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PACIFIC ISLAND SEDIMENTS

by

C. K. WENTWORTH and H. S. LADD

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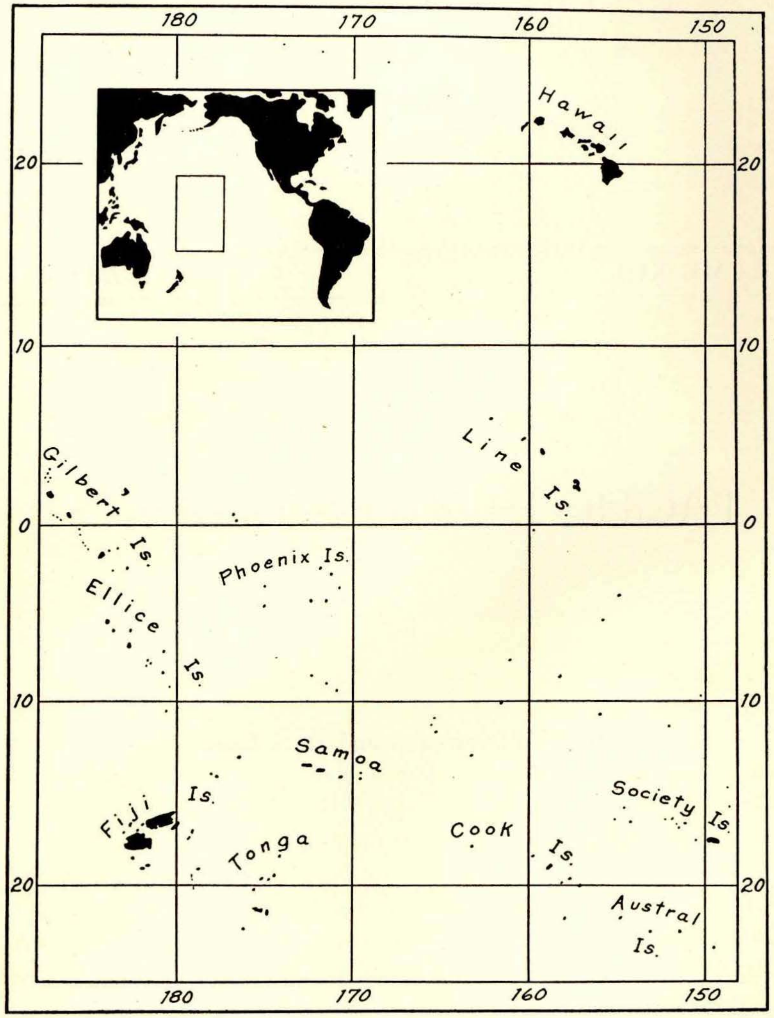

Figure 1

Map of a portion of the Pacific Ocean showing the location of the islands studied. Insert, relation of area studied to Pacific as a whole.

PACIFIC ISLAND SEDIMENTS*

INTRODUCTION

Purpose of Paper

The types of sedimentary rocks made most familiar to students by textbooks of geology are those most common in the great series of sedimentary rocks which make up so large a part of the surface of the earth. Thus conglomerate, sandstone, shale, and limestone constitute the chief classes which the student must recognize. Because so large a part of the stratigraphic record is composed of these four types, it is proper that they should be emphasized in the elementary study of geology and it is evident that the conditions of gradation over the earth as a whole and throughout geologic time have been those resulting preponderantly in the formation of these rocks. It follows that the more unusual times and situations are portrayed in the less abundant types of sedimentary rocks which here and there interrupt the sequence of the more common ones.

This paper is presented to call attention to some of the sedimentary materials common in the Pacific Islands but unusual in relation to sedimentation in general. Some of these rocks are forming at the present time while others are older. The oldest are Tertiary in age but all are relatively unaltered.

As compared to corresponding sedimentary processes in temperate, continental situations, the rock cycle in the parts of the tropical Pacific visited may be regarded as the same old drama played by a new cast. The processes of weathering, transportation, and deposition, taken one at a time, are not far different from those of lands in higher latitudes but the materials available for incorporation into sediments are fewer. Consequently the net effect of the several processes on these materials, in the proportions characteristic of the region, produces a number of highly distinctive sediment types.

In these types one sees the progressive selection of resistant mineral elements, though in many instances these are materials which do not commonly play such a role in continental situations and the forces

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to which they are resistant may be very different from those acting on sediments in other regions. It is this very diversity which makes these rocks of certain tropical islands so significant to the student of sediments.

Scope of Studies

The present paper is based on field work by the authors in three separate areas and on a considerable number of different islands. No attempt has been made to describe the complete series of sedimentary rocks from any one island, but instead, the purpose has been to present a picture of the more typical kinds and to convey some idea of the fascinating diversity found in the region as a whole.

Wentworth spent twelve months in 1923 and 1924 in the Hawaiian group, the larger part of his time being spent on southeast Oahu, Molokai, and Lanai, with short visits to other parts of Oahu, to Maui and Kahoolawe and to the east and south parts of Hawaii. He also took part in the 35 day cruise of the U. S. Minesweeper *Whippoorwill* when Palmyra, Washington, Fanning, Christmas, and Jarvis Islands of the Line group were visited by a party of scientists under a cooperative agreement between the Bishop Museum and the United States Navy.

Ladd confined his activities almost entirely to the large island of Vitilevu in the Fijian group. Six months in 1926 and four in 1928 were spent in making a reconnaissance. In addition to his general studies of this island, which is of about the same size as Hawaii, he spent shorter periods on several of the smaller islands of the Fijian group and, in 1928, in company with J. E. Hoffmeister, he visited a number of the Tongan Islands including the newly formed Falcon Island.[1]

In the preparation of the present paper the writers have drawn on general field notes, collected specimens and photographs, and have made a moderate number of analyses in the laboratory. No attempt has been made to analyze a complete series from any section and detailed statement of several of the analyses made has been omitted, the results having been used simply for the control of general statements.

Acknowledgments

Pacific Island studies by the writers were primarily supported by equal grants from the Bishop Museum and Yale University in the

[1]Hoffmeister, J. E., Ladd, H. S., and Alling, H. L., Falcon Island, Amer. Jour. Science, Fifth Series, Vol. XVIII, pp. 461-471, 1929.

form of Bishop Museum Fellowships. Smaller amounts were granted by other institutions and individuals in connection with special studies. Invaluable assistance was rendered in the form of instruments and equipment loaned for field work to the writers by the Geology Department of the University of Iowa and by the United States Geological Survey. Subsequent studies of materials were made in the laboratories of these institutions.

Wentworth, in connection with field work in Hawaii, was aided in ways too numerous to mention by equipment belonging to the University of Hawaii, made available through the courtesy of Harold S. Palmer, Professor of Geology, whose knowledge of various localities in the islands made his suggestions and assistance of prime value.

SEDIMENTARY PROCESSES

The Rock Cycle

Sediments are the products of a complicated series of processes by which older rocks are disintegrated by the various agents of weathering and the broken rock materials transported, sorted, and finally deposited to form new rocks more suited to the existing environment than were their predecessors. Each of these rocks carries in its composition and structure the marks of a distinctive origin, records of interlocking agencies of disruption, transportation, and deposition which are at once characteristic of the region, the climate, and the nature of the parent rocks themselves.

An analogy may be coined to the well known formula of W. M. Davis by which land forms of many regions may be interpreted in terms of the "Structure, Process, and Stage." Thus the nature of a given sedimentary rock may best be interpreted in terms of the Parent Rock, the Agent of Modification, and the Stage achieved. Space does not permit the complete elaboration of this form of interpretation or the pointing out of numerous analogies that exist between the physiographic development of a region and the cycle of changes in which its rock constituents are modified and recombined. It is sufficient to assert that the enormous diversity shown by the sedimentary rocks of the earth is due to variations in these three fundamental factors which we may call briefly *Parent*, *Agent*, and *Stage*.

Parent Rocks

The explanation of many of the unusual features of Pacific Island sediments is to be found mainly in the parent rocks. There are comparatively few sources of sediments, particularly in the case of strictly oceanic islands. Thus in the Hawaiian Islands the most abundant primary rock is a basic lava. Basalt is the commonest though a number of other types are found.[2] From this basic lava, which probably forms over ninety-nine per cent of the entire mass of the islands, and from very small quantities of basaltic ash and tuff of different structure but very similar ultimate chemical composition are derived practically all of the terrigenous sediments. On many of the islands of the southwest Pacific, for example on the island of Vitilevu in Fiji, basic pyroclastics occupy a position nearly as important as that of the basic lavas of Hawaii.

In Hawaii a second important source of sediments is found in some small masses of coralliferous limestone and other calcareous sedimentary rocks which are exposed to wave attack or which in a few places are emerged so as to be subject to attack by subaerial agents. In the tropical islands of the southwest Pacific these calcareous rocks are much more widespread than in Hawaii. Many of the smaller islands exhibit nothing but limestone on the surface whereas numerous others show but small quantities of volcanic rocks. Thus, in a broad sense, the sea water itself may be regarded as a very important parent rock from which corals and many other marine organisms derive enormous quantities of material used in the building of sedimentary rocks.

A number of the islands in the southwest Pacific exhibit traces of "continental rocks."[3] Vitilevu is such an island but even there the cover of "island rocks" is in most places so thick that, for practical purposes, Vitilevu may be classed with the typical oceanic islands.

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[2]Cross, Whitman, Lavas of Hawaii and their Relations, U. S. Geol. Survey, Prof. Paper 88, 1915.

Washington, H. S., The Petrology of the Hawaiian Islands, Amer. Jour. Sci., 5th Series; vol. 5, pp. 456-502; vol. 6, pp. 100-126; vol. 6, pp. 338-367; vol. 6, pp. 409-423, 1923.

Washington, H. S. and Keyes, M. G., The petrology of the Hawaiian Islands, Amer. Jour. Sci., 5th Series, vol. 12, pp. 336-352, 1926; vol. 15, pp. 199-220, 1928.

Hinds, N. E. A., Weathering of Hawaiian Lavas, Amer. Jour. Sci., 5th Series, vol. 17, pp. 297-320, 1929.

[3]"Continental rocks" include plutonics such as granite and diorite and metamorphics such as schist and slate. As a general rule such rocks are not found except on continents or on islands obviously once connected with continents. The deep-seated plutonics are exposed only after prolonged erosion and most islands have not suffered sufficient erosion even if it be assumed that they have a plutonic core. The metamorphics demand powerful earth movements and these cannot be developed on tiny land masses. Hence, the occurrence of either plutonics or metamorphics on an island suggests that it once was a part of a much larger land mass. The "island rocks" consist largely of volcanics and limestones and sediments derived from these.

Thus on Vitilevu sandstones and shales of the types most familiar to students of North American geology exist in negligible quantities. Sands for the most part are calcareous while the residual clays and the poorly bedded transported clays show clearly their recent derivation from volcanic materials.

Agents of Modification

These include the agents, forces, and processes by which the rocks are broken up, those by which the resulting fragments are transported and redistributed, and those by which, after deposition, the debris is cemented and lithified. To a large extent the relative effectiveness of these agents depends, in any region, on the various elements of climate and topography.

Weathering in these tropical islands is dominated by chemical decomposition which is favored by the high temperatures, abundant moisture, and moderate temperature ranges.[4] The basic composition of the igneous rocks of most of the islands and the solubility of the dominantly calcareous marine rocks still further enhance the effects of the chemical attack. The absence of freezing temperatures or their restriction to high altitudes, the low annual and diurnal temperature ranges as well as the abundance of moisture and vegetation tend in most districts to reduce the effects of physical weathering processes to a minimum. However, due to the great variations of rainfall in short distances, to the great elevation and impressive steepness of some of the topographic features, there are places where physical weathering is of considerable importance.

Among the processes of abrasion, that by the wind may be of considerable prominence near leeward coasts where the low rainfall supports only a slight cover of vegetation. On the one hand eolian abrasion produces rather distinctive results because of the very constant direction of the trade winds but on the other the general lack of quartz or other notably hard minerals materially reduces the sculpturing capacity of the wind.[5]

The comparative shortness of the streams in the smaller islands somewhat limits the effectiveness of stream corrasion and abrasion and it is only very rarely and in restricted localities that it is sufficiently

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[4]Wentworth, C. K., Principles of Stream Erosion in Hawaii, Jour. of Geol., vol. 36, No. 5, pp. 387-397, 1928.

