~~Greetings to Jack [illegible]~~
Chester K. Wentworth

THIRD SPECIAL

REPORT OF THE HAWAIIAN VOLCANO OBSERVATORY

OF HAWAII NATIONAL PARK AND THE HAWAIIAN VOLCANO RESEARCH ASSOCIATION

T. A. JAGGAR, *Director*

ASH FORMATIONS OF THE ISLAND HAWAII

CHESTER K. WENTWORTH

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PUBLISHED BY THE HAWAIIAN VOLCANO RESEARCH ASSOCIATION, HONOLULU, T. H.
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INTRODUCTION

Location and Limits of Area Studied

The Island of Hawaii, largest of the group, is a rudely triangular island of an area of 4030 square miles (Fig. 1). The northern point of the island is 30 geographical miles south-southeast of Maui, next largest of the group, and about 150 miles southeast of Honolulu on Oahu. From Kalae (South Point) to Upolu Point, the northern tip of the Kohala district, is slightly over 95 miles

FIGURE 1.

Index map of official districts, villages, and localities on the Island of Hawaii.

and the greatest dimension. The most remote inland area is a narrow triangle of land along the west margin of the lava flow of 1843 on the north slope of Mauna Loa, which is over 29 miles from Hilo Bay, Kealakekua Bay, Kiholo Bay and the bight west of Keauhou, on the east, west, northwest and south coasts, respectively.

AUSPICES AND PURPOSE OF STUDY

Field work was supported by a generous grant from the Hawaiian Volcano Research Association during the summer of 1929, and the laboratory work

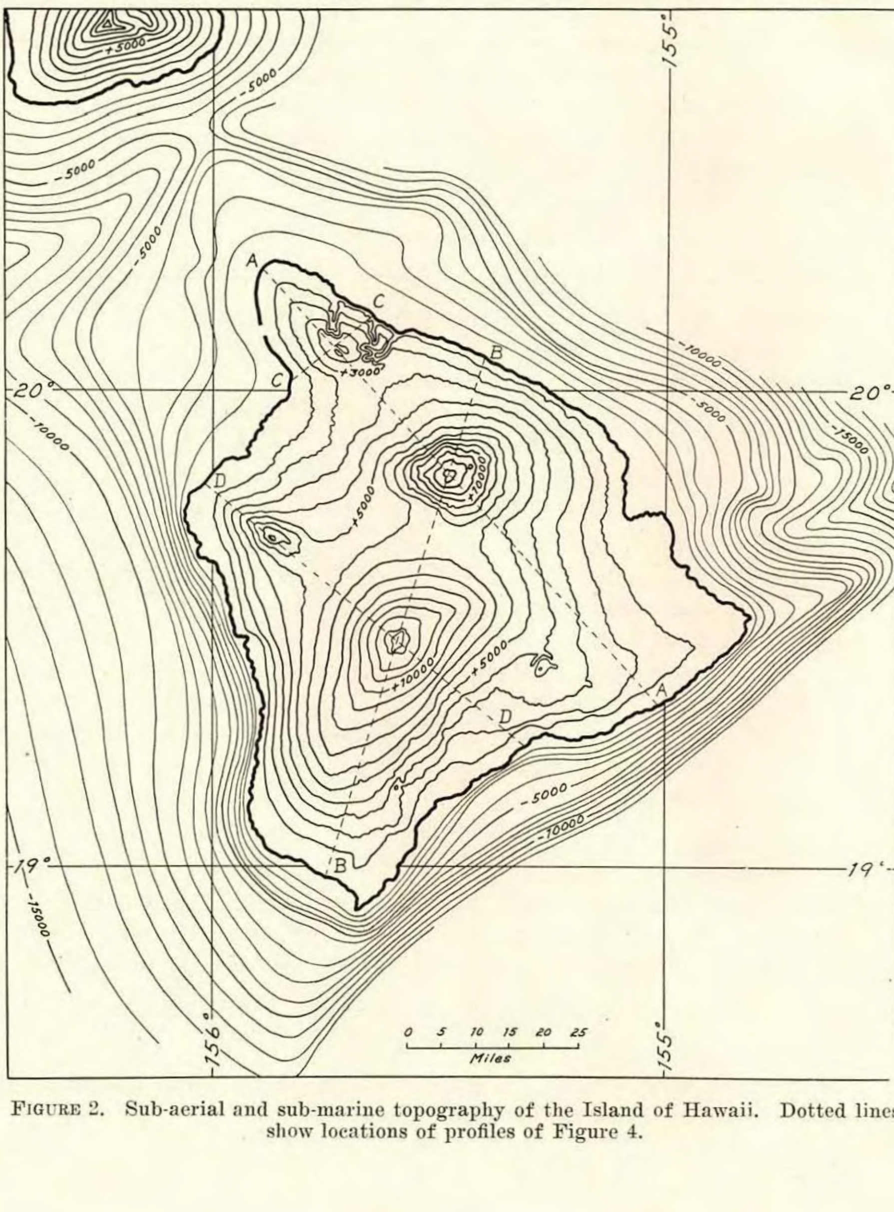

FIGURE 2. Sub-aerial and sub-marine topography of the Island of Hawaii. Dotted lines show locations of profiles of Figure 4.

was largely carried on in the Geology Department of Washington University (St. Louis). The purpose of the study was to determine the areal extent of the various volcanic ash formations, to describe them petrographically and to develop means of discriminating them. The ash formations, long known in a general way, had been only casually observed by geologists. Their interpretation and separation from other surficial materials has been much retarded by great differences in the degree of weathering and appearance of the same material in arid and in humid parts of the island. The wide distribution of ash formations in contrast to lava flows led to the hope that they could be discriminated and correlated and used as key horizons to work out the major events in the geologic history. It was believed that critical study of the effects of weathering on the ash formations, together with systematic tracing from regions of typical expression to others where the features were less typical and more obscure, would throw light on the stratigraphic relations and historical significance of the various units.

Methods and Scope of Work

In the short time available and with the imperfect road system only a general reconnaissance of most of the island was possible. A large central area of triangular form remote from highways and known to be covered by the recent lava flows from Mauna Loa was not visited. Many of the principal settlements are reached by a belt road extending around the island. The highest point on this road is at Kilauea (4000 feet), and in some places it is 15 miles from the nearest coastal point. Branch roads reach points farther inland. or small coastal settlements. The longest inland branch extends 25 miles southeast from Waimea to the saddle between Mauna Kea and Mauna Loa at 7000 feet. The ranch station Puu Oo, a short distance beyond, is the most remote inland point accessible by automobile.

Several coastal stretches 25 miles in length are inaccessible by automobile. There were once many trails, built and used by the natives, but the longer ones are fallen into disuse and are much overgrown, because of the readier travel over longer alternative routes by automobile. Dense vegetation, ragged aa flows,[1] and the lack of drinking water in some areas make many parts of the island difficult of access for a small party operating on a limited budget.

The chief conveyance was a Ford car with which the several base camps were reached. A pack mule was used to establish a camp on the coast south of Kilauea, and the summit of Mauna Kea was reached by horseback from Kukaiau Ranch. Except for traverses by auto along the chief highways, the geologic work was done wholly on foot. Determination of the megascopic character, structure and relations of the various formations was emphasized rather than areal mapping as such, though boundaries were located wherever

[1] Aa is the Hawaiian name for the broken, fragmental type of lava flow, as distinguished from the ropy type, called pahoehoe by the natives.

practicable. Various eolian, fluvial or marine formations, derived from or related to the pyroclastic formations, were also studied so far as time would permit.

Specimens for laboratory study and for thin sections were in part wrapped in heavy paper and sealed by dipping in paraffin in order to preserve the structure. This method proved very successful and a variety of physical properties were determined in the laboratory in addition to ordinary petrographic examination.

History of Studies of Ash Formations

The earliest report of pyroclastic processes on Hawaii consists of the accounts of eye-witnesses of the great explosive eruption of 1790 (or 1789) preserved by the Rev. Sheldon Dibble.[2] The essential facts have been presented by Dana[3] and Brigham.[4] This eruption was of greater violence than that of 1924, producing a greater thickness of ash deposits and characterized by wider distribution of hot "sand" and of suffocating gases, as indicated by the killing of a number of natives, part of the army of one of the native chiefs marching toward the southwest.[5] Dana believed the ash of the Kilauea district was the product of the 1790 eruption, but it has since been shown that only a small part of the entire ash section was ejected at this time, and that there were ash falls separated by periods of quiescence prior to 1790. Though there is evidence to show that pumice, cinders, and other ejecta derived from molten lava were produced at this time, the chief part of such material in the Kilauea ash beds dates from earlier eruptions.

The next reference to explosive action is contained in a letter by the Rev. Titus Coan[6] which mentions sea water chilling the lava of the 1840 eruption, which was "shivered into millions of minute particles, and, being thrown back into the air, fell in showers of sand on all the surrounding country. The coast was extended into the sea for a quarter of a mile, and a pretty sand beach and a new cape were formed. Three hills of scoria and sand were also formed in the sea, the lowest about two hundred and the highest about three hundred feet." Eight months afterward, when visited by Wilkes and Dana, the sand-hills were found to be one hundred and fifty and two hundred and fifty feet high.[7] In 1865, these cones were found to be not over a third of their former height and they have since been largely removed by wave attack,[8] though there is still (1932) a sand hill north of Nanawale Bay.

[2] Dibble, Sheldon, History of the Sandwich Islands, p. 65, Lahainaluna, Hawaii, 1843.

[3] Dana, J. D., Characteristics of Volcanoes, pp. 41-45, New York, 1891.

[4] Brigham, W. T., The Volcanoes of Kilauea and Mauna Loa, Bishop Museum Memoirs, Vol. II, No. 4, pp. 36-40, 1909.

[5] Hitchcock, C. H., Hawaii and Its Volcanoes, pp. 165-167, 1909.

[6] Coan, Titus, Letter to Missionary Herald dated Sept. 25, 1840, Vol. 37, p. 283, quoted from Brigham, W. T., Op. cit., p. 52, 1909.

[7] Dana, J. D., U. S. Exploring Expedition, Volume on Geology, p. 190, 1849.

[8] Brigham, W. T., Op. cit., p. 54.

Probably all the lava eruptions on Hawaii in the last century have produced small amounts of pumiceous cinders, but particular mention is made of the ash and Pele's hair which fell on the roofs of houses in Hilo from the eruption starting on February 20, 1852, which had its source on the eastern slope of Mauna Loa. Drifting in this direction was probably due to a so-called Kona or southwesterly wind. Visiting the source the following summer, Mr. Coan found unusual amounts of basaltic pumice.[9]

In an account of his survey of Kilauea in 1865, Brigham[10] mentions large amounts of Pele's hair and pumice southwest of Halemaumau. Shortly afterward he visited the various craters of the Puna district and described the group at Kapoho, with the enclosed Green Lake.

Several references to pyroclastic phenomena are contained in a vivid account of the eruption of 1868 on Mauna Loa. Basaltic pumice sufficient to cover the ground was carried a distance of ten miles to a point in the vicinity of Kapapala. Mixed with the pumice was Pele's hair carried in the air in quantities sufficient to necessitate breathing through handkerchiefs to avoid inhaling it. The day before the outbreak of lava in this eruption there had been a shower of ashes and pumice ejected from the same vent to a distance of ten or fifteen miles in every direction, generally not over one or two inches in thickness, but in places fifteen inches thick. The pumice was light, so that fragments two or three inches in diameter floated ashore at Kealakekua, forty-five miles away.[11] In discussing the course of the 1868 flow from Mauna Loa, Brigham refers to the subsidence of the ground west of the Mamalu Pali (Cliff) which extends north from Kalae, and to the consequent exemption of the seaward part of Kalae (South Point) from lava coverings in recent time and hence of its value as grass-covered pasture land.

This flow reached the sea along a front two or three miles wide, west of Kalae, and like the flow of 1840 from Kilauea, formed cones of cinders several hundred feet in height through the explosive action of steam due to contact of the hot lava with the sea water. It is stated that this effect is not always present but that in the case of very hot lava, the actual contact of water and lava is prevented by the formation of an insulating blanket of steam. In such cases submarine ledges of pahoehoe are formed.

In a paper on Hawaiian volcanoes published in 1884, Dutton described at length many of the features of Hawaii.[12] In a discussion of the quiet character of the eruptions of Mauna Loa he mentions the very small amounts of fragmental material found on the Mauna Loa and the Kilauea cones, in comparison both with many volcanoes elsewhere in the world and also with the extinct masses of Mauna Kea, Hualalai and Kohala.[13] Since Mauna Loa and

[9] Coan, Titus, American Journal of Science, Vol. 14, p. 219, 1852.

[10] Brigham, W. T., Op. cit., p. 92, 1909.

[11] Brigham, W. T., Op. cit., pp. 105-117, 1909.

[12] Dutton, C. E., Volcanoes of Hawaii, U. S. Geol. Survey, 4th Annual Report, pp. 81-212, 1884.

[13] Op. cit., pp. 85-86, 1884.

Kilauea are still active with a dominantly effusive phase, comparison with these dormant or extinct cones is probably misleading. In describing the phenomena observed at Kilauea, Dutton offers the explanation that Pele's hair is formed in connection with the drawing out of surface vesicles on the swirling surface of the lava of the pit rather than by the spurting upward of molten lava. This is not now thought to be the case. In another section he refers to the cinder cones which were formed at the coast by the flows of 1868 and 1840 and expresses doubt whether these cinders and cones can in any way be distinguished from those formed around inland vents.

Different accounts of the cinder cones and other features of the Mauna Kea summit call attention to the great contrast in this respect between Mauna Loa and Mauna Kea and suggest the possibility that large parts of Mauna Kea may be composed of cinders. From what is now known this interpretation can only apply, and perhaps there only in part, to the Mauna Kea mass above 10,000 feet. Similarities of the summit parts of the Hualalai and Kohala Domes to that of Mauna Kea have also been pointed out.

In an account of a survey of the summit caldera of Mauna Loa in 1885 by J. M. Alexander, mention is made of great quantities of Pele's hair and pumice produced in the eruption of 1859 and which still lie thickly on the ground around the crater which was formed during this eruption.[14]

Hitchcock, in 1901, described the eruption of 1899 and gave an account of the explosive fountaining which took place at the source of the flow at about 11,000 feet on the north-northeast slope of Mauna Loa.[15] To people in Honolulu and on board ships it appeared that, over an area possibly 1200 miles in diameter, the sky was somewhat obscured by finely divided ash or dust from this eruption. Jaggar states that this obscuration was due to fume and that the eruption of 1899 produced no ash.[16] In this paper, Hitchcock discusses at some length the relation between ash formations and fertility, pointing out that the surface materials of much of south Hawaii are of so recent origin that only the ash is sufficiently decomposed and disintegrated to support a heavy growth of vegetation. He mentions particularly the ash formation now known as the Glenwood ash and the ash of the Pahala district. This had earlier been somewhat reluctantly interpreted as a marine formation by Dutton because of the difficulty of regarding it as a fluvial deposit on so steep a slope. It was concluded by Hitchcock that ash deposits covered not less than 2000 square miles of the island of Hawaii, and that Mokuaweoweo, the summit vent of Mauna Loa, was the most probable source of a formation so large and widely distributed.

Much valuable information on the ash and soils of the Kau district is contained in a paper by J. S. Emerson, published in 1902.[17] He discusses at

14 Alexander, J. M., American Journal of Science, Vol. 36, p. 35, July, 1888.

15 Hitchcock, C. H., Bull. Geol. Soc. Amer., Vol. 12, pp. 45-56, 1901.

16 Jaggar, T. A., Personal Communication, 1932.

17 Emerson, J. S., Some Characteristics of Kau, American Journal of Science, Fourth Series, Vol. 14, pp. 431-439, 1902.

considerable length the problem of the source of the Pahala ash and concludes that the vicinity of Puu Iki north of Hilea is the most probable source and that the great eruptions giving rise to this ash must have taken place many centuries ago. Emerson describes briefly the volcanic sand and cinders of the district around Puu o Keokeo and refers to a number of the pre-missionary activities of the Hawaiians in this part of Hawaii which are of considerable importance in discussion of some of the pyroclastic problems. He emphatically repudiates Dutton's suggestion that some of the detrital formations near Hilea may be of marine origin.

Brigham's "Volcanoes of Kilauea and Mauna Loa" published in 1909 is a valuable description of volcanic features and narrative of a century of volcanic activity in Hawaii. It contains many detailed accounts by eye-witnesses of various eruptions. In 1909 there appeared a volume on Hawaii and its volcanoes by C. H. Hitchcock. This work is mainly a compilation from various of the sources mentioned above and in places contains reports and interpretations which have not been generally accepted. Among other contributions on volcanic phenomena at Kilauea, F. A. Perret published a paper on fragmental material from this volcano.[18] This paper contains descriptions and illustrations of bombs of various sorts, Pele's hair and Pele's tears, as well as reference to the beds of older ash in the vicinity. Perret refers to the thread-lace scoria (a name applied by Dana) as a continuous stratum, "indicating formation in situ and therefore not to be included under the head of ejectamenta." This interpretation appears to the present writer quite untenable, since there is abundant evidence in various layers that it occurs as discrete, cindery particles, which were irregularly drifted about by the wind and are clearly of detrital origin.

