addition to the locations mentioned, studies were made at numerous places along the coast between Waianae and Wailupe Valley, a distance of nearly 50 miles. Casual observations made at many other points on the shore of Oahu, disclosed nothing essentially different from what was seen in the reefs studied in detail.

METHODS AND MATERIALS

SCOPE

In choosing a method of work it seemed desirable to make an intensive, rather than an extensive study, to determine, so far as possible, what proportion of the materials composing the reef was contributed by plants, what by animals, and what by inorganic agencies. Formerly coral reefs were supposed to be formed preponderantly, if not almost exclusively, by the coral animals. In recent years, however, it has been increasingly recognized by both biologists and geologists that plants, particularly lime-secreting algae, are active agents in contributing calcium carbonate to the so-called coral reefs, and that for some reefs their contributions were greater than that of the coral animals. Thus in the boring of the coral reef at Funafuti (13, p. 133) corals stood fourth in the amount of material obtained in the boring, while lime-secreting algae—namely, lithothamnium[2] and *Halimeda*—each contributed more material than the true corals. Even Foraminifera stood ahead of the corals.

After considerable study of both the fossil and the living reefs on Oahu, it seems practicable to measure directly the proportions of material contributed by coralline algae and by true corals, respectively, on small areas of the different types of structure.

MEASUREMENTS ON FRINGING REEF

In making the measurements of the living reef, a metal frame was used having dimensions of 1 foot by 2 feet with a crossbar at the middle point, forming 2 areas each a foot square. Strings were tied across the middle of the one-foot squares in the two directions at right angles to each other, dividing the larger squares into smaller ones each 6 inches on a side. The framework and strings thus outlined two one-foot squares and within these, 8 smaller six-inch squares. In this form the apparatus was laid down on the hard surface of the reef and immediately a memorandum was written into a field

---

[2] The term lithothamnium is here used to include all the stony, coral-like algae, and not used as the name of a genus, except in association with the name of a definite species.

note book indicating the character of this surface, whether of coral, of coralline algae or of some other material.

The observations were recorded as so many square inches occupied by the different kinds of material within the borders of the framework. In some places the entire square foot of area was occupied by one kind of growth or material. The reading was then simple, except when, in many places, small patches or areas of a rounded or irregular shape were encountered. After some experience in trying out various methods, the measured areas were finally estimated as to whether the small patches of one kind of growth, if distributed in a regular way, would be equal to a strip across the six-inch square, 1, 2, 3, or more inches wide. As each strip 1 inch wide and 6 inches long was one-twenty-fourth of the whole area of the square foot, the results were expressed merely as the number of twenty-fourths of the whole area occupied by the growth observed. This made the problem of recording results and of calculating the proportions and the percentages relatively simple.

The meter is too large and the decimeter too small to serve as a practicable unit for the size of the squares, hence the foot and inch were adopted. With the small and large squares it was believed possible to make observations whose error would not exceed 5 per cent of the total area measured.

A water-tight box with an open top and a glass bottom was used to facilitate the reading of areas not wholly above the water, or when the rising tide covered it while the measurements were in progress. This water-box overcame the difficulty of observing through a wavy water surface, making it possible to read plainly a surface two or more feet below water, though very few accurate measurements were made at so great a depth. Four strings, each tied to a corner of the measuring frame, were joined to a loop hung around the neck. The frame could then be lifted by the strings, moved forward and placed, thus avoiding much stooping, fatigue and wet hands. The water-box was kept conveniently at hand by a similar string and loop. A towel pinned around the neck, helped to keep the hands dry for recording. The note book was kept dry in the observer's hat.

When the observations had been recorded for the 2 square feet outlined, the frame was moved forward its own length and another observation recorded. Thus records were obtained for a continuous series of squares actually for a continuous strip 1 foot wide and having a length as great as seemed desirable in any given locality, or as great as the working time of the low tide period would permit. Most of these lines of squares were measured from the shore outward toward the reef rim or from the reef rim shoreward, but a few were measured parallel to the reef rim or diagonally. It was practicable to work only at or near low tide.

It may seem that a one-foot strip is too narrow to be representative of an area as large as the whole reef, but experience in making these measurements showed that this was the most practicable unit. The error in reading a larger unit would have been much greater, and the time consumed much greater, rendering it impossible to measure so long a line of squares in one low tide period. As it was, the tide often came up so as to stop the measurements before a line of the desired length had been completed. To insure that the parts of the reef measured should be representative in character, an inspection of the reef over a wider area was made before the starting point for the measurements was selected.

In a few places where the corals seemed particularly abundant, wider and shorter areas were measured off instead of lines of squares 1 foot wide, and all the patches of coral and coralline algae within the areas so selected were measured individually. This was done to obtain the relative areas occupied by each, in order to get some idea of their greatest abundance.

In addition to the lines of squares in which accurate measurements were taken, a number of lines were traversed by measuring the distance, and stopping at intervals of 50 or 100 feet to record observations made in each interval by a general inspection, as far on each side of the measured line as the eye could readily perceive the conditions. The knowledge obtained by the more accurate measurements served as a basis for comparison in expressing the results of this general inspection.

No attempt was made to observe outside the reef rim, except what could be seen from the rim itself.

MEASUREMENTS ON FOSSIL REEF

In making the measurements on the fossil reef, somewhat different methods were used, depending upon the kind of structure the measured portion presented. The same square-foot unit was used for that part of the reef in which the structure was made up of ellipsoidal nodules embedded in a matrix of calcareous sand. This structure (Pl. II, *A*) was best shown in the Wailupe Fossil Reef and on the west side of Black Point. It corresponds almost exactly to the structure found on the sea bottom in the Dutch East Indies (24), where great banks were discovered, composed of rounded ellipsoidal nodules of a single species of the alga, *Lithothamnion erubescens* Foslie forma *haingsisiana* A. Weber and Foslie. In the absence of critical studies of the species of lithothamnium in the fossil or living reefs, whether this species on Oahu is the same as that found in the Dutch East Indies has not been determined—in general external morphology it is similar. Such a critical study is planned for a later paper.

When the square was applied to the exposed surface of a fossil reef having the structure indicated, each of the ellipsoidal nodules lying within the square was measured in the longest and shortest visible diameters at right angles to each other, and these were assumed to be the major and minor axes, respectively, of the ellipsoidal nodules. The volume of each nodule was calculated by the formula $4/3 \pm ab^2$, in which a is the number of units in the length of the radius in the major axis, and b, of the radius in the minor axis. The sum of the volumes of all the nodules within a square foot of reef-rock surface was taken as the amount contributed by the plant as it grew, in the volume of rock whose surface area was 1 square foot, and whose depth was equal to the average of the minor axes of all the nodules measured in the square. Since the volume of a sphere or an ellipsoid is 52-36 per cent of the volume of a circumscribing cube for the sphere or a circumscribing rectangular prism for an ellipsoid, the calculation was shortened by multiplying the product of the three diameters of the ellipsoid by .5236 and the result is the volume of the ellipsoid. From these data the percentage of the total volume contributed to the reef by these growing coralline algae was calculated. The portion not occcupied by the nodules was composed of fine and coarse sand, which in all probability also had its origin chiefly from coralline algae. These measurements were repeated as frequently as seemed practicable on the basis of the amount of exposure of the fossil reef, and the time at the disposal of the observer. The calculations involved in this method consumed a great deal of time as did the primary measurements.

The exposures of the reef which were subject to the wave action near present sea level, as in the Wailupe Fossil Reef, offered much more favorable material for measurement than those in other localities. Here the different kinds of material stood out in bold relief (Pl. II, *A, B*).

The structure just described fills in a considerable amount of space between masses in which a central branching coral is surrounded by layer after layer of thin crusts formed by one of the coralline algae. Here the coral center was measured in different diameters and its volume calculated as that of a cylinder having a diameter equal to the average of those measured. Then the surrounding layers of crustaceous algae were measured on their radii and their volume calculated as that of a portion of a cylinder surrounding the coral center. In this manner were obtained approximate percentages of the total volume occupied by coral and coralline algae.

A third structure is represented by what the workmen in the sewer ditches call "finger coral",—a designation here adopted in want of a better descriptive name. Slender, elongated branches of coral grow vertically and nearly parallel to each other, but many of them anastomosing, the spaces between these connecting branches filled with fine sand and mud. In many specimens the sand was so slightly consolidated that it was quickly washed out on exposure to the waves, leaving the coral branches alone as shown in Plate IV *B, C.* In other specimens the sand was consolidated into fairly hard rock. In some specimens the coral branches were quite closely crowded, the coral forming a large percentage of the volume; in others they were far apart and the sand filling was proportionately large in quantity.

In determining the proportion of coral, the broken ends of the branches were measured in two diameters and their areas calculated as that of ellipses or circles. As the coral branches have the form of columns, with an elliptical or a circular cross section, only their areas, having the same proportion as their volumes, need to be calculated. By measuring all the broken coral ends within a square foot of surface area it was possible to roughly approximate the percentage of volume occupied by the coral. A certain amount of error would be caused by anastomosis and variations in the diameters of the coral branches at different levels.

A fourth structure, found in many localities, was studied in fossil reefs and also in the dredgings at Honolulu harbor and Pearl Harbor. It consists of horizontal layers or dome-shaped masses, the coral layers alternating with coralline algae or with sand or other fragmental material. This is here called "superposed coral." It was difficult to arrive at even an approximate estimate of the coral and non-coral material in this structure. The layers of both are thin, and it was impossible to determine the composition of some of the layers.

A fifth structure consists of solid coral heads, as of *Porites lobata,* growing in the deeper water over the reef flat, and also outside of the reef rim. The structure formed by these growths is here called "massive coral." Very little of this structure was seen either in the fossil reefs or in the material dug from the harbor. (See p. 20.)

A sixth structure is a consolidated calcareous conglomerate which consists of all kinds of fragmental material deposited, more or less rounded by the waves, with almost no material that grew in place. Fragments of coral, coralline algae, shells of mollusks and the harder parts of many other animals, coarse and fine sand, are all mixed together in ways that make it difficult to even approximate their relative proportions. When such conglomerate is consolidated at or just above water line, the mass takes the ordinary slope of the beach, about 10 degrees from the horizontal, and lies in layers that overlap each other in the manner of the shingles or tiles on a roof, those nearest the water, of course, being the latest formed. For this formation the term "beach rock" is used. As it is believed to be formed only at or slightly above tide level, its position decidedly above or below this level may be taken as evidence of emergence or submergence, respectively, of the land in relation to water level. To determine, even approximately, the relative amount of corals and other definable material contained in this conglomerate, a few linear measurements were made along the surface of the exposures, the diameter recorded for every fragment measured and the proportion of the total calculated.

In a few places rocks were observed which might be called *Halimeda* sand rock, the recognizable organic remains being mostly the alga, *Halimeda,* combined with various grades of sand. In some exposures the *Halimeda* was mixed with other coralline algae. *Halimeda* being one of the green algae, or Chlorophyceae, though it secretes a certain amount of lime, is not a member of even the same class (red algae, or Rhodophyceae) as that to which the true coralline algae belong.

In various localities on Oahu are calcium carbonate deposits in the form of a fine, white, impalpable powder, much of it with a coherence sufficiently firm to serve for writing on blackboards, for which purpose it is said to have been used in some of the earlier schools. This has been called "Oahu chalk" (Pl. V, *B*). (See p. 31.)

In all reefs observed, sand of various degrees of fineness or coarseness forms a constituent of greater or less amount, helping to fill in the spaces between the portions that grew in place. Mixed with it in varying proportions are other detrital materials such as volcanic mud, river silt, shells of mollusks, tubes of marine worms, and tests of echinoderms. At nearly all places tested, echinoderms were present in such small proportions as to be negligible so far as the present paper is concerned.

FORMS OF CORALLINE ALGAE

The critical study that would permit the naming of the species of the coralline algae observed has not yet been completed, hence no attempt is here made to designate species identity, even for those which have been tentatively determined. It is desirable, however, to describe the different forms which these algae show, for they have a definite relation to the different structures described in the living and fossil reefs. The morphological groups do not at all coincide with the taxonomic ones, and as morphology has more to do with determining the distinctive structure of the reef, it is less necessary for the present purpose to name taxonomic species.

The coralline algae proper belong to the class Rhodophyceae, and to the family, Corallinaceae. Microscopic sections of the hard, stony structure (made by grinding as the geologist grinds his rock sections) show that the cells composing the plants are almost completely filled with solid deposits of calcium carbonate. This gives the plants an exceedingly firm and stony texture, and a coral-like appearance, which is the reason for calling them coralline algae. In the older literature of biology and geology they were called "nullipores" or "Nulliporae," the earlier observers of these structures considering them to be a kind of coral animal; but before the middle of the nineteenth century they were recognized as plants (20).

The general, morphological classes may be distinguished as (a), the crustaceous; (b), the nodular; (c), the branching forms. Ever since it has been known that nullipores are plants, the crustaceous form has been recognized, in both biological and geological material. On the living reef at Oahu, and wherever coral reefs are formed, these crustaceous algae form a binding or consolidating medium covering over the surface of coral or other material composing the reef, serving, in fact, as a chief consolidating agency. These crusts surround branching corals in the fossil reefs. The ability to form crusts is possessed by numerous species of the coralline algae. This form of algae is probably much more effective in consolidating the materials of the reef than is precipitation of calcium carbonate from solution, at least in the region of the reef where organisms are actively growing.

The nodular forms of coralline algae are of several kinds (Pl. III, *A*), globoid to ellipsoid in shape, some with entirely smooth, hard surfaces, others with short, thick, stony, knob-like branches, and still others with branches which are themselves repeatedly branched. These branches are of various shapes, short or long, cylindrical, terete or flattened. One of the branching forms of nodules is a very prominent constituent in the Wailupe Fossil Reef, but growing on the nearby reef flats between the reef rim and the shore are many different kinds of nodules, and these are exceedingly abundant on the part of the living reef off shore from the Wailupe Fossil Reef. These nodules lie in the shallow depressions over almost the entire distance from the shore to the reef rim, which had here a width of about 1,200 feet (365 meters). They are so abundant that in many depressions they are in contact with one another over the whole bottom or piled up several deep, even where the bottom has a considerable amount of fine mud which is stirred up at every high tide and settled temporarily at every low tide. The mud is so abundant on the shoreward third of the Wailupe Fossil Reef that some of the nodules of algae are completely buried in it at low tide, yet many of them are alive, being reddish or purple. In this locality, and a few others, at every high tide the water on the reef flat is exceedingly turbid. No live corals are found in such muddy water, but as the reef rim is approached the water becomes clear, and both corals and branching forms of coralline algae appear.

Lithothamnium nodules could have a continuous existence, therefore, in regions where the coral animal is utterly unable to survive because of the detrital mud.

The submerged reef, therefore, from the shore out to the reef rim is adding new material to its structure by the growth of these nodular corallines and is therefore properly called a living reef, in spite of the fact that the nodules may be buried in mud or silt. It is clear that this living reef is building up a structure quite similar in morphology to the nodule-bearing portion of the Wailupe Fossil Reef. This does not necessarily imply identity of species in the fossil and on the living reef. Indeed, the general appearance of the nodules in the two places suggests, but does not prove, that the species are not the same, and judging by external appearance alone there appear to be three or more different species of the nodular type on the fringing reef.

Like the nodular forms of coralline algae, the crustaceous forms also are found both in Wailupe Fossil Reef and growing on the surface of the living reef. Indeed, the longer the reefs were studied the more extensive the growth of these crustaceous forms was found to be. At and near the reef rim they cover from less than half to almost the whole of the surfaces of the rocks exposed at low tide. When observed superficially or casually many of the exposed protuberances or hummocks of rock, which would commonly be called coral heads, seem to be completely covered by algae other than corallines and belonging to the three classes of brown, green, and red algae. The genus *Sargassum* covers many of these, apparently completely investing them with a single vegetative growth. In places, entirely different algae, *Laurencia,* a red alga, *Halimeda* and *Dictyosphaeria,* green algae, and many others of all the classes may be found singly or in combinations. Almost invariably, however, whatever else is present, beneath the growth which seems to invest the exposed rocks, more or less completely, is another growth of crustaceous corallines. When broken with a hammer, many of these rocks show a central core, or substratum, of true coral, hence there is forming on the reef rim at the present time a combination of coral and crustaceous corallines exactly like that in one part of the fossil reef. (See p. 8.) The two most abundant structures in the Wailupe Fossil Reef, one characterized by the nodular lithothamnium and the other by the coral center surrounded by the crustaceous algae, are both forming at the present time on the fringing reef. The fringing reef, therefore, is a living, growing reef, not an ancient one.

Not only are the crustaceous corallines covering and adding to almost all the surface at the reef rim, but they are also surprisingly abundant all the way to the shore—a fact not fully appreciated until near the end of this study. In many places where the upper surface of the reef flat seem to be free from such growth, the under side of projecting or over-hanging rocks or the vertical surfaces are covered wholly or in part by smooth, wine-colored to deep purple crusts of some coralline alga.

The branching coralline algae are likewise of numerous kinds, both as to external form, and taxonomic species. Some of them have long, slender, terete branches, which are in certain species very brittle, easily broken by the waves, and therefore, likely to contribute readily to the formation of calcareous sand. Other species have thin, flat, fan-like branches (Pl. III, *B* left), also rather easily broken and contributing likewise to the formation of calcareous sand. These branched corallines are very abundant on the reef flat far enough within the reef to escape the full force of the breakers. In fact, what appeared to be a single species of this type seemed alone to occupy almost as much space on the reef as all the corals combined between the reef rim and the shore.

Other branching corallines have short, thick, stout branches (Pl. III,*C*) capable of resisting the force of the strongest breakers under ordinary conditions. These forms are abundant at the reef rim where the waves break with the greatest intensity, and are, therefore, important constituents of that part of the reef. A similar type exists in the fossil reef, associated in some places with the nodular type of fossil reef structure. In the vicinity of Barbers Point is much of this type associated with *Halimeda* sand rock structure.