[5]Wentworth, C. K., Desert Strip of West Molokai, U. of Iowa, Studies in Natural History, vol. 11, pp. 41-56, 1925.

active to scour either the bedrock surface or the fragments that are in transit so as to expose wholly unweathered material. Vitilevu with its area of more than four thousand square miles, its high mountains, its excessive rainfall and advanced physiographic development, and its core of continental rocks is exceptional. There some of the major streams are large and exceedingly powerful.

Marine corrasion and abrasion on the more exposed coasts are strong and produce large quantities of well rounded and well sorted gravel and sand. However, even in the case of wave work, there are many localities where chemical weathering is so rapid as to precede abrasion and partly weathered material is found in the beach gravel.

Explosive volcanic eruptions, the process of formation of "aa" lava, and the production of disrupted, ash-like material where a lava flow enters the sea are all properly to be considered among the means by which rocks are broken up in preparation for incorporation into sedimentary deposits.

The processes of transport are identical with those of abrasion and similar in effectiveness. Wave transport is most effective. Wind work, for the most part, is important only locally though during pyroclastic eruptions it may be of great importance. Streams on most of the islands are too short to achieve any very pronounced sorting of the sediments.

Stage

The stages attained by various of the sedimentary processes depend upon a number of factors. In general, those agents which operate with great intensity or which have been operative through a long period of time reach advanced stages. Dominance of one process over another is essential for the production of large quantities of pure types of sediments. These conditions are not as a rule found in oceanic islands. No one agent is here operative to the exclusion of other agents for long periods and the lengths of stream courses are not sufficient to favor the long continued handling of fluviatile debris which is essential in the production of well sorted fluviatile sediments and is in many instances a large factor in the origin of similar marine sediments. The work of the sea comes nearest to the necessary dominance in time and space but even here we find rapid changes in configuration of coast line, direction of currents, etc., all of which are circumstances unfavorable to the development of sediments of advanced types. Islands which have long been subject to erosion and on which a considerable degree of adjustment of erosional agents and vegetation and other factors has taken place are most likely to be the sites of production of advanced types of sediments. Among the islands visited Vitilevu in the Fijian group most nearly occupies this position.

Modification and Sorting of Debris

No very pronounced rounding by wind probably takes place in the short distances over which transport takes place. A few sand-blasted pebbles were found in the desert strip of West Molokai but very few typical dreikanter shapes were seen. Lag materials of local origin are common in the drier parts of various islands. In places spheroidal masses of basalt are isolated on pedestals by wind erosion and are then by undercutting caused to tilt forward systematically toward the wind.[6]

In Hawaii and other similar islands of the group the stream pebbles and boulders have a degree of rounding far in excess of that which might be produced by stream abrasion alone on hard rock and it is evident that much of the material is shaped by spheroidal weathering and that in part it is weathered so rapidly by chemical means that stream abrasion works chiefly on the softer exterior parts of the fragments. Much of the stream borne material is poorly assorted, and clean, homogeneous sand is rare, except in those places where beach sand is carried by wind to the headwaters of streams.

Waves and currents along the coasts are more effective, relatively, than streams and in exposed situations some very vigorous milling of materials takes place. Along some of the coasts of Hawaii fresh basalt is maturely rounded and sorted into gravel deposits ranging from sand sizes to boulders several feet in diameter. In such situations sand is produced which is made up of nearly representative minerals from crushed basalt. In Fiji many of the islands are at least partly encircled by a barrier reef which, of course, greatly diminishes the amount of wave erosion along the shore. Adjacent to pyroclastic craters on Oahu and other islands certain minerals like olivine and augite, chiefly olivine, are segregated on the beaches by wave action and suffer considerable battering of the euhedral forms. On islands where the beach sand is largely calcareous the grains are highly polished, an effect partly due to abrasion but partly aided, it is thought, by the deposition of salts from the sea water.

The behavior of shells and other calcareous parts of organisms with

[6]Wentworth, C. K., Desert Strip of West Molokai, Univ. of Iowa, Studies in Nat. Hist., Vol. 11, pp. 47-48, 1925.

respect to wave work is interesting in many respects. Because of the composition and structure of the shells and also because of the varying amounts of air in the cavities of certain shells there is a considerable range of effective specific gravity and hence considerable density sorting. This results in the flinging of such shells as those of echinoids and some of the lighter mollusks onto the upper beach as a line of drift materials. For example, the small chambered shells of Spirula can usually be found in this line of drift along the Fijian and Tongan beaches. After a heavy storm thousands of these shells litter the beaches at all levels but most of them are quickly destroyed. Those remaining are eventually deposited at highest tide mark. Chunky fragments of Tridacna and the heavy opercula of such gastropods as Turbo are commonly found at the wash line of the lower beach.

Various shells have their distinctive mode of abrasion and break-up on the beach and hence certain parts are characteristically the residual portions of each type. The common disk-shaped and lens-shaped foraminifera which range from one-half to two millimeters in diameter are most fragile around their peripheries and gradually break down at the margins. They are for the most part light in weight because of the contained air, and in places constitute a very important part of the beach sand. The beach sands around Vatu Lele in Fiji and Eua and Tongatabu in Tonga as well as at many points in the Line group are largely composed of foraminifera.

Corals are varied in shape and resistance to abrasion. Types with flat, discoid heads persist as cobbles of similar shape on some beaches. Other common types, such as Orbicella, are flat on the bottom with a deeply rounded dome above in which the separate corallites are seen in section. On beaches where the abrasion is very severe these are planed off smoothly but in other situations where leaching is relatively more active the inner structure of the corallites is sharply etched out making an extremely rough surface. Such fragments were used by the natives in primitive times as rasps in fashioning wooden implements. The larger coral heads which are strewn on the beach and because of their lightness handled with much fine material are not uncommonly beautifully perforated by straight or tapering smooth-walled borings made by Lithophaga. There are also considerable quantities of fine sand wedged into the interstices of the coral. The seaward portions of the barrier reefs of Fiji are studded with giant blocks of blackened reef rock, known as negro heads. These are torn from the overhanging reef border during heavy storms. On the

reef flat they are soon riddled by boring organisms and eventually battered to pieces by heavy surf.

Echinoid tests are among the most fragile of all the organic materials and would soon be broken up if it were not for their lightness which facilitates their lodgement in the drift line of the upper beach where they may be preserved for a short time at least. The most persistent and distinctive parts are the spines, some of which are small and appear in the sand grades and others are a half inch in diameter and six inches long and form curious pencil-like pebbles. Short segments of these, which are of dice-like aspect and show purple and white annular ring structure are very striking as pebbles.

Most impressive among the pelecypods as contributors to sediments are the shells of the massive Tridacna which in places form a heavy mantle of shingle or are cemented to form beach conglomerate. The shells of the Line Islands reach an inch in thickness and for the most part remain intact but are slowly battered and rounded on the edges. Presence of occasional fragments of these shells indicates that they are subject to breakage but comparatively few of them are seen in the intermediate stages. This appears to be true in general of the pelecypod shells which exhibit no very systematic or progressive disruption as do the gastropods. Some very fragile ones break up at once but other, thicker types are slowly ground down without breaking.

Progressive abrasion and destruction of the shells of gastropods shows much variation. In the large, low-spired conch shells the body whorl breaks away first and the exposed edges of successive whorls are destroyed leaving only the spire itself. In the Cypraeidae abrasion commences at the top of the dome of the last body whorl which is finally broken through exposing the fragile internal parts. The broken edges of the outer body whorl are commonly neatly trimmed away until a low pan with recurved edges is produced. This finally breaks into two pieces at the two ends of the aperture and these are very persistent as thick, curved, jaw-like fragments.

In the rather massive shells of the Turbo type the thinner parts of the last and next to last whorls commonly break through and expose the heavy columella, the whole producing a fantastic figure-eight or pitcher handle aspect. The opercula of such shells are nearly hemispherical and are resistant to abrasion. In places they constitute an important part of gravel ranging to 25 or 30 millimeters in diameter. Flat based trochoid shells suffer destruction of the spire, and the last body whorl with its section of columella forms a plane-parallel frustum of a cone. Many species of the genus Conus suffer destruction of the entire shell except the low, heavy bowl-shaped spire through which a hole is often developed forming numerous natural buttons.

Distribution of the shells of various types of gastropods is affected to a considerable extent by the activities of hermit crabs and it is probable that certain types are preserved from abrasion to a considerable extent in this way. Gastropod shells are especially likely to have fragments of other shells wedged in the aperture and fourfold examples of this feature have been seen; a small gastropod shell lodged in a larger and the small shell itself containing a still smaller one and so on.

The claws and the carapaces of various crustaceans are rather ephemeral elements of the beach materials and do not appear to withstand destruction for long. The tubes of marine worms are prominent in sediments in a few places and these and the calcareous algae which encrust other shells play a considerable part in thickening them and protecting them from abrasion.

Deposition

The exact location and the composition of any given sedimentary deposit are closely related. For the most part on the small islands uniformity of composition prevails over a very small area only and there is much intermingling of various types of materials. The different varieties in relation to agents of transport and the original sources are better described in the sections which follow.

Though a large fraction of the recent sedimentary material found on most of the islands visited is unconsolidated there are certain places where lithification is going on at present or where comparatively recent materials have been firmly cemented. Beach sands and gravels in many places in Hawaii have been cemented into strong rock in situations so close to present sea-level and in such perfect conformity with the slope and general attitude of the present beach as to suggest that lithification is essentially contemporaneous. Similar deposits are found in Fiji. As Daly has pointed out in the case of Samoan occurrences[7] they are developed along exposed coasts. Thus on Vitilevu they are almost entirely limited to the western portion of the south shore where the island's barrier reef becomes a fringing shelf.

[7]Daly, R. A., The Geology of American Samoa, Carnegie Institution of Washington, Pub. 340, pp. 135-140, 1924.

Calcareous algae and other organisms indirectly by their growth over and around other materials accomplish a large amount of stabilization which subsequently makes for induration of the rock.

Around the margins of shallow salt lakes on Christmas Island as well as at a few other localities on atoll islands the evaporation of capillary waters at the surface of more or less barren areas has deposited mineral material to form a firm crust a half inch or more in thickness which overlies calcareous mud or sand.

Many of the deposits of black ash on the island of Oahu are somewhat cemented by calcium carbonate. Moreover, the larger part of the original black ash has been rather thoroughly indurated to form tuff. For the most part the induration has been brought about by the general transformation of the basaltic glass into palagonite through hydration but the deposition of calcium carbonate leached from the volcanic material has also played a considerable part. The fossiliferous tuffs and marls of Vitilevu are likewise well cemented with calcium carbonate.

In Hawaii eolian sands in dunes and other deposits have been firmly cemented by leached calcium carbonate in various places and subsequently by differential etching show very strikingly the characteristic bedding of such masses. Strongly cemented calcareous root and stem casts are commonly found in these deposits or in some places where the main mass of sand has not been stabilized but has moved forward.

TYPES OF SEDIMENTS

Residual Materials

Weathered residuum which overlies the fresh basalt in various parts of the Hawaiian Islands varies greatly in thickness, in color, and in chemical composition. It is evident that rainfall, temperature, both affected by topographic situation, and depth combine to produce different rates of decomposition and hence different stages in a process of which the end product is laterite. Hinds[8] has commenced a series of papers on the weathering of Hawaiian lavas of which the first has appeared and to which the reader is referred for details. The more completely weathered residuum of the dried parts of the islands is a deep red, somewhat porous material which, though essentially of the

[8]Hinds, N. E. A., The Weathering of Hawaiian Lavas, Amer. Jour, of Sci., 5th Series, vol. 17, pp. 297-320, 1929.

texture of fine silt, is aggregated into small, irregular masses which can be readily pulverized. Analyses show an iron content in this material which ranges from 15 to 40 per cent, averaging around 20 per cent.[9]

There are various types of residual materials in Vitilevu. The widespread marls which are best developed in the southeast part of the island yield a red and a black soil.[10] These two soils show a peculiar distribution; in some places the red soil occupies the higher elevations, in others the black is found above. In general the red soils are thick, the black thin, and over large areas bare marls outcrop at the surface.