The first systematic paper on the petrography of the various islands of the group appeared in 1915.[19] Casual reference is made to cinder cones on a number of the main peaks of the island of Hawaii but there are few data on the petrography of pyroclastic rocks. Special mention is made of the trachytic composition of the cinders of Puu Waawaa and of the lava of the Anahulu terrace. Cross regarded the Puu Waawaa cone as belonging to the epoch of building of Hualalai, since it clearly antedates some of the later Hualalai flows but is not sufficiently eroded to be assigned to a period entirely older than Hualalai. The composition of certain blocks included in the detritus of the 1790 or earlier explosive eruptions of Kilauea is discussed by Cross but the value of these data lies principally in the light they throw on the composition of earlier Kilauean flows which are not exposed to view in accessible positions. A few paragraphs are devoted to basaltic tuffs and ashes of the

[18] Perret, F. A., Some Kilauean Ejectamenta, Amer. Jour. Sci., 4th Series, Vol. 35, pp. 611-618, 1913.

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

secondary craters of southeast Oahu and these are of interest by analogy with the similar materials on Hawaii.

One of the earliest papers dealing exclusively with pyroclastic rocks of Hawaii was published in 1916.[20] In this paper there is given an account of the eruption of 1790 and the suggestion that the destructive and suffocating blast which killed a large number of men of Keoua's army and their families may have come from the Cone Crater near Puu Koae, rather than from Kilauea. A number of sections of the ash of 1790 and earlier are described in considerable detail and the view is expressed that the earlier of the explosive eruptions may have preceded the formation of the present sink of Kilauea. Brief references are made to ash of the Pahala and Hamakua districts. Perret's view that the thread-lace scoria might be formed in situ was quoted by Powers and considerable evidence adduced to show that it is truly of explosive origin. He expresses the view that thread-lace scoria has probably not been formed in any eruption since 1868.

In 1924 came the first historic explosive eruption of Kilauea and a number of students have prepared accounts dealing with it. Jaggar and Finch presented a detailed account of the eruption with a resume of the earthquake and other phenomena during several months previous to the eruption. Though some of the blocks ejected during this eruption were incandescent, there was not a trace of new, or juvenile lava, pumice or Pele's hair produced at this time.[21] Additional data are contained in numerous publications of the Volcano Observatory at this time.[22] An account covering similar ground was prepared by H. T. Stearns.[23] Considerable data on quantities of debris thrown out, the distances to which this was thrown and other numerical information are included in this paper.

John B. Stone, in 1925, made a study of Kilauea in which some attention was given to fragmental materials, both as related directly to Kilauea and also of importance as interpreting the history of the surrounding region.[24] He reached the conclusion that the origin of the present Kilauea volcano was an event closely connected with a downfaulting and collapse incident to the eruption of the Pahala ash. Numerous sections are described and information is presented concerning the relations of various ash formations to the basalt flows of Kilauea and Mauna Loa.

[20] Powers, Sidney, Explosive Ejectamenta of Kilauea, Amer. Jour. Sci., 4th Series, Vol. 41, pp. 227-244, 1916.

[21] Jaggar, T. A., and Finch, R. H., Explosive Eruption of Kilauea in Hawaii, 1924. Am. Jour. Sci., Vol. 8, pp. 353-374, 1924.

[22] Hawaiian Volcano Observatory, Monthly Bulletins and Weekly Volcano Letter, Honolulu, Hawaii.

[23] Stearns, H. T., The Explosive Phase of Kilauea Volcano, Hawaii, in 1924, Bulletin Volcanologique, Nos. 5 et 6, 3.e et 4.e Trimestre, pp. 1-16, Plates I-XVII, 1925.

[24] Stone, John B., The Products and Structure of Kilauea, Bishop Museum Bulletin, No. 33, 1926.

Acknowledgments

Thanks are due to the Hawaiian Volcano Research Association for the grant making field work possible. In the course of the field work, with general headquarters at the Volcano Observatory, the writer was placed under obligation to the Research Association and to the U. S. Geological Survey by the loan of various instruments and equipment and for the use of photographic facilities. Thin sections used in this study and seven chemical analyses were also made by the Geological Survey. Washington University loaned a number of instruments for field use and various laboratory facilities were made available in St. Louis. A part of the latter was provided by allotment from the grant made to Washington University in 1930 by the Rockefeller Foundation to aid research in science.

The writer is specially indebted to T. A. Jaggar, Director of the Volcano Observatory, for suggesting the investigation and arranging for the assistance of the Research Association, as well as for frequent advice and suggestions in the course of field work. Space will not permit mention by name of all those residents of the island who assisted in material ways in the course of the summer and to whom the writer's thanks are due. Mr. Alfred Carter, of the Parker Ranch, Mr. Jennings, of Kukuihaele Plantation, Mr. A. M. Brown, of Ainahou Ranch, and Mr. D. M. L. Forbes, of Kukaiau Ranch, are among those who rendered indispensable aid in the form of animals for transportation or the use of living quarters and other equipment.

Mr. W. O. Clark, formerly of the Geological Survey and now geologist for the Hawaiian Sugar Planters' Association, made a number of trips in the field with the writer and was of great assistance with his knowledge of the ash formations of the Pahala district. Dr. H. A. Powers, petrologist at the Volcano Observatory, accompanied the writer on a number of trips which led to much helpful discussion. Finally, a large measure of substantial assistance was rendered by Edna C. Wentworth, who took part in field and camp activities throughout the summer.

In preparing the manuscript, many suggestions and helpful criticisms have been offered by G. R. Mansfield, F. E. Matthes and C. S. Ross of the U. S. Geological Survey; T. A. Jaggar and H. A. Powers of the Volcano Observatory, and H. S. Palmer of the University of Hawaii. All these aids and courtesies are here gratefully acknowledged.

PHYSIOGRAPHY

Geographic Relations and General Configuration

Hawaii stands at the southeast end of a chain of volcanic mountains nearly 2000 miles long, which rises to heights of 20,000 to 31,000 feet above the surrounding floor of the ocean. Of the height of the island, measured from the ocean bottom on the east, almost six-tenths is below sea level; of its volume possibly not over a thirtieth rises above the sea. This great bulk, submarine as well as subaerial, is the product of an enormous number of volcanic eruptions. Most of them have been lava eruptions, but associated with them have been a few explosive eruptions, the products of some of which are described in this report.

Hawaii is composed of five principal volcanic domes located over crustal rifts or intersections of rifts. The larger two of the domes, Mauna Kea and Mauna Loa, form the chief mass of the island, extending from the southern point to the curving northeast coast. Kilauea is an independent dome occupying a spur extending out from the east flank of Mauna Loa, and Hualalai lies nearly due west of the saddle between Mauna Loa and Mauna Kea. The Kohala dome forms the northern lobe of the island. Boundaries of the five domes and their areal relations are shown in Figures 3 and 4.

Though the Kohala mass at the north end of the island has generally been regarded as oldest of the volcanic mountains, there has been much speculation concerning the order of formation of the domes and their relations to buried land masses. Present state of knowledge has been summarized by Stearns in a statement based largely on the work of Jaggar.[1] The oldest land mass of the island is thought to be the buried dome of Ninole basalt probably poured from a vent about eight miles southwest of the summit of Mauna Loa. Next the Kohala dome was formed on the line of weakness known as the Kea rift. Stearns believes that the erosion and great amount of subsequent filling of the valleys of the Ninole dome by lava flows indicates that this dome was formed and dissected at an earlier date than the Kohala dome, though no direct and immediately conclusive evidence is known.

Following the formation of these two domes, volcanic activity apparently shifted to the point of intersection of the Loa and Kea rifts and much of the present dome of Mauna Kea was formed. Following a period of faulting which involved parts of the Ninole and Kohala domes, it appears likely that the Kilauea vent was opened at the point of intersection of faults of the Mauna Kea rift system with faults which had been developed on the east side of the

[1] Stearns, H. T., Geology and Water Resources of the Kau District, Hawaii, U. S. Geol. Survey, Water Supply Paper 616, pp. 102-104, 1930.

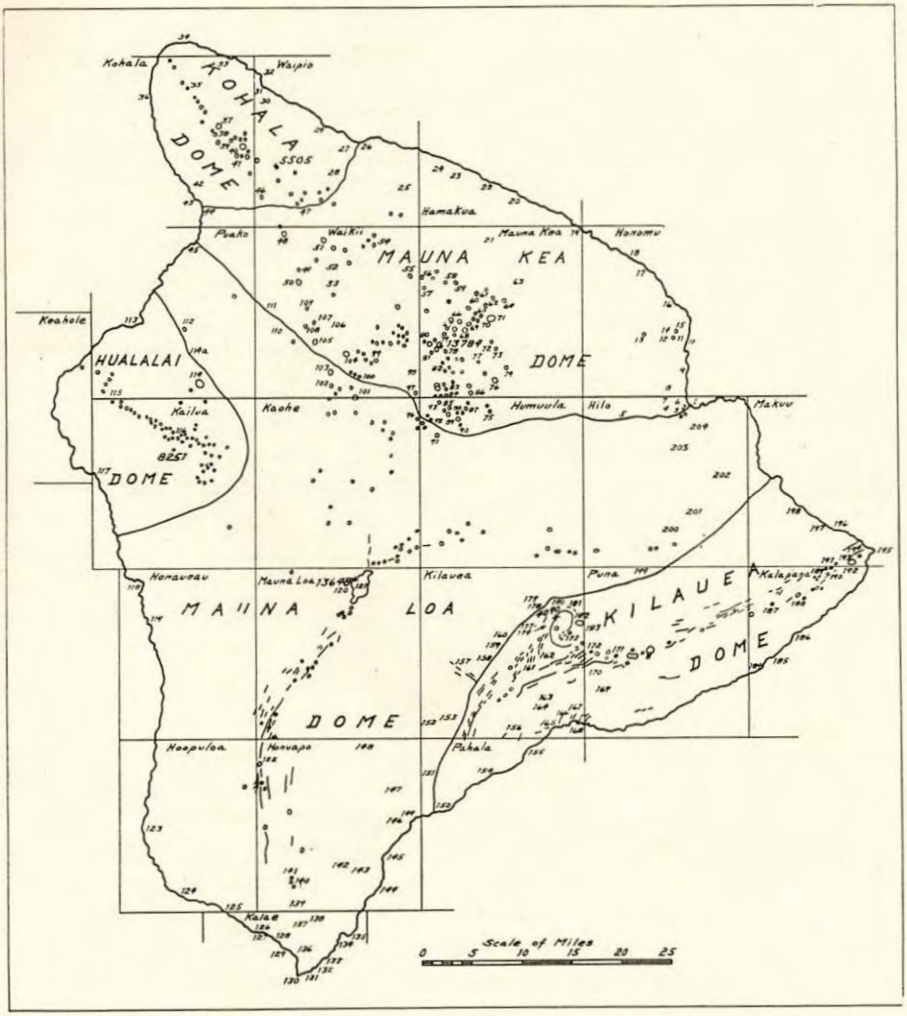

FIGURE 3. Map of Hawaii showing subdivision into five principal domes together with the distribution of cones, vents and cracks. The following list is a key to localities:

74	Aahuwela	66	Cone 11988	145	Honuapo	184	Kalapana
104	Ahumoa	201	Ferndale	84	Hookomo	64	Kalepa
170	Ainaho Ranch	199	Glenwood	116	Hualalai	22	Kalona Church
157	Ainapo	192	Green Lake	115	Huehue Ranch	57	Kaluamakani
32	Akakoa	3	Halai	89	Huikau	53	Kamakoa Gulch
14	Alala	174	Halemaumau	55	Huluhulu Gulch	189	Kamaoa Homestead
171	Aloi Crater	132	Hanalua	92	Humuula	150	Kamehame Hill
6	Amauulu	172	Keake Crater	187	Ilewa Crater	105	Kanalopakanui
114a	Anahulu Terrace	146	Hilea	25	Inoino Gulch	123	Kanewaa
134	Awawaloa	164	Hilina Pali	62	Iolehaehae	12	Kanoa
106	Auwaiakeakua Gulch	2	Hilo	135	Kaalualu	165	Kaone
177	Bird Park Kipuka	1	Hilo Bay	23	Kahawailiilii Gulch	158	Kapapala Halfway House
204	Camp Two	41	Hoepa Church	136	Kahawai Kolono	153	Kapapala Ranch
195	Cape Kumukahi	51	Holoholoku	108	Kahekili	193	Kapoho
38	Cone 3068	119	Honaunau	141	Kahuku Ranch	56	Kapula
88	Cone 7203	17	Honohina	117	Kailua	162	Kau Desert
94	Cone 8123	30	Honokane Gulch	185	Kaimu	13	Kauku
93	Cone 8151	24	Honokaa	4	Kaimukanaka Falls	67	Kaula Gulch
84	Cone 8676	42	Honokoa Gulch	130	Kalae	131	Kaulani Bay
		16	Honomu	90	Kaleha		

43 Kawaihae
10 Kawainui Stream
118 Kealakekua Bay
110 Keamuku Village
173 Keanakakoi
63 Keanakolu
168 Keauhou
180 Keauhou Ranch
52 Kemole Gulch
175 Kilauea
183 Kilauea Iki
113 Kiholo Bay
163 Kipuka Keana Bihopa
179 Kipuka Ki
178 Kipuka Puaula
191 Kohalua o Kahawali Crater
33 Kohala Village
20 Kukaiau
156 Kukalauula
26 Kukuihaele
37 Lahikiola
81 Lake Waiau
19 Laupahoehoe
87 Loaloa
140 Luapoai
109 Mahelua
36 Mahukona
8 Maili Stream
54 Makahalau
198 Makuu
44 Makeahua Gulch
139 Mamalu Cliff
144 Maniania Pali
18 Maulua Bay
79 Mauna Kea
120 Mauna Loa
58 Moano
121 Mokuaweoweo
200 Mountain View
143 Naalehu
196 Nanawele Bay
124 Na Puu a Pele
155 Na Puu o na Elemakule
49 Nohonaohaeiki
50 Nohonaohae
202 Olaa
96 Omaokoili
151 Pahala
9 Pahoehoe Stream
137 Pali o Kulani
14 Pepeekeo
159 Peter Lee Road
39 Pohakuloa Gulch (Kohala)
97 Pohakuloa Gulch (Mauna Kea)
31 Pololu Valley
111 Popoo Gulch
45 Puako
7 Pukihae Stream
149 Punaluu
101 Puuahi
112 Puu Anahulu
147 Puueo Pali
95 Puu Haiwahine
156 Puu Hole
40 Puu Hou
99 Puu Honuaula
148 Puu Iki
65 Puu Kaaliali
73 Puu Kahinahina
126 Puu Kaimuuwala
72 Puu Kaiwiiwi
83 Puu Kalepeamoa
188 Puu Kaliu
70 Puu Kanakaleonui
102 Puu ka Pele
166 Puu Kapukapu
99 Puu Kauha
77 Puu Kaupakuhale
46 Puu Kawaiwai
60 Puu Kea
103 Puu Keekee
180 Puu Keonehehee
61 Puu Kihe
125 Puu Ki
190 Puu Kii
161 Puu Koae
86 Puu Kole
97 Puu Koohi
194 Puu Kukae
78 Puu Lilinoe
76 Puu Loa
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47 Waimea
142 Waiohinu
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182 Waldron Ledge
152 Wood Valley

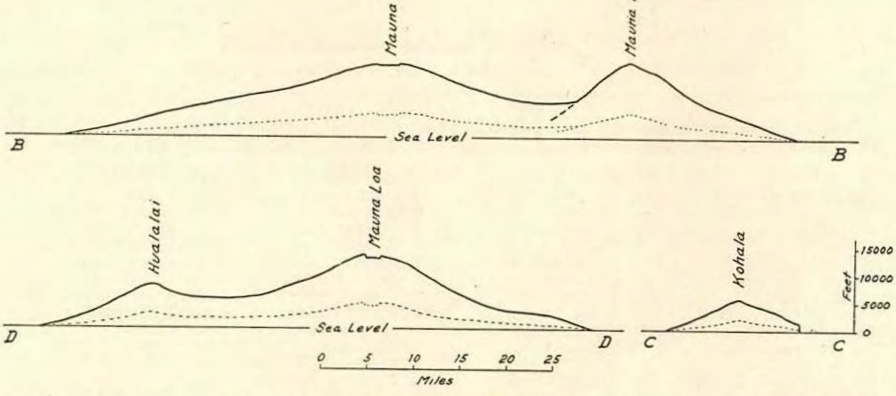


FIGURE 4. Profiles of the Island of Hawaii. *A-A* from southeast to northwest through Mauna Kea and Kohala. *B-B* from southwest to northeast through Mauna Loa and Mauna Kea. *C-C* from southwest to northeast through the Kohala dome. *D-D* from northwest to southeast through Hualalai and Mauna Loa. The dotted lines show the true relief. See Figure 2 for locations.

Ninole dome. At about the same time and in a similar manner, it is thought that the growth of Hualalai commenced.[2] Still later, a new vent on the northeast slope of the old Loa Ridge became active and the present summit dome of Mauna Loa and the caldera of Mokuaweoweo were formed. This, in brief, is thought to have been the sequence of dome formation by which the subaerial portion of the present island of Hawaii was built up.