From an ecological point of view, certain crustaceous species and the stout-branched species form an association in the region of the breakers at the reef rim. The thin-branched, taller type grows in a zone on the reef flat, where the force of the breakers is much diminished, but is rare near the shore and on the reef rim. The nodular types lie free in depressions anywhere on the reef flat where the force of the waves is not sufficient to sweep them entirely away, being most abundant on the wider parts of the reef where the power of the waves is less. Many of the nodules are pale purple on the upper surface and much deeper purple or reddish below. They may be alive, however, on the whole circumference as shown by the degree of reddish or purple color, as they quickly fade and become colorless when dead. Undoubtedly, waves of ordinary intensity are able to roll the nodules about during the periods of the high tide; hence all portions of the surface of the nodules are, for more or less of the time, exposed to the direct rays of the sun. As many are paler on the top than on the bottom, when undisturbed for some time, it seems not improbable that growth may be more active on the bottom. Observations in 1923 at Wake and Johnston islands (14) indicate that the direct rays of the tropical sun are more or less detrimental to these algae, and that their growth in that latitude is much more luxuriant on the under side of projecting ledges. In fact, it has been noted by several observers in the tropical regions that the algae generally grow abundantly only where somewhat shielded from the sunlight. Setchell (22, p. 152) has recently called attention to this fact.

RESULTS OF OBSERVATIONS

WAILUPE FOSSIL REEF

The fossil reef studied in greatest detail was that at Wailupe. In this reef the lithothamnium nodules and coral centers surrounded by lithothamnium crusts are in evidence. The two structures are quite distinct in the partly eroded surface. Many of the nodules stand out in half-rounded forms. Large blocks broken from the exposed face of this reef lie on the beach, making it possible to see the structure in three dimensions. In some of these fallen blocks weathering has revealed the different components of the reef structure. Firm masses of coral surrounded by crustaceous algae remain after they are freed from the nodules and sand which originally filled in the space between them. In similar structural masses the coral core stands out quite clearly surrounding the thin strata of coralline crusts are exhibited, capping a branch, or completely surrounding it. (See Pl. II, *B.*)

One small portion of the Wailupe Fossil Reef differs in structure from any others seen (Pl. II, *C*). To the naked eye it consists of a series of short, anastomosing branches, branching again at intervals of 3 to 6 inches. The segments of the branches vary in diameter from 2 to 4 inches and in shape from nearly cylindrical to decidedly flattened and widened. These branches are of a distinctly brownish tinge which makes them stand out in contrast to the surrounding reef rock. On exposed surfaces they are partly weathered into relief. On breaking them with a hammer, so as to show the internal structure, the outer brownish portion is seen to have a fine-grained texture with no organic remains visible under a pocket lens. At the center of each branch, however, chambers are visible, which run lengthwise of the larger branches and appear to branch out from each other. Running outward and upward at intervals along the rows of chambers are almost cylindrical cavities filled with a reddish-brown structureless deposit, so soft as to be readily removed with the point of a knife blade. The rest of the structure has the firmness of an ordinary rock.

Preliminary study led to no satisfactory interpretation. Later investigation showed that the structure resembles closely one which Semper (21) interprets as an association of a red alga and a sponge (*Spongia cartilaginea*):

> The branches which are sometimes cylindrical and sometimes flat, divide in one place and reunite in another, thus forming an irregular network, with the meshes and branches spreading almost in a plane. . . . . But a more minute investigation with the microscope shows us, beyond a possibility of a doubt, that this body consists of two distinct organisms, namely, of a sea-weed associated with a sponge exactly as is the case with the lichens among plants, and it is impossible, with only specimens preserved in alcohol, and without investigating their vital properties, to decide whether the form of the whole mass owes its origin to the sponge or the vegetable. The thick and somewhat vitreous, transparent branches of the internal network [Semper's fig. 93] which give rise, where they anastomose, to the broader branches, on one side of which we find the stomata of the sponge, are undoubtedly filaments of a sea-weed. . . . . . probably an undetermined species of Floridea; and the spaces between these internal branches of the sea-weed lead directly into the cavities which, on one side of the main stem, pass into the stomata of the sponge. Here the margins of these are actually composed of the filaments of the alga. On the other hand, the soft tissue of the sponge proper lies in a very thin layer on each filament; the sponge has no true fibres, though it has spiculae which are scattered through the soft substance.

Without expressing an opinion as to the correctness of Semper's interpretation of this structure as an association of an alga and a sponge comparable to the association of an alga and a fungus in lichens, the very perfect resemblance which the Wailupe Fossil Reef bears to Semper's figure 93 may be pointed out. The resemblance appears externally in the shape and anastomosing of the branches, and internally in the rows of chambers which Semper interprets as filaments of a red alga and also in the cavities which he calls the stomata of the sponge. In the Wailupe Fossil Reef the cylindrical cavities filled with a soft, fine-grained sediment are in size, shape, position, and direction like the stomata of the sponge shown as *a* in Semper's figure 93.

At Wailupe Fossil Reef, in addition to measuring the details of structure within the squares, more extensive measurements were made to determine the relative proportions of the chief kinds of grosser structure in a larger part of the reef. The following method was used: with a foot rule, measurements were made from top to bottom on the face of this exposure, generally at horizontal intervals of 2 feet, and for each measurement the number of inches and fractions of an inch required to pass through each kind of structure was set down in a separate column, with one column for the measurements of uncertain structure. This was continued along the face of the exposure in a horizontal direction for about 220 feet. The length of the individual vertical lines varied from 16 to 74 inches, the average being 44 inches, that is, the measureable part of the reef exposure varied in height to that extent. The total number of vertical lines measured was 99, and the total length measured vertically was about 360 feet.

Taking the measurements as a whole, that part of the reef composed of nodular lithothamnium and sand filling amounted to 31 per cent; the portion composed of branching coral closely invested by lithothamnium crusts, 52 per cent; coral fragments not so invested, 1.5 per cent; and structure that is uncertain, 15.5 per cent. These figures, however, require further analysis. The 31 per cent included both lithothamnium nodules and the sand filling in which they were imbedded; but the detailed measurements of these in the 1 foot squares show that the nodules alone compose from 35 to 59 per cent of the material in the different units measured, and average 46 per cent in all. Recalculating these quantities shows that the reef as a whole contains more than 14 per cent of the nodular lithothamnium alone, representing merely one of the three different types in the group of coralline algae, and that the sand filling between the nodules is almost 17 per cent.

Similarly, recalculations for that part of the reef made up of coral branches surrounded by lithothamnium crusts show that the true coral varies 10 to 72 per cent, the lithothamnium crusts 28 to 90 per cent in the individual units measured, the averages being 58 per cent true coral, 42 per cent of the combination lithothamnium crusts. As this combination composes 52 per cent of the structure of the reef as a whole, it may be said that the Wailupe Fossil Reef contains 22 per cent of true coral branches that are in place as they grew, and 30 per cent of crusts of lithothamnium also in place as they grew. These results are exhibited in Table 1. In Table 2, they are recalculated to show the composition of the reef as a whole.

TABLE 1. VARIATION IN MATERIAL WAILUPE FOSSIL REEF.

MATERIALS	RANGE OF VARIATION PER CENT	AVERAGE PER CENT	
Branching corals that grew in place	5—37	22	
Lithothamnium crusts that invested them	15—47	30	
			52
Lithothamnium nodules. Either growing in place or rolled by the waves	11—18	14	
Sand filling between the nodules	13—20	17	
			31
Coral fragments deposited by waves	1— 5	2	
Structure and origin uncertain	11—17	15	
			17
			100

TABLE 2. COMPOSITION OF WAILUPE FOSSIL REEF

Corals alone	22 + 2	=	24 per cent
Lithothamnium alone, nodules and crusts	14 + 30	=	44 " "
Detrital material, sand and coral fragments and part uncertain	17 + 15	=	32 " "

WAIALAE FOSSIL REEF

For comparison the Waialae Fossil Reef was studied. At this site, an exposure about 100 feet long and 14 feet high was made accessible to observation through quarrying of lime rock for industrial purposes. On the basis of measurements and estimates in comparison with the measured Wailupe Fossil Reef, it was concluded that the Waialae site is composed of the branching coral surrounded by algal crusts to the extent of 30 to 50 per cent; that there is very little nodular lithothamnium, its place being taken here by the branching forms or their broken fragments; and that true corals, predominantly some species of *Pocillopora* also in broken fragments, are present as wave-deposited material in larger amount than in the Wailupe Fossil Reef.

Study of these two reefs and an inspection of numerous others revealed the fact that the wide range of variation in the structure and composition of the fossil reefs is one of their most striking characteristics, and of as great if not greater significance than the averages. Both a casual inspection and detailed measurements show that the easterly seven-tenths of the Wailupe Fossil Reef as measured contains a much larger proportion of the nodular lithothamnium with sand filling than does the westerly three-tenths. The figures are 39 per cent and 13 per cent, respectively, while the percentage of the nodules alone was 18 per cent and 6 per cent. Indeed, no reef seen elsewhere contains so much nodular lithothamnium as does one part of that at Wailupe; in other localities its place is taken in part by the branching types of lithothamnium, and in part by fragments of broken corals. With this modification, however, it is believed that the Wailupe and Waialae sites are representative of reefs in many other localities.

From the structural aspect, then, this type of reef consists of:

1. A fixed framework of materials that grew in place, made up partly of coral animals and partly of coralline algae, members of the plant kingdom. The corals are of rather slender branching forms and are closely and completely invested by the thin, concentric crusts of the algae. As measured, the plants predominate over the animals in the amount of material contributed, but there is a wide range of variation in their relations. When weathered out, this framework has the form of irregularly rounded obconical masses of rock having a high degree of firmness and forming the more solid parts of the reef. These masses, when weathered out of the fossil reef have their counterpart in structure and origin in some of the isolated or more protuberant rocks on the fringing reef off the shore of Oahu.

2. Between the masses of rock constituting what is here called the fixed framework lies material which has been deposited by the waves. Though variable according to locality and conditions, it is composed of a sand matrix containing lithothamnium nodules, fragments of broken coral, shells of mollusks, tests of echinoderms, or any other material capable of being washed in by the waves. Only in the region of Pearl Harbor were the shells of mollusks sufficiently abundant to require special notice. Hitchcock (16, p. 32) mentions a "bed of oyster shells, 1 to 2 feet thick" in the "Pearl River series." A similar shell layer, though not so thick, lies between beds of volcanic tuff on the southeast side of Makalapa crater. In general, however, such materials are so small in amount that they are believed to be negligible for the present problem.

The structure exhibited by the Wailupe Fossil Reef is recognizable in many other localities, particularly in the Kalihi region, where many knobs of rock exposed along the streets and in the vacant lots exhibit it distinctly. The cores of coral, with the surrounding lithothamnium crusts and the ellipsoidal nodules of the nodular form of lithothamnium, are easily recognized on many exposed surfaces.

FINGER CORAL

In determining the proportion of coral in finger coral, six blocks were measured at Sand Island, Honolulu harbor, and four at the mouth of the Alawai. The percentage of coral calculated for these blocks ranges from 16 per cent to 67 per cent, with an average of 38 per cent. One measurement shows 85 per cent, but this requires a special interpretation. In the blocks measured at the mouth of Alawai the sand-mud filling has been washed out by the waves, but in the similar blocks measured at Sand Island the filling consists of less mud and more sand, being consolidated into a coarse-grained sand rock in which the coral was distinct to the eye because of its color, as well as by its structure. In amount the coral on the top surface of certain blocks exceeds that on the bottom surface, the change taking place rather suddenly near the top. In the block shown in Plate IV the relation is top 85 per cent, bottom 29.32 percent. The top surface of this block is believed to be also the top portion of the reef out of which it came. It is believed to represent the structure produced where the coral is no longer able to grow vertically upward, possibly because of a change in sea level, or because the coral has reached the surface of the sea, but before ceasing growth entirely has expanded so as to occupy nearly all of the horizontal space. A similar condition was seen in some exposures in sewer ditches at the upper surface of the coral growth. It seems probable, therefore, that this structure represents the very top layer of the reef out of which it came, and that the other side of the block, the bottom, shows the structure where the coral was still free to grow vertically upward. Thus the surface of such a reef would be considerably more solid than the portions below it.

These finger-like coral branches form a large amount of the material dredged from Alawai and also appear in the bottom of the ditches excavated for the sewers in certain portions of Waikiki. As the canal approaches the foot of Diamond Head, the finger corals thrown out by the dredging machine are very slender, mixed with considerable volcanic mud. The sewer ditches nearest Diamond Head along Kalakaua Avenue disclose only sand.

Sewer ditches in those regions indicate that the present land surface between Honolulu and Diamond Head is underlain in part by a marly clay, in part by consolidated sand, in the swampy regions by muck, and in the Waikiki District chiefly by the finger coral type of structure, or by loose sand.

The finger coral structure shows in a raised reef near Pier 19, Honolulu harbor, and also at certain places around Pearl Harbor, but it does not form a very large proportion of any of the raised reefs studied. It is more abundant in the material dredged from both Honolulu harbor and Pearl Harbor and in certain parts of Waikiki than in the raised reefs. As determined by Mr. J. M. Ostergaard, the common finger coral of the Waikiki district is *Porites compressa.* The finger coral structures contain 18 to 30 per cent coral.

SUPERPOSED CORAL

What is here called "superposed coral" was seen in considerable quanity both in raised reefs and in the dredged material. Many of the fragments on Sand Island are of this type and a considerable part of the material dredged from Pearl Harbor also is thin sheets of coral superposed horizontally one upon another, or in the form of small domes or rounded elevations. The rocks whose surfaces show in numerous knobs along Kapahulu Road near the foot of the Kaimuki lava flow are predominantly of this type, as may be seen for a considerable distance along the surface, and a ditch in this vicinity, dug in order to lay a water pipe to the Fair Grounds, allowed observations to be made several feet below the surface. However, the part of this ditch nearest Waikiki showed more and more sand in the composition of the rock, and finally it was little else but loose sand, very slightly or not at all consolidated.

A superposed coral is associated with some finger coral in the raised reef near Pier 19, and is also found with a certain amount of nodular and branching lithothamnium in an exposure of an elevated reef at Moanalua along the Puuloa Road not far from its junction with the Kamehameha Highway. In places coral is superposed on coral. In other places it alternates with crusts of coralline algae, so thin that accurate measurements of the different components were impracticable. It was estimated that the coral constitutes in some structures more than half of the total.

This structure is in process of formation on the fringing reef, on the shoreward slope of the reef rim. It is not forming on all portions of this slope, nor even on all parts which are covered by coral.

MASSIVE CORAL

The term "massive coral" is applied to structure characterized by a solid growth of coral with little or no admixture. *Porites lobata* and some other species form dome-shaped or irregularly rounded masses or coral heads which gradually enlarge and reach a considerable size. Agassiz (1, p. 144) and Dana (11, p. 12) have described single heads with a diameter of 12 to 15 feet or even of 25 feet. The largest one measured on the fringing reef of

Oahu is 4 feet in diameter. In the elevated reef near Waianae Station, the only one in which this massive structure was seen (Pl. I, *D*), single heads are 6 feet in diameter. The separate heads here are closely crowded, with relatively little crustaceous alga surrounding them or of sand filling between them. On the basis of a few measurements and a general inspection it was estimated that this reef contains about 70 per cent coral.

Some blocks of massive coral were seen at Sand Island, where they presumably had been dredged from Honolulu harbor. The pieces are 5 to 6 feet in diameter and of an irregular shape, indicating that they have been broken off from larger masses.

The foreman in charge of the drilling and blasting preparatory to excavating the new channel from Honolulu harbor into the Kalihi basin—an excavation to extend 35 feet below sea level—said that the first 16 feet was through finger coral and mud, the next 18 feet through a solid coral ledge, and below that clay. It is possible that what he called solid coral ledge belonged to the massive coral type. At the time these studies were made the excavations had not proceeded far enough to determine to what extent the ledge was actually composed of massive coral. It is perhaps significant, however, that of all the raised reefs observed, only one showed massive coral.

HALIMEDA SAND ROCK

On Oahu a species of the genus *Halimeda* is common on the fringing reefs, but is not nearly so important in reef formation as the species at Funafuti, so far as may be judged by the results of the present study. (See p. 5.) In the vicinity of Barbers Point Lighthouse, *Halimeda* and a stout-branched lithothamnium are very conspicuous elements in the raised reef (Pl. VI, *B*). As observed in depressions about three feet deep and several feet across, which correspond to pools in the actively growing reef, both of these organisms appear to exceed corals in the amount of materials contributed. Parts of this reef are formed wholly of *Halimeda* joints embedded in rock (Pl. V. *A*).

The genus *Halimeda* was also found in relatively small amounts in reef material as filling at Sand Island and at Kewalo. On the whole, the amount of *Halimeda* seen in old reefs, raised or dredged, was small in comparison to its abundance on the fringing reef.

THE LIVING REEF

Accurate measurements on the fringing reef were made in the region from Waikiki to Wailupe, most of them at right angles to the shore line and reef rim. A few were taken diagonally. In addition to the lines of squares measured, a few wider areas were marked off, all the growths of certain kinds within these areas being measured individually and the areas occupied by them expressed as a percentage of the total. One line was measured parallel to the reef rim in the region in which corals were most abundant.

In general, the lines selected for measurement were chosen after an inspection of the reef in the vicinity, and because they were believed to be representative of the general conditions on the reef. However, some selection was made in order to find the maximum proportions of coral and of coralline algae where they seemed to be growing most abundantly.

A total of 20 lines was measured as accurately as the method would allow, 10 of which were distributed from Waikiki to Black Point and 10 from Black Point to Wailupe. They extended along the coast about 8 miles.