Where original volcanic rocks weather *in situ* they give rise to red lateritic materials similar in appearance to those of Hawaii.

An unusual example of residual soil formation was seen in an abandoned quarry at Tholo-i-suva, nine miles from Suva on the Prince's Road to Nausori. The rock at this place is a marine, shell-bearing conglomerate with a surprisingly small amount of matrix. The boulders range in size to six feet in diameter and are composed of porphyritic diabasic basalt. Fifteen feet of fresh rock are exposed and are overlain by an equal amount of soft weathered material. Some of the boulders in a creek bed at the foot of the outcrop and some of those in the outcrop exhibit spheroidal weathering (see fig. 5) but in parts of the quarry face a series of horizontal laminations is developed. These pass through partially weathered boulders with scarcely any deviation. All stages may be seen, otherwise it would be difficult to believe that the "bedded" clays of the upper fifteen feet could be derived from the conglomerate below—which, with its small amount of matrix, resembles an outcrop of solid igneous rock.

Coarse Clastic Sediments

Cliff breccia—The principal examples of cliff breccia observed consisted of angular fragments of palagonite tuff cemented by calcium carbonate into a caliche-like mass. It was found at several points around the margin of the Diamond Head crater of Oahu.[11] In a few

[9]Kelley, W. P., McGeorge, Wm., and Thompson, A. R., The Soils of the Hawaiian Islands, Hawaii Agric. Exper. Station, Bull. 40, Table 1, 1915.
[10]Wright, C. Harold, Report on the Soils of Fiji, Pt. 1, Bull. No. 9, Dept. Agriculture, Fiji, 1916.
[11]Wentworth, C. K., Pyroclastic Geology of Oahu, Bishop Museum Bulletin, No. 30, pp. 43-44, 1926.

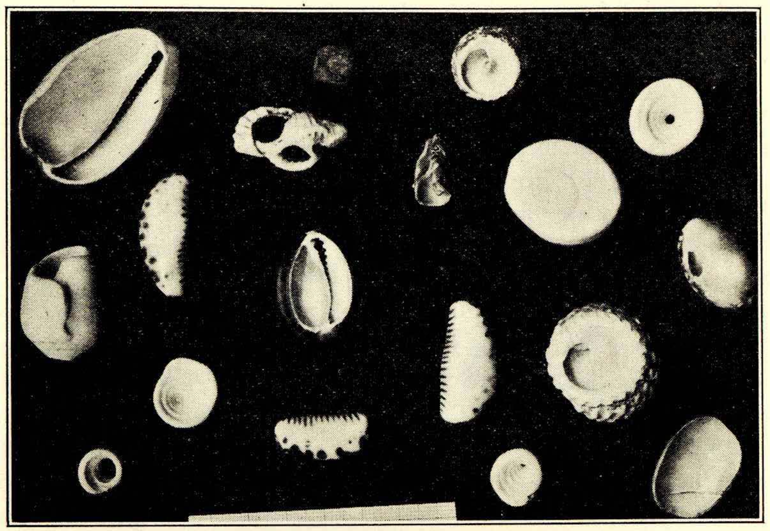

Figure 2—Typical abraded and broken shell fragments, Line Islands. Photograph by C. K. Wentworth.

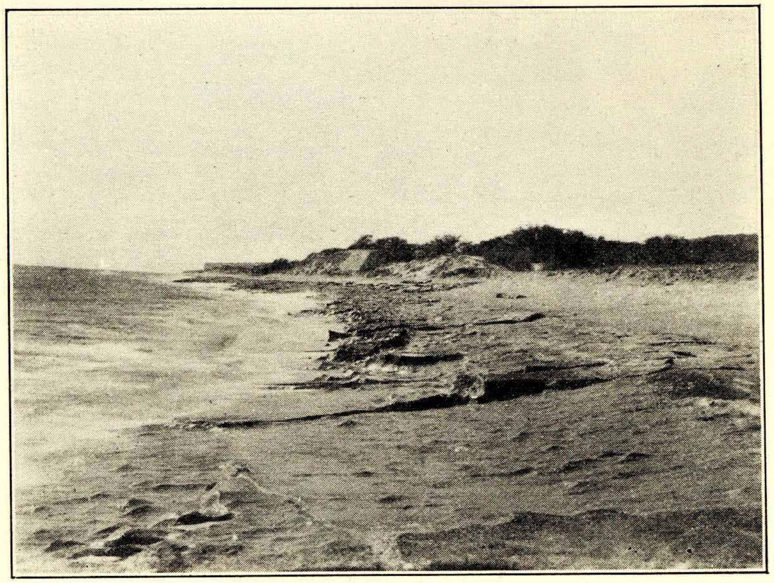

Figure 3—Lithified beach sandstone, south coast of West Molokai. Note the channeled and pitted surface of the outcrop with its sharp cuspate forms characteristic of the weathering of soluble rocks. Photograph by C. K. Wentworth.

places angular fragments of basalt are incorporated in calcareous conglomerate but hardly in sufficient amounts to constitute a breccia.

Coral rubble—There are considerable deposits of coral masses ranging from six inches to two feet in size which lie on a storm beach or are parts of an emerged beach on Fanning and other islands of the Line Group, which are so little rounded and so leached by atmospheric waters as to be distinctly a rubble. Most of the fragments are light and porous and have been differentially etched so as to be extremely rough and sharp-edged. Where the fragments have lain for long away from the action of waves they are dark gray in color.

Along the seaward margin of the broad reefs surrounding Vitilevu the most abundant coral is a species of Acropora having branches about the thickness of a man's thumb. The drab reef flats behind the marginal zone are, in many places, covered with fragments of this coral. The pieces near the seaward edge appear quite fresh but as the lagoon is approached they become smaller, more worn, and gray in color. This type of coral is very fragile compared to some of the other reef

Figure 4
Shell-bearing conglomerate at Tholo-i-suva, Vitilevu. Photograph by H. S. Ladd.

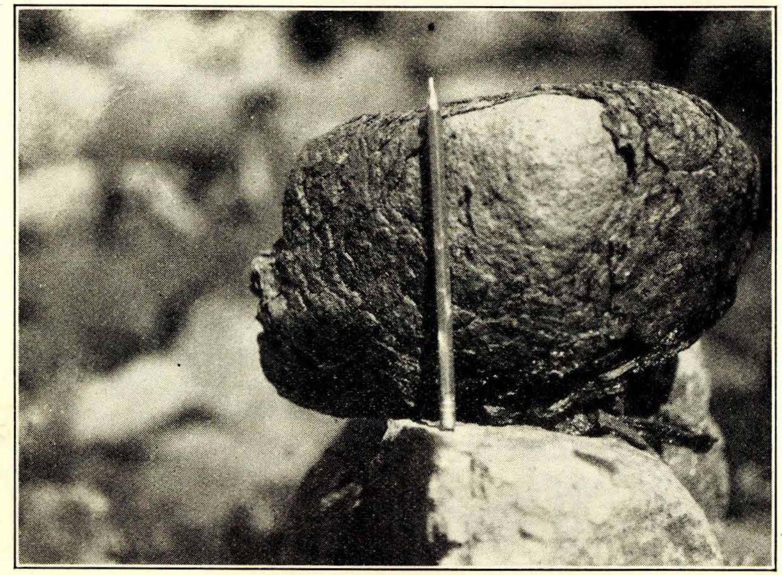

Figure 5
Exfoliated boulder of porphyritic basalt, Tholo-i-suva, Vitilevu. Photograph by H. S. Ladd.

builders and no doubt it is a very important contributor to the calcareous sands found in the tidal pools and in portions of the lagoon.

Fluvial gravel—There is no fluvial gravel in the Line Islands because there are no streams. In the Hawaiian Islands there are considerable amounts of rounded masses of basalt which are carried by streams. For the most part the rounding of these boulders has been accomplished by weathering rather than by abrasion.[12] Moreover, taking into consideration the mountainous character of much of the area, it is probable that gravel of all sizes is much less abundant and less well characterized than would be the case in a region of similar ruggedness where physical weathering rather than chemical was predominant. The abnormally rounded character of the basalt boulders is especially striking where nearly spherical boulders several feet in diameter are found in the channels of small streams or even dry gulches where their rounding by abrasion could not possibly have taken place.

[12]Wentworth, C. K., op. cit., pp. 29-30, 1926.

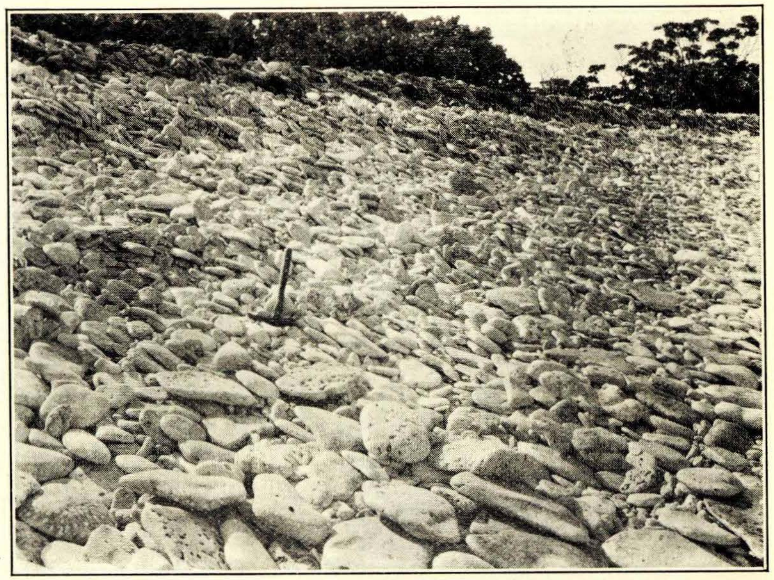

Figure 6—Beach formed of coral head gravel south of Whaler's Landing, Fanning Island, Line Group. Many if not most of the flat, disk-like cobbles have been formed by the slight shaping of slab-like coral heads. Photograph by C. K. Wentworth.

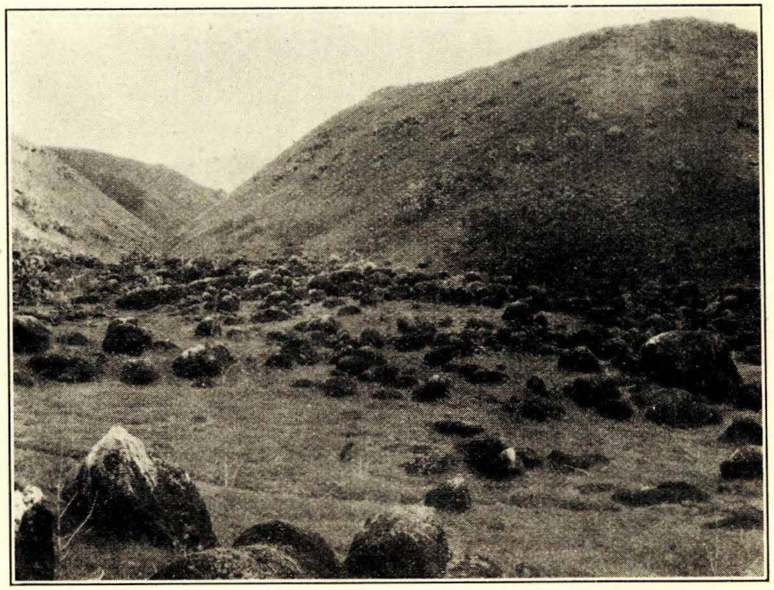

Figure 7—Rounded "boulders" of basalt produced by spheroidal weathering. Near Palawai Basin, Lanai. Photograph by C. K. Wentworth.

At various places in the vicinity of the Salt Lake craters of southeast Oahu there are deposits of old alluvial gravel associated with tuff formations. These are deeply weathered, the boulders in the main being quite soft and decomposed. The gravel has been named the Fort Shafter formation[13] and appears to be the combined work of a number of streams which drained off the Koolau Range in Pleistocene time when the sea stood higher than at present.

The major streams of Vitilevu carry much coarse material. In the high mountains where these streams rise, their channels are choked with angular masses of rock many feet in diameter. These blocks are the source of the well rounded cobbles and pebbles that form extensive bars at lower levels. For example, in the Mba river at Tonge (13 miles, in a straight line, from the river's mouth) there are bars of well rounded gravel, some of the cobbles reaching eight inches in diameter.