Component Volcanic Domes

General Summary

General dimensions of the five domes are given in the following table:

Table of Dimensions and Form of the Domes of Hawaii

Name	General Outline	Length (miles)	Width (miles)	Area		Summit Elevation
				Sq. Miles	Per Cent	
Kohala	Elliptical	22	15	234	5.8	5505
Mauna Kea	Elongate	51	25	919	22.8	13784
Mauna Loa	Three-pointed star	75, 73	64	2035	50.5	13680
Hualalai	Paraboloid	24	20	290	7.2	8251
Kilauea	Sigmoid Belt	51	14	552	13.7	4090

The Kohala Dome

The southwestern side and northwestern end of the Kohala dome are only slightly eroded and the surface retains the almost unbroken symmetry of the original domed surface. Following the slopes around the north end of the island, the dissection becomes more and more pronounced as a result of the heavier rainfall of windward exposure and at the southeastern end of the Kohala dome is the profoundly dissected sector extending from Honokane Gulch to Waipio Gulch. This contrast in degree of dissection and some probable differences in history, together with the concentration of cinder cones in the summit area of the Kohala dome, constitutes the basis for recognizing three geomorphic areas listed below. Seaward parts of the dome surface range in slope from 800 feet per mile on the extreme southwest side to 400 feet per mile on the western side at Mahukona. Slopes of the higher parts average 600 feet per mile.

The Mauna Kea Dome

The northern part of the Mauna Kea dome is lapped against the Kohala dome. In turn, along its southern and southwestern sides, the Mauna Kea dome is overlapped by Mauna Loa lava flows along lines extending east and northwest from the saddle at Humuula. Between the Mauna Loa flows and the Kohala dome the western shoreline of the Mauna Kea dome is only 4

[2] Jaggar, T. A., Jr., Seismometric Investigation of Hawaiian Lava Column, Seis. Soc. Amer. Bull., Vol. 10, p. 195, 1920.

miles long. Between Hilo and Waipio the northeastern slope of the dome passes under sea level along a coastline of approximately 45 miles, interrupted only by wavecut cliffs ranging from fifty to several hundred feet in height and by corresponding submarine benches.

The lower slopes of the Mauna Kea dome have an average gradient of 500 feet to the mile. The central portion of Mauna Kea is sub-circular and is more cone-shaped than the dome of the lower part of the mountain. On all sides there is a pronounced steepening of slope above elevations of six to seven thousand feet, and continuing to the level of the great summit bench. On the east slope toward the south this steeper slope extends from 6500 to 11,500 feet. On the north side, above Makahalau, the limits are 6300 and 11,750 feet. On the west there is a gradual increase between 6000 and 8000 feet and the summit bench is reached at 12,500 feet. Pronounced steepening on the south side is found at 7200 feet.

Disregarding the cinder cones, the summit area of Mauna Kea is a nearly flat, only slightly domed surface, about 5 miles in diameter and has elevations of 12,500 and 11,500 feet on its west and east margins, respectively. The lateral slopes of this summit area fall not over 500 or 600 feet to the mile in contrast to the border slopes of the summit mass, which generally slope 1500 to 2000 feet to the mile. The center of the upper dome reaches about 13,000 feet and is surmounted by a group of summit cones which rise nearly a thousand feet higher.

The Mauna Loa Dome

The three-pointed ground plan of the Mauna Loa dome is due to its overlapping of the Mauna Kea and Hualalai dome and the interfingering of its lavas with those of Kilauea on the southeastern side. Between these bounding domes two narrow Mauna Loa fingers reach the coast, one south of Hilo and the other at the northwest shore south of Puako. The third arm of the Mauna Loa dome includes the entire southwestern part of the island, extending from Punaluu nearly to Kailua.

The eastern finger has an average slope of about 250 feet to the mile down to the elevation of about 200 feet. Seaward, the slope is about 40 feet to the mile and the topographic details of certain parts of this surface suggest that they may be remnants of an older surface, only parts of which have been veneered by Mauna Loa flows. The eastern slope of the south arm averages 1000 feet to the mile. The southwestern and western slopes adjacent to the great southwest ridge, do not exceed 400 feet per mile, but increase to 750 feet and continue at this gradient down to the smoothly curving shoreline of the Kona district. The profile of the southwest ridge has a slope scarcely exceeding 250 feet to the mile. The average slope of the northwestern finger from Humuula to Puako is less than 250 feet to the mile. At the summit of Mauna Loa is the great caldera of Mokuaweoweo.

The Hualalai Dome

The summit of the Hualalai dome lies about 3100 feet above and seven and one-half miles northwest of the saddle between it and Mauna Loa. The upper portion of the dome, down to 5000 feet on the southeast and 3000 feet on the north and west sides, has steep slopes which in places reach 1400 feet to the mile. Below these elevations the slopes decrease and do not exceed 500 feet at the west coast and 300 feet at the northwest shoreline.

The Kilauea Dome

The exposed part of the Kilauea dome has the form of a long, slightly sigmoid belt which parallels the southeast coast of Hawaii. The summit of the dome is almost buried by Mauna Loa flows and only about 4 square miles of its surface slope toward Mauna Loa. The eastern slope, extending 25 miles to the east cape of the island, averages only about 150 feet to the mile. South of the eastern rift zone, all the slopes face the southeastern coast and have gradients of 250 to 400 feet per mile in the eastern part. South and southwest of the summit caldera the Kilauea slopes down to 2500 feet range from 100 to 200 feet per mile. Seaward from this contour is a system of fault scarps which account for a marked steepening of the slope. Westward is a belt of Kilauea slope which falls toward the southwest and parallel to the Mauna Loa margin at the rate of about 165 feet to the mile.

Geomorphic Divisions

On the basis of original volcanic forms and the subsequent modification by erosion, the island has been divided into the thirty geomorphic areas listed in the following table:

- Kohala Dome:
  - Kohala summit area
  - Kohala slopes area
  - Waipio bight area
- Mauna Kea Dome:
  - Mauna Kea summit area
  - Hamakua slopes area
  - Keanakolu slopes area
  - Northwest Mauna Kea slopes area
  - Waimea Plain area
- Mauna Loa Dome:
  - Mokuaweoweo caldera area
  - Mauna Loa East Rift area
  - Humuula Saddle area
  - Hualalai Saddle area
  - Mauna Loa southwest rift area
  - Kona slopes area
  - Ainapo slopes area
  - Hilo slopes
  - Northwest Mauna Loa slopes
  - Hilea blocks area
  - Kalae slope area
- Hualalai Dome:
  - Hualalai Rift area
  - Northwest Hualalai area
  - Kona Hualalai area

Kilauea Dome:
- Kilauea caldera area
- Kilauea Saddle area
- Kilauea East Rift area
- Eastern Kilauea slopes area
- Makuu Apron area
- Kalapana slope area
- Kapukapu cliff area
- Kau Desert area

More detailed description of these areas with a map showing boundaries, has been presented elsewhere.[3]

Climate and Vegetation

Hawaii is near the northern limit of the belt of northeast trade winds. Its climate is a characteristic oceanic climate as experienced by a high island in this belt.[4, 5]

The mean annual temperature as determined at 52 stations having an average elevation of 1270 feet is 69° F. August is the warmest month with a mean temperature of 71.6° and February is the coldest with a mean temperature of 66.4°. The range between means for the warmest and coldest months is thus only 5.2°, an equability of temperature showing the dominant effect of the sea. Study of mean temperatures and elevations above sea level for stations on the windward side of several of the high islands of the Hawaiian group shows a very regular decrease of temperature with increase of elevation. On Hawaii the temperatures fall nearly 4° in the first thousand feet, with a rate near 3° per thousand feet at higher elevations, agreeing closely with the rate deduced from the principle of adiabatic cooling. The sea level mean annual temperature for the island is probably about 74.5°.

At Hilo, on the east coast in latitude 19° 44′, mean annual, high monthly mean and low monthly mean are 72.5°, 75.0°, and 69.9°, respectively, and the highest and lowest temperatures recorded in a period of 14 years are 91° and 51°, respectively. At Humuula (6685 feet) the corresponding mean temperatures for a period of nine years were 52°, 55.5°, and 48.5°, and the extremes were 84° and 25°. Both as to means and extremes, the Humuula station shows greater ranges than the Hilo station, as might be expected from its great elevation and distance from the coast. Practically all the temperature variations of the island fall within the ranges indicated for these stations. A

[3] Wentworth, Chester K., Geomorphic Divisions of the Island of Hawaii, University of Hawaii, Occasional Papers, No. 29, pp. 1-15, 1936.

[4] Daingerfield, Lawrence, Summary of Climatological Data for the United States, Hawaii Section, pp. 1-6, 1918.

[5] In revising this section the writer has been greatly aided by suggestions and recent data furnished by Mr. J. F. Voorhees, officer in charge of the Honolulu Weather Bureau station.

few west coast stations occasionally experience slightly higher temperatures than the extreme indicated for Hilo, 98° at Mahukona being the highest ever officially recorded on the island or in the Hawaiian group. The minimum for Humuula, 25° in March, is the lowest ever officially recorded at any station in the group. No continuous records are known ever to have been made at a higher station than Humuula but it may fairly be assumed that minimum temperatures between 0° and 5° are occasionally reached at the summits of Mauna Kea and Mauna Loa and that here temperatures as low as 20° are fairly common. The most probable mean annual temperature at the summit of Mauna Kea is 36°. Freezing temperatures are probably experienced with decreasing frequency down to stations as low as 4000 feet.[6]

Wind direction is remarkably persistent in nearly all parts of the Hawaiian group. On islands of moderate elevation, such as Lanai, Molokai and Kahoolawe, there are areas of windswept upland where vegetation is wanting and where the bare ground is furrowed and striated by the wind with such distinctness that wind direction may be measured to the nearest degree by the compass needle.[7] According to Daingerfield, in the summary cited, there are two areas in the Hawaiian group which are exceptions to the rule of northeasterly winds. These are southwest Hawaii (Kona and Hualalai) and the southwest slope of Haleakala on East Maui. The great mass and height of the Mauna Kea and Mauna Loa domes and of Haleakala appear sufficiently to obstruct the trade winds and at the same time to exert a heating effect and thus bring about sea-to-land winds over the southwestern slopes during the entire year. Except for the Kona and Hualalai portions of Hawaii, prevailingly northeast winds may be assumed for all stations except as these are slightly modified by local configuration of valleys or mountain peaks.[8]

Most of the rainfall of the Hawaiian group is due to the cooling of moist trade winds as they are forced to rise in passing over the elevated masses of the islands. In general the windward slopes of the islands are characterized by heavy rainfall and the leeward slopes by very little rainfall. Local details of configuration, heights of mountains, etc., are all variables which give individuality to the different districts and there are numerous exceptions to the

[6] Climatic conditions on upper Mauna Kea and additional meteorological observations are dealt with in recent papers based on the Hawaiian Academy of Science expedition of 1935.

Gregory, H. E., and Wentworth, C. K., General Features and Glacial Geology of Mauna Kea, Bull. Geol. Soc. Amer., Vol. 48, pp. 1727-1729, 1937.

Wentworth, C. K., Mauna Kea, the White Mountain of Hawaii, Mid-Pacific Magazine, Vol. XLVIII, No. 4, pp. 291-296, 1935.

Coulter, J. W., Journal American Meteorological Society, Vol. ...., pp. ...., (in press).

[7] For the stations of Hilo, Humuula, Kapoho, Kaneleau, Kiolakaa, Kohala Mill, Mahukona, Niuhi, Olaa Mill, and the Volcano Observatory, 107 out of 120 monthly prevailing wind summaries were northeasterly, 7 were northerly and 6 easterly. Seven of the ten stations showed prevailing northeasterly winds for twelve months of the year.

[8] Thus, Holualoa in North Kona shows twelve monthly summaries of prevailing wind as southwesterly.

rule enunciated. On the island of Hawaii, the Kona district, though it is a leeward slope so far as the trade winds are concerned, is nevertheless well watered as a result of the sea-to-land winds mentioned above. The general distribution of rainfall on the island is indicated in Figure 5. Two features remain to be mentioned. The first is the remarkable contrast in rainfall exhibited by stations separated by only a few miles. Daingerfield cites some striking examples of this relationship from the islands of Maui and Oahu, but almost equally striking instances may be found on the island of Hawaii. For example, the annual rainfall at Humuula in the high saddle between Mauna

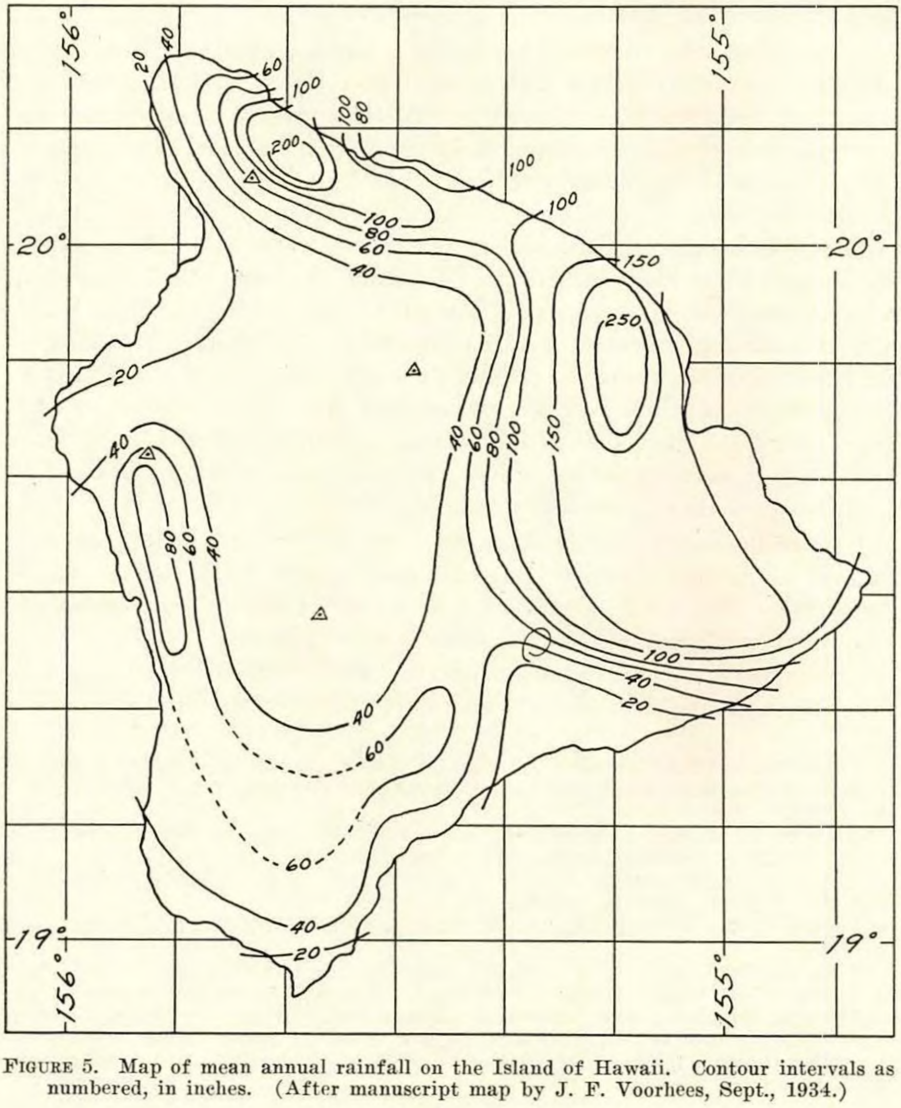


FIGURE 5. Map of mean annual rainfall on the Island of Hawaii. Contour intervals as numbered, in inches. (After manuscript map by J. F. Voorhees, Sept., 1934.)

Kea and Mauna Loa is 32 inches, whereas at Puu Oo, six miles distant and just around the flank of Mauna Kea toward the windward side annual rainfall is 102 inches.

Sufficient data are at hand to show that the maximum rainfall is reached far below the tops of the highest domes. According to Voorhees[9] the maximum precipitation on a broad, fairly gentle, windward slope like the Hamakua section occurs at elevations of 1800 to 2000 feet. Steep palis may carry the maximum higher, to 2500 or 3000 feet, and windward-facing, V-shaped valleys with precipitous heads carry the maximum rainfall still higher, in places reaching 5000 or 6000 feet. Thus on the Kohala dome the greatest rainfall is nearly at the summit.

Contrasts in vegetation are as striking as those in climate. In those parts of the island where rainfall is abundant there is a dense tropical vegetation characterized by several varieties of tree ferns and many other plants of varied origin. Some are very ancient in the islands and certainly antedate the arrival of the Hawaiians, others have been introduced intentionally or otherwise during the one or two thousand years of Polynesian occupation and many others have been introduced during the historic period. At higher altitudes the lower temperatures are unfavorable to some of the plants and the composition of the flora changes, even where there is an adequate rainfall.

On the leeward slopes many places are practically desert in character, especially if the lava flows which form the surface are of recent origin and are only slightly weathered. The amount of immediately available water for plant use depends not only on rainfall but on capacity for water retention by the soil. In general the lava rock of Hawaii is extraordinarily pervious and even in districts of abundant rainfall the water table is commonly very low. In some places the weathered mantle rock overlying the bedrock is somewhat more retentive of moisture and less permeable than the basalt so that vegetal cover is much influenced by the degree of weathering on this account as well as through availability of plant food in the weathered rock.

The presence of ash as a surface cover in a given district is important not only because the ash weathers more readily than the basalt but also because even in its unweathered condition, if sufficiently fine grained, it is capable of retaining considerable moisture. As a result of these conditions there is much difference between the vegetation of certain ash-covered districts and that of non-ash-covered districts in the same climatic situation. An ash cover also operates to promote the development of a more minute and elaborate drainage system in the initial stages of drainage evolution and this in turn modifies the vegetational aspect of a district.