The 20 lines varied in length from 27 to 709 feet, only 4 being less than 100 feet long. The average length was 259 feet; the combined length, 5180 feet—100 feet less than one mile. As the line of squares was 1 foot wide, the number of linear feet is the same as the number of square feet of area measured, the numbers for length and area being thus interchangeable. Where the reef flat is so broad that the silt deposited upon it by floods from the land is never completely carried out into the deep water, but remains to be churned up by the waves at every high tide and to settle over the reef as mud at low tide, no living corals were found. The nodular forms of lithothamnium, however, could survive under these conditions. Where the line of measurement traversed these muddy areas, coral was found only in the region near the reef rim, where the water gradually becomes clear. Along four lines in such places coral covers less than 1 per cent of the area measured. In only one, the shortest, was there no coral.

The area covered by coral varied from less than 1 per cent of coral in four of the lines measured to 23 per cent, and averaged for the total area measured 2.88 per cent. The line with the 23 per cent was 120 feet long and was parallel to the reef rim in the region where inspection showed the coral clusters to be most numerous. No other line had as much as 10 per cent covered by coral.

The coralline algae varied in the individual lines from 0.54 per cent, with only two lines less than 1 per cent, to 40.73 per cent, and with an average for the total of 4.55 per cent. The line showing the maximum was 140 feet long, and only one other line gave a result higher than 10 per cent. The results show that the coralline algae cover a greater area on the reef flat than do the corals, both for the maximum and for the average. The difference in favor of the algae is much greater than the numerical results indicate. The algae measured in comparison with the corals are mostly confined to one species—the form with thin fan-shaped branches, which grows most abundantly in nearly the same region on the reef flat as the corals, but on the whole somewhat farther from the reef rim toward the shore. The crustaceous forms are most adundant at and near the reef rim, where exact measurements were generally impracticable owing to the danger from the breakers. The "giant combers" of the Pacific are not to be trifled with, and they roll in at very uncertain intervals. Besides, the surge and foaming of the water at and just outside the reef rim made detailed measurements in this region impossible.

The line that showed the maximum was measured on a day particularly favorable because of an excessively low tide and complete exposure of that part of the reef. Even where the reef was measured most accurately the crustaceous corallines are more abundant than the results indicate, as they are present in considerable amounts on the under side of projecting portions of reef rock, where it was impracticable to measure them, and one or another species of the crustaceous forms grows over a greater extent of the reef than any other of the organisms under consideration. In greater or less amount they extend all the way from the reef rim to the shore, but are more nearly continuous at the rim.

As in the fossil, so on the fringing reefs, the variation in abundance of the different organisms under consideration is of as great significance as the averages. A few measurements were made with the object of determining their maximum occurrence. The significance of the variations may be best shown by comparing the details for two lines of measurements in which the corals were the most abundant of all the parts of the Oahu fringing reefs that came under observation. One of these lines was on the Waikiki reef northwest of the Elks' Club and across the dredged channel from it. Here the coral was the most abundant of any place seen, and this line was selected in order to determine its maximum occurrence. It was begun near the reef rim, and the first part of it went directly toward the shore, though the latter part veered off at an inclination, in the direction in which the coral seemed to be most abundant. The first 24 feet measured had 43.95 per cent of that area occupied by coral. The next 22 feet had 27.9 per cent. The first 101 feet averaged 22.77 per cent and the next 200 feet 1.91 per cent. The entire line, 301 feet in length, averaged 3.62 per cent.

The variation represented in the above figures is quite typical for all the lines measured from the reef rim toward the shore. The zone of greatest abundance of coral generally begins 30 to 50 feet shoreward from the highest part of the reef rim, and is not much, if any, over 100 feet in width, in some places not over 50 feet. It was in the zone where every breaking wave at or near mean low tide, after expending its fiercest energy on the reef rim, flows down over the gentle inner slope in a sheet of water a few inches deep. The coral here is not exposed to the fierce beating of the breakers, and almost all of the little that grows in the breaker zone is on the sides or bottom of some pool, or behind some protecting rock. On the other hand, crustaceous coralline algae and some of the stout-branched forms are in greatest abundance where the waves beat most fiercely.

A second line selected for the maximum growth of coral was located some distance east of Black Point, opposite the residence district of Kahala. It was measured directly in the densest zone of coral, and was therefore parallel to the reef rim instead of at right angles to it. The first 10 feet had 49.16 per cent of coral—a somewhat denser stand than the first 24 feet on the Waikiki line, but thereafter it was slightly less than the denser part of that line. Successive intervals of 10 feet in the Kahala line contained respectively 33.75 per cent, 30 per cent, 20.83 per cent, 14.16 per cent. Then 50 feet has 20.41 per cent, and the last 20 feet, 14.79 per cent. The whole line of 120 feet, all in the zone of greatest density, averaged 24 per cent of coral, as against 22.77 per cent in the first 101 feet of the Waikiki line. This would seem to indicate slightly greater density at Kahala than at Waikiki, except for the fact that the Kahala line was wholly within the zone of greatest density, and that at Waikiki was across this zone. The densest 42 feet of the Waikiki line had 36.03 per cent and the densest 40 feet on the Kahala line 33.93 per cent. These two localities appear to have a greater abundance of coral than any other part of the Oahu fringing reef visited, and there is little difference between them at the maximum.

Besides the lines that were measured in detail, 14 lines were measured by inspection, memoranda being made at intervals of 50 to 100 feet as to the organisms observed as far as the eye could readily perceive them on both sides of the line traversed. This method was used when the line was too long to measure in detail during one tide period, when detailed measurements were not practicable, or when a general survey of some part of the reef was desired. Two of these lines were between Waikiki and Black Point, and 12 between Black Point and Wailupe.

The lines measured by the inspection method varied in length from 150 to 1,000 feet, the average length of the 14 lines was 545.6 feet, the total length was 7,638 feet. The combined length of all the lines measured, both in detail and by inspection, was 12,818 feet, or 2.427 miles.

The reefs were also traversed and notes taken where no measurements were made. The general description of the fringing reef is based on all these observations, as well as in part upon the findings in the fossil reefs.

THE FRINGING REEF

REEF RIM

The structure of the fringing reef of Oahu, like that of the fossil reefs, varies somewhat in different localities. As studied from Waikiki to Wailupe, it consists mainly of a reef rim and a reef flat, with channels cutting across both, most of them at nearly right angles to the direction of the rim but some at a considerable inclination to it. The rim is the highest part of the reef, generally awash at mean low tide, and exposed above the low spring tides from several inches to a foot or more in certain spots. The reef flat is the portion between the rim and the shore. At high tide the waves break just outside the rim and crash upon it with their utmost power. At low tide they break a little farther out, but each wave sends a sheet of foaming water over the rim, and as the wave recedes this sheet of water drains both ways, part of it flowing down the gentle slope toward the shore, and part flowing down the steeper outer slope, only to be met by the next wave. On Oahu the rim is not always a continuous exposed ridge such as has been described for many coral reefs, even at the low spring tides, but there are certain stretches of such a ridge east of Black Point opposite Kahala. Off Waikiki and elsewhere, instead of a continuous ridge there is a series of separate hummocks, protuberances or patches of rock, commonly called "coral heads," which alone are exposed above water even at the lowest tides. None of the heads exposed at low tide is composed of coral alone and few have coral on them above low tide level. Coral found associated with them is in a spot somewhat protected, on the shoreward side of the protuberant rocks, or on the sides or bottom of some pool. Coral, then, is almost entirely absent in what may be called the breaker zone.

On the other hand, practically all the reef rim, whether of the continuous ridge type or of separate protuberant heads, has associated with it one or more species of the coralline algae. Two structural types of the lithothamnium are found in the breaker zone, a crustaceous form which is the more abundant of the two, as to area covered by it, and a branching form with short, stout, compactly crowded branches. It is quite certain that several species of the lithothamnium are represented in each of the two structural types. Both of these types can withstand the heaviest surf.

Instead of a single line of separate rocks marking the position of the reef rim, several such lines are visible above the low spring tides; or from near the reef rim at low tide, may be seen similar rocks to seaward, or brown patches that indicate their presence, as the trough of each wave passes them. These observations mean that in these localities the sea bottom deepens very gradually outside the reef rim. It was noted also that at times of especially heavy surf the water for a distance estimated at several hundred feet outside the reef rim was distinctly turbid because of the mud or silt stirred up from the bottom. This also indicates a gradual deepening of the sea outside the rim. (See p. 42.) My field notes record only two points at which the reef drops off abruptly to an invisible bottom, one opposite the Diamond Head end of Kalakaua Avenue, the other on the west side of Black Point. Both may be said to be on the submarine slope of Diamond Head.

Many of the projecting heads of the reef rim or the more protuberant parts of the ridge are covered by algae other than the corallines, both brown and green algae as well as other red algae being common. Three species of *Sargassum* are abundant, some *Turbinaria* is present. Species of *Laurencia, Halimeda, Dictyosphaeria,* and others not identified, are not uncommon. Even *Ulva* was found coating the rocks of the breaker zone in a locality just east of Black Point. Any one of these or an association of two or more might be dominant in a given place. They cover many of the highest rocks with so dense a growth that a single species appears to be almost a pure stand. This is especially true of *Sargassum.* However, the removal of such a growth revealed a coating of crustaceous lithothamnium, a living layer of which might cover the underlying rock completely or partially. Whatever else was present, only lithothamnium was certain to be there in greater or less abundance. No other species show anything like a general zoning arrangement of distribution, but appeared in patches rather than in zones.

Upon breaking with a hammer, these highest projecting rocks were found to be composed of successive layers of crustaceous coralline algae to a depth of one to several inches, but somewhere within most of the rocks branches of true coral could be found. That is, the structure of these rocks was exactly the same as that found in the framework of the Wailupe Fossil Reef. Where eroded out of their fossil reef positions, they have more than a superficial resemblance to the separate rocks of the fringing reef, where they are separated from each other by relatively narrow channels, in the region near the reef rim. The two are counterparts.

REEF FLAT

The reef flat comprises the area between the rim and the shore. On the measured lines it varied in width from 316 feet to 1,200 feet. The narrowest reef flat is on the submarine slope of Diamond Head, where the reef drops off abruptly immediately outside the rim. The widest measured is opposite the Wailupe Fossil Reef. Opposite Kahala the reef flat is 600 to 700 feet wide.

The reef flat as well as the rim is interrupted here and there by channels having a width of several rods, some of the channels lying opposite the mouths of fresh water streams. In those regions where the rim is a continuous or fairly continuous ridge, the channels are the outlet for the sea water thrown over the rim by every wave, and a current flows constantly seaward in these gaps so swiftly that even good swimmers may be carried out into the breakers. There is also a current parallel to the shore toward these outlet channels, but nowhere were there observed definite channels or "moats" such as have been described for typical fringing reefs, running parallel to the shore on the reef flat. Where the rim is not continuous but consists of separate rocks, the water can flow out between these at all tide levels with the backwash of the waves, and the definite, broad, outlet channels are less likely to occur, except opposite the mouths of streams.

The surface of the reef flat is more or less uneven, the irregularities varying in different regions both in degree and in kind. In some places the reef flat consists of roughly parallel ridges and channels extending in the direction from the rim to shore, with a difference in elevation between the top of the ridge and the bottom of the channel rarely exceeding 2 to 3 feet. In certain regions near the rim the channels are deeper, completely surrounding patches of reef rock, and communicating with the sea outside the rim, so that the water surges in and out through these channels with the advance and recession of every wave. If such channels should become filled with detrital materials containing much of the nodular lithothamnium and the whole then become consolidated, it would form a structure exactly like that of much of the Wailupe Fossil Reef.

Besides the irregularities produced by ridge and channel form, there are depressions below the general surface of the reef flat—irregularly rounded pools completely surrounded by rock, and varying in depth from 1 inch to 3 or more feet, and correspondingly in diameter. The bottom of both pools and channels, unless constantly swept by the rush of the waves, is occupied at low tide by a coarse white sand, which is stirred up by every wave at high tide but quickly settles again after each wave. The sand in the pools is much coarser than that on the beach, because the finer grades of sand, once lodged on the beach, are not carried out again, while in the channels and the pools the finer grades are continuously removed and supposedly are deposited in deep water beyond the reef rim. The instability of the bottom of the pools and channels probably accounts for the fact that few fixed organisms are to be found there. Some mollusks and holothurians may be found in the sand, but neither corals nor coralline algae, with the exception of the unattached nodular form were seen in that situation. Most of the deeper pools and channels are near the reef rim, and corals grow on their sides, provided the rush of water through them is not too violent. No violence of the waves, however, seems too great for the growth of the crustaceous coralline algae, nor of the stout-branched forms.

Anywhere on the reef flat, in the pools or in the shallowest depressions, may be found the free, nodular forms of at least three different species of lithothamnium (Pl. III, *A*). The nodules are most abundant where the reef flat is wide and the force of the waves that come over the reef rim at high tide much reduced. This condition prevails opposite the Wailupe Fossil Reef, and it is probably not a mere coincidence that of all fossil reefs seen, that at Wailupe includes the largest proportion of the nodular structures and that of all the fringing reefs studied the growing nodules are most abundant there. It is not yet established whether or not the fossil species, of which only one nodular type is apparent to superficial observation, is identical with some one of the living species found in the same locality.

One of the living species, more fragile than the other two and readily ground up by wave action into a fine-grained sand or marl, was noted particularly on the shore of Waipio Peninsula in Pearl Harbor. Material similar to that in process of formation was observed along the edge of cane fields on Waipio Peninsula mixed with other material to form a marly earth. The locality where Hitchcock (16, p. 32) found "2 to 8 feet of limestone and marl" is across the middle loch from the point where the marl was seen in process of formation. It may be said then that the nodular forms of lithothamnium not only contribute a substantial proportion to the formation of the reefs, where they may be recognized almost unchanged from their original state of growth, but also that the more fragile ones by their disintegration contribute products to the finer sand and marl of the reefs and the sea bottom, and to the soil when the sea bottom is raised above sea level.

Measurements were made at two places to ascertain the relative abundance of the nodules on the fringing reef, of the contents of two depressions—one at Wailupe which has a bottom area of 2 square feet and a smaller one at Waikiki. In the depressions selected the nodules not only lay in close contact with one another but were more than one deep. All nodules sufficiently large to be measured were taken from each depression and their surfaces calculated according to whether they more greatly resembled a sphere or an ellipsoid. The sum of the areas of all the nodules in the Waikiki depression was two and one-half times the area of the bottom of the pool in which they had been collected. For the larger Wailupe depression, which had 404 nodules, the total area of all the nodules was more than six times that of the bottom of the pool in which they lay. The difference is even greater than the calculations indicate, as the irregularities in shape would increase the difference in area. As growth takes place all over the surface of the nodules, where they are most numerous on the reef the area on which growth is taking place is considerably greater than the total area of reef occupied by them. Some of the nodules were found alive even though completely covered by mud or silt at low tide. The explanation suggested for this rather astonishing fact is that when the mud is stirred up by the waves at high tide the nodules receive sufficient diffuse sunlight to carry on photosynthesis. No live corals were found at any point where the water over the reef is turbid at every high tide.

On the fringing reef as a whole the most conspicuous species of lithothamnium is an upright-growing form with most of its branches more or less flattened and many widened to the shape of an opened fan (Pl. III, *B, left*).

As its branches are too thin and brittle to withstand the power of the breakers, this species was found only at some distance shoreward from the reef rim. To some extent this species and the true corals grow on the same areas, but the regions of greatest abundance for the two do not coincide—the lithothamnium is nearer the shore. Many of the larger clusters of this species are as much as 7 or 8 inches in diameter and attain a height equally great. The coralline algae recorded for the measured lines of squares are chiefly this species. The area covered by it is greater in some places and less in others than the area occupied in the same line by the coral. General inspection, however, gives the impression that on the reef flat as a whole, algae occupy a slightly greater area than the coral. This impression is confirmed by the results, which show that the coralline algae predominate over the coral to a slight degree on the total of the lines on which both were measured.

A form of lithothamnium with branches approximately terete in shape and very brittle was found in some numbers, but not so abundantly as the other branching forms. It was not generally seen attached, and its occurrence gives the impression that it was mostly washed up from some place beyond the general area of observation. The brittleness of the branches of the two species of lithothamnium described makes it quite certain that both contribute substantially to the sand among the detrital material of both the fossil and the fringing reefs. Only one species of true coral (*Pocillopora caespitosa*) seen growing on the Oahu reefs, approaches the two species of coralline algae in the brittleness of branches and the ease with which they could be broken into small fragments by the waves.

There are coral islands where the sand on the beach and that tossed up to form the islets of atolls is almost wholly of coral origin. An example is Cocos-Keeling Island in the Indian Ocean, as described by Darwin (12), said to be the only true atoll which Darwin personally ever visited. Similar conditions were observed on Wake Island, also an atoll, where the material seen on the beach in all sizes from boulders to moderately coarse sand, shows very distinctly coral origin. The conditions on Oahu, however, are quite different. While corals do contribute a certain amount to the detrital material, the impression is gained that both the coralline algae and the Foraminifera contribute as much or more than do the corals to the sand of the detrital materials on the beaches and perhaps also in the reefs. The Waianae sand, used for building purposes, is particularly high in Foraminifera. Moreover, if to the area occupied by the coralline algae with the fan-shaped branches, which is alone approximately as great an area on the reef flats of Oahu as that occupied by corals in the regions studied, there be added the areas covered by the nodular, the crustaceous and the branching forms of lithothamnium, it is certain that a far greater area of the Oahu reefs is occupied by coralline algae than by the true corals, and it is equally certain that the same algae contributed more materials than the corals to the fossil reefs of this region. Certain also is the conclusion that the fringing reefs off the shore of Oahu and the fossil reefs raised along the shore are of the same essential formation and origin, they having in common the following: 1, a framework of branching coral surrounded by successive thin crusts of lithothamnium; 2, the spaces between the parts of the framework, originally in the form of channels or pools, filled with detrital materials among which are found a large proportion of nodular lithothamnium, or of broken corals, buried in a matrix of sand; 3, regions where the type of structure is that called superposed coral; 4, small portions showing the massive structure characteristic of *Porites lobata* or similarly growing species of coral.