Beach gravel—Along the coasts most subject to wave attack in the Hawaiian Group are large quantities of basalt beach gravel in which the boulders range to several feet in diameter. Gravels in which two foot boulders are well rounded are not uncommon and in many such places the rounding is clearly due to abrasion on the beach though here as well as in the channels of streams there is room for the effect of spheroidal weathering.

At one point on the south coast of West Molokai a boulder about a foot in diameter was found in a pothole in the basalt just above tide level. Both the boulder and the pothole were almost perfectly round with respect to a vertical axis, though the boulder was somewhat oblate and the pothole somewhat more so. Evidently the boulder and the hole had developed together, through the rotation of the boulder by wave action. (Figure 8.)

At numerous places where the beach gravel is coarse and somewhat stable peculiar faceted cobbles were found which have been named chink-faceted pebbles. These have sharply localized spots, grooves, and facets produced by abrasion while they were imprisoned between larger boulders in such a way that they were free to move only to a limited extent.[14]

Around the shores of southeast Oahu gravels and conglomerates con-

[13]Wentworth, C. K., op. cit., pp. 64-68, 1926.
[14]Wentworth, C. K., Chink-faceting: A New Process of Pebble-shaping, Jour. of Geol., vol. 33, pp. 260-267, 1925.

Figure 8
Exceptionally round basalt boulder found in marine bench pot-hole but slightly larger than itself in which it was being very accurately milled to the form of an oblate spheroid. South coast of West Molokai. Photograph by C. K. Wentworth.

tain pebbles of palagonite tuff in many places and near Diamond Head are gravels whose pebbles are made from calcareous talus breccia and tuff fragments.

Along coasts in Hawaii where wave attack on the land is less vigorous and where there are extensive reef formations or old calcareous beach rocks the gravel is composed progressively more of coral and shell fragments and less of basalt. However, the most striking development of the calcareous gravels is found on the atoll islands of the Line Group.

Here they are found in great variety. Some are coarse gravels mainly composed of small boulders and large cobbles with very little sand and others are of pebbles with a considerable matrix of sand. Among the larger constituents the most important are the coral fragments, some porous and fragile and others compact and hard, according to the type. Tridacna shells, fragments of old beach rock, and the

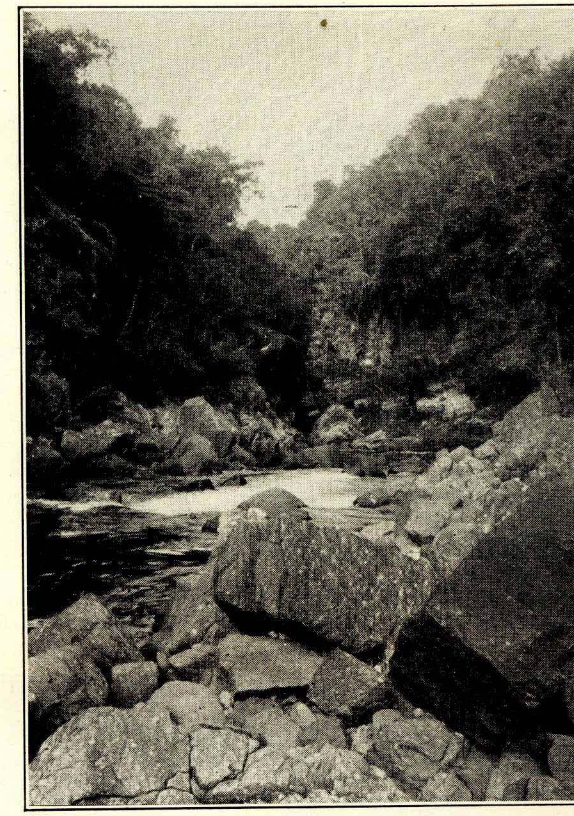

Figure 9
Fresh blocks near the end of the Navua River, Vitilevu. Material such as this furnishes the well rounded cobbles and boulders of the lower Navua. Photograph by H. S. Ladd.

shells of large gastropods are the chief very coarse materials other than coral fragments. Among the pebbles are found coral fragments, mollusk shells and fragments, the spines of large sea urchins, the opercula of gastropods, and such accidental elements as bunker coal from the wrecks of steamers. An instance of this last sort was the occurrence of well-rounded coal pebbles from 4 to 64 millimeters in diameter on the northwest beach of Jarvis Island. These had been rounded during the period from 1913, when the steamer *Amaranth*

Figure 10—Pebbles of tuff talus breccia and fragments of reef rock on a wave eroded pavement of tuff talus breccia. Shore of Oahu, south of Diamond Head. Photograph by C. K. Wentworth.

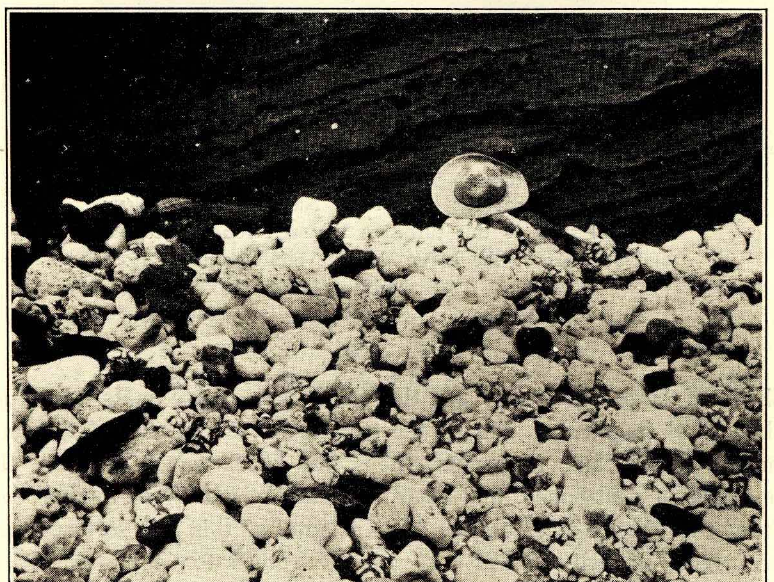

Figure 11—Coral and tuff gravel in pocket on eustatic bench, west shore of Hanauma Bay, Oahu. Photograph by C. K. Wentworth.

Figure 12
Old fluvial gravel, Aiea road west of Halawa Gulch, Oahu. Photograph by C. K. Wentworth.

was wrecked, to 1924 when the island was visited by Wentworth.* In a few places the coal had been segregated so as to form perhaps 25 per cent of the material.

Perhaps more curious is the segregation in a few localities of the opercula of gastropods so as to form 50 per cent or more of the gravel of certain narrow lenses or zones of the beach. These range from 4 to 32 millimeters in size, though smaller ones are occasionally noted in the sand grades. Among the pure types, after coral gravel, Tridacna shell gravel is probably most abundant, though enormously less than the corals in amount.

In the interior of Christmas Island, around the margins of the shallow salt lakes, which are remnants of the uplifted lagoon, are found a number of rather pure types of fine gravel. In some places these are almost wholly composed of high-spired gastropod shells ranging to about 25 millimeters in length, and in others the gravel is practically all pelecypod shells of similar size.

Of nearly all of the beach materials of these islands it may be said

*For further details see Wentworth, C. K., Pebble Wear on the Jarvis Island Beach, Washington University Studies, Science and Technology Series, No. 4, 1931.

that their composition is very variable within short distances because of the restricted character of the source material. This variability is in part influenced by the natural ecological grouping of organisms. It is also influenced by the fairly rapid rate of destruction of material in the more mobile parts of the beach and by the fact that there are but few places where the material is transported for any great distance.

Vitilevu with its protecting barrier does not exhibit such a variety of beach sediments as do the islands of the Hawaiian and Line Groups. The waves spend their force upon the barrier which is admirably constructed to withstand their attack. The seaward face of the reef is channeled and cavernous so that the impact of each wave is spread over an exceedingly large surface. Also these waves lack tools. Any fragments dislodged by the waves are jammed into crevices (and soon cemented there), or, as is more often the case, they are carried landward and come to rest on the broad reef flat, in a tidal pool or in the lagoon itself. The lagoon is really a great settling basin which eventually receives all sediments. Only in times of heavy storms are waves of any size generated on the lagoon. Furthermore, much of the shore of Vitilevu is composed of non-resistant tuffaceous marls. These yield grayish mud which mixes with the calcareous debris from the barrier and forms, on the lagoon floor, a marl high in lime content. Hence, true beaches are rare on Vitilevu. Long stretches of its coast are fringed with muddy mangrove swamps. Locally, as along the southwest coast, where the barrier becomes a fringing reef and where the shore rock is a Tertiary limestone, sediments of the types described from the Line Islands are developed. Some of these are being formed today, others have been recently lithified.[14a]

Beach conglomerate—No examples of cemented basalt beach gravels were found in Hawaii though it would be rash to assert that there are none. However, it is certain that in the main only the pure calcareous gravels or those containing a few basalt cobbles or tuff cobbles in a calcareous matrix have been indurated into conglomerate along these coasts. Masses of such conglomerate are mostly small and mostly found in places where they lie in somewhat protected places, in pockets adjacent to cliffs, and other such situations. Their occurrence in these places in the attitude of the modern beach materials suggests the possibility not only that these conglomerate remnants have been preserved

[14a]Ladd, Harry S. and Hoffmeister, Recent Negative Shift in the Strand Line in Fiji and Tonga, Jour. of Geol., vol. 35, pp. 542-556, 1927.

in these places but were more effectually formed here where the beach materials were temporarily stable and susceptible to lithification under existing modern conditions. Others have described the lithification of beach materials in parts of the tropics and have discussed the conditions under which it may take place.[15] Strongly cemented calcareous conglomerates were seen on all the islands of the Line Group and showed diversity of composition as do the gravels described above.

Tertiary conglomerates are widely developed on Vitilevu. Many of the occurrences are merely thin lenticular masses included in the main agglomerate-tuff-marl series that covers so much of the island (see pp. 35-40), but there are extensive deposits of thick conglomerate in the hills bordering much of the south coast. Two main types of conglomerate may be recognized. The first contains well rounded pebbles and cobbles of plutonic rocks as well as of volcanic rocks. The matrix may be tuffaceous or calcareous and in the latter case is highly fossiliferous. In the second type of conglomerate the pebbles are entirely volcanic and as the angularity of the pieces increases the type grades into typical agglomerate.

Medium Clastic Sediments

Eolian sand—On most of the islands visited there were shore dunes in situations where onshore winds were prevalent. These are predominantly composed of calcareous grains derived from the ocean beach. In most places the dune belt is but a fraction of a mile in width along the shore and the sand has essentially the types of sorting and rounding that have been developed on the beach. In a few places, such as the desert strip of West Molokai,[16] where the sand is blown several miles inland, it becomes progressively etched, and mingled with local terrigenous materials loses its whiteness and polish. At Manele, Lanai, a fine, speckled gray sand, composed partly of basalt fragments, is drifted across a narrow headland to reach the coast at another point. In more arid parts of the interior of various of the Hawaiian Islands the eolian sand is strewn in thin layers or low mounds on the surface and is commonly a poorly sorted material consisting mostly of irregular grains of weathered basalt or pellets of the lateritic mantle rock derived locally.

In the Line Islands beach sands are carried inland by the wind in

[15]Daly, R. A., The Geology of American Samoa, Carnegie Institution of Washington, Pub. 340, pp. 135-140, 1924.
[16]Wentworth, C. K., op. cit.

various places and commonly form the highest parts of these islands, dunes reaching elevations of fifty feet or more above sea level on Christmas Island. In places considerable amounts of lag gravel are concentrated on the upper part of the beach where the material is placed by wave action but from which the finer grains are removed by the wind.

Only one extensive area of siliceous sand was seen in the islands visited. This was on Vitilevu where such a sand forms a well developed belt of dunes along the coast to the west of the mouth of the Singatoka river. The belt is more than two miles long and is one-quarter of a mile in width. Impelled by the prevailing southeast trades the dunes are traveling to the northwest. One at least reaches a height of one hundred and fifty feet but most of them are flat-topped at about the one hundred and thirty foot level. As Foye has pointed out[17] the Singatoka river drains an area of crystalline rocks and much quartz sand is brought to the sea. However, it is also possible that much of the sand is swept along the coast from the area to the east where extensive outcrops of granite occur near the coast. Numerous small streams erode this granite and carry siliceous sand to the sea. This is a windward coast and the reef is fringing and narrow so that wave transportation is unusually effective.