Not only has ash been of importance in the development of a native vegetational cover but it has been of fundamental significance in determining the areas successfully used for agriculture and grazing. With the exception of

[9] Voorhees, J. F., Personal communication, Sept. 11, 1934.

the longer weathered surface of the Kohala dome and a few areas of agglomerate or old and much-weathered aa lava, most of the sugar cane raised on the island of Hawaii is found on weathered ash surfaces. With its moderate rainfall the Pahala-Kau district would not produce any sugar were it not for the Pahala ash and its significance both as a water barrier in the lava terrane and as a fertile, readily tilled soil. The grazing lands on the higher slopes of Mauna Kea and in Kalae, Kapapala, and Kaalualu are almost wholly underlain by ash. It must be recognized, however, by the reader, that this relationship is especially pronounced on a young volcanic island like Hawaii and that it is much less important on older islands like Oahu or Kauai.

NATURE OF PYROCLASTIC PROCESSES AND PRODUCTS

Definition of Pyroclastic Action

Pyroclastic rocks are those composed of fragmental materials thrown into the air during a volcanic eruption and deposited from the air. As thus defined the class does not include quite all fragmental volcanic rocks since lava balls and much of the material of aa flows is excluded, nor is it restricted to the strict products of major volcanic explosions. Thus we include Pele's hair, some pumiceous lapilli and some reticulite ("thread-lace scoria"), all of which may be the product of the bursting of lava bubbles or various locally explosive phenomena on the surface of lava pools, such as that of Kilauea. However, when all the types of pyroclastic rocks are considered, the genetic importance of a shorter or longer aerial flight is apparent. These rocks grade into derivatives of pyroclastic materials, such as various types of sedimentary tuff, which have suffered transport by surface agents subsequent to the aerial expulsion.[1, 2]

Pyroclastic action consists of all those processes, volcanic and aerial, which are of essential importance in determining the nature and distribution of pyroclastic rocks. Its complete study would thus include the important problem of volcanic explosions, the nature of rock magmas and the manner of their movement toward the surface of the earth, as well as the normal and abnormal atmospheric conditions which might markedly affect the distribution and deposition of the fragmental material thrown out during an eruption.

Causes of Volcanic Explosions

Stearns lists five types of volcanic explosions which occur in Hawaii.[3] These are magmatic explosions, pyro-explosions, littoral explosions, submarine explosions, and phreatic explosions. Those in which the expansive force is due to juvenile gases and which throw out fluid, essential material are known as magmatic explosions. Pyro-explosions are defined by Stearns as a variety of magmatic explosion in which there is more or less continuous fountaining of incandescent lava, commonly at the source of a lava flow, but which do not throw out accessory or accidental material and which do not commonly throw ejecta to greater heights than 500 feet.

[1] Wentworth, C. K., and Williams, Howel, The Classification and Terminology of the Pyroclastic Rocks, Nat. Research Council, Bull. 89, pp. 24-25, 1932.

[2] The term pyroclastic in this sense has come into common use since 1900. Chamberlin and Salisbury, Geology, Vol. I, pp. 404, 406, 472, 1904; Grabau, Principles of Stratigraphy, p. 285, 1913; Pirssen, Am. Jour. Sci. Vol. XL, p. 191, 1915; Lahee, Field Geology, p. 112 (see index also), 1916.

[3] Stearns, H. T., Geology and Water Resources of the Kau District, Hawaii, U. S. Geol. Survey, Water Supply Paper 616, pp. 141-157, 1930.

Littoral explosions are those caused by the contact of a hot lava flow with sea water at the coast. Sub-marine explosions are similar to littoral eruptions in their origin except that the contact with the sea water takes place at some point on the ocean bottom. A phreatic eruption has been defined as one in which no essential, juvenile material is ejected. Such are usually due to the contact of ground water or surface waters with heated rocks and the consequent production of steam explosions. From a strict standpoint the term phreatic refers to ground water. A more generally applicable term for explosions due to steam from any kind of water would be hydro-explosion. Study of the various tuff cones on Oahu suggests that whereas the source of most of the erupted material is clearly magmatic, the location of the vent and the incorporation of fragments of older lavas and reef rock indicate a hydro-explosion. Such eruptions are described as hydro-magmatic.

All these types are illustrated by pyroclastic accumulations found on the island of Hawaii. Taken as a whole, the magmatic explosions, including some that are hydro-magmatic, have been the most numerous and have produced a predominant part of the pyroclastic mantle. If numerous purely hydro-explosions producing lithic accessory dust and lapilli falls have occurred at other vents than Kilauea, their product must now be largely buried. Explosions, mainly magmatic, have been responsible for the Ninole tuff, the Kohala pyroclastic materials, the Pahala tuff of the several districts of its occurrence, the numerous cinder cones and the widespread yellow tuff phase of the Waiau formation, and the cones of Hualalai, Puu Waawaa, as well as large parts of the Keanakakoi formation of Kilauea. Pyro-explosions have been very numerous and probably accompanied a large share of the effusive eruptions on Hawaii during all time. Their contributions to the pyroclastic record have been, however, confined almost wholly to the immediate cone and the near vicinity of the vent and any slight amounts of material which were drifted in the atmosphere to greater distances are not commonly identifiable. The Pele's hair which is regularly produced during the pool type of Kilauean activity must be included in this category. Associated with each of the pyroclastic formations are derivatives of fluvial or eolian deposition which differ but little from the primary pyroclastics, but no district is known where these are dominant except Kemole Gulch.

Sites of Explosive Eruptions

Explosive eruptions occur in a great variety of situations. Certain types such as littoral eruptions are defined by the locality of their occurrence. Others, like phreatic explosions, are also in considerable measure fixed in locality by physiographic and hydrologic conditions. Pyro-eruptions of the fire-fountain type which are commonly located at the sources of flows have their positions determined by the same subterranean factors as operate in the case of flows in general.

Thus, on the flanks of great domes, like that of Mauna Loa, lava most commonly reaches the surface at elevations several thousand feet below the summit, though flows extending into the summit caldera are also known. The eruptions on the flanks of the dome, as well as those at the summit and practically all other eruptions in Hawaii take place along the lines of definite fissures or rift systems. Many vents of secondary eruptions are arranged along definite lines with remarkable precision. An example has been described in the Koko Head system on Oahu, in which 14 separate vents lie within a rectilinear belt six miles long and less than a third of a mile wide.[4] Similar lines may be seen on Figure 3 of this report.

It is evident that if nearly circular domes like those of Hawaii are formed of great numbers of lava flows, it must be due to the predominance of a central vent, or at least of a closely spaced group of such vents. Some appear to be located at the intersection of two important rift lines. Though most of the vents occur along rift lines, there is a broad dominance of the domes formed around particular parts of these rift lines and no really long or independent ridge of even sub-uniform height appears to have been formed along a rift. A similar dominance of vents around a center is shown in the pyroclastic vents of certain systems. For example, there is a well marked alignment of the Kohala cinder cones, with some occurring at fairly low elevations near Upolu Point, but there is also a marked clustering of cones in the summit area of Kohala. Precisely the same relationship is shown by the cones of the Hualalai system. The writer is well aware that he is here dealing both with cause and effect; however, the pattern is a fact.

The most notable example of fairly broad summit clustering is that of the cinder cones of Mauna Kea where an area more than fifteen miles in diameter is marked by cinder cones. Pyroclastic activity which produces numerous cones of fine material has commonly been regarded as the closing type of activity of great volcanic domes. It may also be regarded quite naturally as the summit expression of the rise of relatively small amounts of highly gaseous lava. Under any given condition a pyroclastic eruption may be expected to take place at a higher elevation than an effusive eruption. Pyroclastic eruptions give way to effusive action when sufficient quantities of liquid material rise to the vent to emerge as flows.

Magnitude of Pyroclastic Action

The quantities of magmatic material thrown out during individual pyroclastic eruptions on Mauna Kea have been estimated in another section to be comparable to the volumes of the known individual lava flows of the historic period on Hawaii. Most of these have been of the order of magnitude of 50,000,000 cubic meters with a maximum of possibly 1,000,000,000 cubic

[4] Wentworth, C. K., Pyroclastic Geology of Oahu, Bishop Museum Bulletin 30, p. 19, 1926.

meters of lava. Pyroclastic craters on Oahu, such as Diamond Head, also approach this order of magnitude as a maximum.

The great Katmai eruption of 1912 has been estimated to have thrown out 6.25 cubic miles or approximately 26,000,000,000 cubic meters.[5] The Krakatoa eruption of 1883 was more violent but apparently did not result in so large a volume of fragmental material. The amount was estimated at one and one-eighth cubic miles or 4,700,000,000 cubic meters.[6] These were phreatic in origin but may serve as measures of the energy potentiality in volcanic outbreaks.

It is evident that in volume, the individual Hawaiian eruptions, both pyroclastic and effusive, are very much smaller than the largest known and it appears from what is known of the structure of the Hawaiian range that it has been built up from the products of large numbers of eruptions of moderate size, a view also supported by the relative thinness of most Hawaiian lava flows. Of course we have no knowledge of the magnitude of a vast part of the earlier eruptions.

Expulsion of fragmental material from a vent may take place as a lifting of light material upward in an updraft of heated gases, or it may take the form of extremely violent expulsion of fine-grained materials in a violently agitated gas cloud, or of throwing out of larger blocks in definite trajectories to considerable distances from the vent. Fine-grained ash or dust has been observed to rise at rates of 100 or 200 feet per second to heights of 15,000 to 20,000 feet in the air and thence, from a number of eruptions, at least of the hydro type, has been known to have drifted completely around the earth. Blocks weighing a number of tons have been thrown certainly several thousands of feet and probably several miles.[7]

In some major pyroclastic eruptions, ash or dust deposits have collected to a thickness of one foot at distances from the vent as great as one hundred miles, and in some eruptions this magnitude of drifting has probably been exceeded in certain directions both in distance and thickness. Some of these very great dust-producing eruptions have doubtless been phreatic, nevertheless, some of the eruptions producing known bentonite beds must have been of this magnitude and were magmatic.[8] So far as known, no Hawaiian eruptions have produced accumulations in excess of some such thickness as a foot at a distance of five to ten miles. This estimate is a very liberal one, based on the known volumes of certain cones in proportion to all cones of the Mauna Kea series and on the thickness of certain tuff deposits on Hawaii. No historic eruption or one readily identifiable in a pre-historic section has a magnitude of drift of so much as one-tenth of this value.

[5] Griggs, R. F., The Valley of Ten Thousand Smokes, National Geographic Society, pp. 29-31, 1922.

[6] Admiral Wharton, Report of the Royal Society, p. 89. (Also Nature, Vol. 39 (1889), p. 303.)

[7] Geikie, A., Textbook of Geology, 4th Ed., Vol. 1, pp. 292-293, 1903.

[8] Geikie, A., Op. cit., pp. 292-295.

The Morphology of Pyroclastic Accumulations

Very little has been written on the sub-aerial forces which produce the characteristic morphology of ash and cinder cones. Volcanologists have devoted considerable attention to the problem of initial formation of vents through which lava reaches the surface but most often were primarily concerned with deep-seated causes and less with the effect of the mechanism of expulsion and accumulation on the shapes of cones.

Within historic times, a number of pyroclastic eruptions have been observed in various parts of the world and the rapidity with which many cones of considerable size have been formed is a matter of record. Bishop gave especial attention to the brevity of such eruptions.[9] One of the most famous of such eruptions is that which formed Monte Nuovo in the Bay of Naples in the year 1538.[10] Here a cone of lapilli, scoria and ashes 489 feet in height above sea level and a mile and a half in circumference was formed in twenty-four hours. The several successive appearances of Falcon Island in the Tongan Group of the South Pacific Ocean are also matters of record.[11]

Cinder cones have a great variety of shapes, some of which are only in a broad sense entitled to be called cones. Most of them contain conical elements but because of the depression in the center the simple cone is rarely completed.

The shapes of cinder and ash cones appear to be determined by two principal mechanisms. In the very early stages of an eruption the ejected material will accumulate at various points in thicknesses which depend on distance and direction from the vent and on the sizes of fragments, velocity of ejection and angle of trajectory. In this way a circular zone of maximum accumulation is determined. As the eruption continues this zone may be built up to a ring of such height that its sides reach the angle of repose for the material in question and the maintenance of this angle by sliding becomes the second mechanism referred to above. In the case of high cones the central funnel may have its form rigidly controlled by the cascading of ejecta back to the central vent and thence to be again thrown into the air.

There is little doubt that some cones are so conditioned but there are others, such as Diamond Head and others on Oahu, which have so wide an internal saucer and such low angles of slope and structure near the center that it seems more probable that here the position of the rim and the shape of the internal bowl, like that of the exterior cone, have been mainly determined by an optimum accumulation of detritus at a distance somewhat farther from

9 Bishop, S. E., Brevity of Tuff Cone Eruptions, Amer. Geologist, Vol. 27, pp. 1-5, 1901.

10 Geikie, A., Textbook of Geology, 4th Ed., Vol. 1, p. 290, 1903. (Various earlier references are cited.)

11 Geikie, A., Op. cit., pp. 334-335, 1903.
Alling, H. L., Hoffmeister, J. E., and Ladd, H. S., Falcon Island, Amer. Jour. Science, Vol. XVIII, pp. 461-471, 1929.

the vent than would be required by the mechanics of an internal funnel of cascading. A few cones on Hawaii probably have similar, large radius rims. This radius of maximum accumulation may be determined in either or both of two ways. One controlling condition is the range of the trajectory in which the bulk of the material is thrown out. Another is the maintenance, during a nearly continuous eruption, of a strong circular updraft column of a diameter determined by the size of the vent, the amount of gas expansion, and perhaps other factors, within which it is impossible for other material than the coarsest to fall back. These two conditions, together with the depth of the repose funnel, would thus determine the size and shape of the crater bowl.

Even in the cones which are initially of this type, continued accumulation will result in increased height of the rim and if the diameter of the rim is small, such increase in height is likely to result in increase in diameter, since this is fixed by the necessary upper diameter of the internal funnel which leads to the vent.

Though many cones are quite symmetrical, others depart widely from this form, many, especially, being considerably higher in one part of the rim than in another. Most commonly on Hawaii as well as on other islands of the group the high portion of the rim is to leeward of the vent and is a direct result of the trade wind drift at the time of the eruption. Asymmetries of different azimuths from this may be due to eruption during prevalence of wind from other directions or to irregularities in the vent of expulsion.

In extreme asymmetries the trade winds appear to have so shifted the zone of optimum accumulation that its windward side has fallen athwart the vent and a sector of it has been thus inhibited from formation during the eruption. In this way a crescentic cone is formed, of which Koko Crater on Oahu is a magnificent example. No large cone of this type was seen on Hawaii. As others have pointed out, the extreme case is where enormous quantities of fine-grained material are thrown so high into the air and wind drift is so effective that no ring of accumulation is formed and no cone of any sort is formed.

So far as the external dynamics of cone formation are concerned there appear to be three principal conditions which influence shape of the resulting cone. The first of these is the mechanical composition of the detrital material thrown out. The second is the element of velocity distribution throughout the fountain of expelled material, and the third is the velocity and direction of motion of the wind and upper atmosphere at the time.

Mechanical composition affects the radial distance to which the material is carried by the initial trajectory and by the subsequent drift. Coarse material tends to follow nearly parabolic trajectories, once it has left the more immediate influence of the central gas fountain. Such material accumulates near the vent. Finer material of lesser settling velocity in air may drift to greater distances. Under given conditions the path of settling for particles of a given size is a resultant between the constant velocity attained through the action of gravity and the intensity of the forces which produce dispersal. Where the velocity of fall is high, the path is little modified by the comparatively feeble forces of dispersal outside the immediate fountain and the angle of the path is nearly ninety degrees, but where this velocity is very low the dispersal forces may predominate and the path of fall may have a very low angle. Thus fine material may be drifted to almost any distance from the vent.

Only a few suggestions as to the probable conditions of formation of the Hawaiian cinder and ash cones can be made on deductive grounds. The present writer agrees with Bishop as previously cited that such sharp-crested and symmetrical craters as Diamond Head and others on Southeast Oahu must be due to a rapid and nearly continuous expulsion of gaseous and detrital solid matter under rather constant conditions. From what is known of the mechanism of volcanic eruptions in general and from the coastal position of many of these cones it is probable that the gas was largely steam. Thus these were in part phreatic eruptions but not wholly, because magmatic material predominates. On Hawaii there are numerous pyroclastic cones near the coast which have been formed by steam explosions. Even in the magmatic eruptions of Mauna Kea it is believed that steam may have played an important part.

No wide-rimmed, symmetrical craters formed of very fine ash or tuff, such as Diamond Head and others on Oahu are known on Hawaii, and the fact that fine-grained yellow ash is drifted over wide areas on Hawaii and thickens toward the positions of the central cones indicates transitional relationships. The cinder cones of Hawaii of the type of Ahumoa are believed to be the results of lesser steam pressure. Velocities of expulsion were lower, the effective diameter of the fountain was less and the diameter of the rim is less in the Ahumoa type than in the Diamond Head type.

A gamut of types of pyroclastic eruption might be given, ranging from the type producing driblet cones on the one hand to those in which the gas expansion is so violent that no prominent central cone is produced. Here the first type is magmatic, the latter usually phreatic. Quite possibly nearly all the Oahu eruptions were pheato-magmatic, as well as some of those of Hawaii. In that scale most of the cinder cones of Hawaii may be regarded as nearer the driblet cone type than those of Oahu. The cones of Hawaii are in the main formed of material which was sufficiently fine in grain to solidify in the air and to form notably symmetrical craters. On the other hand the greater part of the constituent material was coarse enough so that it was not markedly affected by trade wind drift, though some show moderate asymmetry due to this cause.