The finger coral structure due to *Porites compressa* was seen more abundantly in the materials dredged from the harbors, the sewer ditches, and the drainage canal than in the raised fossil reefs or on the reef flats—that is, there is more of it below present sea level than above. Nevertheless it was seen in a few places in the raised fossil reefs, but most of the very small amount seen alive on the reef flat had evidently been washed in by the waves. If it be assumed, however, that the finger coral which now underlies Waikiki developed in the period when the sea stood 20 feet higher than it does at present, its absence on the reef flat is explained, since it made its best development in deeper water than is found at any place on the flat. That it grows outside the rim is indicated by the fact that it is occasionally washed up over the rim onto the reef flat. The parallelism, then, between the fossil and the fringing reefs is practically complete. There remains the question as to the identity of the species of the coralline algae in the fossil and on the fringing reefs.

FORAMINIFERA

The engineer in charge of cement construction for the oil tanks at Pearl Harbor called attention to the fact that the Waianae sand he was using, "is composed of grains that are hollow." Examination with a hand lens showed the sand to be made up almost entirely of shells of Foraminifera—the statement that they are hollow is correct. The exact source of the sand was not ascertained, but since this material is brought in by the train-load for use in Honolulu, there must be great beds of it somewhere on the island. Sand on the beaches of Oahu is composed to a considerable extent of shells of Foraminifera, enough to show that in Hawaii, as at Funafuti, Foraminifera is a substantial contributor to the reef structure. While not observed in the fossil reefs of Oahu, the materials from these have not been studied microscopically so the Foraminifera are not excluded.

OAHU CHALK

Dana (11, pp. 112-114), Agassiz (1, p. 157), Hitchcock (16, p. 44), and others who have written on the coral reefs and the geology of Oahu, have mentioned the chalk found at Diamond Head. None of them has given a satisfactory explanation of its origin, though Dana refers to Darwin's observation that coral mud appears to be a fit material for its production, and suggests a possible connection with warm springs for its origin. He offers no evidence, however, of the presence of warm springs where the chalky deposits are found, nor of the terraces of travertine or calcsinter usually found associated with them. The striking characteristic of the Oahu chalk is its state of extremely fine division. Much of it is an impalpable powder, too fine to feel gritty to the fingers. It is this physical characteristic that requires explanation.

At Diamond Head the chalky material examined is mixed with the tuff of the Diamond Head crater. It is not confined to definite strata within strata of tuff, but mixed in it, and in places completely surrounded by it, are lumps of tuff varying in size from a pea to balls more than an inch in diameter. The manner in which the chalk and tuff are mixed seems to preclude deposition from solution—the tuff fragments are too far apart and too irregularly distributed. Deposition from solution would have formed a firm crust over the tuff, or between the tuff strata. While such crusts may be seen in Diamond Head, they are not chalky.

Four different forms of calcareous deposits were seen on and in Diamond Head, not all of which have been distinguished previously: (a), the chalk; (b), wind-blown sand rock; (c), thin crusts deposited from solution between tuff strata above sea level; (d), thicker strata of lime between tuff layers, too thick to have been deposited from solution subaerially, as the tuff strata would not have been so far apart as the thickness of the lime strata indicates. Hence the lime strata are not in the talus slope, but in the body of the tuff cone proper, and must have been deposited as layers of sand or organic growth below sea level, and at intervals between explosive periods of Diamond Head. Wentworth and Palmer have shown that a shift of sea level of 12 or more feet has occurred later than the formation of the youngest tuff cones on Oahu (26, pp. 521-544). Facts presented on page 34 indicate that the shift was 18 to 20 feet, and that before the shift Diamond Head was submerged to that depth above present sea level, thus providing conditions favorable for such deposition of lime between submerged tuff layers, and indicating that sufficient time for its deposition elapsed between the explosions.

It is possible that the origin of the chalk is connected with volcanic eruptions. Diamond Head and numerous other volcanic tuff cones on Oahu erupted through coral reefs, and fragments of the calcareous reef rock were thrown up along with the material of igneous origin. Such fragments with their original chemical, physical, and structural features unchanged by volcanic action may be seen at several places. Hitchcock has reported coral, with its structure easily recognizable, within the Diamond Head crater, and at Koko Head and Koko crater are similar fragments which quite certainly were thrown up in a volcanic eruption. Some of them are too large to have been transported by any other probable means to the position which they occupy, and are mixed with the tuff in such manner and in such quantities as to be accounted for by no other agency.

In addition to these unchanged reef fragments, it seems highly probable that some part of the coral material which came up through a reef in a volcanic eruption, would be heated to a sufficiently high temperature to drive off the carbon dioxide from the calcium carbonate. It would then be in the condition of quick-lime fresh from the lime kiln (Ca O), and on mere exposure to the air would undergo the process of air-slaking and would again absorb carbon dioxide and return to the state of calcium carbonate, with the difference that it would then be in the physical state of a finely divided, powder-like, air-slaked lime, exactly like the chalk of Diamond Head.

But the chalk deposits on Oahu are not confined to volcanic cones. In the Ewa district, which includes the raised reef between Pearl Harbor and Barbers Point, deposits of chalky limestone appear along the Oahu Railroad. A very extensive deposit was found in the vicinity of Waianae Station on the northern slope of Mailiilii Hill. The bed of the road running east from the shore just south of Waianae Station, and opposite Kaneilio Point, partly excavated in this deposit, rises along the slope to an elevation of about 80 feet as indicated on the contour map issued by the United States Geological Survey. The highest point of the chalky deposit along this road measured 75 feet, as independently determined by hand level.

Along this road several observations were made which seem to be significant as to the origin of the materials composing this particular chalky deposit. At several points on the upper side of the ascending road this chalky material is several feet thick, and most of it readily crushes to the impalpable powder. At several points in the exposures, slightly lighter colored material was seen, which in shape and size is like the fragments of coral imbedded in sand at numerous places in the fossil reefs and in some of the dredging from Honolulu harbor (Pl. V, *C*), which included 18.75 per cent of coral. A study of these lighter-colored portions of the Waianae chalk show in some of them very clearly characteristic structure of coral. This structure was easily recognized under the magnification of a pocket lens and justified the preliminary suspicion that the lighter colored portions of this deposit actually were the remains of coral. (See Pl. V, *B*.) Even those fragments in which the coral structure was clear and definite could be crushed to the impalpable powder between the fingers.

A memorandum made in the field contains the following statements:

> The exposure beside the road showed white circles and cylinders mostly horizontal, but some vertical or near it, looking like finger coral. On pulling some of them out of the bank they break very easily into short pieces, and are in shape like coral branches. Some of them showed under the lens typical coral structure. The others were so rotten they did not show the coral structure; but I have no doubt whatever that it was rotten coral, and that this chalky bed had something like 5 to 15 per cent of coral in it. Whether it grew in place is doubtful, since so much of it seemed to be in a horizontal position.

Those notes were almost the last taken in the two years' study of the coral reefs, hence the experience of that study was available in the interpretation. The facts that the light-colored portions look like coral embedded in sand rock as seen in materials dredged out of Honolulu harbor; that they readily separate from the surrounding material and come out with the shape of coral branches; that on the two occasions on which this locality was visited true coral structure was recognized in fragments collected at several different elevations, and that those in which the coral structure was recognizable were so decayed that they could readily be broken into pieces and crushed to a fine white powder in the fingers seem to require as a logical conclusion that this chalk was originally a marine deposit, probably mostly of a detrital nature, consisting of corals and sand and in all probability of some other calcareous materials, but that it has undergone a process of physical decay so complete as to mask its origin, except to most careful and properly directed observation. Furthermore, the fact that this chalk bed rises to an elevation of 75 to 80 feet at the highest point, that coral structures are found in it at an elevation of 50 feet above present sea level, and that apparently the same kind of structure continues all the way to the top compel the further logical conclusion that this region of Oahu was once submerged to a depth of 80 feet more than it is at present, and that this submergence was earlier than the one recently reported by Wentworth and Palmer.

The question still remains as to the origin of the chalky, powdered state of this deposit. There is no reason to suppose that it could have originated by the method suggested for the Diamond Head deposit (p. 30). What proof is there that coral, shells and other hard, calcareous materials, formed by plants or animals, would disintegrate into this finely powdered state? Darwin (12, p. 134), has noted a similar phenomenon in South America. In a dry, almost rainless region he noted a bed of shells that "could be traced scaling off into flakes, and falling into an impalpable powder"; and on another upper terrace he "found a layer of saline powder" about which he had "no doubt that this upper layer originally existed as a bed of shells; but it does not now contain even a trace of organic structure."

The conditions at Waianae are very similar to those noted by Darwin in South America. In both the rainfall is slight. It is certain that remains of animals as highly organized as corals have in this deposit undergone a process of disintegration which is so nearly complete that only rarely can the coral structure be recognized.

Other possible origins for the Waianae deposit might be considered. Could they have been deposited by the wind? The answer is no. In the first place, it is not in any respect like the well known wind-blown deposits of calcareous sand rock seen in several regions of the island, notably east of Diamond Head and at Laie Point on the northeastern side of the island. In Diamond Head itself as one of the four kinds of lime deposits, there are considerable quantities of these wind-deposited strata (Pl. VI, *A*), which are entirely different in bedding and in relation to the tuff, and there is no evidence of a genetic relationship between the chalk and wind-blown sand rock. These eolian deposits are composed of moderately fine and coarse sand, consolidated in cross-bedded strata very characteristic of wind-blown deposits. If the Waianae bed were deposited by the wind, the disintegration into the fine, white powder has still to be accounted for; and since wind deposits would not contain the salt present in those from marine sources, there would be absent here one of the conditions which Darwin postulated as requisite for such physical disintegration. In the second place, the coral fragments recognized in the Waianae deposit are far too large and too numerous to have been deposited by the wind. There is no evidence, then, in favor of the interpretation of this as a wind deposit. If it be asked whether this deposit could have been made by fresh water stream, the answer is again in the negative. It is entirely too pure a calcium carbonate to have any such origin, and again the coral in it makes that interpretation inadmissible.

The only alternative is that the Waianae chalk represents a marine deposit, but whether of an actual coral reef, with materials in place as they grew, or merely wave-washed material deposited on the protected side of a projecting promontory, cannot be decided with certainty. Some of the lighter colored masses believed to be coral might have been from their outlines, such as grew in place, but much of it is in a horizontal position and seems not to have grown in place. At least it is quite certainly not like the fossil coral reef on the north side of Kaneilio Point, where the coral is the most massive seen in any fossil reef on Oahu and has retained its original structure perfectly.

Because of the close resemblance of its structure to that of certain materials dredged from Honolulu harbor, it seems best to interpret this chalk deposit as having originated from wave-washed detrital materials, composed chiefly of sand and corals of the finger coral type. At the point where it was most clearly visible the lighter colored material believed to be of true coral origin was estimated to be about 5 to 15 per cent of the total deposit.

Whatever their original nature, these materials have undergone a physical disintegration similar to that described by Darwin in South America, where he had evidence that even shells of mollusks could undergo such a disintegration. In the Waianae chalk, coral fragments which still show typical coral structure under a lens may be crushed to powder in the fingers, and it seems very certain that the physical disintegration has gone so far in many of these fragments that the original coral features are no longer visible under a lens, though the difference in color from the surrounding material still allows the coral origin to be inferred.

CORAL CONGLOMERATE REEFS

Some distance to the southeastward of Waianae, in the region where the railroad first approaches the sea after traversing the Ewa coral plain, the reefs exposed at the shore are of coral conglomerate. Fragments of coral of many sizes and shapes and in all possible positions are mingled with sand, shells, and other hard parts of lime-secreting animals and detrital materials, and this overlies lava, which is exposed just at high tide level. The limestone rises in places to about 20 feet above low tide (Pl. VI, *C*). Raised reefs of this structure are common along the west shore of Oahu, some with much sand and few corals. It seems likely that the chalk bed on the slope of Mailiilii Hill was originally of this nature, but that the coral conglomerate just referred to is of recent origin and has not undergone the physical disintegration that would obscure its origin.

SUBMERGENCES

The possibility of a former submergence of Oahu to the amount of 80 feet is worthy of further discussion. Wentworth and Palmer conclude that in recent geological times the island of Oahu has been submerged to the probable amount of 12 feet more than at present (26). There is much evidence to confirm these conclusions as to the submergence, but the amount of such submergence can perhaps be fixed more accurately as the result of observations made on the slope of Makalapa crater, along the oil pipe ditches at Pearl Harbor, and at certain other points.

For the Pearl Harbor region, maps made for the construction engineers who were building the oil tanks had intervals of 10 feet between the contour lines, stakes being set on the slopes to indicate the elevations. As traced along the sloping surfaces of some of the pipe line ditches, the highest points at which the calcareous material was found are between 20 and 25 feet, at which level it runs out to a thin edge and ceases. The highest portions of it are composed of the kind of material found on the highest part of the beach, where it is tossed by the waves, a little above high tide. At lower levels coral was recognized in certain places, part of which certainly is in place as it grew, some of it finger coral. Along the railway embankment near Submarine Station on the Oahu Railway, a small amount of finger coral was seen, but most of the material exposed here is detrital material, deposited by the waves, as is much of the limestone along the shores of the islands and peninsulas of Pearl Harbor.

Observations at Makalapa crater indicate a greater emergence than the 12 feet assigned by Wentworth and Palmer. If the highest calcareous deposits were at the top of the beach above high water, as was indicated by their composition, by their thinning out to nothing at 25 feet, and by their greater abundance at 22 or 23 feet elevation, high tide level probably would not be more than 3 to 5 feet lower, especially in a protected bay like Pearl Harbor. High tide would thus be 20 to 22 feet, low tide 17 to 19 feet, and mean tide about 18 to 20 feet above the present sea level. This is very near the 20 feet suggested by Daly (7, p. 257) as the amount of recent world-wide sinking of ocean level.

The coral conglomerate reef southeast of Waianae chalk beds furnishes another bit of evidence on the amount of the last emergence of the island of Oahu. The position of the raised reef (Pl. VI, *C*) and the unmodified materials composing it both give evidence of recent origin. Its summit is not far from 20 feet above low tide level, and as mean tide would be 1½ to 2 feet above this low tide level, the top of this coral deposit is 18 or 18.5 feet above present sea level, and is probably slightly lower than the sea level of the time of its completion. These figures are in almost exact agreement with the results obtained at Makalapa crater. It may be concluded then, that the last emergence of the island of Oahu was very nearly 20 feet. The coral reefs are a more reliable measure of the amount of that shift than is the eustatic bench, which has been eroded in different proportions in different places. The coral, on the other hand, could not be higher than the sea level of the period in which it was deposited and probably would be slightly lower.

From a study of the relation of sea caves to the tide level, Daly (8) draws the conclusion that the shift in Samoa was about 6 meters or 20 feet, and that the "Emergence appears to be due to a world-wide sinking of sea-level, not more than 4000 years ago"; and Chamberlin (5) concludes that "The sloping benches of Tutuila were cut while the strandline stood somewhere from 12 to 20 feet higher than at present." The observations on Oahu seem to fix the exact amount of the shift more accurately than any hitherto made here or elsewhere.

Wentworth and Palmer (26, p. 529) state that

> . . . on the south coast of Oahu, from Makapuu (the most easterly point of the island) to Barbers Point, there is a great deal of raised reef. The maximum elevation of raised reef is about 35 feet, and a considerable portion of the reef formation of Oahu is too high to be associated definitely with the eustatic shift under discussion.

On this point also new evidence was obtained. In the region between the Wailupe Fossil Reef and the Waianae Fossil Reef calcareous deposits containing coral extend up the base of the ridges to a height of about 40 feet.

On Ford Island and on Waipio Peninsula, calcareous rocks, some of them containing coral, extend to elevations of 40 feet as shown by the topographic map, and in the Ewa district, along the right-of-way of the Oahu Railway, calcareous rocks lie at an elevation nearer to the 80-foot contour than to the 40-foot line.

As the Waianae chalk bed, a marine deposit, reaches an elevation of about 80 feet and the last submergence was about 20 feet, the submergence which covered Ford Island, Waipio Peninsula, and the Waianae chalk bed must have been an older as well as a greater one.

Wentworth and Palmer assert that the Koko Head craters "are enormously younger than the Salt Lake craters." The long, gently sloping ridge extending from the Salt Lake crater southwest as far as the channel entrance of Pearl Harbor was formed by the finer tuff from the Salt Lake craters drifting on the Trade Winds. Near the coal dock in the Navy Yard the tuff strata of this ridge are exposed for a few feet above low tide, capped by coral conglomerate of the last submergence. The strata become gradually thinner toward the top, and are exactly like those on Ford Island, where at one place they lie between beds of coral. They suggest deposition by the last expiring efforts of a volcano. The coral that overlies the tuff near the coal dock was followed to an elevation of 15 feet above sea level, and was also traced to a point about halfway to the entrance to the Navy Yard, where the elevation is 25 feet, but where no coral or calcareous rock is present. The conclusion is that the calcareous rock containing coral overlies the latest tuff thrown out of the Salt Lake craters to the same height as at Makalapa crater, and that any submergence greater than 20 feet must have been previous to the extinction of the Salt Lake craters as well as of Makalapa crater. The age of the Waianae chalk bed, consequently must be much greater than the time elapsing between the extinction of the Salt Lake craters and the formation of Koko Head.