Cemented eolian sands are not uncommon around the shores of Hawaii, especially southeast of Diamond Head and at Kahuku Point on Oahu and at Moomomi Beach on the north coast of West Molokai. In some places these eolian sandstones merge almost imperceptibly into beach sandstones just as such material merges around the modern shore.

Fluvial sand—Fluvial sand, even more than fluvial gravel, is a very poorly characterized material in the Hawaiian Islands. It contains fragments of weathered basalt, fragments of olivine and augite, and in a few places other minerals. Neither the length of the streams nor the durability of the constituent materials permit the thorough sorting and rounding necessary to produce somewhat homogenous or selected material. In the main the grains are irregular and angular and contain pebbles and silty and clayey admixtures. Adjacent to some of the pyroclastic craters of Oahu the sands in dry rill channels carry a large percentage of olivine grains, potential phenocrysts separated from the basaltic magma without weathering during explosive eruptions.

[17]Foye, Wilbur G., Geological Observations in Fiji, Proc. Amer. Acad. Arts and Sci., vol. 54, No. 1, p. 14, 1918.

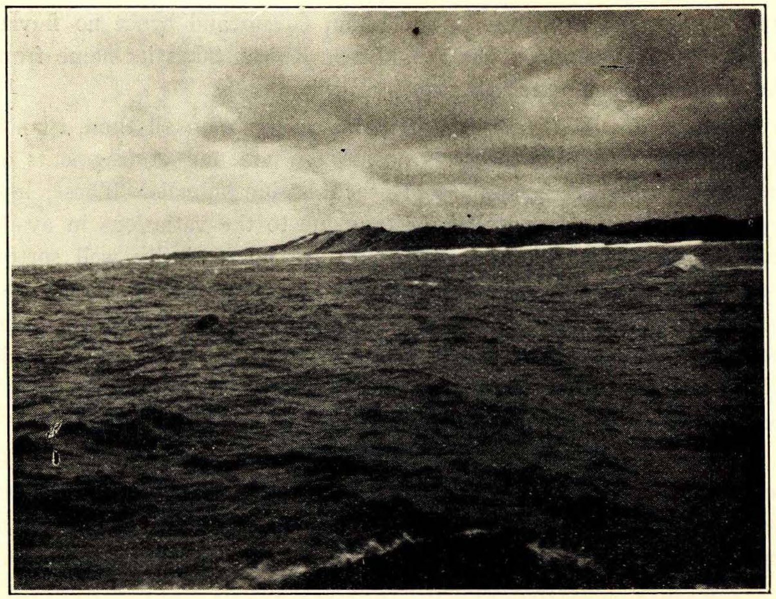

Figure 13
Sand dunes west of the mouth of the Singatoka River, Vitilevu. This is the only large area of silicious sand seen in the islands visited. Photograph by H. S. Ladd.

In one place fluvial sand carrying much magnetite from the same source was found. A large percentage of these grains are euhedral and they have suffered very little abrasion. In some of these sands augite forms a smaller proportion of the whole, placed in the same way and also euhedral. Though rare in Hawaii due to the quantitative unimportance of pyroclastic action such augite is quite common in Fiji. The crystals in the original agglomerate are fresh and suffer but little alteration when reworked. In some localities as, for example, south of Levuka on the island of Ovalau the crystals in the agglomerate are perfect and exceed one-fourth of an inch in diameter. During the eruption which produced this rock there must have been literally showers of augite crystals.

There are localities where beach sand is blown inland by the wind and lodges in the valleys of streams where it then becomes a part of the stream load but these occurrences are quantitatively unimportant. There is scarcely any true fluvial action on the Line Islands and on the smaller islands of the Fijian Group and hence no fluvial sands. In Vitilevu the "Wailoa" (Black River) takes its name from the magnetite sand found so abundantly in its bed.

Beach sands—The most abundant beach sands on all these islands are those composed of the tests of foraminifera and of fragments of the shells of mollusks, corals, and other marine animals. These, like the beach gravels, vary in composition due to the variations in available debris. As a rule, however, they are mechanically well sorted (see figures 16 and 19) and many are notably well rounded and smoothed. There are considerable differences in the porosity of the grains, the gastropod debris in general being solid while the foraminiferal tests are hollow and therefore much lighter than most of the shell fragments.

In the Line Islands and in many of the smaller islands of the southwest Pacific the beach sand is exclusively of the organic varieties mentioned above. In Hawaii along the more rocky coasts there is a considerable admixture of terrigenous debris derived by wave action

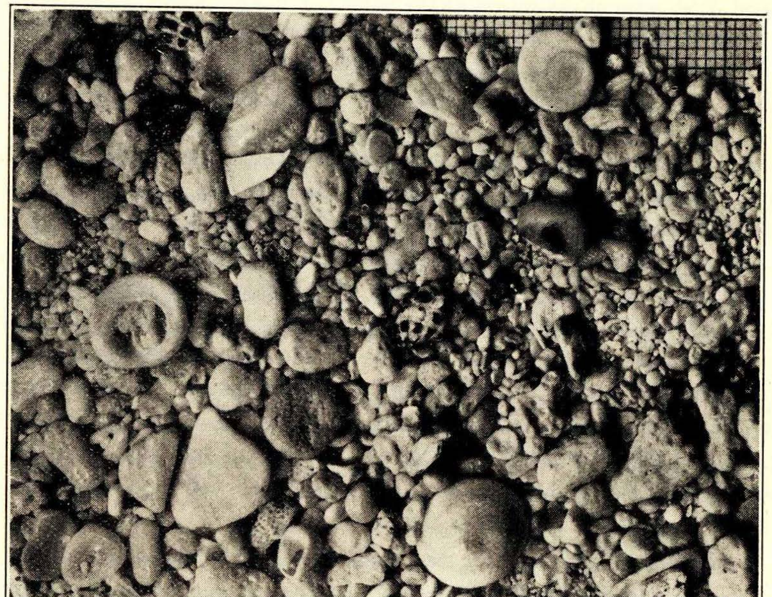

Figure 14
Fine beach gravel and coarse sand, Christmas Island.

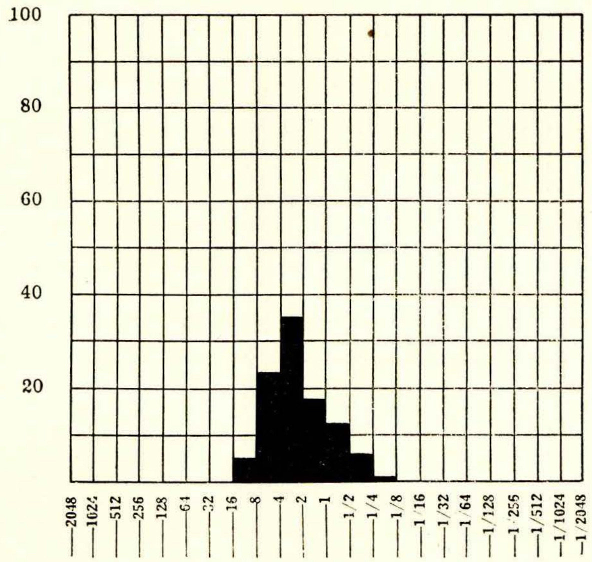

Figure 15—Diagram showing mechanical composition of beach gravel from west shore of Christmas Island south of Paris. Considerable lag material which had been winnowed by the wind was included in this material and accounts for the poor sorting. This gravel consists wholly of organic debris, largely coral fragments, gastropod shells and foraminifera. Sizes shown in millimeters. Sample No. 2553-B.

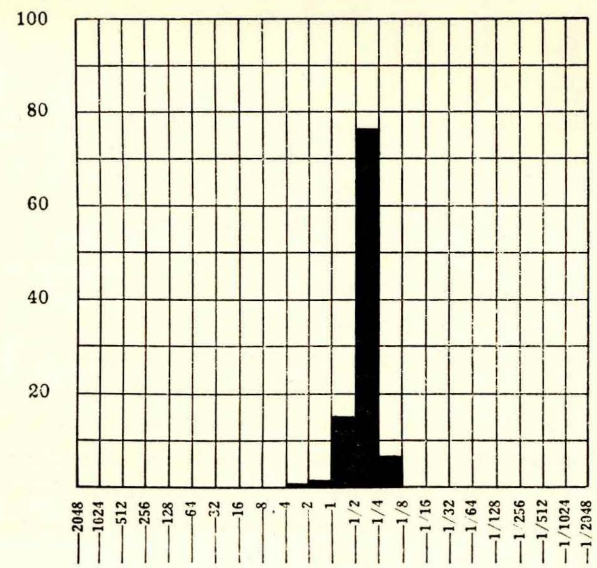

Figure 16—Diagram showing mechanical composition of beach sand from west shore of Christmas Island north of London. This is an average sample of calcareous beach sand from these islands. Sample No. 2538.

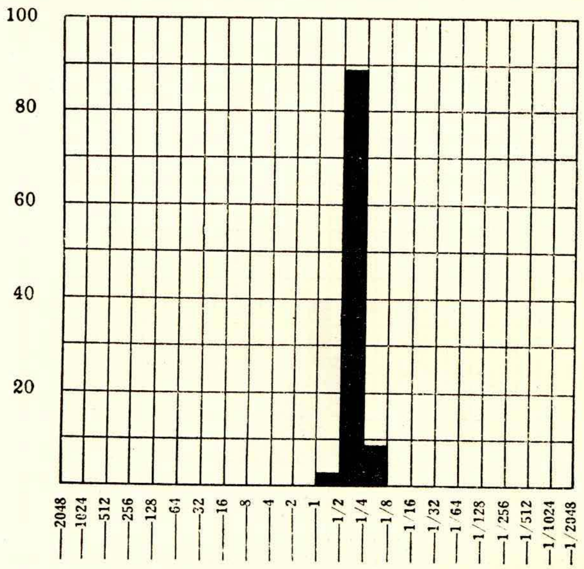

Figure 17

Diagram showing mechanical composition of olivine beach sand. From the shore southeast of Diamond Head, Oahu. Over ninety-nine per cent of this sand has a density over 2.73. Sample No. 21-B.

from the cliffs. In most of these places the terrigenous element consists of fragments of somewhat weathered basalt which are less well sorted and rounded than the organic fraction. Adjacent to the secondary craters of Oahu there are small accumulations of olivine sand with occasionally smaller amounts of augite which have been blown out in the course of pyroclastic eruptions and segregated by wave action. In some places olivine forms as high as 97 per cent of natural deposits.

Deposits high in olivine also occur in a few localities on Vitilevu. One such is to be found on the northeast coast one and a half miles north of Navalou. There a bank of olivine sand ten feet in width and lying just below high tide mark parallels the coast for a considerable distance. Some of the material has been carried inland above high tide mark by wind and storm waves. The country rock in the vicinity is a diabase high in olivine.