During the 1929 eruption of Kilauea, which the writer was fortunate enough to witness, the maximum height of fountaining was about 300 feet. The material expelled appeared to consist mainly of molten blebs ranging from fist size to several cubic meters in volume. These followed simple parabolic paths and fell within a circle not over 300 feet in diameter. During the eruption moderate quantities of pumiceous cinders $\frac{1}{4}$ to $\frac{1}{2}$ inch in size were carried in the gaseous up-draft and deposited around the margins of the fire-pit. Many of the larger blebs thrown out broke their thin congealed crust on landing and the molten and incandescent interior was strewn down the sloping surfaces. Such an eruption produces a steep-sloped driblet cone. It is conceived that with greater quantities of steam and a more intimate mixing of the gas with the molten lava, leading to a continuous high-pressure spewing of the gas-liquid mixture, finer-grained and more uniform sized material would be produced which according to the height and diameter of the fountain would form a ring crater of the type so common on Mauna Kea. In such an eruption it appears almost inevitable that large quantities of material finer than that falling in the central cone would be carried into upper air currents and drifted and dispersed over the surrounding country. This material is believed to be represented by the yellow tuff found on the lower slopes of Mauna Kea and in other parts of Hawaii.

Dispersal is mentioned in the preceding paragraph as a process of transport. The term is here used to denote the irregular fall by which many small particles released at one point in a static fluid might tend to reach a point on the ground directly vertically under the point of release but would actually be distributed over a considerable area on the ground. The diametrical profile of this accumulation on the ground would be some sort of probability curve, more or less skewed, and it is believed that this principle together with the effect of drifting is important in determining the distribution of thicknesses in widespread dustfalls.

Mechanical Composition of Pyroclastic Accumulations

Reference is here made to the mechanical or size composition of the fragmental material as determined by the conditions of the eruption. It is evident from the foregoing discussion on the morphology of cones and the conditions of their formation that the larger part of the coarser material which is expelled is deposited close to the vent and that the remoter parts of a pyroclastic deposit are composed of fine-grained material.

If equal quantities of material consisting respectively of large and of small grains are released from a given height it will be found that the finer material will be deposited over a broader area since its grains settle more slowly and are thus exposed for a longer time to the random effects of horizontal and vertical movements. This is the essential reason for wider dispersal of finer-grained material. Still more pronounced dispersal results from atmospheric currents moving steadily in one direction.

As a result it is found that if material consisting of grains of several different sizes is released from a central position in the atmosphere to settle over the surrounding country, a larger share of the coarser grades will settle at any point at a given distance from the center than of a finer grade, provided, of course, that the coarser grade has not already been completely deposited still closer to the center.

Hence it comes about that the common and ideal size distribution of particles in a volcanic ash or other comparatively fine pyroclastic material at a moderate distance from the vent shows the largest quantities in the coarsest or next to the coarsest grade represented, with the finer grades in successively smaller amounts. This process of deposition of successively finer grades may be called winnowing. Many of the ash samples analyzed and described in the section on petrography show the results of this process as do also the samples described in an earlier report on the pyroclastic rocks of Oahu.[12] This distribution of sizes is most pronounced in pyroclastics of sand and fine gravel sizes and it is apparent that the process described would not operate effectively in the deposition of large bombs and lapilli near a vent, nor in the accumulation of the finest dust at a great distance.

Some pyroclastic formations appear to consist of a dominant finer material which has been contaminated sporadically by the falling of coarser materials or a few larger particles in zones. The bedding thus takes on a distinctive form which is described in the section on structure.

Structure of Pyroclastic Accumulations

In a previous section the morphology of pyroclastic deposits has been discussed. If accumulation always took place on level, smooth surfaces, the structures of growing pyroclastic deposits would be developed always parallel to the upper surface of the deposits and the bedding would express the growth of the deposit according to the general principles enunciated above. In actuality, the bedding of these rocks usually parallels the existing surface of the earth and is in many places not so much expressive of the thickness of accumulation of pyroclastic materials as of the ruggedness and irregularity of the pre-existing surface.

On an irregular surface, due to gravitational forces, action of wind and water, and perhaps some other factors, the accumulation of materials will take place more rapidly in the hollows and at the foot of slopes than in other situations. Hence these irregularities are likely to become less and slopes will be reduced in steepness and height so that the surface will be less rugged than formerly. Thus, while the ash bedding in a small pre-existing hollow is at first parallel to the surface of the trough, higher beds show less sag and the effect of the irregularity decreases upward. The same effect is shown in

[12] Wentworth, C. K., Pyroclastic Geology of Oahu, Bishop Museum Bulletin 30, pp. 96-98, 1926.
See also, Wentworth, C. K., The Diamond Head Black Ash, Jour. Sed. Petrol., Vol. 7, pp. 91-103, 1937.

gradual fading out of the arched structure which commonly overlies a block of rock or any other protruding object which has been covered by ash. On surfaces of moderate relief such smoothing of the topography and the production of what the writer has called "mantle bedding" is dominant.

On the other hand, if ash deposits are laid down on pre-existing cliffs, or if pyroclastic materials accumulate to such excessive amounts in particular places that the angle of repose of the material is reached, bedding will be produced which is the counterpart of talus bedding for material of the same character. The slopes of this material will be mantled by new ash and will tend to be perpetuated since they are adjusted to existing conditions.

As in other sediments, pyroclastic accumulations show unconformities due to cessation of deposition and the intervention of other surface processes. Because such deposits are the product of rapid and unusual depositional agencies and are commonly somewhat unstable against the force of gravity, the work of wind, running water, or of the sea, they are subject to rapid slumping or erosion. Such erosion may be hastened by excessive falls of rain accompanying the eruption. Considerable channeling and other modification of their surfaces may therefore take place in a few days or even in a few hours and unconformable relations of a new series of deposits on an older may not indicate any significant difference in age. Much caution and search for soil zones or other more positive evidences is necessary in interpreting age relationships.

Ash deposits show various minor structures such as bomb sags, where falling bombs or blocks have broken through or depressed the newly fallen finer materials. These are commonly overlaid by beds showing a diminishing dome structure, the lower and upper beds together constituting a lenticular system enclosing the bomb or block. A slight raising of the beds in a cuspate configuration adjacent to the buried trunk of a standing tree or bush is commonly developed and has been called cuspate bedding. It may be due either to settling of the newly fallen ash or to the slight excess of material accumulation around the trunk.[13]

The fundamental character of the bedding is worthy of brief description. In general the individual beds are rather massive in structure and show little or no lamination of the type which would result if a depositing fluid were moving over the surface. Within the range of sizes being deposited at a given time there is little sorting by layers, large and small particles settling in random order. Changes to the material of an overlying bed are fairly definite but rarely very abrupt. Changes in the quantities of coarser particles take place more frequently than in finer materials so that the chief fluctuations in bedding are in the presence of occasional zones of greater or lesser thickness, in which coarse particles are bedded in a matrix of the type of material which is deposited continuously throughout the whole period. The successive waves

[13] Wentworth, C. K., Op. cit., p. 28, 1926.

of coarser material are evidently episodes or pulsations of more violent explosions during which the finer material continues to settle as before.

Fairly sharp changes of the type of material deposited take place where systems of talus beds are overlain unconformably by other material, or where shifts in the violence or direction of expulsion, or of the direction of the wind bring distinctly new types of detritus to a given site of deposition.

Names of Pyroclastic Rocks

General Statement

A review of pyroclastic nomenclature has been published elsewhere.[14] The following table, taken from the paper cited is an analytic scheme to incorporate the various types of pyroclastic rocks and show their several diagnostic features. There are several variable characters which determine the names of these rocks. These include size of fragment, shape of fragment, magmatic or pre-solidified origin, structure, presence or absence of crystallinity, and degree of induration. The incorporation of all these characters as primary headings in a simple tabular scheme is impossible and the form below was chosen in order to overcome this difficulty.

Table of Pyroclastic Rock Names

A. Grain is greater than 32 millimeters (1¼ inches).

1. Fragments are of material chiefly plastic at time of ejection and have forms, surface markings or internal structures assumed in response to forces acting during flight.

   Fragments are *Bombs;* varieties *Breadcrust, Spheroidal, Almond-shaped, Rotational,* Ribbon, etc.

   Aggregate or indurated aggregate is *Agglomerate, Essential.*

2. Fragments are composed of material chiefly plastic at time of ejection and have shapes, surface markings, or internal structures assumed chiefly in response to forces acting at time of detachment, or at, or after, landing.

   Fragments are *Driblets; aggregate* or *indurated aggregate* is *Driblet Lava,* or *Driblet Agglomerate.*

3. Fragments are composed of previously solidified volcanic rock of cognate origin and are in broken, angular forms.

   Fragments are *Blocks, Accessory.* Aggregate is *Volcanic Rubble, Accessory.* Indurated aggregate is *Volcanic Breccia, Accessory.*

4. Fragments are composed largely of non-cognate igneous rock or of any other sort of country or sub-marine rock, angular.

   Fragments are *Blocks, Accidental.* Aggregate is *Volcanic Rubble, Accidental.* Indurated aggregate is *Volcanic Breccia, Accidental.*

[14] Wentworth, C. K., and Williams, Howel, The Classification and Terminology of the Pyroclastic Rocks, National Research Council, Bulletin 89, pp. 19-53, 1932.

B. Grain is from 32 to 4 millimeters (1¼ to 1/6 inches).

1. Fragments chiefly of juvenile material.

   Fragments in general are *Lapilli, Essential*. Aggregate the same. Indurated aggregate is *Agglomerate, Essential*. If moderately vesicular, usually glassy, fragments and aggregate are *Cinders* and indurated aggregate is *Cinder Agglomerate*. If very light and cellular, usually glassy, material is *Lapilli, Pumiceous*, or *Agglomerate, Pumiceous*.

   If extremely tenuous (mostly retiform) and glassy, material is *Lapilli, Reticulite* or *Agglomerate, Reticulite*.

   If of crystalline structure, fragments are *Lithic Lapilli*, indurated aggregate is *Lithic Agglomerate*, both *Essential*.

   If formed from fine dust or ash through falling of raindrops through air or by nuclei rolling along ground, round pellets are *Accretionary, Lapilli, Essential, Accessory*, or *Accidental*, as case may be.

2. Fragments chiefly of previously solidified cognate igneous rock, usually angular.

   Fragments are *Accessory Lapilli;* aggregate is *Accessory Rubble;* indurated aggregate is *Accessory Breccia*.

3. Fragments chiefly of unrelated igneous or sedimentary rocks, commonly angular.

   Fragments are *Accidental Lapilli;* aggregate is *Accidental Rubble;* indurated aggregate is *Accidental Breccia*.

C. Grain is from 4 to ¼ millimeters (1/6 to 1/100 inch).

1. Fragments consist chiefly of juvenile material.

   Aggregate in general is *Coarse Ash, Essential*. If indurated is *Coarse Tuff, Essential*.

   If particles are mostly glass, usually somewhat vesicular, material is *Vitric;* if mostly crystals is *Crystal;* if mostly stony is *Lithic*.

   If particles consist of long threads of spun glass, aggregate is *Pele's hair*. If they are glass droplets, pendant from thread, or arranged in dumbell fashion, they are *Pele's tears*.

2. Fragments consist chiefly of previously solidified cognate igneous rock.

   Aggregate is *Coarse Accessory Ash* and indurated aggregate is *Coarse Accessory Tuff*, either is *Vitric, Crystal* or *Lithic*, according as particles are glass, crystals or stony.

3. Fragments consist of unrelated igneous or sedimentary rocks.

   Aggregate is *Coarse Accidental Ash;* indurated aggregate is *Coarse Accidental Tuff*, either is *Vitric, Crystal*, or *Lithic*, according as particles are glass, crystal or stony.

D. Grain is less than ¼ millimeter (1/100 inch).

1. Fragments consist chiefly of juvenile material.

   Aggregate is *Fine Essential Ash;* indurated aggregate is *Fine Essential Tuff*. Either may be *Vitric, Crystal,* seldom, if ever, *Lithic*.

2. Fragments consist chiefly of previously solidified cognate igneous rock, irregular angular.

   Aggregate is *Fine Accessory Ash,* indurated aggregate is *Fine Accessory Tuff*. Either may be *Vitric, Crystal,* or *Lithic*. Aggregate is also *Fine Volcanic Dust, Vitric, Crystal* or *Lithic*.

3. Fragments consist chiefly of unrelated igneous or sedimentary rocks.

   Aggregate is *Fine Accidental Ash*. Indurated aggregate is *Fine Accidental Tuff*. Either may be *Vitric, Crystal* or *Lithic*. Aggregate is also *Fine Volcanic Dust, Vitric, Crystal* or *Lithic*.

DISTRIBUTION AND STRUCTURE OF PYROCLASTIC FORMATIONS ON HAWAII

Classification of Formations

For the purpose of this paper a formation is defined as the identified product of a single eruption from one vent, or the combined and at present indistinguishable products of related eruptions from one or more vents of a genetic group. So far as possible such formations include various lithologic phases in one genetic group but lack of fossils and dependence largely on lithologic similarity for identification imposes considerable difficulty and with more detailed work revisions will doubtless be required. Pyroclastic deposits which have not been studied in detail are referred to as materials of a given area, such as Kohala pyroclastic materials, to avoid the prejudice which treatment as a formation might impose on future studies.

The ash deposits of Hawaii occur in different districts, in each of which certain features and modes of occurrence are dominant. In some districts there are several different formations and certain formations are found in more than one district (Figure 6). Cinder cones occur chiefly in the summit area of Mauna Kea, corresponding parts of Kohala and Hualalai domes, the Kapoho area (Puna), the Mauna Loa rift zones and at several points on the Mauna Loa coast. The relationship between cinder cones and ash formations has not in general been recognized in previous work on Hawaiian geology.

No wholly satisfactory subdivision of the pyroclastic formations has been devised. Material believed to be a genetic unit may show such variations in aspect in the proximal and distal portions that these merit separate descriptions. On the other hand analogous materials from different sets of eruptions may closely resemble one another. The following grouping is historical as far as possible and thus is potentially stratigraphic.

The oldest pyroclastic member known on the island is the Ninole tuff,[1] a part of the Ninole formation as described by Stearns and Clark.[2] Next younger than the Ninole tuff are lithologic units of which the age relations are not known with certainty. These are the Olaa agglomerate, the Waimea agglomerate and the Kohala cinder cone materials. The first two of these are older, respectively, than the Glenwood tuff and the yellow tuff phase of the Waiau formation. The Kohala cinder cone series is probably in the main

[1] For these thoroughly lithified members the writer prefers the term tuff, rather than ash as used by Stearns and Clark. The term ash appears permissible as an informal term, especially in connection with younger, less indurated masses like the 1790 formation but the writer regards the Ninole and Pahala pyroclastic members as tuffs.

[2] Stearns, H. T., and Clark, W. O., The Geology and Water Resources of the Kau District, Hawaii, U. S. Geol. Survey, Water Supply Paper 616, pp. 60-68, 1930.

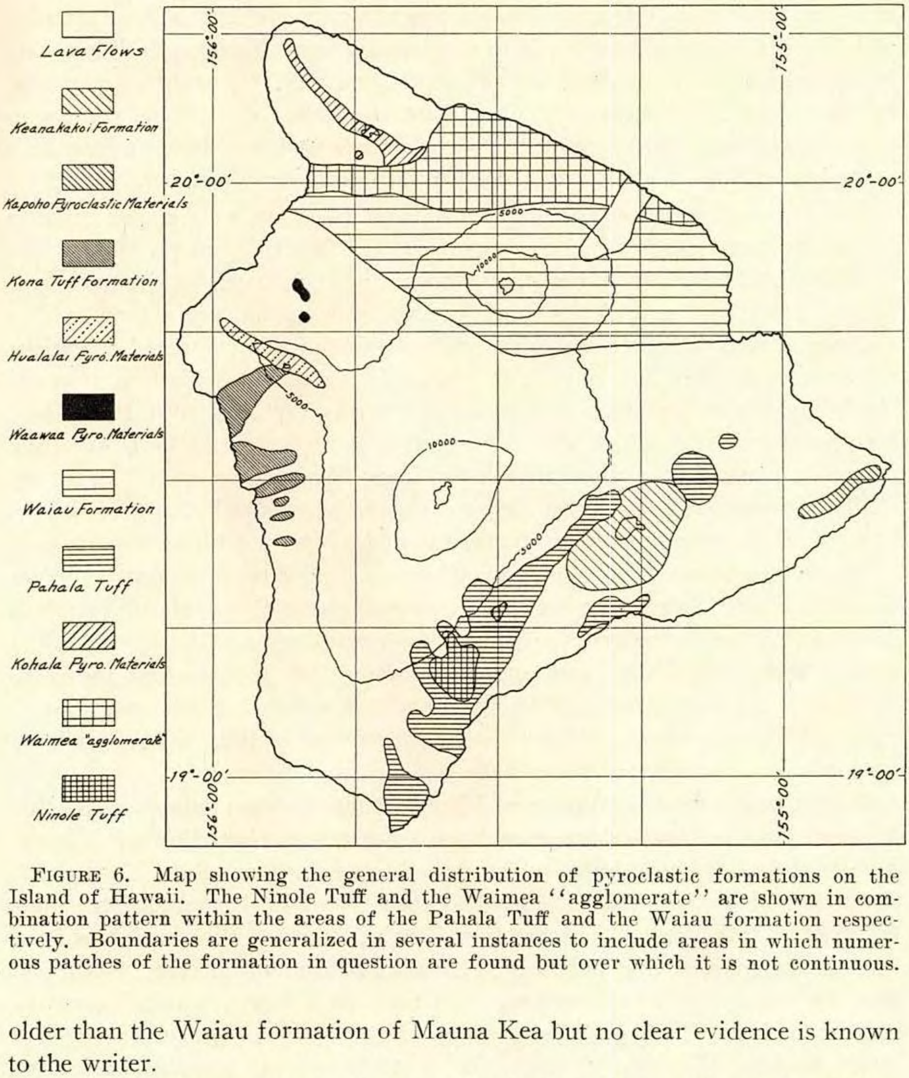


FIGURE 6. Map showing the general distribution of pyroclastic formations on the Island of Hawaii. The Ninole Tuff and the Waimea "agglomerate" are shown in combination pattern within the areas of the Pahala Tuff and the Waiau formation respectively. Boundaries are generalized in several instances to include areas in which numerous patches of the formation in question are found but over which it is not continuous.

older than the Waiau formation of Mauna Kea but no clear evidence is known to the writer.