The question obtrudes itself, whether more than two submergences are indicated, one sufficient to account for the deposits in Pearl Harbor and Waialae at 40 feet, and another for the Waianae chalk bed at 80 feet. A greater age for the chalk bed is indicated by the complete disintegration of the calcareous material composing it, as compared with the lime rock in Pearl Harbor which shows no chalky disintegration. The greyish marl on Waipio Peninsula and similar material reported by Hitchcock along the railway between Waipio and Pearl City are forming at the present time on some of the beaches in Pearl Harbor. Marl has nothing to do, therefore, with the formation of chalk, and is no indication of age. (See p. 28.)

On Black Point two large patches of coral reef which certainly grew in place rest on a substratum at elevations 50 and 65 feet respectively above sea level. There is more than a possibility, however, that these reef patches were pushed up from their original horizons by the welling lava which burst through the reef and formed the promontory of Black Point. The present altitude of the coral patches here may not indicate so great a change of level in the whole island, but only a local shift of land rather than a general shift of land or of water.

Hitchcock (15, p. 484) has reported that he saw on the fields of the sugar plantation at Waialua "shells and opercula of the marine gasteropods in numerous localities and Melanias up to 250 feet altitude." Both Dana (10, p. 303) and Hitchcock (6, p. 30) have reported true coral reef rock up to altitudes "estimated at 50 to 60 feet above tide-level" in the region of Kahuku; Hitchcock (loc. cit.) also says that Alexander "reports a ledge of coral 79 feet above the sea, at Keha . . . another ledge 56 feet above the sea and a quarter of a mile inland . . . at the south end of the ridge called Mailiilii, the limestone reaches a height of 81 feet." This limestone is on the opposite side of the ridge which supports the Waianae chalk bed. If these statements are even approximately accurate—and there is no reason for doubt—there are a considerable number of reef deposits on the island of Oahu lying with their upper surfaces at altitudes of 20, 40, 60, and 80 feet. The extent of some of these suggest strongly that the sea stood for a considerable period of time at or near each of these levels. The evidence for the lowest of these levels is essentially beyond doubt. That for the 80 foot level is also strong. There is considerable evidence for the 40 foot level; but the one at 60 feet is less well supported, as the Waianae chalk bed which demands the 80 foot level has an apparently homogeneous structure that descends below 50 feet and chalk in the Ewa district at about 60 feet might be of the same age. The very definite line of demarkation between the coral reef rock and the overlying aeolian sandstone reported by Dana and Hitchcock at Kahuku, would seem to show a definite sea level at 60 feet, provided their estimates as to the altitude of that line of demarkation are correct.

The view of Hitchcock that there was also a submergence of 250 feet has very little evidence in its favor, but if it occurred, convincing evidence for it probably can be discovered. The fact that the highest marine deposits are at the western and northern parts of the island suggests a differential movement or tilting of the island at some period in its history, but the question is raised to stimulate the search for evidence rather than to give an answer.

The evidence available at the present time indicates that Oahu has been submerged to different levels above that of the present, certainly at about 20 feet, almost certainly at 80 feet, probably at 40, possibly at 60, and with a very remote possibility at 250 feet.

AGE OF THE REEFS

Wentworth and Palmer furnish the best starting point for a discussion of the age of the Oahu reefs, both fringing and fossil. Referring to the emergence for which they furnish good evidence, they remark (26, p. 530):

> No means is at hand for fixing the date of the shift with great accuracy. The emergence postdates the latest secondary eruptions on Oahu, for the youngest tuff craters in the Koko region carry the exposed wave cut bench around their margins. These craters are enormously younger than the Salt Lake craters, which are associated with terraces and other physiographic features believed to have been formed in Pleistocene time. The later Koko region craters are estimated to be no more than five, or possibly even one, thousand years old, and an upper limit is thus set for the age of the eustatic shift.

Daly estimates the shift in Samoa as "not more than 4,000 years ago," and if it was world-wide, as he believes, it is the same age in Hawaii.

Accepting these estimates as the best available, and considering the shift established as about 20 feet, it may be said that the fossil reefs around the shores of Oahu lying between present sea level and 20 feet above that level were formed in a period which ended at a time not more than 20,000 years ago, and may have ended at any time between 20,000 and 1,000, most probably 4,000 or 5,000 years ago; and that any of the fringing reefs around this island that have developed to the normal position of coral reefs in relation to present sea level have grown within the last 5,000 years. That these fossil reefs are geologically recent in their origin is indicated by the condition of the materials composing them, since they show their nature and source almost as well as the organisms growing on the reef today. Also, at many places they come down to shore line and are washed by the sea at the present time. They must, therefore, belong to the period immediately preceding the last eustatic shift. That the rim of the fringing reef is of recent origin is shown by the fact that it is in actual process of construction at the present time, through the activity of organisms similar in type of growth to those known to be forming reefs in other parts of the Pacific, even if the species concerned on Oahu are not wholly identical with those of the other regions. Then, too, the relation of the reef rim to the present sea level is hardly intelligible except on the view that at least the upper portion of it has developed by active growth and adjustment to that level. Why should there have been anything like a reef rim in 20 feet of water before the last shift of sea level? Why, also, if such an anomalous structure had developed in that earlier period, should the shift be so exactly adjusted as to bring this submarine reef rim into the same position in relation to present sea level as it would reach by the normal processes of reef growth?

The alternative view that both the fringing and fossil reefs on Oahu are ancient, possibly of Tertiary age, finds no support in the study of the reefs themselves, neither of the fringing reef rim, nor of those fossil reefs between present sea level and an elevation of 20 feet. Undoubtedly there are calcareous deposits around Oahu that go back to a far more ancient time than that of the last shift or of the period during the submergence of 20 feet that preceded it, and all fossil reefs raised to a greater height than the amount of the last shift must belong to a time more ancient than the period of that submergence. If the statement of Wentworth and Palmer that the Koko craters are enormously younger than the Salt Lake craters refer to the time after the extinction of Salt Lake craters, all marine deposits on Oahu raised to an elevation greater than 20 feet must belong to an age still more enormously ancient.

Age relations are suggested by a study of the rock forming the Ewa coral plain. In the vicinity of Barbers Point this raised reef, barely above sea level, has preserved its original structure (Pl. VI, *B*). The pools retain their original outlines and dimensions, and the organisms composing the rock are perfectly preserved. Midway between the lighthouse and the Oahu Railway the surface of the reef is much eroded in a manner characteristic of calcareous rocks, very irregularly with many sharp points and rounded hollows, making it exceedingly difficult to traverse. Along the railway about 2½ miles inland, however, some of the calcareous rock has undergone the chalky disintegration. Is not the most likely cause for the difference in character of the different parts of what is essentially a continuous calcareous deposit, a difference in age? The whole region has a very low precipitation and subaerial erosion must be exceedingly slow. Hence the lowest part of the raised reef, exposed to such erosion only since the last shift of sea level, say 5,000 years, shows almost no effect of such action.

The middle portion of this deposit, at an elevation probably not more than 20 feet, shows marked erosion, hence must be of a much greater age. It may be wave erosion of the shore when the sea stood at the level just preceding the last shift. Is the chalky portion, at 60 feet or thereabouts, of a still greater age? As it is in a similar state of disintegration it might be comparable in age to the Waianae chalk bed, which lies at an elevation of from something below 50 up to about 80 feet.

The question of age is closely bound up with that of submergence, as each submergence has its own age. It is certain that all marine deposits higher than 20 feet above present sea level are of an age greater than those laid down immediately preceding the last shift, and it might be presumed that the deposits which have undergone the greatest amount of disintegration, as the Waianae chalk bed, are the oldest.

Agassiz (2, p. 74) has stated that,

> . . . the elevated reefs of Cuba and of the West Indies have been shown to be Tertiary coralliferous limestones, and the same is the case with the elevated reefs of the Pacific, if we are to judge of their age by that of the elevated coralliferous limestone reefs resembling them observed by me in Fiji.

Dall writing of his observations at Diamond Head, says (6):

> The conditions appear to be incompatible with the reference of the fossiliferous beds to a period as late as the Pleistocene. It is difficult to make an exact comparison from the paleontological data, as the recent fauna is still imperfectly known, and we have no standard of comparison in the whole Polynesian region by which the species could be compared with those of Tertiary beds of known age; but the fossils have every characteristic of those generally assigned to the Pliocene or upper Miocene in their aspect and state of fossilization. . . . on the shores of Pearl Harbor, a very similar series of beds to those at the base of Diamond Head were exposed. The usually perpendicular face of the rock fronting the beaches usually rises about 30 feet above tide, but is largely reef rock with shells and corals in abundance, and with several feet of alluvium above it; . . . . it should be noted that the reef rock which underlies the western part of the city of Honolulu and crops out at water line in Honolulu harbor appears to be of an extremely similar if not identical character. . . . In the alluvium around Pearl Harbor quantities of kitchen-midden material was observed, chiefly Avicula and *Ostrea sandwichensis,* now found living abundantly in the adjacent waters.

These quotations indicate that the fossil material studied by Dall probably came from the reef formed in the period immediately preceding the last shift of sea level, which took place probably not over 5,000 years ago, and his evidence seems entirely inadequate to justfy his conclusion that they belong to any stage in the Tertiary.

Hitchcock also considered his Pearl River series to be of Tertiary age, but his evidence appears no more convincing than Dall's, on whom he relied for confirmation of his conclusions.

Raised reefs of Fiji and of Christmas Island (4, pp. 226-264) (Indian Ocean) have been assigned to the Tertiary; they contain fossil Foraminifera (*Orbitoides*), various species of which are accepted by paleontologists as definite indicators for the Miocene or other divisions of the Tertiary. I have been unable to find any similar convincing evidence of the Tertiary on Oahu in the literature of the subject.

Christmas Island is reported to show a succession of limestone terraces, each one formed at a definite stage of sea level, and ranging in age from the oldest at the top to the youngest next to present sea level. At each stage a fringing reef of recent reef-forming corals was formed as a veneer over the Tertiary limestone as a foundation. These modern reefs, therefore, vary in age as do the terraces, the oldest being at the top, the youngest at the bottom of the series. In the limestone of the Tertiary foundation, however, the order of age is reversed. The lowest and oldest part, considered to be Eocene or Oligocene, is overlaid in turn by a thick bed of basalt and a limestone of Miocene.

In the submergences for Oahu there is a certain parallelism to Christmas Island, and as the highest deposit seen on Oahu is the most completely disintegrated, it is probably the oldest. Except that those just above present sea level are probably about 5,000 years old, no definite age can be assigned to any part of the raised reefs on Oahu. Some of the dead reefs exposed along the shore between present tide levels were formed in the same period as those immediately above sea level,—that is, in the period before the last shift. The reef at the mouth of Alawai and westward along the Ala Moana road, the reef materials dredged from that canal, and the seaward extension of the raised reefs in the Kalihi district and at Barbers Point belong to that period.

On the other hand, the reef rim, extending a few hundred feet to more than 1,000 feet off shore in the regions studied, is not a part of the reef formed before the last shift of sea level, now in process of erosion, but has grown up to sea level in its present position since that shift. The foundation upon which this modern reef has grown up was a part of the sea bottom at the time of the shift, and its depth at that time may be ascertained approximately by taking the slope of certain reefs from above sea level to shore line and projecting it seaward to the present position of the line of breakers on the same inclination.

If this projection were made in the Kalihi district, it would reach a depth of about 5 fathoms, or 30 feet, at the present line of breakers. However, this location is in the lee of Sand Island, a fact that in all probability has had the effect of shifting the breaker line farther seaward than it would have been along a free shore. Hence, 30 feet probably exceeds the depth of that part of the old sea bottom on which the recent reef rim has grown up in most localities.

The vicinity of Barbers Point is probably a better location for this study. Here there are no islands to serve as a disturbing influence, and no streams which pour their detritus into a neighboring basin, as at Kalihi. There is also a greater extent of raised reef than at any other location on the island. If the inclination of the lower 40 feet of the raised Ewa coral plain is projected below sea level it reaches a depth of only 1½ to 3 fathoms at the point where the line of breakers is indicated on the hydrographic map. Just outside the reef rim here the depth increases quickly, though not precipitously, to 2 or 3 fathoms, then continues with a gentle slope to near the 50 fathom line where the downward inclination increases rapidly. Not only here, but everywhere around Oahu, the sea bottom drops much more steeply from near the 50 fathom line to the 100 fathom line than it does nearer the shore. Measured horizontally, these two lines are much closer than is the 50 fathom line to the 10 fathom line. Using the same map to measure the horizontal distance from the line of breakers to the 4 fathom line, of 13 measurements between Wailupe and Barbers Point, the shortest is 520 feet, the longest 3,150 feet, and the average 1,567 feet. When made in the same way and in the same localities, the average of 20 measurements shows that while the 50 fathom line is 3,680 feet farther out than the 10 fathom, the 100 fathom is only 1,150 feet farther out than the 50 fathom line.

The slope of the sea bottom between Honolulu harbor and Diamond Head (fig. 2) probably represents the average slope of the shore around Oahu more nearly than do other areas of comparative size. The slopes in the region between Barbers Point and Pearl Harbor are typical for depths of 10 fathoms, but the 50 and 100 fathom lines curve decidedly seaward. Between Barbers Point and Kaena Point, the slope of the sea bottom is considerably steeper than near Honolulu, but on the northwest and northeast sides of Oahu it is decidedly less steep.

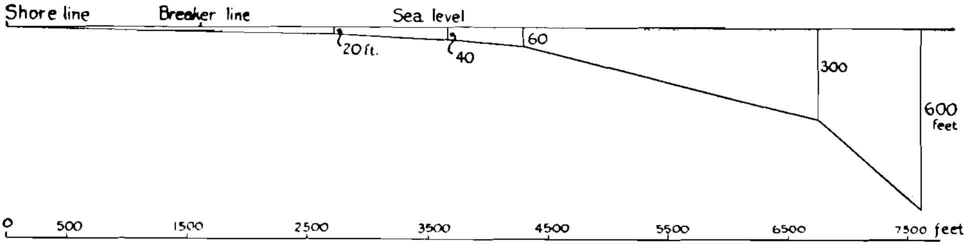


FIGURE 2.—Graph showing the form of the sea bottom between Honolulu harbor and Diamond Head based on the mean of 21 lines measured on map no. 4110, United States Coast and Geodetic Survey. The curve is plotted on a scale of 25 feet horizontal and 10 feet vertical. The points of reference extend from the shore line to the breaker line, and on to depths of 20, 40, 60, 300, and 600 feet (3 1/2, 4 2/3, 10, 50, and 100 fathoms). The breaker line representing the reef rim at high tide, and exposed at low tide along much of the shore, may be considered as lying at sea level.

Considering the reef rim as at the level of the shore line, figure 2 shows that the drop from sea level to a depth of 20 feet takes place over a horizontal distance of 1120 feet, thus confirming observations made from the reef rim at low tide, that the sea bottom does not descend to great depths immediately outside the rim, but that patches of the bottom are visible in the trough of the waves several hundred feet seaward. From reef rim to the 20 foot line, the sea bottom descends only 1 foot in 56 feet of horizontal distance; but from the 50 fathom line to the 100 fathom line, the descent is 300 feet in a distance of 850 feet, or 1 foot in 2.83 feet.

The bottom has a very gentle slope from shore to a depth of 40 feet, beyond which the slope rapidly increases, being quite steep at the 100 fathom line. There is no evidence of a submarine escarpment immediately outside the reef rim nor at any other level within the limits of the soundings taken for the graph.

The original dip of the lava flow strata from the Koolau Range is about 1 foot in 7 feet. If this slope is projected seaward from the original surface of Oahu, as indicated by what Wentworth (27) calls the "flow slope facets," the depth of the basal lavas of the island in the region of the 100 fathom line is not far from 2,000 feet. The difference between 600 and 2,000 feet may indicate that the calcareous deposits are as much as 1,400 feet deep, above the basal lavas at 7,500 feet from the shore.

While the area of sea bottom from Honolulu harbor to Diamond Head is probably the best region for determining the general slope of the present sea bottom around Oahu, the Ewa coral plain is by far the best area for determining the form and position of the sea bottom at the time when the sea level superposed upon the present one, and the depth of the two compared in the region of the present breaker line.

As the higher level is assumed to be about 20 feet, the point on the curve marking that depth is made to coincide with the present strand line in placing the curve for the higher level. This makes the strand line at the higher level about 325 feet farther seaward than it would be if it were situated halfway between the 40-foot contour line and the present strand sea stood 20 feet and 40 feet higher than at present. Along the 6 miles of coast between Barbers Point and the entrance to Pearl Harbor, the reef rock forms a continuous belt uninterrupted by fresh water streams and is a region so nearly rainless that erosion has but slightly modified the surface of the Ewa coral plain since it was raised above sea level.

To determine the slope of this raised sea bottom, 26 lines were measured from the 40-foot contour line on land to the 100 fathom line on the sea bottom. The belt of land thus measured is wider and flatter as it approaches Pearl Harbor probably owing to tidal currents at different levels of the sea during the development of the harbor. There is a corresponding widening of the belt from shore to a given depth of the sea bottom, undoubtedly due to the same cause, so that the relative widths of the land zone and the zone on the sea bottom do not vary much down to 10 fathoms.

It is beyond that depth that the sea bottom contours curve seaward around what is believed to be the submarine extension of the Waianae ridge. The correspondence in proportion between the wider and narrower part of the land zone and the wider and narrower parts of the sea bottom zones justified the use of all the lines measured on both zones between Barbers Point and Pearl Harbor in order to determine the probable depth at the present breaker line of the sea bottom of the higher sea level.