On the south coast of Molokai at one point small quantities of

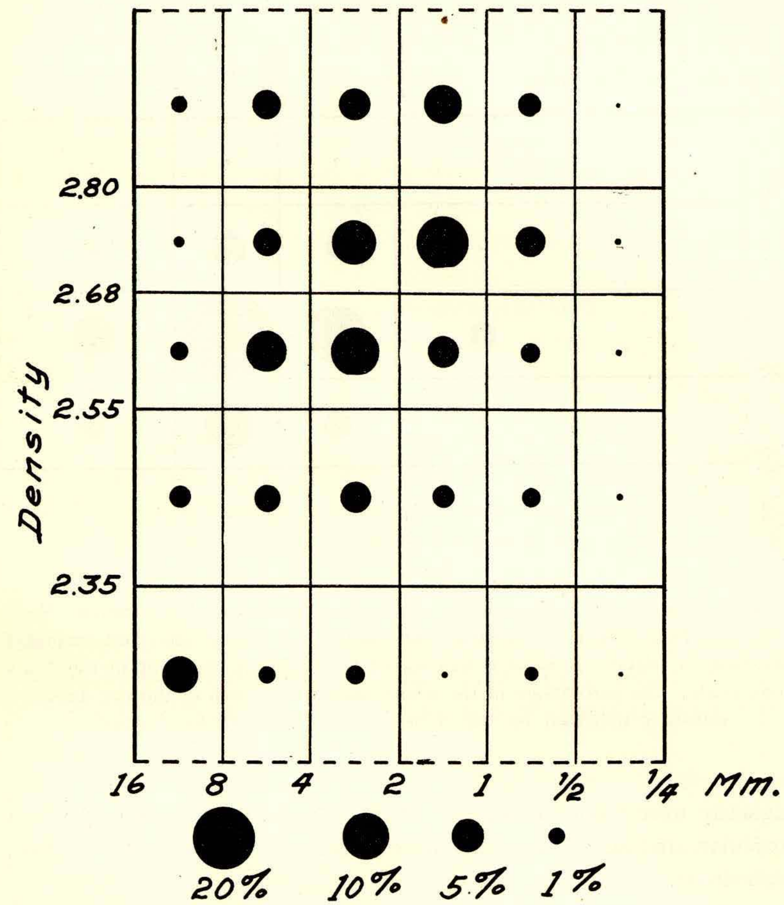

Figure 18

Diagram showing the size-density composition of gravel sample No. 2555-O. This gravel was collected from the upper surface of the beach on the west shore of Christmas Island about one-half mile south of Paris. It is only moderately well sorted, about 80 per cent of the material being distributed nearly evenly from 1 to 8 millimeters. Heavy liquid separations were made at densities 2.35, 2.55, 2.68 and 2.80 taking the material in its natural state and without boiling or other treatment to drive out air. The percentages of the whole contained in each of the size-density classes is indicated by the circles, the areas being proportional to the percentages.

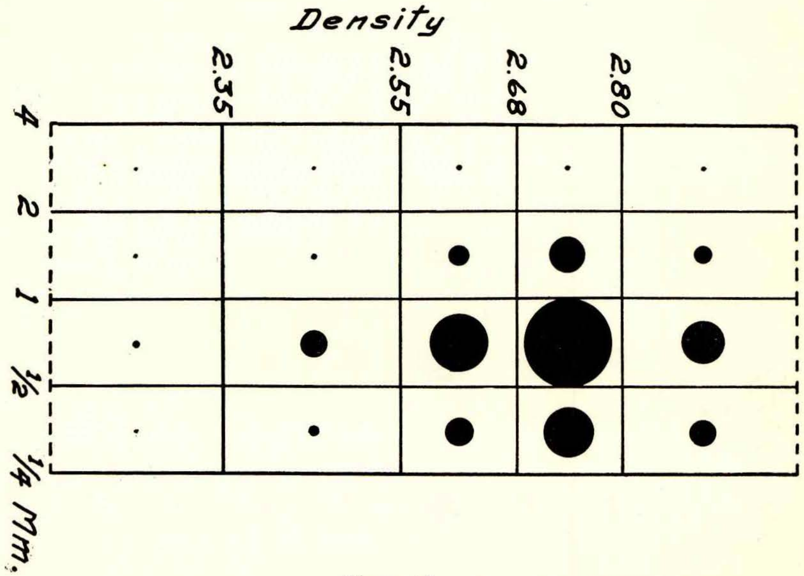

Figure 19

Diagram showing the size-density composition of coarse sand sample No. 2572-A. This sand was collected from the high beach at the west end of Washington Island. It is very well sorted with over 70 per cent in the 1½ mm. grade. The percentages of the whole contained in each of the size-density classes is indicated by the circles. (See Figure 18 for legend.)

magnetite were found segregated by the waves from the alluvium of a particular stream. The grains were mostly crude, somewhat etched, octahedrons.

Perhaps the most interesting sand in the Hawaiian Group is a type found at several points along the north coast of East Molokai. This is derived by the very vigorous wave attack and milling of gravel which takes place along this steep and rocky coast and is more nearly the product of abrasion alone than any of the sands seen by the writers elsewhere in Hawaii. It consists largely of angular and slightly rounded, unweathered grains from the basalt of the cliffs. The principal constituents are basalt fragments, shell fragments and olivine, augite, plagioclase (andesine to labradorite), and small amounts of sideromelane and palagonite.

Beach sandstone—Indurated sediments similar to the sands named above are found in a few places in the Hawaiian Group. Calcareous

sandstone has in some instances been used locally for building purposes. Sandstone of this type containing olivine crystal grains from the pyroclastic rocks is found around the shores of southeast Oahu. One of the most interesting beach sandstones noted in Hawaii was found east of Manele on the island of Lanai and consisted of basalt fragments averaging around a millimeter in diameter. The basalt grains constitute so large a fraction of the whole that the rock closely resembles a medium gray basalt and is distinguished from such only on close scrutiny.

Calcareous sandstones showing considerable variety of composition are found in the uplifted and modern beaches of the Line Islands.

Fine Clastic Sediments

Eolian silt—On the more arid parts of islands of the Hawaiian Group there are considerable amounts of silty material which has been deposited by the wind in layers from a few inches to several feet in thickness. This material consists mostly of weathered basalt fragments and ferruginous grains from the lateritic soils. East of Hanauma Bay on Oahu a few small remnants of loess-like silt containing bird bones were observed. The material had been derived chiefly from the tuff along the adjacent coast and it seems probable that it may be a few hundred years old. The maximum thickness is three or four feet.

Fluvial silt—A large fraction of the alluvium of the Hawaiian Group is of silty texture, though commonly it carries some coarser material. In the lower courses of the larger streams considerable aggradation has taken place in which silt is the common constituent but in which there is considerable coarser talus and colluvial material. Along such coasts as the south coast of Molokai and the northeast coast of Lanai where there are moderate or large amounts of rain but where wave action is moderate there are considerable alluvial accumulations at the mouths of streams which merge to form an alluvial plain marginal to the coast. Such material consists in part of gravel, with subordinate and poorly sorted sand, and considerable silt. From the amount of such accumulation around the bases of the kiawe trees (a mesquite) which were first introduced in 1837 we may conclude that deposition is somewhat rapid.[17a]

Most of the major streams of Vitilevu are building deltas, especially

[17a]Wentworth, C. K., Geology of Lanai Bishop Museum, Bulletin 24, p. 30, 1925.

those streams which drain extensive areas of marls and tuffs. The Rewa, whose basin includes about one-third of the island, is depositing large quantities of silt. The Mba, on the opposite side of the island, is depositing similar material. Thousands of acres on these delta flats are heavily overgrown by mangroves and creepers. The Singatoka and Navua, also major streams, carry a much higher percentage of sand. The Singatoka has not built a delta but much of the material which it brings to the coast has been built into sand dunes.

Marine silt and clay—In the Hawaiian and Line Groups little is known of fine grained, off-shore materials. In the bays and sheltered parts of the coast of Hawaii much fine grained terrigenous debris is laid down but this is of substantially the same character as the material described above. In the Pearl Harbor district of Oahu considerable amounts of fine grained ash from secondary eruptions has fallen or been carried into the sea at various times and formed buff-brown clayey strata which are interbedded with coral reef masses. Washed tuff formations, both marine and fluvial, are also known in other districts of Hawaii but they have not been studied in detail.

At Fanning, Christmas, and Palmyra Islands large amounts of fine and medium grained calcareous debris from the outer shore is carried by currents through breaches in the atoll rim and strewn over the floor of the lagoon which thus tends to become aggraded practically up to the level of mean tide. The deposition of this material as well as the lack of new sea water are factors which tend to reduce the growth of corals and other reef making organisms inside the lagoon.

Pyroclastic Sediments

Rocks of this type are exceedingly abundant in certain island groups, though quantitatively unimportant in others. In general it seems that pyroclastic action has played a much more important role in the tropical islands of the southwest Pacific than it has in the Hawaiian Islands of the north Pacific.[18] On the island of Vitilevu in Fiji, pyroclastic action has, in later geologic times, dominated all other forms of volcanic activity. During Tertiary times, and possibly even later, tremendous quantities of volcanic agglomerate were thrown out of what appear to have been more or less linear volcanic vents, or lines of individual volcanic vents. These eruptions resulted in the high

[18]Hoffmeister, J. Edward, Ladd, H. S. and Alling, H. L., Falcon Island, Amer. Jour. Sci., vol. XVIII, pp. 461-471, 1929.

mountain ranges which now traverse the islands in many directions and are composed almost exclusively of agglomerate. These agglomerates form the *parent rock* of most of Vitilevu's sediments. Genetically associated with the agglomerates are great thicknesses of tuffs and somewhat marly beds, the whole forming what may be termed the agglomerate-tuff-marl series. Outcrops of rocks belonging to this series are found from sea level to elevations of over 4,000 feet and form the surface rock over most of the island.

The typical agglomerates are made up of sharply angular blocks of glassy basalt or porphyritic basalt embedded in a tuffaceous matrix. This matrix may be coarse or fine. In at least one locality angular fragments of granite are included in the agglomerate. The angular blocks in many places measure two to three feet in diameter, elsewhere they are smaller and as they decrease in size the rock grades into tuff. Many of the agglomerates appear to have been deposited close to the centers of eruption and show no indications of sorting. Others contain marine fossils and exhibit rude or well developed bedding planes. In many exposures the blocks are concentrated at certain levels though the rock shows no other evidence of stratification. As the angularity of the blocks decreases these rocks pass into conglomerates. These relations are shown in figure 23.

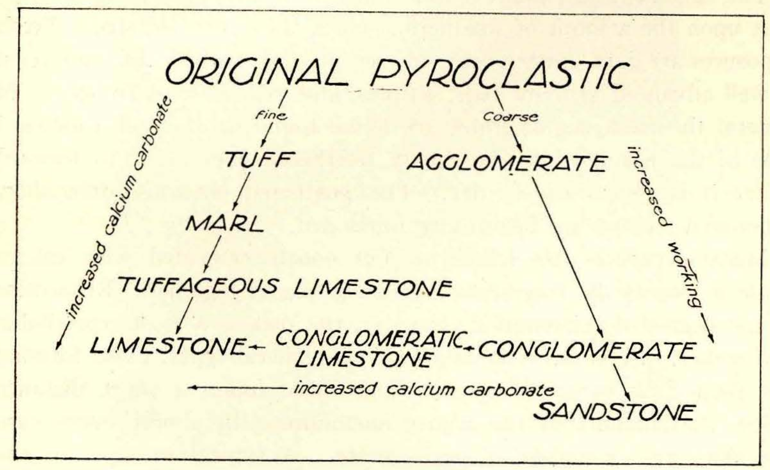

Figure 20

Diagram showing relationship of pyroclastic rocks to various other original and derivative rocks on Vitilevu.

Figure 21
Cliff of agglomerate, Lami River, Vitilevu. Almost without exception the cliffs on Vitilevu are formed of this type of rock. Photograph by H. S. Ladd.

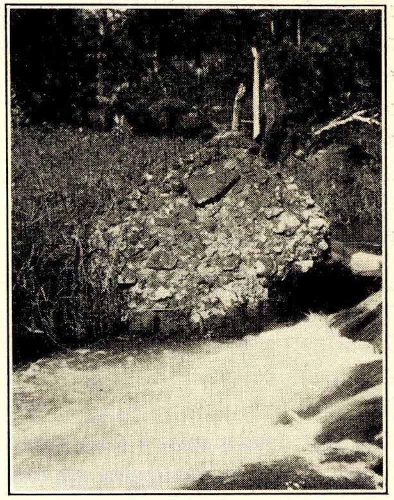

Figure 22
Detail of agglomerate boulder showing angularity of the fragments. Near Numbumakita, Vitilevu. Photograph by H. S. Ladd.

The agglomerates exhibit a wide range of colors, depending in large part upon the amount of weathering which they have suffered. Fresh exposures are dark gray, brown, or even black but where decomposition is well advanced brilliant reds, purples, and yellows may be seen. In general the fresh agglomerates are to be found on the wet windward side of the island while the deeply weathered ones occur to leeward where it is comparatively dry. The weathered outcrops often show spheroidal weathering beautifully developed.