The next younger pyroclastic formation is the Pahala tuff, and its equivalents as defined by Stearns and Clark. This consists of tuff beds interbedded with or capping Pahala lava flows. The yellow tuff deposits of Kalae, Kapukapu, Kilauea and Glenwood are considered to belong to the Pahala formation. The writer believes the Pahala tuff to have been derived from the numerous secondary vents on Mauna Kea and hence to be correlative with the mantle of tuff which covers the lower Hamakua and Keanakolu slopes and parts of the northwest Mauna Kea slopes as well as with the cinder cone formation of the Mauna Kea summit area.[3] Nevertheless it seems inadvisable

[3] This problem is discussed in detail in the section on the Pahala tuff which follows.

at present to extend the name Pahala formation to the Mauna Kea complex and likewise it seems inadvisable to displace the name Pahala which has long been used for the tuff beds of the Pahala district. In this connection it should be recognized that Stearns and Clark have used the name Pahala for a volcanic formation of which the tuff is only a small part, and hence the name is scarcely available to apply exclusively to any pyroclastic member.

From several standpoints the application of the name of a major dome to one of its component formations seems unwise, hence the name Mauna Kea is rejected. Though from the standpoint of the significance of the tuff cover of the lower northeast slopes in connection with agriculture a type locality and name from this district might seem best, this procedure would repeat the dilemma which now exists with reference to the name of Pahala. On the whole, therefore, it appears best to select a formation name from the Mauna Kea summit district which will call attention to the supposed locus of origin of the formation. For this purpose the name Waiau is proposed, from the shallow summit lake of Mauna Kea, a lake which lies in a hollow surrounded by great cinder cones and near the center of the Mauna Kea summit area.

The Waiau formation is here defined as consisting both of the central cinder cone phase and of the more remote yellow tuff phase of pyroclastic materials produced by explosive eruptions from numerous vents in the Mauna Kea summit area. The Pahala tuff component of the Pahala formation, the Glenwood tuff, and the Kapukapu tuff are correlated with it but these names have priority for local use and it appears best at present to treat them as distinct units.

Next younger than the Waiau and Pahala tuffs are the cinder beds of Puu Waawaa on the Hualalai slope and the Uwekahuna formation of Kilauea. Which of these is the older is not known. Stone[4] first named the Uwekahuna formation which is interbedded with Kilauean flows in the walls of the present Kilauea caldera. This formation clearly antedates the development of the existing major topography of the Kilauea district and is thus much older than the ash series, consisting largely of accidental debris, which lies on the present surface. The latter, comprising several distinct members, is typified by the so-called 1790 ash. Above the 1790 ash lies a small amount of ash from the 1924 eruption, and below it the products of several more ancient eruptions separated by long intervals, all of which apparently postdate the foundering of the larger Kilauea floor and establishment of the Uwekahuna bluff with a height much greater than at present.

The most recent pyroclastic activity on the west slope of Hawaii is that of the rift zone of Hualalai and of certain craters on the southwest rift of Mauna Loa. The thin and scattered remnants of the Kona tuff formation are probably derived from both these central cone activities.

[4] Stone, John B., The Products and Structure of Kilauea, Bishop Museum Bulletin 33, pp. 27-28, 1926.

The Kona ash formation escaped the attention of the writer during a brief reconnaissance of the Kona district but was later recognized by H. A. Powers, who has kindly contributed the brief description given below. This formation must be comparatively young since it mantles the Kona slopes of Mauna Loa and Hualalai on which many successive lava flows have been formed in recent time.

The ash of 1790 and earlier associated members are well exposed near the southeast wall of Kilauea near the pit crater of Keanakakoi, and the name Keanakakoi formation is here proposed for this series which consists of the 1924 and 1790 ash members and their earlier analogues. In part contemporaneous with these are the pyroclastic materials derived from various vents in Puna along the Kilauea east rift. For these the name Kapoho is used. There are native traditions of "liquid fire and stones" thrown from Kapoho crater in approximately the 14th century.[5]

The last pyroclastic series to be described is found in the various littoral cones and their local products. These are, in part, of historic date, and in part are quite ancient, some of pre-Pahala age being known, but all are characterized by association with the present coastline.

The Ninole Tuff

In the Pahala district, two, distinct, old series of lava flows have been recognized by Stearns and Clark (Pahala and Honuapo quadrangles). Associated with each of these are one or more beds of yellow and red tuff. The older lava series and associated tuff beds constitute the Ninole formation which is believed to be of pre-Pleistocene age.[6] The younger, the Pahala tuff, is considered by the same writers to be of Pleistocene age, though in neither case has unequivocal stratigraphic or paleontologic evidence been found.

The Ninole tuff is twelve feet thick at the type locality of the Ninole formation where it occurs about 500 feet below the top of a 1000-foot exposure. It varies in thickness from 2 to 15 feet. Since the absolute top or bottom of the Ninole series of lava flows is unknown its relative position within the larger formation has not been fixed. The Ninole basalt is considered by Stearns and Clark to be a part of the old Ninole dome which underlies the present Mauna Loa dome and probably came from a volcanic vent about eight miles southwest of Mokuaweoweo on the southwest rift. The basalt of this formation is now exposed in a number of small inliers which extend along the Mauna Loa slopes in the vicinity of Hilea and Wood Valley. The total area of exposure is not over seven or eight square miles. The outcrops occur in the sides or tops of island-like masses which consist of the protruding parts

[5] Jaggar, T. A., Seismometric Investigation of Hawaiian Lava Column, Seis. Soc. Amer. Bull., Vol. 10, p. 197, 1920.

[6] Stearns, H. T., and Clark, W. O., Geology and Water Resources of the Kau District, Hawaii, U. S. Geol. Survey, Water Supply Paper 616, pp. 60-61, 1926.

of a rugged topography, parts of the ancient Ninole dome, now generally surrounded and almost submerged by recent pre-historic flows from Mauna Loa. The tops of many of these "islands" are capped by Pahala tuff.

The Ninole tuff occurs at various places within the Ninole section and its surface occurrence is restricted to the Ninole terrane described above. The writer visited several localities where Ninole tuff was exposed but no attempt was made to map its outcrop and most of the data here presented are from the work of Stearns and Clark. The Ninole tuff consists of a fine-grained, dark red palagonitic material.[7] In places where it remains moist it is very durable and the walls of water tunnels cut in it stand for years without artificial support (Plate 1*A*). The attitude of the tuff bed is quite uniform, its dip being generally a few degrees to the southeast.

Little is known concerning the location of the vent from which the Ninole tuff was erupted. As mentioned above, the lavas of the Ninole dome dip away from a point some eight miles southwest of the present summit of Mauna Loa and this is thought to have been the position of the apex of the Ninole dome. Whether the closing stages of Ninole activity were marked by pyroclastic eruptions and the Ninole tuff derived from groups of central cinder cone vents on the Ninole dome, like those on Mauna Kea, or whether the Ninole tuff came from another such group, possibly even those of Kohala dome, is not known.

The Waimea and Olaa Agglomerates

For a number of miles northwest of Hilo the yellow tuff of the Waiau formation lies on weathered lava flows of the Mauna Kea series. A few miles southeast of Laupahoehoe near Honohina the same tuff lies on hummocky accumulations of agglomerate, which in places are 15 to 20 feet thick. Northwestward from Honohina the agglomerate nearly everywhere underlies the tuff and because of the thinning of the tuff is much more in evidence. The formation is apparently present along the entire coastal district from Honohina to the margin of the Waipio district and at the north it extends inland nearly or quite to Waimea. Hence the name Waimea formation is proposed (Honomu, Mauna Kea, Hamakua and Waipio quadrangles).

Very little work was done by the writer on the Waimea formation and the following description is based on a few observations along the highway from Honohina to Waimea. In places in the vicinity of Honohina the agglomerate lies in irregularly spaced mounds and is only partially covered by the thin mantle of tuff which occurs in the district. At an exposure a mile east of Laupahoehoe there are driblet lava flows associated with thick accumulations

[7] Palagonite is a red-brown, resinous, isotropic mineraloid produced by the alteration of basaltic glass. The alteration consists largely of hydration. Palagonite gives to the yellow and red basic tuffs their distinctive colors and has been described from Iceland and other regions of basaltic tuffs. The term has been in use since 1845 when it was first applied to Sicilian tuffs by Von Waltershausen.

of agglomerate. East of Kukaiau the topography is rolling and dominated by mounds of agglomerate which are only irregularly and imperfectly mantled by tuff. At two exposures east of Kukaiau, are steeply dipping beds of detrital material which consist of gray to lavender lapilli ranging to 16 and 32 millimeter sizes with weathered and cemented ash layers. West of Kalona Church there is a twelve-foot section of coarse agglomerate containing fragments a foot in diameter and showing a rudely bedded structure. All these materials are clearly of local origin but as a whole constitute a rather continuous and widespread formation.

Northwest of Honokaa on the Kukuihaele road, agglomerate is conspicuous in road cuts at numerous points. In some localities it lies in two distinct series. Similar material is exposed in road cuts along the Waimea road west of Honokaa at elevations mostly above 200 feet. At the Inoino Gulch crossing, the road cuts through several small cones of irregularly-bedded, purplish-gray agglomerate with fragments ranging to two feet in diameter. Several driblet flows interbedded at steep angles are contained in these cones. Thin remnants of yellow tuff of the Waiau formation pass over the tops of these piles.

Northwest of Honokaa, both above and below the road and over an area of a number of square miles, the slopes of the Mauna Kea dome are broken by numerous tiny hummocks and pits, of which a few are so situated as to be shown by closed contours on the Waipio topographic sheet, but of which the majority are too low to be indicated by contours at the 50-foot interval. Little study of this area has been made but the writer believes that these irregularities of surface are expressions of the widespread occurrence of the above described Waimea agglomerate. Since there appear to be on the island of Hawaii both true agglomerate formations and surface accumulations of unusually rugged and fragmental aa lava which resemble agglomerate, careful study of this material will be needed to determine its origin and its relations to other rocks of the region. Though according to the writer's casual observation this agglomerate shows rather uniform characteristics and relationships throughout the described range and is thought to be a genetic unit, it is quite possible that two or more distinct and unrelated rock series have been confused as one.

At a number of places under the Glenwood tuff along the Volcano-Hilo road and in various surface exposures inland from Olaa and Camp Two on the Waiakea Plantation Railroad is an accumulation of detrital material arranged in mounds five to twenty-five feet high[8] (Hilo quadrangle). The writer regarded it as a pyroclastic formation but more detailed studies by H. A. Powers suggest that it more probably consists of one or more very rugged

8 H. S. Palmer has pointed out that on the Waiakea Plantation loose rocks are piled in mounds in the course of clearing fields. Possibly a few mounds have been built or accentuated in this way but, as he states, this cannot apply to any in the Waimea area and to but few at Waiakea.

aa flows. Whether this interpretation is correct and also applicable to the Waimea agglomerate can only be determined by additional field work.

Kohala Pyroclastic Materials

Very little time was spent on the cinder cones of the Kohala summit area. No widespread, yellow palagonitic tuff was found which might have come from these cones. Whether a mantle of this type was formed and is now mainly buried beneath later flows or whether the quantities expelled were so small in amount as to form no recognizable mantle is not known. The district merits more extended study and it is probable that evidences of a much more complicated pyroclastic history than is now suspected will be found (Waipio and Kohala quadrangles).

Puu Kawaiwai is about five miles northwest of Waimea and is an elongated bowl with two high rim points. It rises about 250 feet above surrounding slopes. It is composed chiefly of agglomerate ranging to two-foot sizes with some material as fine as 8 millimeters. The whole is weathered to a deep red color. Along the next three or four miles of the road toward Kohala are numerous exposures of red and gray agglomerate ranging from 16 millimeters to 15 centimeters in size with interbedded driblet flows. North of Hoepa Church are several cones which show pronounced crescentic rims lying mostly on the northwest sides and indicating moderately fine material. Along the road southwest of Puu Honu are exposures of black, glassy cinders mingled with other beds of lithic lapilli and alluvial wash from above.

Near the crossing of Pohakuloa Gulch is a small cone showing lower layers consisting of yellow streaked, gray-black ash particles, ranging up to two millimeters, which dip in thin laminae 10 to 12 degrees toward the coast. These beds are overlain by lava flows and these in turn by several two- to three-foot beds of cemented lapilli. The lava flows are discontinuous and in places the cemented beds lie directly on the lower black ash. Cone 3068[9] and Lahikiola are both agglomerate cones so far as can be discerned from the road. A few rods north a four-foot section of 8 millimeter, lithic lapilli is exposed in a road cut.

Between Puu o Nale and the village of Kohala there are numerous exposures of detrital material which appears to be either true pyroclastic agglomerate or surface detritus from an old aa flow. In a few places, fine, sandy material which might be ash was seen but it seemed to be local in character. The writer believes that parts of the coarse material are of true aerial origin though the vents may have been secondary features of a thick lava flow, rather than true crustal vents.

[9] Throughout the following descriptions, various cones not carrying names on the U. S. Geol. Survey maps are indicated by the appropriate elevation figures, enabling them to be readily located on the proper topographic sheet.

Along the northeast Kohala coast the lava flows are deeply weathered and much of the height of the shore cliffs is cut in material which had probably already become weathered before marine invasion commenced. Casual observations lead to much doubt as to the possibility of so much weathering taking place while so small an amount of marine abrasion was accomplished. One is thus led independently to the hypothesis of recent subsidence of the Kohala mass which has already been suggested by Jaggar on the ground of the aggradation of Waipio Valley. Jaggar has observed and the writer also saw the large, weathered masses of coarse, bouldery alluvium which lie on the north bank of Waipio Stream near the Waima fork and which are clearly much more ancient than the principal flood plain deposits. All these facts suggest a more complicated physiographic history than has yet been elaborated. By themselves these facts point equally cogently to crustal depression or to the rise of sea level, and of course show the comparatively great age of the Kohala mass as compared to most of the remainder of Hawall.

The Pahala Tuff

General Statement

The Pahala tuff consists of several beds of yellow to dark red, fine-grained palagonitic material which are interbedded with or lie at the top of basalts of the Pahala formation as defined by Stearns and Clark.[10] It is found at the surface over extensive areas in the vicinity of Pahala, 21 miles southwest of Kilauea (Kilauea, Pahala, Honuapo and Kalae quadrangles). It is also found in the Glenwood district, the Kapukapu, Kaone and other localities in the vicinity of Kilauea, and at Kalae. Most of the Pahala formation is now buried by later lava flows from Mauna Loa and Kilauea vents and it occurs at the surface only in the areas which, because of their higher or more remote positions, have not been covered by these later lava flows. Erosion, which, in many parts of the earth, uncovers ancient formations which have been buried, is here negligible in amount and is confined to the immediate channels of a few streams.

The upper tuff bed, now exposed on the present surface in many places, is the basis for fixing the upper limit of the formation. This tuff bed is found to cap a number of parts of both the Kilauea and Mauna Loa domes, some of which were disturbed by faulting prior to the burial of adjacent areas by newer lavas. Hence the top ash bed marks the upper limit of a series which is unconformable beneath the recent pre-historic series and which is likewise unconformable on the inliers of the Ninole series. This stratigraphic unit is designated by Stearns and Clark as the Pahala formation. The conclusions of these writers, supplemented by his own field studies, lead the present writer

10 Stearns, H. T., and Clark, W. O., Geology and Water Resources of the Kau District, Hawaii, U. S. Geol. Survey, Water Supply Paper 616, pp. 60-65, 1930.

to regard the identity of the top member of the Pahala tuff series, together with other lower tuff beds, as they are exposed in cliffs, to be established from the Glenwood, Kapukapu and Kaone localities and the Keauhou inlier areas southwestward past the type locality to the Kahuku and Kalae localities. So far as known to the present writer there is no exposure of any considerable thickness of the Pahala series in the vicinity of Pahala, so that the exact vertical position of the internal tuff beds at the type locality is unknown.

As Stearns has pointed out, the top tuff member probably contains the products of Kilauean eruptions in its upper layers in its northeastern occurrences. It is evident on a little consideration that though single ash beds are extremely valuable for correlation in a volcanic terrane, it is not possible to assert that a thick ash bed everywhere includes the products of the same pyroclastic episodes. The reason for this is that without one other distinct and readily identifiable and aerial material interbedded with the ash, a given bed of the latter can only be separated from later beds in those regions where an important and long continued series of volcanic flows makes a complete cover over the earlier layer before the deposition of the later layer. Only a slight acquaintance with the limited areal extent of Hawaiian flows is required to appreciate how readily two ash beds might, in one region and on one dome, be separated by flows representing many tens or hundreds of thousands of years, and, in another district, be nearly indistinguishable parts of the same ash complex.