As shown in figure 2, the sea bottom descends with a curve that decreases its radius of curvature as it recedes from shore, dropping more and more steeply to and beyond the 50 fathom line. Out to depths of 40 feet the curve of the bottom deviates very slightly from a plane, but before a depth of 60 feet is reached, the change in curvature becomes appreciable. It follows that a straight line from the shore of the older and higher sea level to the present shore would not deviate appreciably from the old sea bottom now raised above sea level and forming the shoreward zone of the Ewa coral plain, but that a line projected out to sea on the same inclination would not conform in slope to the sea bottom of former sea level, where the present breaker line appears. The relations may be more accurately represented, if instead of projecting seaward the line from the older shore to the present shore, the curve of the present sea bottom be shifted to the position that it would have as the sea bottom of the older and higher sea level. This method has been followed in constructing figure 3, which shows the higher line. The error, if any, cannot be considered excessive because it changes the final result aimed at by only a little more than 1 foot of depth, as compared with the result if half the distance from the 40 foot contour line to the sea were assumed as the location of strand line at the former sea level.

Comparison of the two curves in figure 3 shows that in the region of the present breaker line the upper curve has a depth of 14 feet and the lower a depth of 26 feet, if the curve is plotted by drawing straight lines from shore to a depth of 20 feet, from 20 to 40, and 40 to 60 feet. However, as the sea bottom is really a gradual curve instead of a succession of straight lines as drawn, it follows that these depths indicated are greater than they should be. The depth to the upper curve should probably be about 1 foot less, to the lower one 2 to 4 feet less.

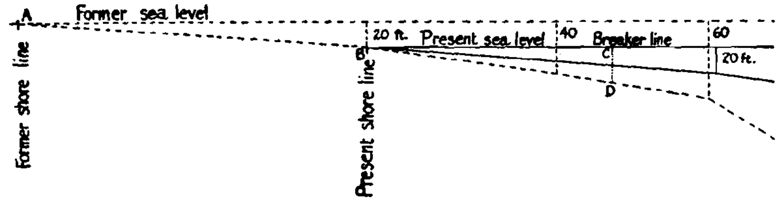


FIGURE 3.—Graph showing the curve of the sea bottom between Barbers Point and Pearl Harbor, solid lines representing present conditions, dotted lines the conditions when the sea level was 20 feet higher than at present: A, former shore line; B, present shore line; C, present breaker line; C-D, probable depth of the sea at present breaker line immediately after the last shift of shore line—the measure of the probable amount of upbuilding of the present reef since the last shift. Measurements based on map no. 4110, United States Coast and Geodetic Survey. Scale of 26 lines measured is 25 feet a unit horizontally, 2 feet a unit vertically.

The measurements show with a high degree of certainty that immediately after the last shift of land or sea that brought the shore line to its present position from one about 20 feet higher, the sea bottom in the region of the present breaker line could not have been less than 13 feet deep, nor more than 24 feet deep. Probably it was near 20 feet (3½ fathoms), certainly not over 4 fathoms. Since that shift of the shore line, the modern fringing reef has grown up to present sea level from that depth.

Writing of coral reefs, Dana says (11, p. 137):

> From the outer margin seaward the water usually sinks rapidly from 3 to 6 fathoms,

> then falls away more gradually for many rods, or it may be some hundreds of rods. . . . . Finally there is a rather abrupt descent to depths beyond the reach of the ordinary sounding lead.

This quotation shows how the fringing reef around Oahu differs from the typical coral reef as Dana describes it, in that the descent of the bottom immediately outside the rim is much less marked than most. The small depth immediately outside the Oahu reef rim may be explained by the fact that in its present location it began growing up on the gently sloping sea bottom formed during the period preceding the last shift of sea level, some distance seaward from any reef rock exposed at the sea level of that period. The location at which it began after the shift to build up faster than elsewhere and thus become the reef rim of the present time, was determined by the depth at which the waves were so much retarded by friction on the sea bottom as to cause them to become breakers. This made the conditions favorable for the growth of those organisms that find their favorite habitat in the breaker zone. The depth from which the new reef rim has grown to sea level since the shift was not great, certainly not more than 4 fathoms, and probably only 3 fathoms. It cannot be determined accurately. Beyond the reef rim, the sea bottom sloped gently, as it does now, and the organisms concerned in the formation of the present reef rim could grow over a zone of considerable extent. The last shift has been too recent to allow for the development of a continuous reef rim all around the island. The interpretation here offered accounts for a considerable number of observed facts: (a), the absence of a continuous rim exposed at present sea level all around the island, such as that opposite the Kahala shore; (b), the presence in many places of reefs composed of coral heads, separated by rather wide spaces across which the bottom has not been built up to the present sea level; (c), the sea bottom does not drop off to the usual depth just outside the rim as exposed at low tide, but continues as a gentle slope; (d), in this zone numerous patches of rock are visible from the reef rim at the extreme low tides, or in the trough of the waves from some hundreds of feet seaward from the rim that is exposed at low tides; (e), the dead reefs along the shore that are exposed between present tide levels, where they are not in process of growth yet have not been subject to much erosion by the waves at present sea level.

With this interpretation of the facts derived partly by direct observations and partly by a study of sea bottom contours, I am able to see no evidence that the reef rim at present sea level is part of an ancient reef, but rather the contrary—that it is a product of recent development. It has grown up to present sea level since the time of the last shift of that level, from a foundation that was probably not more than 3 fathoms in depth immediately after the shift.

The interpretation applies to those parts of the reef visible at or near present sea level, but of course there is a deeper foundation of reef rock that requires its own interpretation. Evidence shows that the deeper calcareous rocks around Oahu go down to at least 1,000 feet below the sea level of today. Dana (10, pp. 293-94) has given the details of the Campbell well bored in the plain near the west foot of Diamond Head, to a depth of 1500 feet. As reported there was a continuous layer of "hard coral" 505 feet thick lying from 320 to 825 feet below sea level; "soft white coral" 28 feet thick reaching to the level of 1048 feet; and 110 feet of "brown clay and broken coral" going down to 1178 feet. Underlying the lowest bed with calcareous material was "hard blue lava." Farther from the tuff craters the calcareous beds must be continuous for 1,000 feet or more. Agassiz (1, p. 152) reports a well at Waimea, Oahu, drilled 900 feet "through hard ringing coral rock."

In a recent study of wells in the Honolulu artesian basin Palmer (19) reports certain facts to support one of his conclusions that in some past time,

> . . . the island of Oahu became submerged a thousand feet deeper than it had previously been. This submergence appears to have been due to a foundering of the island. The reporting of a layer of coral with its base at about two hundred feet below sea level in 29 out of 43 available well logs suggests that there was a halt after 800 feet of submergence had occurred, but as indicated above this is not provable. This submergence, when complete, brought the shore line about 40 feet higher on the island than it is now.

The facts cited by Palmer in support of this conclusion are the subterranean contour lines joining wells where they enter the underlying lava below calcareous and other detrital deposits. Some of these contour lines are 700, 800, and 900 feet below present sea level. The critical fact about them is that they run landward from the present shore line showing that at a level of more than 900 feet below the present sea level there are eroded valleys in the basal lavas underlying the island of Oahu. These valleys could only be the product of subaerial erosion hence the island must have stood about 1,000 feet higher than at present when such valleys were cut. These ancient valleys are found below the present erosion valleys.

If this view is correct, the calcareous deposits now 1,000 feet below sea level may have been deposited near to the sea level of the time of their deposition. Of course the deeper strata are older than those that overlie them, but how much older? Agassiz (3, p. 166) offers some information on this point based on observations during the drilling of a well:

> . . . about 2500 feet from shore and perhaps 7 feet above high water mark. Down to a depth of 80 feet nothing but recent reef coral rock was encountered, but from that point to a depth of over 300 feet the limestone passed through was of very different character. It contained but few corals, being composed almost entirely of the shells of mollusks, mainly bivalves. The rock was white, chalky and resembled in every way the rocks of Vicksburg age of Florida and of Yucatan; but their age has not been

accurately determined. Enough, however, is clear to show that the limestones which form the substratum upon which rests the recent fringing reef of Honolulu do not belong to the present period.

It seems that no decisive facts are even yet available to settle the question as to the age of the lower portions of the Oahu reefs. However, the problem may be attacked in another way.

Mayer (17) made a careful study of the fringing reefs of Pago Pago harbor, Tutuila, one of the best of such studies ever made. He measured certain coral clusters growing on the reef flat in marked out areas, and again a year later he measured the same specimens. With the use of a diving hood that left his arms free, he studied the reefs to depths of 1 to 6 fathoms outside the reef rim, writing notes under water on a white board.

Mayer refers to Gardiner's report on an average upward growth of corals of the Maldives and Laccadives, as 26.6 mm. per annum. This very nearly agrees with Mayer's calculated growth of corals in Samoa of 24 mm., about one inch.

If the whole reef grew upward at the rate of one inch a year, a reef 1,000 feet thick could develop in 12,000 years—a period less than that since the last glacial epoch, as generally estimated by geologists. This is obviously much too short a time for the limestone 1,000 feet deep around Oahu, particularly in view of the estimates of 4,000 to 5,000 years since the last shift of sea level. Therefore, the average rate for the growth of corals in Samoa cannot be taken for the growth of the reef as a whole around Oahu. This might be inferred from the fact stated by Mayer that less than one-tenth of the reef flat is occupied by coral. Yet multiplying the 12,000 years by ten would carry the beginning of the lime deposits only into the later portion of the Glacial epoch, which is estimated by Chamberlin (5) as having had a duration of "280,000 to 900,000 years."

It has been shown that the fringing reef of Oahu as well as the latest fossil reef, is composed to a greater extent of lithothamnium, than of coral. It seems appropriate, therefore, to take the growth of lithothamnium rather than of coral as a measure of the growth of the reef as a whole.

In measuring some of the fossil reef structures it was noted that the different strata of the crustaceous lithothamnium, each one of which probably represented the product of one growth period, varied in thickness from 0.7 to 1.5 mm. At least one of these strata could form each year, providing a minimum figure. If it be assumed that the average thickness of the stratum formed in each year is a trifle more than 1 mm., one inch in 25 years is the rate of growth for the reef as a whole. This seems highly possible. At this rate, to produce a reef 1,000 feet thick would require 300,000 years, a time reaching back barely to the middle of the glacial epoch, and far from any period of Tertiary age.

The above calculations are based on the assumptions that the growth of the reef was due chiefly to the crustaceous lithothamnium, and that it was uninterrupted throughout the period of its development. As to the first assumption, it is worthy of note that of 31 specimens examined by Sherlock (23) from the raised reefs of Fiji, 26 contained lithothamnium, 24 Foraminifera, 8 had *Halimeda* and 11 contained corals. Some of those with Foraminifera had species identifying them as of Tertiary age. The second assumption is probably not true, because in the glacial epoch, at each period of greatest advance of the ice, the growth of reef-forming organisms may have been partially or even wholly suppressed. There even may have been a destruction of reefs already formed at those times, as Daly has assumed (9).

Chamberlin (5, pp. 170-72) reports that on the basis of the average of the estimates of seven glacial geologists, the time of maximum advance of the ice at all the different periods did not exceed 4 per cent of the total time of the glacial epoch, while the time of advance and retreat of the ice occupied 16 per cent more. The other 80 per cent is counted as interglacial time. If the development of the reef ceased completely during these times of greatest advance, and even resulted in destroying an amount of reef equal to what had been previously formed in the same time, the time necessary for the development of the whole reef probably would not be doubled. If, as indicated at Barbers Point, the present reef rim began to grow on the sea bottom at a depth of three fathoms and the time since the shift is 5,000 years, the calculated rate of growth is 1 foot in 278 years, or 1 inch in 23 years—a result surprisingly close to that calculated for the growth of the crustaceous lithothamnium (1 inch in 25 years.)

There is still the possibility that the deeper part of the reefs around Oahu are chiefly of foraminiferal origin, and that their rate of deposition was even slower than the growth of lithothamnium. The preponderance of Foraminifera in the Waianae sand offers some support for this possibility. I have no exact knowledge as to how rapidly Foraminifera multiply, but at a guess, it would seem not impossible for them to produce a deposit on the sea bottom of 1-10 mm. a year. At this rate it would require 3,000,000 years to deposit 1,000 feet of calcareous material. That, perhaps, is a sufficiently long period to carry the beginning of the deposits back into the Tertiary.

The problem of the rate of growth of the organisms forming the reefs and the age of the reefs has in it so many variables whose effect cannot be evaluated properly that the calculations above have largely only a speculative value, and yet the extremes in the time limits well may be the maximum and minimum within which the 1,000 feet of calcium carbonate in the submarine beds about Oahu has been deposited. As applied to the recent reefs that have grown up since the last shift of sea level, they have a higher value, as there is a good basis in observation for considering the crustaceous lithothamnium as the predominant contributor of calcium carbonate to the reef, a basis for the rate of its growth used in the calculations, and also for the assumed depth from which the recent reefs have grown. Perhaps they strengthen the probability that the time since the last shift of sea level was about 5,000 years. Whether or not any of the deposits are of Tertiary age can be satisfactorily determined only by finding in them some of those fossils which paleontologists have learned to depend upon as indicators for that geological age.

Wentworth (25) states that "the physical evidence does not appear to indicate the emergence of any part of the Hawaiian group above sea level before the later part of the Tertiary period." This estimate for the age of the Hawaiian islands would still allow sufficient time for the development of 1,000 feet of reef, even if a considerable part of the deeper strata were formed chiefly by Foraminifera and only the upper portions of corals and coralline algae. Such a reef might develop to that thickness about an island during a stand-still.

OAHU REEFS AND THE SUBSIDENCE THEORY

To one who has already accepted Darwin's subsidence theory for the origin of coral reefs generally, the mere fact that a given reef is 1,000 feet thick is sufficient proof that it originated in accordance with that theory; but neither Darwin's theory nor any one of those opposed to it have received universal acceptance by the group of scientists interested in the problems involved, it seems best to study the reefs of each locality without regard to any theory, and to compare the results of such study with the requirements of a given theory. The facts brought out in the study of the reefs of Fiji and of Christmas Island (Indian Ocean) prove conclusively that reefs 1,000 feet thick may be formed by organisms other than modern reef-forming corals, whose limited vertical distribution in the sea, at not more than 40 fathoms in depth and mostly not more than 20 fathoms, are a logical necessity for the support of the subsidence theory. Unless it can be shown, then, that great thicknesses of reef were actually built by modern reef-building corals, there is no logical necessity for concluding that the reef originated with subsidence. In the absence of convincing evidence on this point for the Oahu reefs, no inference can be drawn from the thickness of the reef, supporting subsidence.

The absence of barrier reefs around Oahu is decidedly adverse to the theory of subsidence. If a reef 1,000 feet thick grew up with subsidence so gradual that corals or other reef-forming organisms could grow at or near sea level continuously, then, according to the Darwinian theory of subsidence a barrier reef should develop, separated from the land that recedes from the reef as subsidence goes on, by a moat or lagoon channel which should not exceed 40 fathoms in depth. No such barrier reefs and no such lagoons or channels are found around Oahu.

From the evidence by Palmer (19) that at some time in the past the island of Oahu stood 1,000 feet higher above sea level than it does at present. it may be inferred that since that time it has subsided an equivalent amount unless there has also been a change of water level such as is demanded by Daly's "glacial control theory." Indeed, if Hitchcock's view is correct that Oahu had once been submerged 250 feet more than at present, the vertical change in shoreline has been about 1,250 feet. The raised reefs show that the island has at some time been submerged probably 80 feet more than it is now. Does the subsidence of 1,000 feet or more prove Darwin's theory for the origin of the Oahu coral reefs? I think not.

The absence of barrier reefs around Oahu shows that subsidence may occur without the development of a barrier reef. Of course Darwin recognized this possibility, and accounted for it by supposing subsidence to occur suddenly in amounts that submerged the reef-forming corals so much they were not able to keep pace with it in their upward growth. It was said that such corals could not grow much below 20 fathoms and not at all below 40 fathoms. The coralline algae probably do not have the same limitations. Finckh (13, p. 115) reported encrusting types of lithothamnium growing at Funafuti to a depth of 200 fathoms. The depth at which they might grow is limited by the depth at which light can penetrate water with an intensity sufficient for photosynthesis. Whatever the limiting depth, the rate of growth at the lower limits would be reduced so much that the organisms would have very little effect as reef builders.

It seems probable that in the latitude of Hawaii the temperature is so near the lower limit for the growth of the reef-building coral that their effect in building up reefs is less than in the more tropical seas. The coralline algae, which play a larger part in the building of Hawaiian reefs, are not limited so closely to the breaker zone and its vicinity, and in all probability the total assemblage of such algae that contribute calcareous material, including a considerable number of species of both the red and the green algae, grow over a much wider zone of sea bottom than do the reef-forming corals. Hence, reefs in which algae predominate are not built up in so distinctive a way as the reefs of more tropical seas. Many of the coralline algae, particularly certain species of the red algae, and the lime-secreting species of the green algae generally, readily break up into fragments so small and light that they are easily transported by the waves, and are distributed over the sea bottom beyond their place of growth. The result of these conditions is that no distinct rampart with a steep outer front is built up at the reef rim, and beyond the rim the sea bottom is built from the fragments of these fragile algae, with a very gentle slope far to seaward, and nearly as rapidly as the reef grows upward in the breaker zone. This view is supported by the structure of the raised reef near the shore at Barbers Point (p. 20).

This building up of a gently-sloping sea bottom far off shore may help account for the submarine platforms and shoals around the reefs and islands that form the northwest portion of the Hawaiian chain, as described by Palmer (18).