Many exposures are friable or but poorly cemented with calcite while in others the fragments are firmly bound together. Regardless of the degree of cementation, however, the rock is a most remarkable cliff-maker. Cliffs on Vitilevu are of two general types, those forming the immediate banks of streams and those found a short distance below the summits of the higher mountains. In almost every case the cliffs are composed of agglomerate. A typical example of the first type is shown in figure 21. Many of the streams whose valleys exhibit such cliffs are surprisingly small.

In a number of widely separated localities the agglomerates contain

scattered coral heads. Almost invariably these are the heads of Porites, a common reef builder, and many of them show evidence of transportation. In cases where such evidence is lacking the corals may represent portions of an ancient reef destroyed by the eruption which furnished the volcanic material of the agglomerate. In the Mba district there are poorly bedded agglomerates consisting of angular and subangular blocks in a matrix of coarse tuff. The blocks range in size to a foot in diameter yet in between them may be found well preserved shells of mollusks. It is surprising to find such shells as Rostellaria with their delicate processes preserved perfectly in such a rock. Corals also occur in this agglomerate.

The tuffs of Vitilevu are gray, drab, green, or chocolate brown in color and of variable texture. In the more typical examples the frag-

Figure 23
Conglomerate near Rewasau, Vitilevu, containing both limestone and igneous pebbles. Photograph by H. S. Ladd.

ments composing them range in size up to two millimeters in diameter. These fragments commonly include broken feldspars, volcanic glass, some of which is palagonitized, and crystals of augite. Many are stained with limonite. Most of them are loosely consolidated, the commonest cementing substance being calcite. Gentle dips and uniform bedding together with the widespread occurrence of foraminifera and other shells indicate that most of the tuffs and many of the agglomerates are marine.

Over large areas the tuffs have been reworked by streams and waves before coming finally to rest. During this process much clay, from the weathered volcanics, and much calcareous shelly material was added so that many of the rocks may now be classed as marls. A number of the mollusk-bearing marls were deposited in shallow water but other horizons, judging from the foraminifera, were laid down in water which probably approached, or even exceeded, 200 fathoms. One locality of the latter type has yielded 95 species of smaller foraminifera.[19]

Plant remains, in the form of lignite seams, impressions of leaves and stems, and indistinct carbonaceous films, are found at many horizons in the marls and tuffs. Where exceptionally well preserved these probably indicate deposition close to shore.

These three rock types—the agglomerates, tuffs, and marls—form an unbroken series. Doubtless some of the tuffs which show unusually high dips and no marine fossils are the landward equivalents of the more level-bedded shell-bearing tuffs and marls but considered as a whole the series is marine.

In Hawaii coarse pyroclastic rocks are only developed locally in small quantities.[20] There is an almost imperceptible gradation between flow lava and black ash commencing with the minor sputter cones where irregular twisted gobs of lava are spattered around the vent, through the more explosive coarse agglomerate cones and thence to the craters formed of finer grained, more completely atomized material. In the case of some of the craters, twisted, spun bombs have been formed of juvenile lava, but in most of the craters of southeast Oahu there have been no essential bombs of this type. For the most

[19]Dr. Joseph A. Cushman has completed a report upon the smaller foraminifera of Vitilevu, describing material collected by Ladd. This will appear as a section of a general report upon the geology and paleontology of Vitilevu.

[20]For a general description of the pyroclastic rocks of southeast Oahu see Wentworth, C. K., op. cit. 1926.

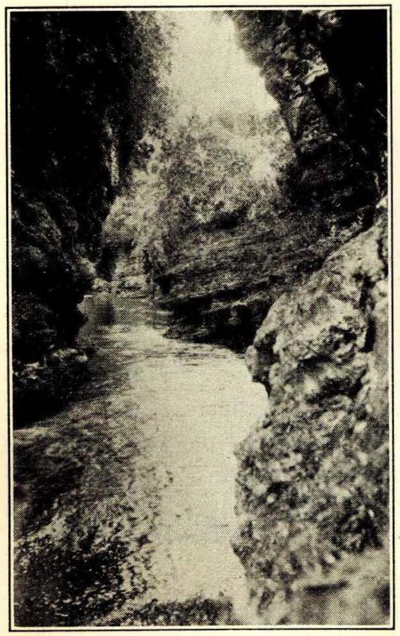

Figure 24
Marls and conglomerates in the gorge of the upper Navua River, Vitilevu. Photograph by H. S. Ladd.

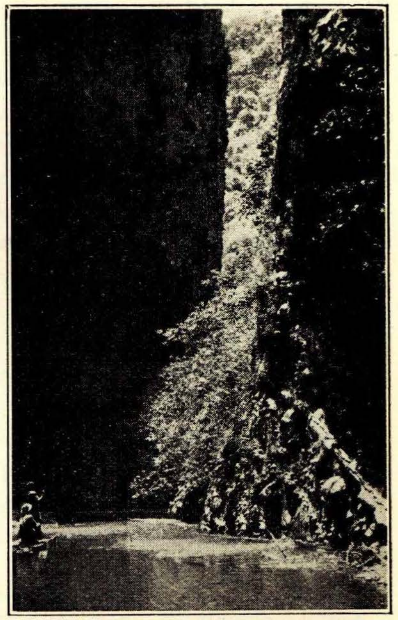

Figure 25
The steep-walled gorge of the Wainga River, Vitilevu. The rock is agglomerate and dipping upstream at this point. Photograph by C. R. Harley-Nott.

part the larger bombs of this district are merely blocks of lava or of reef rock torn from the walls of the vent. In a number of localities in Vitilevu, as well as on Oahu, blocks of this type are very abundant.

Of the finer grained pyroclastic materials there are two chief types in the Hawaiian Islands. One is the so-called black ash which consists of small pellets, droplets, etc., of vesicular basaltic glass, or sideromelane which is commonly more or less altered, at least on thin edges, to palagonite. Large parts of the ash of this type which has been deposited in the secondary eruptions of southeast Oahu have been almost completely palagonitized to form the buff to red-brown tuff. This material has been described in detail elsewhere.[21] The other type of finer grained material is that of the 1924 explosive eruption of Kilauea which consists of triturated rock dust and larger particles

[21]Wentworth, C. K., op. cit. 1926.

from the walls of the crater. So far as known there was not a particle of juvenile lava or essential volcanic material thrown out during this eruption. The dust consists of basalt fragments, grains of olivine, and other minerals found in the basalt.

In the eruption of 1789 there were considerable amounts of pumice expelled, though in this eruption, as well as that of 1924, the dominant material was broken rock from the walls of the vent.

Pumice is one of the commonest materials to be found on the beaches in Fiji and Tonga. There is invariably a line or ridge of well rounded pieces of pumice at the line of highest tide. In many localities it litters the short flats several feet above the reach of ordinary waves. Most of the pieces are one-half inch in diameter. A few reach two inches. Much of the material seen in Fiji probably originated in Tonga where there are several active volcanoes, some of which are submarine. The drift is from Tonga to Fiji. From time to time ships arriving in Fiji report extensive areas of floating pumice in the waters to windward.

Chemical Sediments

Small amounts of chemically deposited sediments of various sorts are widespread in these islands. Calcium carbonate in the form of cement or of vein filling is most abundant though no particularly notable deposits were seen. On drier parts of the Line Islands, notably Christmas Island, the evaporation of ground water brought to the surface by capillary action results in a crust a half inch or more in thickness formed of precipitated salts, largely calcium carbonate. On certain islands where sea birds nest, their droppings add nitrogenous and phosphatic constituents which in course of time are carried downward into the rocks by leaching and redeposition.

The only quartz seen in the Hawaiian Group was contained in certain amygdules exposed deep in the valley of Pelekunu stream on East Molokai.

Organic Sediments

By far the most important organic sediments now being formed in the area here described are the "coral" reefs themselves. Debris worn from these structures is contributed in large quantities to the sands and other calcareous deposits previously mentioned. The most important organic sediments of the past are the uplifted reefs and other organic limestones which have been formed at various times from the Tertiary to the present day. Other types of organic deposits,

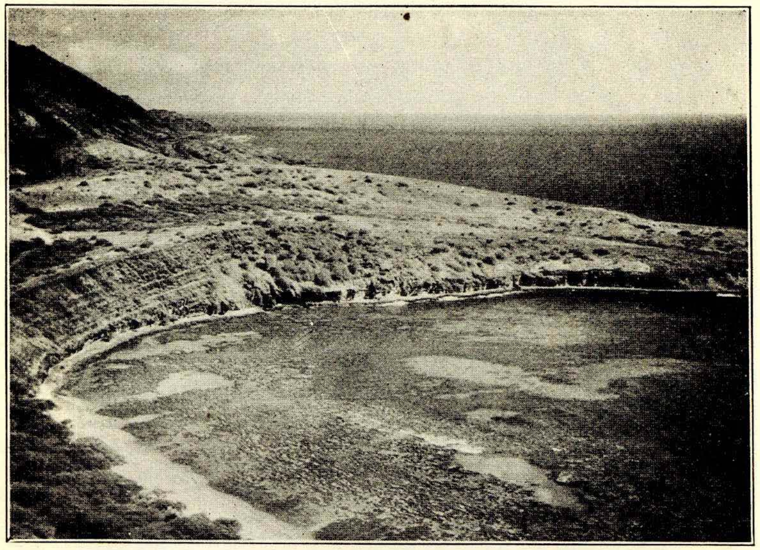

Figure 26

Fringing coral reef under water in Hanauma Bay, Oahu. Light areas are gaps in the reef which are paved with coral sand. These pools are three to fifteen feet deep; the reef is just awash at low tide. Photograph by C. K. Wentworth.

such as modern peat and Tertiary lignite, are known but are much less important quantitatively.

Modern coral reefs are fairly well developed around a number of the Hawaiian Islands, particularly around the island of Oahu. These reefs are of the fringing type. Around many of the Fijian Islands, including Vitilevu, the barrier reef is the common type. Christmas Island in the Line Group is a broad atoll. The explanation of these differences—of Oahu's fringing platform, Vitilevu's off-shore barrier, and Christmas Island's broad reef flat and shallow lagoon—involves the entire coral reef problem and can hardly be considered here. But it is obvious that whether or not an island has a reef or, having one, whether the reef be fringing or barrier will be a factor of very great importance in determining the kinds and amounts of sediments which will be formed. Thus, in the case of Vitilevu, the presence of a barrier reef curtails marine erosion much more effectively than would a simple fringing platform. Consequently, the explanation of many

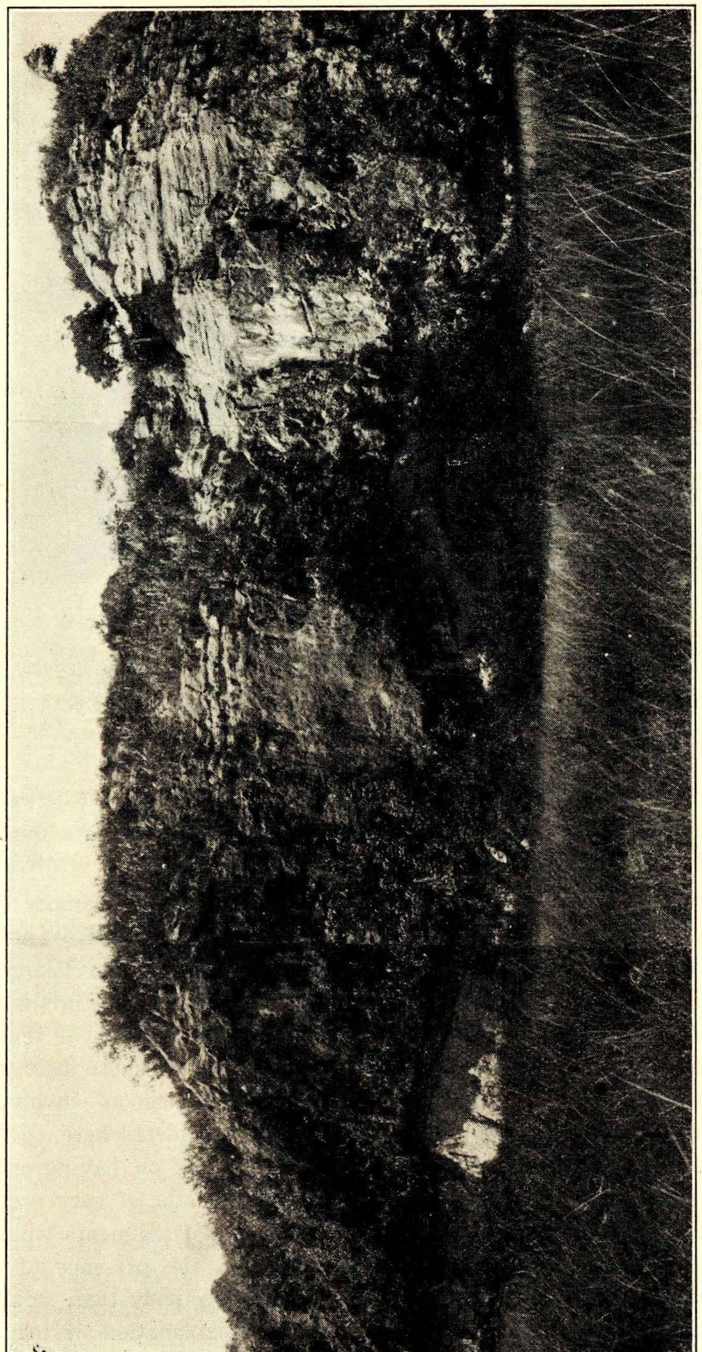

Figure 27.—Elevated Tertiary "coral reef" exposed in an abandoned quarry on Walu Bay, Vitilevu. The limestone is a lenticular mass with a maximum exposed thickness of thirty feet. Portions of the rock are coralliferous but most of it is made up of foraminifera. Bedded marls can be seen outcropping above and below. The exposure has been cut by several small block faults. Photograph by H. S. Ladd.

of the differences between the recent sediments of Vitilevu and those of Oahu is to be found in the reefs surrounding these islands, a barrier in the one case and a fringing in the other.