Indeed, the products of the 1924 Kilauean eruption now lie alike on surfaces and stratigraphic sequences representing widely different histories, and in those cases where the new materials are similar to the old, only a few years of weathering may be required to make the one quite indistinguishable from the other. These are the difficulties which lie in the way of bed-by-bed correlation of the contained tuff beds of the Pahala series shown in the Kahuku pali of the Mauna Loa dome and in the Kapukapu pali of the Kilauean dome. This problem will be alluded to again in another section.

The Pahala Region

The upper Pahala tuff, the only one exposed in the district under consideration is about 55 feet thick as exposed in a gulch on the top of Puu Enuhe.[11] This exposure is stated by Stearns to overlie immediately the Ninole basalt of Puu Enuhe and thus to be a "complete section of the top member of the Pahala formation." To the present writer and in view of the principles enunciated above it appears that this section of Pahala tuff in a situation inaccessible to Pahala lava flows, is probably not only a section of the top member of the Pahala tuff but an integrated section of all the ash which fell during Pahala time. It is not, therefore, strictly equivalent to the top member elsewhere but is equivalent to all the tuff members of the Kahuku section or

[11] Stearns, H. T., and Clark, W. O., Op. cit., p. 66, 1930.

of the Kapukapu section, combined (Kilauea, Pahala and Honuapo quadrangles).

The tuff of the Pahala series is described as having "uniformly fine-grained texture, although it is generally a little coarser than the tuff in the Ninole basalt. It shows very little cross-bedding but usually good laminations, indicating deposition only slightly affected by the wind. Its color is red or yellow. The yellow is limited to the semi-arid regions, and the red to the rain belt, indicating that the difference in color is due to the effects of climate and vegetation. The ash consists of comminuted particles of basaltic glass. In places on the slopes above the village of Pahala it resembles loess."

This resemblance to loess is also very striking in other places and is probably due to the similar mode of formation by the deposition of fine material in a porous configuration out of the atmosphere. In many places, lacking distinctive laminae of coarser capilli, it is difficult to distinguish primary tuff from an eolian derivative which some geologists might call loess. The red-brown silty material which forms the surface in the Kalae area has indeed been described as a loess by H. S. Palmer, who gives many interesting details on its occurrence and characteristics.[12] There is no doubt that considerable parts of the upper layers of the Kalae tuff complex are of truly subsequent, eolian origin and hence properly designated as an eolian tuff. Whether a material resulting from a fitful and more or less local rearrangement of fine-grained materials essentially during the course of an eruption should be called loess is a matter of opinion. The same is true of later eolian deposits of re-handled tuffaceous materials. The writer would be disposed to use the terms primary tuff and secondary eolian tuff for the rather difficultly distinguishable parts of the Kalae and Pahala units. To him the term loess has a regional and quasi-stratigraphic connotion in its ordinary North American and Eurasian usage which makes its use undesirable as a generic term for eolian silts of a given degree of fineness, though structural and textural resemblance of much of the Pahala material, both primary and secondary, to typical loess is quite evident. Application of the term loess thus hinges both in difficulty, in places, of separating secondary from primary deposits and an interpretation of the specific term loess. To the writer, while agreeing on the general facts, the term secondary eolian tuff preserves both the volcanic and eolian connotations, which he considers essential, without adding the objectionable regional and stratigraphic implications which the term loess carries for many geologists.

[12] Palmer, H. S., Loess at Kalae, Hawaii, Volcano Letter No. 350, Hawn. Volc. Obs., Sept. 10, 1931.

The following section of Pahala ash was measured by the writer at Maniania Pali southeast of Naalehu.

	Feet
Top:	
Brown-drab, dry, irregularly columnar soil	2
Yellow-cream-colored tuff at the top which grades downward to red-brown tuff at bottom. Calcareous plant stem casts in lower part. Material shows columnar structure in places	14
Dry, fairly hard, lavender-gray tuff	5
Base: Top of basalt.	
Total	21 feet

An incomplete section measured at a point southwest of the end of the spur track at Honuapo Bay is as follows:

	Feet
Top:	
Brown ash soil	1
Powdery yellow tuff	4
Somewhat cemented gray ash	½
Yellow tuff	?
Base: Concealed.	
Total	?

The two sections which follow are quoted from a report by Stone.[13] The first was measured in a dry channel near the northernmost tank on the Peter Lee Road.

	Feet
Top:	
Loose, ochre-yellow ash	13
Stratified, indurated, gray ash	15
Base: Not exposed.	
Total	28 feet

The second section was measured in a short valley just north of the Kau-Volcano road at an elevation of 2570 feet.

	Feet
Top:	
Loose, yellow ash	15
Well bedded ash, mostly gray	15
Slight unconformity.	
Light yellow ash, contains pebbles and seems to be reworked	2
Thin bedded, yellow and gray ash	4
Base: Not exposed.	
Total	36 feet

The general areal distribution of the Pahala formation is shown in Plate 1 of the report by Stearns and Clark. On this map are shown the areas where the Pahala series, capped by a greater or lesser thickness of the top ash, lies essentially at the surface; steep cliff faces show the Pahala series in section and contain commonly one or more component tuff beds.

[13] Stone, John B., The Products and Structure of Kilauea, Bishop Museum Bulletin 33, pp. 24-25, 1926.

The Kalae Region

The period of historic and recent pre-historic lava flows from Mauna Loa and Kilauea vents has been essentially free from explosive episodes of sufficient magnitude to produce widespread and thick ash beds. In the course of this period much of the surface of the Mauna Loa and Kilauea domes has been covered by lava flows, which in their entirety, both pre-historic and historic, have been designated by Stearns as the Kamehame Basalt.[14] As a result the only parts of Mauna Loa or Kilauea where ash formations are known, with the exception of the recent Kilauean ash formations in the immediate vicinity of the Kilauea caldera, are those localities which for one reason or another have been islands in a sea of Kamehame flows. Some of these are true kipukas (Hawaiian word referring to an area of older land surface surrounded by the lava of a new flow), and the others differ only in that they are larger areas surrounded not by the lava of a single flow but by several flows and in some instances bounded by the sea along the present coast (Honuapo and Kalae quadrangles).

Some of these areas were left as kipukas because they are higher than surrounding areas (the analogues to nunataks) but others are not higher and have been avoided by the lava flows because of increased retardation at certain points by causes not always readily discernible. It is easily seen around the margins of recent flows as well as by those who have seen flows in progress that a moderate amount of retardation of the lower part of the front of a flow which has nearly reached its limit of advance effectually blocks the flow at that point. This is because at this stage the flow largely moves on the small amount of fluid in its lower portion and if this be slightly retarded so as to congeal, the entire thickness of the flow is blocked. Flows which are slowly advancing in their lower portions do not commonly fill a trough in which they are contained with a level surface out to the banks on either side, but usually show a lateral "moat" between the flow and the bank. This is because the foot of the margin of the flow was retarded by the first few feet of the rising ground and the upper part of the flow at once formed a permanent talus facing the higher part of the bank or other barrier. The relations are not unlike those shown by the lower ends of valley glaciers and for somewhat analogous reasons.

The largest of the areas in which the Pahala tuff lies at the surface is Kalae. The western edge of this area consists of the fault scarp known as the Kahuku escarpment, or Pali Kulani. This forms essentially the eastern margin of the Mauna Loa Southwest Rift province at the south point of the island. Much of the mass of the Kalae region was built of Pahala flows from vents in the southern part of the southwest rift zone, so far as can be judged from its present slope and southern extension. When the faulting occurred and the

[14] Stearns, H. T., and Clark, W. O., Op. cit., p. 69, 1930.

larger part of the zone from which the flows had come was downthrown, the upthrown side, with its higher part immediately adjacent to the fault scarp, naturally became an area somewhat inaccessible to flows, either from vents on the adjacent, downthrown rift zone or from vents higher up on the Mauna Loa dome. As a result this region has not been deeply buried by Kamehame flows, though a part of its surface has been veneered by such flows. The chief remnants of Pahala surface consist of a strip about a mile wide which is adjacent to the escarpment at the west edge, a somewhat narrower strip extending southeastward nearly to Kaalualu on the coast and a number of smaller coastal kipukas between Kaalualu and the south point of the island.

The cap member of the Pahala tuff in the Kalae region ranges from 6 feet to 25 feet in thickness and is exposed at many points around the coastal margin and along the edge of the Kahuku escarpment as well as in a few deep gulches which streams have cut through it (Plate 1*B*).

There are many different phases of the pyroclastic material of Kalae and these at first appear to be most confused in their arrangement. However, there appear to be a few principal types. The oldest of these is a hard, lavender-colored tuff which breaks into small irregular blocks and is characterized by much calcareous cement. In most places where the base of the section is reached, especially in localities not on the coast, a few feet of this tuff is found to lie directly on the basalt. The next younger material is a dark brown or red, compact, massive tuff which commonly contains numerous stem casts. Its top is commonly marked by several inches of calcareous laminae of secondary origin (Plate 1*C*). Above this is a lighter, more powdery, yellow material of which the origin in part is in doubt. In places it appears to be entirely secondary, eolian tuff. In others a part of it more closely resembles the dark tuff below and only the upper part appears definitely to be eolian. This material is commonly of columnar structure and shows much resemblance to loess. Above it there commonly appears a thin band of black sand with olivine fragments. In places this is practically the top of the section; in others a few inches of yellow eolian tuff overlies it. Locally, thin flows of basalt, 6″ to 24″ in thickness, are found overlying the uppermost eolian tuff and appear to come from tiny dikes associated with a series of small spatter craters which are found at a number of points south of Kamaoa Homesteads.

The following sections will indicate the general character:

Section 1 Mile East of Kalae on Shore of Kaulani Bay

Top:	Feet	Inches
Golden yellow, wind-blown dust, containing lenses of dark lag sand with much olivine (Post-Pahala)	1	6
Fine-grained, earthy tuff, dark red-brown when wet, yellow-brown when dry, contains calcareous stem casts 1 to 2 millimeters in diameter	2	6
Base: Consists of lava blocks, possibly a beach shingle.		
Total	4 feet	

SECTION AT HANALUA 1½ MILES EAST OF KALAE

Top:	Feet	Inches
Light to yellow-buff silt, with marked vertical columnar, loess-like structure in places. (In part eolian?)	6	
Thin bedded, white flaky calcareous crust		3
Dark red, hard, massive tuff with ramifying slender calcareous casts	?	
Base: Concealed.		
Total	6 feet	3 inches

SECTION IN EDGE OF LUA POAI 1 MILE SOUTH OF KAHUKU RANCH

Top:	Feet	Inches
Recent washed material near margin of funnel	2	
Old, ash-covered surface with humus		3
Yellow tuff, poorly exposed (Pahala)	10	
Granular, resin-colored, olivine tuff (Pahala)		6
Yellow tuff (Pahala)	5	
Compact, lavender tuff (Pahala)	5	
Base: Consists of basalt flows.		
Total	22 feet	9 inches

SECTION AT 350-FOOT CONTOUR ON KAHAWAI KALONO

Top:	Feet	Inches
Thin, discontinuous cover of eolian yellow silt		6
Basalt from dike		6
Columnar yellow tuff, probably eolian	4	
Zone of calcareous crusts		4
Yellow tuff (Pahala)	2	
Dark buff tuff (Pahala)	1	
Base: Concealed.		
Total	8 feet	4 inches

Near the top of the uppermost yellow tuff member of this section and also at the middle of the same bed is a zone of discontinuous lenses and pockets of gray-black loose ash. Similar black ash lenses are found at many other points in the Kalae region near the top of the eolian tuff.

SECTION ON SAME STREAM CHANNEL, ⅓ MILE SOUTH

Top:	Feet	Inches
Basalt from dike, average thickness	4	6
Yellow tuff, possibly eolian	4	
Massive buff tuff, with calcareous crust at top (P.)	1	6
Irregularly crumbly, lavender tuff in places with a gray ashy phase (P.)	3	6
Base: Concealed.		
Total	13 feet	6 inches

SECTION ON EAST COAST, ⅓ MILE NORTH OF AWAWALOA

Top:	Feet	Inches
Gray humus and eolian silt		4
Yellow-buff material with fragments of basalt up to 32 mm. in size	2	
Gray, cindery ash, dull basalt fragments and olivine	1	
Basalt, in two flows	6	6
Yellow tuff (P.)	6	
Base: Concealed.		
Total	15 feet	10 inches

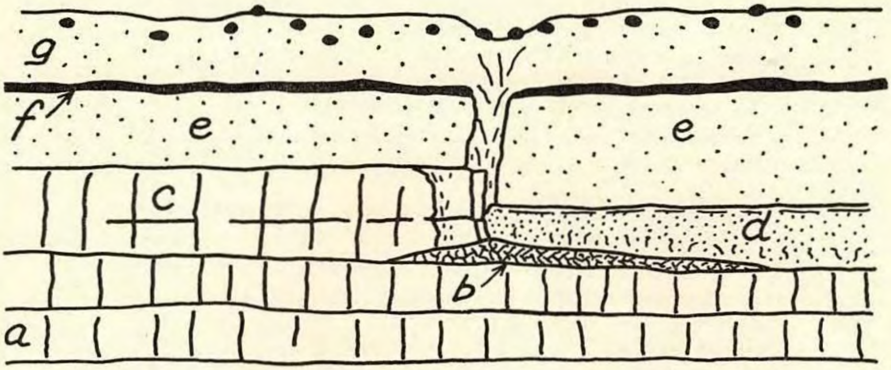


FIGURE 7. Section at top of pali at west margin of Kalae. (*a*) basalt flow, (*b*) lavender, calcareous tuff, (*c*) basalt flow which appears to overlap and postdate (*b*), (*d*) normal yellow tuff, (*e*) yellow tuff with calcareous stem casts, may be eolian, (*f*) one to two inch zone of black, vitric ash, (*g*) eolian yellow tuff. Total thickness about 15 feet.

On the west coast of Kalae, about three-fourths mile north of the lighthouse, a section was seen which indicated the following history (Figure 7). An upper basalt flow is later than the lavender and the lower part of the yellow tuff, and flowed down a valley cut in these. Then followed the deposition of the remainder of the yellow tuff. Still later a thin layer of the black ash was drifted over the surface, probably more or less locally at the mouth of the Kahawai Kalono, aided by alluvial transport. Finally the upper layer of eolian tuff was deposited, a prcoess which may still be in progress to some extent. It is regarded as a possibility that the upper part of the yellow tuff beneath the black ash layer is also eolian.[15]

At several points along the above-mentioned stream channel where Kamehame aa lava is exposed in the east bank, its base rests on buff tuff at a level considerably below the top of the eolian material of the west bank. It appears from this and other evidence that much of the eolian material has been deposited after the placement of the aa flows.

South of the Kamaoa Homesteads is an area characterized by low dunes of black ashy sand which contains much glass and olivine. The black sand cover is thin and the underlying terrane is composed of yellow silt or tuff. In places there are alternating layers of these two materials in eolian deposits. The source of the black sand is not known with certainty. It was evidently the product of an explosion late in post-Pahala time. A number of littoral ash and tuff craters formed by lava flows entering the sea during Kamehame time are

[15] Palmer has described small carbonaceous lenses in the "loess" section in this vicinity. The writer also saw several thin layers of humus material in sections at Kalae but was more impressed by the olivine and black glass content of certain dark layers. There is no doubt that both materials are present and both imply a break in the deposition of yellow ash, either secondary or primary. (Volcano letter 350 and personal communication.)

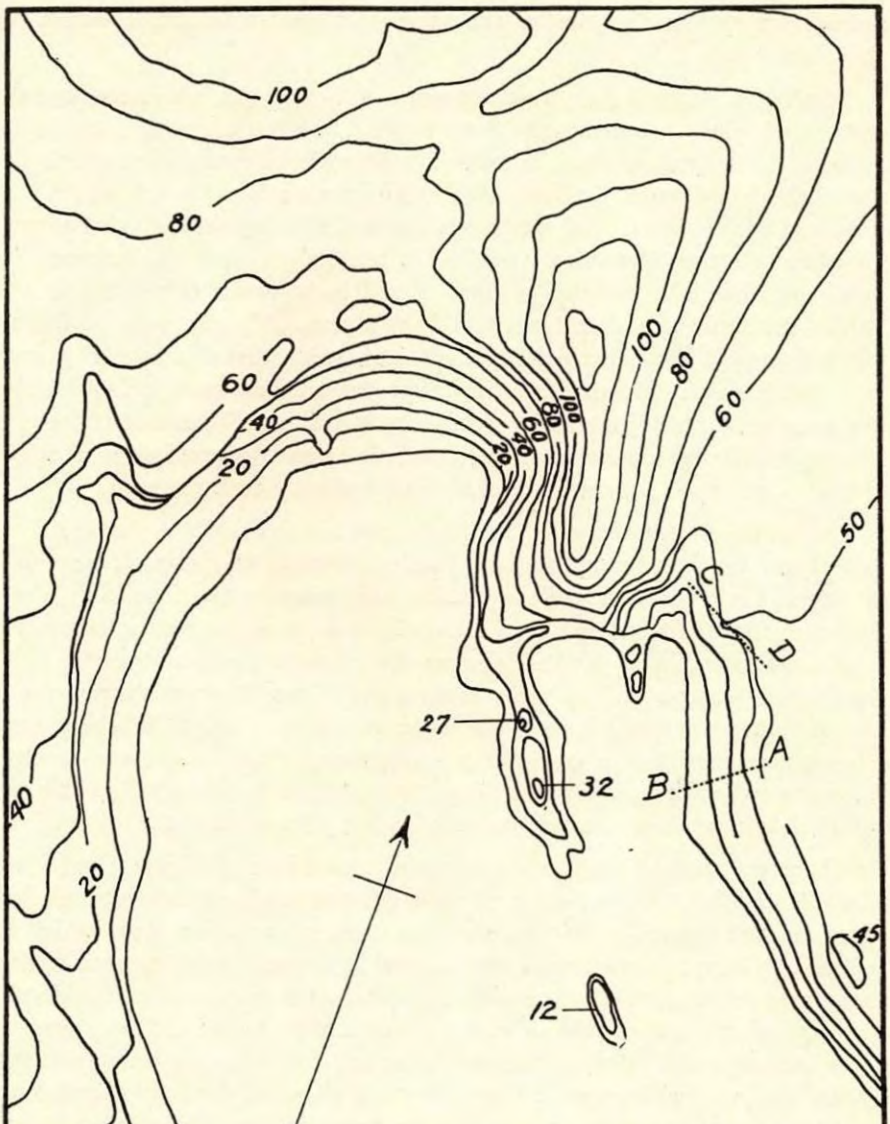


FIGURE 8. Topographic map of small bay at Puu o Mahana, east of Kalae Point. Contour interval 10 feet. Broken lines show the location of sections reproduced in Figure 9.

found northeast of this locality and some of these are probably sources for this black ash.