That the sea bottom around Oahu has a much steeper inclination from near the 50 fathom line to the 100 fathom line than nearer shore, is probably a significant fact, but what it signifies is not entirely clear. Three possible interpretations occur to me: (a), does it represent a submarine escarpment of an ancient drowned reef of the typical kind, formed when the land stood considerably higher than now, or which grew up during a period of slow subsidence of the island; (b), does it represent destructive work of the sea while it stood at a lower level than now; (c), is it the counterpart around the island of the continental shelf, which has its steep inclination at about 100 fathoms? Palmer has mentioned evidence for a stand of the sea about 200 feet lower on the land than present sea level, though he notes that his evidence is not conclusive. However, with the sea 200 feet lower than at present or the land 200 feet higher, there would be no close correspondence between that sea level and the steep inclination under consideration. It would still be 100 to 400 feet deep. There is equal lack of correspondence between the steep inclination and the "glacial control theory," since this theory postulates an ocean of the glacial period not more than 200 feet below present sea level. The most probable interpretation appears to be that the declivity corresponds to the steeper part of the continental shelf. This implies a relatively long period during which the sea has stood at a level not many hundred feet from the present one, and on the whole at a higher level than now. Evidence is here presented that the more recent changes of sea level required to explain the observed facts have been in a direction to cause the land to emerge probably as much as 80 feet, possibly as much as 250 feet compared to the present level. These changes would bring the declivity of the sea bottom around Oahu approximately to the depth characteristic for the true continental shelf. The presence of the fragile coralline algae would furnish much material for the waves to transport, and lead to the building up of such a shelf more rapidly than would occur on continental shores as an average.

It is greatly to be desired that specimens of reef rock should be obtained from the wells in the vicinity of Honolulu in condition to be examined microscopically after suitable preparation, in order to discover, if possible, the predominant organisms contributing materials that built up the 1,000 feet of calcareous deposits, at all the various levels. A "diamond drill" boring, such as was made with so much difficulty at Funafuti, could be made easily on Oahu. Until such evidence has been obtained it is hardly profitable to speculate further on the origin of the Oahu coral reefs, or the age of the older portions.

SUMMARY

A detailed study was made of fossil reefs along 40 or 50 miles of the south and west coasts of Oahu, and of the fringing reefs for 8 miles or more of the same coasts.

The fringing reef rim is in a state of active growth, and is not an ancient reef rim in process of erosion. It is forming essentially the same kind of structure by the growth of the same types of organisms as are found in the fossil reefs between sea level and 20 feet above that level.

The organisms chiefly contributing calcium carbonate to both fossil and fringing reefs are corals and coralline algae. The algae contribute more than the corals. The algae are called by the general name of lithothamnium.

The coralline algae are of three structural types, crustaceous, nodular, and branching. It is quite certain that there are several species of each of these types, but the study of the species has not yet been completed.

Crustaceous and stout-branched forms of the algae are characteristic of the breaker zone at the reef rim, where they are the most abundant and the most constant in occurrence of all the organisms observed. Crustaceous forms also cover large and small areas on the reef flat all the way from the reef rim to the shore. They cover the lower side of many projecting ledges.

A form of alga with thin branches, many of them fan-shaped, grows in a zone not sharply marked, in a region 100 feet to several hundred feet shoreward from the reef rim, where the force of the waves is very much reduced. This one form of alga covers an area slightly greater than that covered by all the corals growing on the reef flat, but its zone of maximum growth is farther shoreward than is that of the corals.

The nodular forms of lithothamnium may be found in depressions anywhere on the reef flat, but are most abundant where the flat is wide and the rim far from shore. In many places they are so abundant as to be piled upon one another several deep, and their total surface area may be much greater than the area occupied by the depression in which they lie. They are able to grow in turbid water, where they are covered by mud at low tide, but where the mud is stirred up at high tide.

Very few corals are found at or near the reef rim in the breaker zone, and these only in protected locations. They apparently are unable to endure the force of the breakers. Their zone of maximum growth where there is a definite reef rim is 50 to 200 feet shoreward from the rim, where they are bathed by a sheet of flowing water which each wave throws over the rim at low tide, except that they may be exposed above water for a short time at extreme low tides. A few scattered clusters of coral may be found at any point from the reef rim to the shore, except in areas where the water is turbid at every high tide. In such places no live corals were found.

All the types of structure found in the fossil reefs were seen developing on the fringing reefs except the finger coral type. Very little of this was seen on the reef flat, and that usually could be recognized as having been washed in by the waves. It is believed that this type of coral grows best in deeper water. It is abundant in the fossil reef underlying Waikiki and in the dead reef near the mouth of the Alawai. It is frequently dredged from Honolulu and Pearl harbors.

The sand of the beaches along Oahu shores has a considerable proportion of shells of Foraminifera. The "coral sand" used for building is predominantly of foraminiferal origin. Foraminifera may have played a considerable part in the development of the Hawaiian reefs.

The suggestion is made that the "Oahu chalk" associated with Diamond Head and other tuff craters may owe its origin to the heating of the reef limestone at the time of the volcanic eruption through the reef, and the subsequent air-slaking action. The chalk-like nature of the Waianae bed on the north slope of Mailiilii Hill is believed to indicate its great age as compared with the Diamond Head chalk and with other reef deposits on Oahu.

The Waianae chalk bed is of marine origin, as proved by the coral found in it. It is estimated that this bed contains more than 5 per cent coral.

Oahu has been submerged at several different levels. The latest and lowest level is about 20 feet. The exact number of such submergences is not certain. The Waianae chalk bed indicates a submergence of about 80 feet, and raised reefs a submergence of 40 feet. There may have been a submergence of 60 feet, but probably not of 250 feet.

On the sea bottom around Oahu no evidence appears for a submarine shelf such as is demanded by the glacial control theory, nor for a drowned reef belonging to an earlier time. Just outside the reef rim the bottom descends to about 3 fathoms, not precipitously, only 1 foot in 56 feet horizontally. The slope is very gentle to a depth of 40 fathoms whence it descends more and more rapidly, and between 50 and 100 fathoms the drop is 1 foot in 2.8 feet horizontally. As a whole the seabottom has a slope very similar to that of a continental shelf.

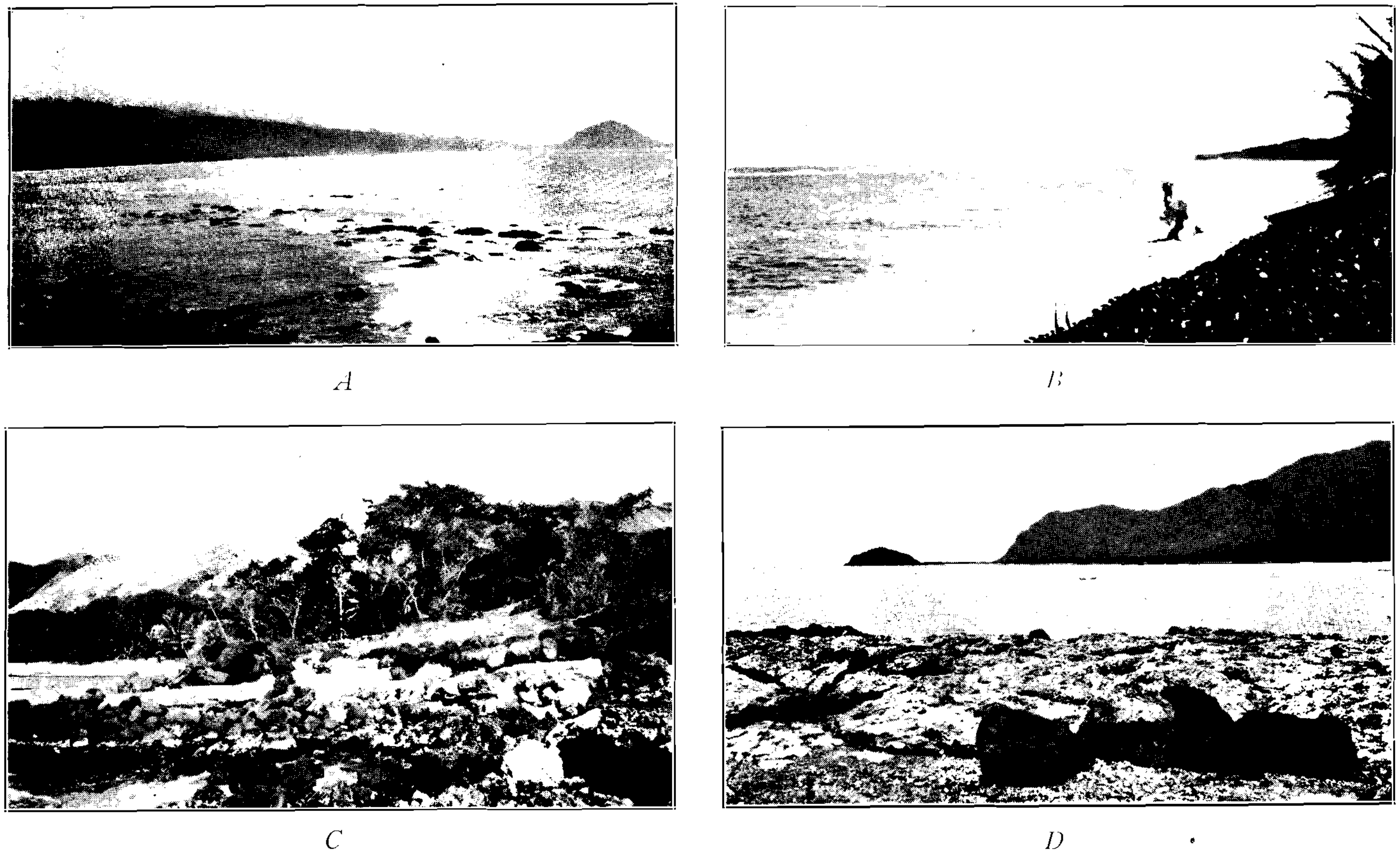
The present fringing reef has developed since the last shift of sea level, estimated by Wentworth and Palmer as about 5,000 years ago, and began its growth on a foundation perhaps not more than 3 fathoms deep. If the most abundant organism growing at the reef rim, namely, the crustaceous lithothamnium, is selected as a basis for calculating the growth of the reef as a whole, the rate of growth is 3 fathoms in 5,400 years. This increases the probability that the time since the last shift was about 5,000 years.

No direct evidence was obtained for determining definitely the age of the reefs raised above 20 feet or of the deeper parts of the submerged reefs. If the same rate of growth used in calculating the age of the modern reef is applied to the submerged reefs, 1,000 feet thick, their beginning dates from about 300,000 years ago, or at the most to twice that time if full allowance is made for the possible effect of the glacial epoch on the growth of reefs. This would place their development in the middle of the Pleistocene, and not in the Tertiary. If, however, the older reefs were chiefly of Foraminifera, and these deposited only 0.10 mm. a year, the 3,000,000 years necessary to deposit 1,000 feet of reef might carry the beginning back into the Tertiary. Only the discovery of some "indicator" organisms can furnish satisfactory evidence. The fossil reefs just above sea level date from the time immediately preceding the last shift of that level, and are threfore recent, geologically. Their formation ceased about 5,000 years ago, or at whatever time the shift took place.

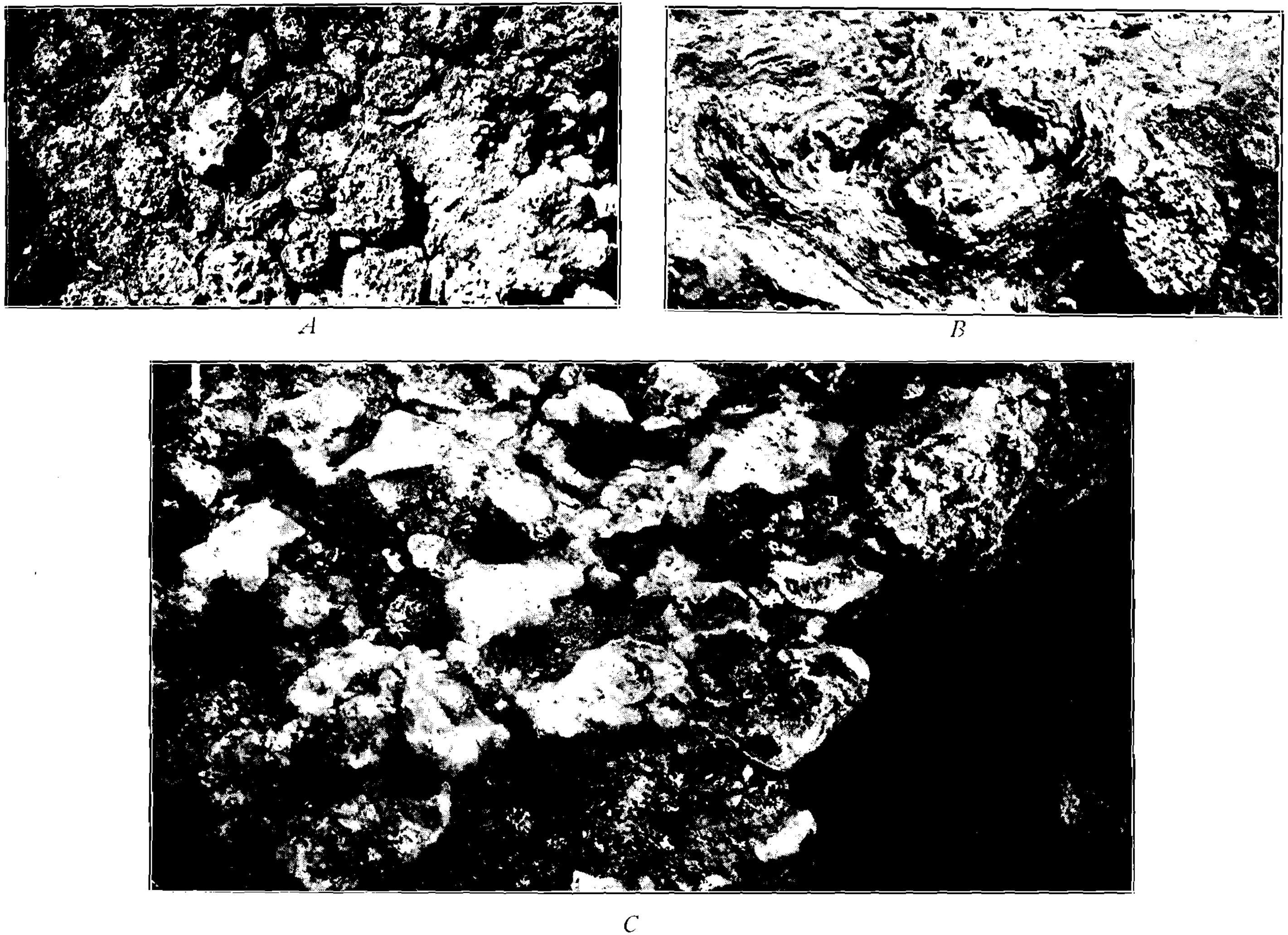
This study of the reefs around Oahu has revealed no evidence of origin in accordance with Darwin's subsidence theory, in spite of the evidence from wells that this island once stood 1,000 feet higher than it does now. The characteristic features of reefs that develop in accordance with Darwin's theory are not shown by the Oahu reefs. There is no barrier reef with its accompanying lagoon channel, but only fringing reefs with rims a few hundred feet from the present shore line. The reef rim is a continuous structure for only short stretches, whether continuous or composed of separate coral heads, the bottom seaward from the rim has a very gentle slope to near the 50 fathom line. The present reef rim has grown up to sea level from a depth of not much over 3 fathoms during a stand-still of the sea at present level. The fossil reefs from sea level to about 20 feet above, and also the reefs underlying the surface of the land at Waikiki, as well as some of the dead reefs exposed at low tide along the shore in certain districts, were formed during a stand-still of the sea at a level of about 20 feet higher than at present, during a period that preceded the last shift of sea level, within which period the eruptions in the Salt Lake crater region came to an end.