The coral reefs of Oahu have been described in some detail by Pollock.[22] He estimates the present fringing reef to be the product of growth during the past 5,000 years at a rate of approximately one foot in three hundred years. As in the case of most such reefs he finds that corals do not predominate but are exceeded quantitatively by the lime-secreting algae. Ancient reefs around Oahu show somewhat similar relations. Ostergaard[23] has studied the fossil mollusks contained in these elevated limestones. Out of 82 species and varieties identified only three are now extinct and he concludes that these rocks are not older than Pleistocene. It is probable that reefs adjacent to other islands of the Hawaiian Group are similar to those of Oahu

[22]Pollock, J. B., Fringing and Fossil Coral Reefs of Oahu, Bishop Museum Bulletin 55, 1928.

[23]Ostergaard, J. M., Fossil Marine Mollusks of Oahu, Bishop Museum Bulletin 51, 1928.

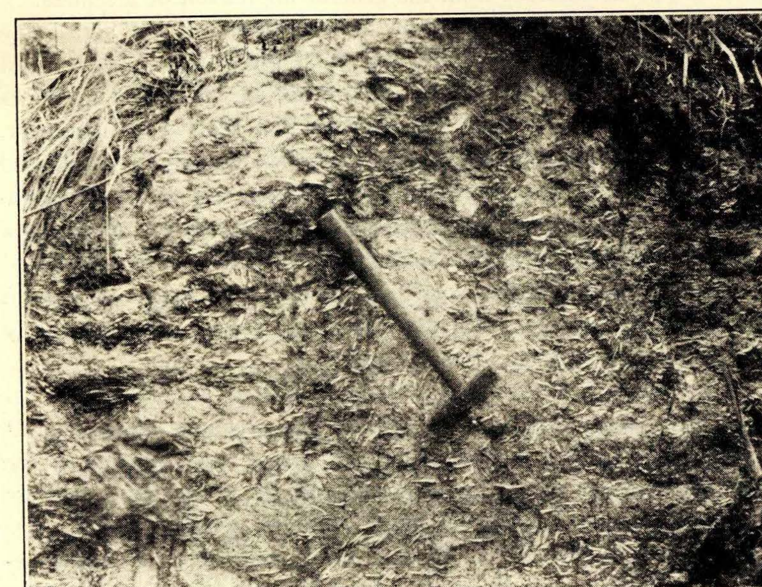

Figure 28

Elevated limestone composed almost entirely of unusually large foraminifera. Kalambu, Vitilevu. Photograph by C. R. Harley-Nott.

though no other island has such a development of reefs as does Oahu.

The shores of Vitilevu are well protected by reefs. In most places, as previously mentioned, the reef is a barrier but in others it swings toward the land and becomes a fringing reef. These reefs exhibit great diversity in size, configuration, and constitution. Apparently also they have originated and developed in diverse ways. They appear to be comparatively young structures. They have been studied in a number of places.[24] They are broad flats which are, for the most part, easily accessible at low tide. The average width of the exposed flat exceeds one-half mile and in a few places the width is more than twice as great. The surf breaks heavily on the projecting seaward edge and pours over the marginal zone which is not defended by a distinct Lithothamnion ridge. Colonies of living corals are often abundant near the seaward border and in the tidal pools elsewhere. They make a strikingly beautiful sight but the reef as a whole impresses one as a drab and featureless plain whose monotonously level surface is occasionally broken by large blocks of blackened coral or by hummocks of finer reef debris. The tidal pool depressions, nearly filled with water, do not detract from the general impression of levelness.

In spite of much local variation a generalized section across the surface of the reef can be constructed which will hold for most, if not all, of the reefs of the island. In such a section the following zones occur, beginning at the seaward edge of the reef: (1) a narrow, flattish marginal zone where living corals are usually accompanied by calcareous algae, (2) a broader zone where Acropora is the dominant coral, (3) a zone where Porites replaces Acropora, and (4) a broad flat scored by echinoid borings or silted over with sand and coarser reef debris. Other zones of living corals occur in certain sections. In general there is a fair variety of living corals but rarely do the colonies cover large areas of the reef.

Like the modern reefs of Vitilevu the uplifted limestones of that island are by no means built entirely of the skeletons of corals. It is difficult to say how important a part corals have played in the past in the building of the reefs which now lie at sea level, because only the surface is available for study. At the present time the role of the corals is unimportant. In any event when the elevated limestones of Vitilevu are considered all honors must go to the foraminifera. A limestone formation totaling several hundreds of feet in thickness

[24]In this work the junior author had the active collaboration of Doctor J. Edward Hoffmeister.

outcrops widely in the interior of the island and in most outcrops the remains of foraminifera are exceedingly abundant. At only one locality was an undoubted fragment of a coral to be found. In some of the coastal limestones, such as that shown in figure 27 the corals are more abundant but even here the reef grades laterally into beds composed almost entirely of foraminifera.

The foraminiferal limestones of the interior are remarkably pure and apparently were formed during a period free from volcanic activity. The coastal limestones, on the other hand, often show a high percentage of foreign material. Some are tuffaceous and others are conglomeratic, in fact these limestones grade imperceptibly into tuffs, in some cases, and into conglomerates in others.

The interior limestones reach great thicknesses and are spread widely over the island while the coastal limestones are usually relatively thin lenticular masses included in the marl series. Both types contain numerous caves. The coastal limestone is a soft and porous rock while the limestone of the interior is dense and hard, its outcrops being fantastically carved into knife-edged pinnacles.

As is often the case the modern reefs of Vitilevu are best developed along the windward coasts. It is interesting to note that the elevated coastal limestones are likewise best developed in this area.

Among the organic sediments of the Line Islands one of the most notable is the peat of Washington Island which has been formed by the accumulation of vegetation growing adjacent to the fresh water lake which was formed at the time of the recent eustatic shift of sea level.[25] The peat deposits have been described by Christophersen.[26]

Seams of lignite occur at a number of horizons in the tuffs and marls of Vitilevu and many of the bedding planes of these rocks show fragmentary plant remains in the form of carbonaceous films. In a few places stems, root casts, and sections of carbonized logs occur in association with a fauna of marine shallow water mollusks. Dr. W. A. Setchell has examined some of this material and suggests[27] that it is an old mangrove formation, the trees being possibly the same as one of the species of mangroves living in Fiji today.

[25]Wentworth, C. K. and Palmer, H. S., Eustatic Bench of Islands of the North Pacific, Geol. Soc. Amer. Bull., Vol. 36, pp. 521-544, 1925.

[26]Christophersen, Erling, Vegetation of Pacific Equatorial Islands, Bishop Museum Bulletin No. 44, 1927.

[27]Setchell, W. A., written communication, Nov. 14, 1928.

CONCLUSION

In the variety of sedimentary materials which has been described and commented upon thus briefly in the foregoing pages, one sees the products of certain combinations of *Parent, Agent,* and *Stage.* Parent formations include basic effusive and pyroclastic rocks, sea-water and the hard parts of marine organisms, the continental rocks of Fiji, and the plants of Washington Island. Only the first of these occurs over large areas in the interior of any island; the others, by their very restricted and specialized distribution, give a provincial character to the derivative sediments.

A number of the common agents of rock disruption, transportation, and deposition are represented but here again the distribution of many is sporadic. Chemical weathering under the influence of high temperatures and somewhat abundant moisture, and operating on rocks which are largely basic, may be regarded as the "normal"

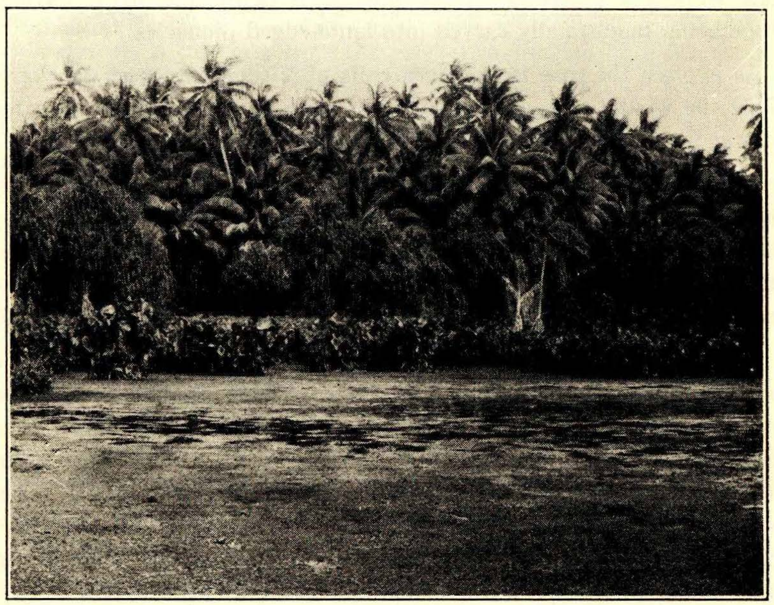

Figure 29
Surface and margin of peat bog, Washington Island, Line Group. Foreground to distance successively are peat bog, and taro, pandanus and coconut zones, stages in the advance of vegetation over the made land of the bog. Photograph by C. K. Wentworth.

process of disruption. The heavy precipitation on the windward sides and elevated parts of the islands provides for certain areas a fairly steady runoff and a somewhat organized transportation and deposition of fluvial sediments. This is far more true of parts of Vitilevu in Fiji than it is of any part of the Hawaiian Group. In Hawaii, even in the best drained districts, the sediments fall far short of the degree of sorting and segregation which would be called "mature" in a continental area.

In a few districts in Hawaii eolian transport and erosion dominate to an extreme degree and produce some very striking topographic and sedimentary effects. The geologic work of the sea is the most dominant agency in these islands, and it has a continuity in both time and space more nearly comparable to that which it might have on a continental area than is the case with any other agent. Not only does the work of the sea achieve a degree of maturity in its products not reached by other agents but the very feebleness and limited zone of action of other agents renders their work subject to interruption by the sea and liable to be wholly obscured by marine action.

However, the small size of the several islands, the shortness of stretches of shoreline which extend continuously in any one direction, and the rapid and extreme changes from place to place in such factors as declivity of the land and the amount of stream flow from the land, operate to produce rapid variations in the nature of marine action. These in turn are reflected in the distribution and types of reefs and reef organisms. The effect of these on the character and disposition of terrigenous and organic debris has been described in an earlier section.

We may say in conclusion that the sediments described constitute a random mosaic reflecting basic lavas and tuffs, a tropical oceanic climate impinging on small and rugged islands, and a generally immature stage of rock derivation. These islands may be regarded as a patchwork of *ideal,* rather than *typical* realms of sedimentation. As such, they are of much interest to students of sedimentary processes.