LITERATURE CITED

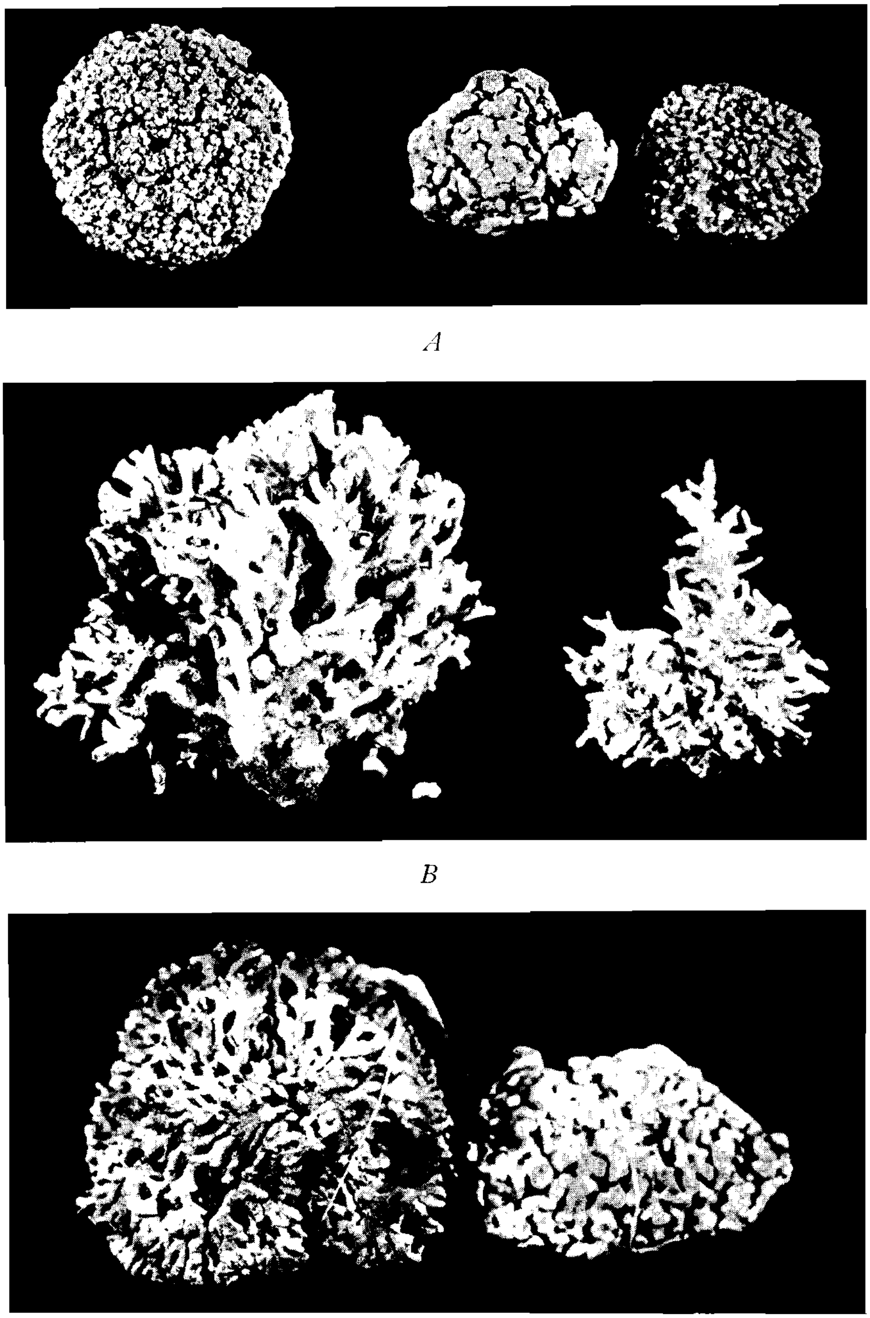
1. Agassiz, A., The coral reefs of the Hawaiian islands: Mus. Comp. Zoology, Harvard, Bull., vol. 17, pp. 121-170, 1889.
2. Agassiz, A., The islands and coral reefs of Fiji: Mus. Comp. Zoology, Harvard, Bull., vol. 33, pp. 1-167, 1899.
3. Agassiz, A., The Tertiary elevated limestones of Fiji: Am. Jour. Sci., 4th ser., vol. 6, pp. 165-167, 1898.
4. Andrews, C. W., and others, A monograph of Christmas Island, London, 1900.
5. Chamberlin, R. T., The geological interpretation of the coral reefs of Tutuila, American Samoa: Carnegie Inst. Washington, Dept. Marine Biology, vol 19, pp. 147-178, 1924.
6. Dall, W. H., Notes on the Tertiary geology of Oahu: Geol. Soc. Am., Bull., vol. 11, pp. 57-60, 1900.
7. Daly, R. A., A recent world-wide sinking of ocean level: Geol. Mag., vol. 52, pp. 246-261, 1920.
8. Daly, R. A., The geology of American Samoa: Carnegie Inst. Washington, Dept. Marine Biology, vol. 19, pp. 93-143, 1924.
9. Daly, R. A., Problems of the Pacific islands: Am. Jour. Sci., vol. 41, pp. 153-186, 1916.
10. Dana, J. D., Characteristics of volcanoes, New York, 1891.
11. Dana, J. D., On coral reefs and coral islands, 3d. ed., New York, 1890.
12. Darwin, Charles, Journal of researches . . . . . voyage of H. M. S. Beagle, Am. ed., vol. 2, New York, 1846.
13. Finckh, A. E., The atoll of Funafuti: Royal Soc. of London, Rept. Coral Reef Comm., sec. 6, 1904.
14. Gregory, H. E., The Tanager Expedition, Report of the Director for 1923: B. P. Bishop Mus., Bull. 10, p . 19, 1924.
15. Hitchcock, C. H., The geology of Diamond Head: Geol. Soc. America, Bull., vol. 17, pp. 469-496, 1906.
16. Hitchcock, C. H., The geology of Oahu: Geol. Soc. America, Bull., vol. 11, pp. 15-60, 1900.
17. Mayer, A. G., Growth rate of Samoan corals: Carnegie Inst. Washington, Dept. Marine Biology, vol. 19, pp. 51-72, 1924.
18. Palmer, H. S., Geology of Kaula, Nihoa, Necker, and Gardner islands, and French Frigates Shoal: B. P. Bishop Mus., Bull. 35, 1927.
19. Palmer, H. S., The geology of the Honolulu artesian system: Honolulu Sewer and Water Comm., supp. report, 1927.
20. Philippi, R. A., Beweis dass die nulliporen pflanzen sind: Archiv. für Naturgeschichte, vol., 3, pp. 387-393, 1837.
21. Semper, Karl, Animal life as affected by natural conditions of existence, pp. 343-346, figs. 92, 93, London, 1881.
22. Setchell, W. A., American Samoa: Carnegie Inst. Washington, Dept. Marine Biology, vol. 20, p. 152, 1924.
23. Sherlock, R. L., The Foraminifera and other organisms in the raised reefs of Fiji: Mus. Comp. Zool. Harvard, Bull., vol. 38, pp. 347-365, March, 1903.
24. Weber-Van Bosse, A., and Foslie, M., The Corallinaceae of the Siboga Expedition, Mon. 51, pp. 4, 5, 2 figs., 1904.
25. Wentworth, C. K., Estimates of marine and fluvial erosion in Hawaii: Jour. Geol., vol. 35, pp. 117-133, 1927.
26. Wentworth, C. K., and Palmer, H. S., Eustatic bench of islands of the north Pacific: Geol. Soc. America, Bull., vol. 36, 1925.
27. Wentworth, C. K., Pyroclastic geology of Oahu: B. P. Bishop Mus., Bull. 30, 1926.



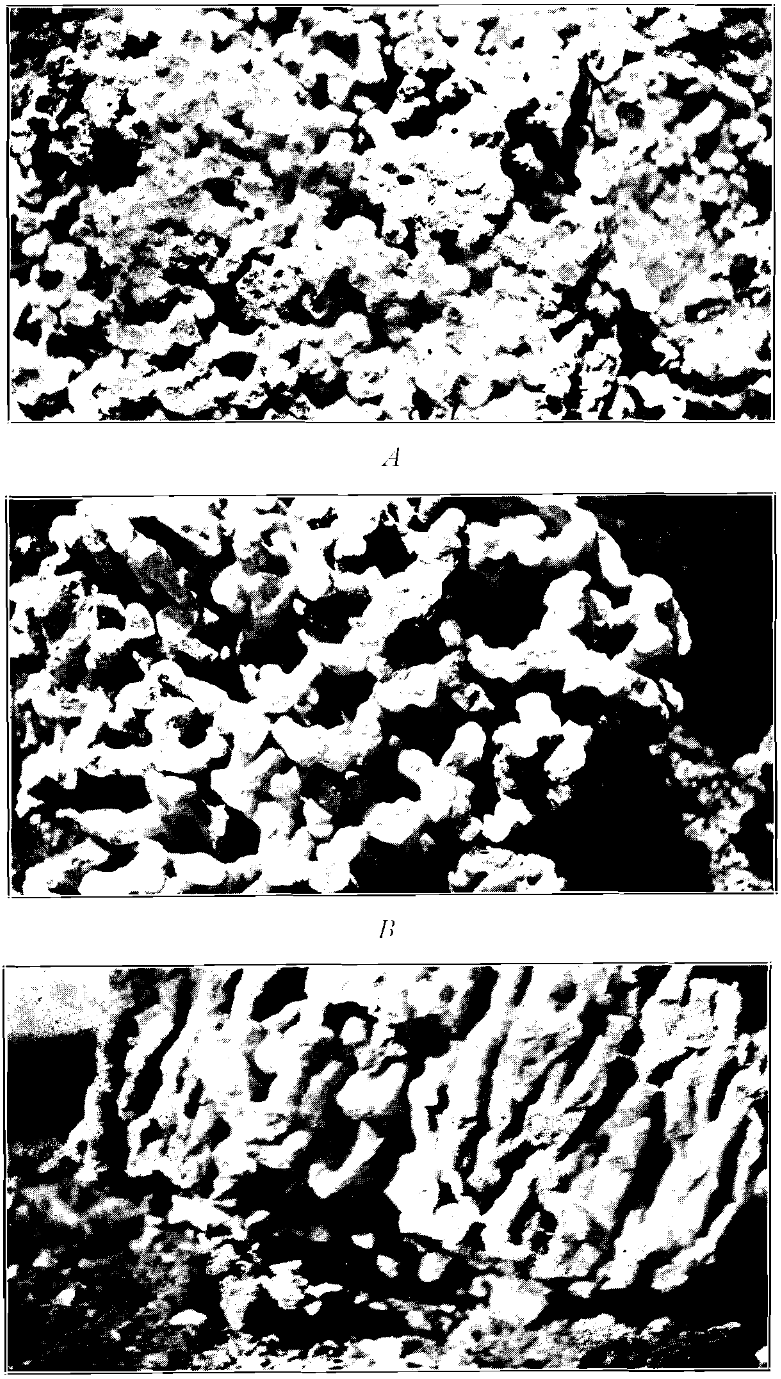
REEFS OF OAHU: *A*, REEF BETWEEN BLACK POINT AND KOKO HEAD, REEF RIM MARKED BY LINE OF WHITE SURF; *B*, REEF RIM AND BLACK POINT VIEWED FROM KAHALA; *C*, WEST SIDE OF BLACK POINT, LOOKING TOWARD DIAMOND HEAD, SHOWING LIMESTONE CLIFF TOPPED BY LAVA BLOCKS; *D*, RAISED REEF OF MASSIVE CORAL, NEAR WAIANAE STATION.



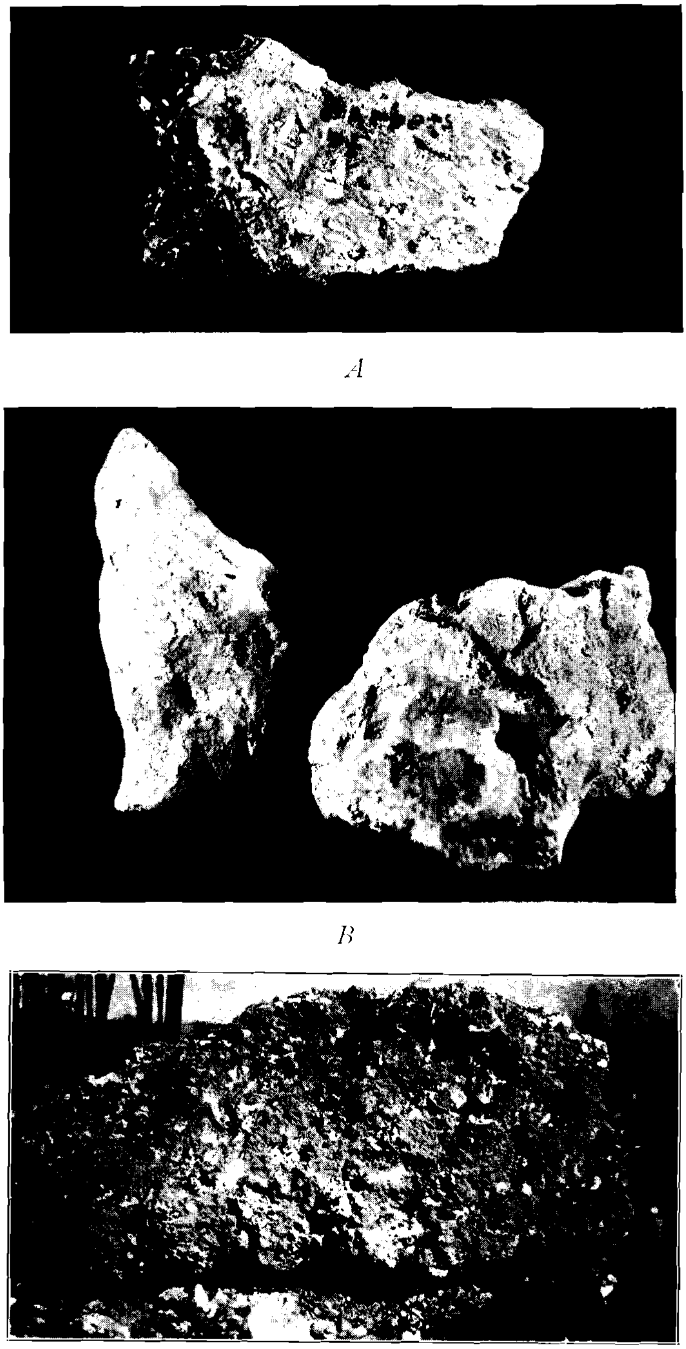
STRUCTURES IN CORAL REEFS: *A*, NODULAR LITHOTHAMNIUM FROM FOSSIL REEF, WEST SIDE OF BLACK POINT; *B*, CORAL SURROUNDED BY LITHOTHAMNIUM CRUSTS, NODULES IN RIGHT FOREGROUND; *C*, STRUCTURES IN WAILUPE FOSSIL REEF RESEMBLING SPONGIA CARTILAGINEA AS DESCRIBED BY SEMPER.



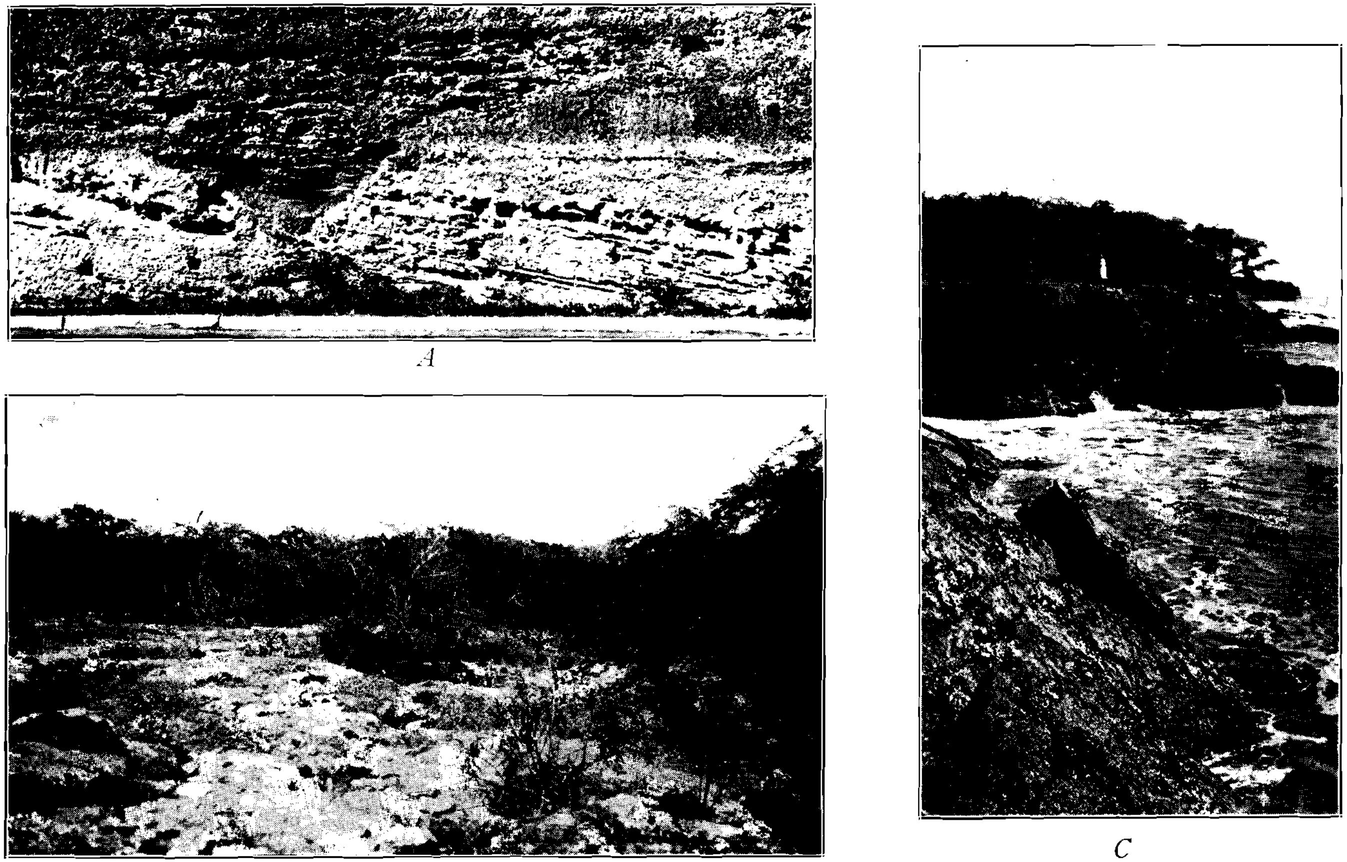
FORMS OF LITHOTHAMNIUM: *A*, THREE FORMS OF NODULAR LITHOTHAMNIUM FROM THE FRINGING REEF FLAT; *B*, TWO FORMS OF BRANCHING LITHOTHAMNIUM; *C*, TWO SPECIMENS OF THE COMPACT, STOUT-BRANCHED LITHOTHAMNIUM, FROM THE REEF RIM IN THE BREAKER ZONE (LEFT, BOTTOM VIEW; RIGHT, TOP VIEW).



FINGER CORAL: *A*, TOP VIEW; *B*, BOTTOM VIEW; *C*, SIDE VIEW. A BLOCK FROM THE DEAD REEF NEAR THE END OF THE ALAWAI. CORAL COMPRISES 85 PER CENT OF THE TOP AND 29.52 PER CENT OF THE BOTTOM.



REEF STRUCTURES: *A*, SAND ROCK FROM FOSSIL REEF AT BARBERS POINT, SHOWING JOINTS AND SECTIONS OF HALIMEDA; *B*, TWO SPECIMENS FROM THE WAIANAE CHALK BED; *C*, REEF ROCK FROM HONOLULU HARBOR, CONTAINING 18.57 PER CENT OF CORAL.



A

B

C

FEATURES OF FOSSIL REEFS: *A*, AEOLIAN SAND ROCK AT DIAMOND HEAD; *B*, SURFACE OF FOSSIL REEF NEAR BARBERS POINT, SHOWING UNERODED SURFACE AND REEF POOLS; *C*, CORAL CONGLOMERATE REEF WEST OF BARBERS POINT, 18.5 FEET ABOVE MEAN LOW TIDE, OVERLYING LAVA.