South of Kahuku Ranch are a number of pit craters of which the origin is not entirely clear. According to Stearns and Clark the largest and most symmetrical of these, Lua Poai, is the result of a phreatic explosion which followed the deposition of the lower 20 feet of Pahala ash and which was in turn followed by deposition of about 10 feet more of Pahala ash.[16] If this be true, the date of crater formation would be in late Pahala time; if, however, the tuff which overlies the small amount of visible explosion debris is eolian in origin, the crater may date from post-Pahala time. The character of the upper tuff has not been clearly determined but it seems that this possibility must be borne in mind. Moreover, to the writer it seems important to indicate that the amount of explosion debris in evidence is very small and that it does not seem plausible to assume that the crater is essentially explosive in origin, though a moderate amount of explosion undoubtedly took place.

One of the most interesting localities in the Kalae district is the cone, Puu o Mahana, which is located about 2½ miles northeast of Kalae. This cone is a littoral explosion cone built in Pahala time prior to the deposition of the lavender tuff. The relationships shown here were so interesting that a day was spent in making a detailed base map by Brunton Compass traverse on an improvised plane table. This map is shown in Figure 8, where the position of the sections shown in Figure 9 are indicated. The principal lithologic units shown here consist of a gray Mahana agglomeratic tuff, a Mahana basalt, a lavender tuff with an associated gray-green sandy ash, a buff tuff, a thin bed of black ash overlain by a few inches of eolian yellow silt at the top.

Characteristic relationships are shown in the sections of Figure 9 and Plates 2*A*, 1*D*, and 3*A*. Apparently late in the effusive epoch of Pahala time a lava flow reached the sea at this point and entered an explosive phase which resulted in a cone of agglomerate surmounted by a considerable amount of finer gray ash. As might be expected in such a case, there was a considerable amount of cliff-cutting and slumping in the new material. After a time the lava became sealed off from the sea water and entered again on a quiet flow phase, the lava in places cascading over steep slopes of the newly eroded tuff and agglomerate. It appears that another explosive phase followed and gray-green ash was deposited in the vicinity. Lying on, and in some places apparently interbedded with the gray-green ash, is a bed of lavender tuff which appears to be identical with that found in many places at the base of the Kalae ash series. By its relation it might at first appear that the lavender tuff is a product of the Mahana explosions but since it has been found at points several miles northeast of Mahana as well as westward in Kalae and that it everywhere has a uniformly fine-grained texture, it appears most probable that it

[16] Stearns, H. T., and Clark, W. O., Op. cit., pp. 154-155, 1930.

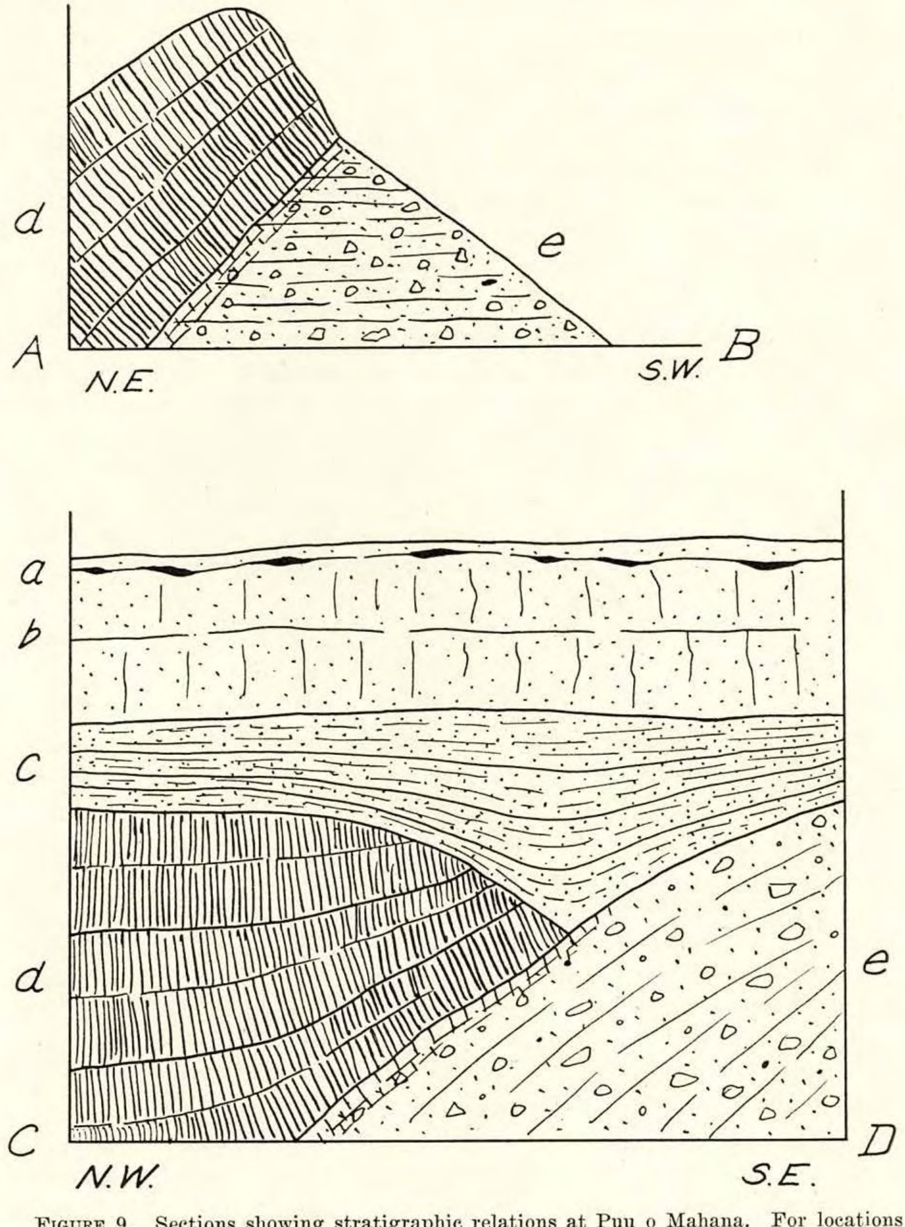


FIGURE 9. Sections showing stratigraphic relations at Puu o Mahana. For locations see Figure 8. *a*, eolian yellow silt; *b*, buff tuff; *c*, lavender tuff; *d*, Mahana basalt; *e*, Mahana agglomeratic tuff.

is a product of a more remote vent. If it was not deposited almost simultaneously with the upper gray-green ash it must have come very soon after.

After these events there was deposited a thick bed of buff tuff, which now carries stem casts and a calcareous crust, and this is overlain by another bed of buff tuff with fewer stem casts and capped by a zone of black ash and a few inches of eolian yellow tuff. It is thus apparent that the normal section of Kalae, commencing with the lavender tuff, lies above the local Mahana series. Lava flows of Kamehame series have been laid down over this Pahala series at the west side of the bay which the sea has cut in the center of the Mahana cone.

Palmer has recently described tree moulds and carbonaceous soil zones in the Kalae area which suggest that at a certain period in the past vegetation grew more vigorously than it now does, and also that a large part of the Kalae buff silt may be of secondary eolian origin.[17] The writer recognizes the evidence pointing to extensive eolian drift of tuffaceous material but is most impressed by the similarity of sequence of the pyroclastic beds in the Kalae area and in the apparent indication of successive pyroclastic episodes. However, it might well be expected in this southwesternmost area of the Pahala ash that a larger percentage of secondary tuff would be found and that the discrimination of primary and secondary beds would be most difficult.

The Kilauea Region

In this section are described those Pahala occurrences which are found on and near the Kilauea dome, with the exception of those of the Glenwood locality (Kilauea and Puna quadrangles).

The existence of a cap of yellow and red tuff on the summit of Puu Kapukapu as well as on the surface of Puu Kaone and in a number of kipukas on the Mauna Loa slope northwest of Kilauea has been known for a great many years and various authors have speculated as to its origin. The chief occurrences have been briefly described by Stone.[18] This yellow tuff is found not only as a cap on early lava terranes but also is exposed in the face of Puu Kapukapu, at a number of horizons several hundred feet below the top, and similarly interbedded in old flow sections in other cliffs of the district. Because of the generally local character of lava flows it is evident that in places the whole series of ash falls of later Pahala time have been combined in a single tuff bed lying on the surface of the latest Pahala flows of that particular locality, whereas in other places where lava flows intervened the same ash falls have formed several tuff beds separated by fairly thick sections of lava flows.

[17] Palmer, H. S., Loess at Kalae, Hawaii, Volcano Letter No. 350, Hawn. Volc. Obs., Sept. 10, 1931.

[18] Stone, John B., The Products and Structure of Kilauea, Bishop Museum Bulletin 33, pp. 24-27, 1926.

According to Stone, the Pahala tuff may reach 95 feet in thickness in a scarp back of the Kapapala Halfway House, though it is possible that faulting has produced some duplication. According to Noble, as quoted by Stone, the ash has a maximum thickness of 75 feet. Stearns and Clark describe the Pahala ash as having a total thickness of 55 feet. In view of the conditions under which the tuff has been accumulated and subsequently eroded the difficulty of determining a maximum or a normal total thickness is readily appreciated.

The mode of occurrence of the yellow ash of the Kilauea district in relation to the structure and history of the region is precisely the same as in the Pahala and Kalae districts, though it should be recognized that the very relationship of the ash has been essential in interpretation of this history. Three types of occurrence are found: first, those on the surfaces of elevated fault blocks or of non-elevated areas which for other reasons have not been submerged by late lava flows. In the second type, a similar cap of yellow tuff is seen to overlie an early lava series and to be in turn capped by late flows, the exposure being near the top of a cliff not covered or only partly covered by late lava flows. In the third type the yellow ash is interbedded in an early lava series which may or may not be capped, either by more yellow tuff or by the late lava.

It appears, therefore, as interpreted by Stearns, that the cessation of ash falls of this type marked the end of an epoch which he has called Pahala time. Since the close of Pahala time, great quantities of basalt of the Kamehame series have been poured out from vents on the Mauna Loa and Kilauea domes and large parts of the area once mantled by Pahala tuff have thus been buried beneath lava flows.

The easternmost exposure of Pahala tuff known in this vicinity is in the face of Puueo Pali two miles north of Keauhou at an elevation of about 1000 feet. Here there are at least two tuff beds in the upper part of the cliff. The uppermost one is at least 10 feet in thickness and is overlain by 40 to 50 feet of post-Pahala lavas which cascaded down the face of the pali. Makahanu Pali to the west is likewise veneered by post-Pahala flows but none of the tuff which must lie beneath it was seen.

Next westward is the exposure of beds which cap the summit of Puu Kapukapu and the exposure of the edges of several beds which are interbedded with Pahala lavas in the face of Kapukapu. The tuff which caps Puu Kapukapu is about 24 feet thick at one point. The lower portion is in part grayish and ash-like in texture but this grades upward into a weathered, yellow, palagonitic tuff. At the top 6 to 8 inches of eolian yellow dust lies under the grass roots, this material being underlain by about 4 inches of gray-black sandy ash similar to that seen in the Kalae district. The latter material is possibly part of the Keanakakoi formation.

In the face of Kapukapu, four tuff beds are about two-thirds of the height of the cliff above sea level, hence about 300 to 350 feet below the top (Plate 3*B*). These beds were estimated to be not less than 10 to 15 feet in thickness. The eastern end of one of these was examined and found to consist of blocky, yellow tuff marked by grayish layers of somewhat more ashy texture.

The eastern margin of Puu Kaone is a fault scarp trending northeast. Northwest of this cliff the summit of Kaone over an area of about one-fourth square mile is capped by a mantle of 35 to 40 feet of alternating gray and yellow tuff beds. At one point in the seaward face of Kaone six feet of tuff is capped by a four-foot lava flow below the summit section. The areas of Pahala rocks in the vicinity of Kapukapu and Kaone have been mapped by Stearns.[19] The actual areas of Pahala tuff exposed in the district are much smaller than those shown for the Pahala formation because of the very slight areal exposure of the tuff in the cliff faces. In the lower slopes of the kipukas proper the areas of tuff constitute nearly the whole Pahala surface.

According to Stone, there is a section of at least 60 feet of yellow and gray tuff exposed in the face of Hilina Pali southwest of Kipuka Keana Bihopa.[20] This exposure was seen by the writer from a distance but was not visited. Stone also reports ash beds similarly exposed in other parts of the Hilina Pali and in the Kukalauula Pali (spelled Kulalauula in Stone's report but doubtless a misprint). At several of the exposures of tuff in Hilina Pali it may be plainly seen even from a distance that these are at or near the top of an ancient lava series (the Pahala), since cut by normal faults, and the resulting scarps now smeared by post-Pahala flows which have capped the tuff surface.

With the exception of the Glenwood districts, no other exposures of Pahala tuff are known on the Kilauea dome. The remaining exposures in the Kilauea region are on the margin of the Mauna Loa dome. Northwest of Kilauea Crater there is a total of about a dozen small grass-covered kipukas which exhibit a deep soil and stand in sharp contrast to the surrounding lava flows. The largest of these areas is nearly two miles long and somewhat less than half a mile in width. The smallest is about 1/10 mile in diameter. Kipuka Ki, Kipuka, Puaulu, and Bird Park Kipuka are among these areas and all are mantled by several feet of yellow Pahala tuff, though well exposed sections are difficult to find.

Southwest along the margin of the Mauna Loa dome are several more such kipuka areas of Pahala tuff. They become larger in the vicinity of the Kapapala Ranch where they merge into the larger patches of the type locality of the Pahala formation. At several places thick sections of Pahala tuff are exposed in situations where the cascading Mauna Loa flows have not completely covered the face of the low pali which forms the Mauna Loa margin. At elevation 2552, southwest of the Halfway House, both Stone and the writer

19 Stearns, H. T., and Clark, W. O., Op. cit., Plate 1, 1930.
20 Stone, John B., Op. cit., p. 25, 1926.

measured a section consisting of about 6 feet of yellow and gray ash overlain unconformably by 12 to 15 feet of mostly gray laminated ashy tuff, above which in turn is about 15 feet loose, yellow tuff. The upper part of the lower member contains small fragments which Stone considered to be pebbles and indicative of reworking but which the present writer regarded as lapilli contemporaneously deposited.[21] Similar exposures are found at several points farther southwest. Here, as elsewhere in the Kau district, the Pahala tuff is found typically on the non-buried edges of ancient upthrow blocks and interbedded in the lavas which form these blocks.

THE GLENWOOD REGION

For about ten miles along the volcano road from Hilo to Kilauea in the vicinity of Glenwood and Mountain View there are thick exposures of a red-brown earthy, laminated material which has been recognized by several observers as a weathered volcanic ash or tuff, and which is considered by the writer and others to be the equivalent of the Pahala tuff.[22] There appear to be two separate areas of tuff and the total area underlain by it is probably about 25 square miles. Like other areas of Pahala tuff which lie to the southwest, the Glenwood occurrences consist of a large and a small kipuka, areas which have escaped burial by recent Mauna Loa and Kilauea flows and which hence are still mantled by the yellow tuff. On the north and west the Glenwood tuff district is bounded by Mauna Loa flows and on the south and east by Kilauea flows (Puna quadrangle). At its southwest margin where it is overlain by Kilauean flows, these are in turn overlain by a thin mantle of not more than one or two inches of Kilauean ash of the 1790 and earlier eruptions. This ash doubtless continues as a thin film on the Glenwood tuff but is scarcely distinguishable in the field.

The maximum thickness of the Glenwood tuff is apparently about twelve feet, though it is usually about nine or ten feet thick. It is commonly a sticky, moist, dark red or brown material showing a faint horizontal banding. In some places it is partially dried out and becomes more porous by the development of contraction jointing and a pellet structure. Some parts of it are dark drab or nearly black in color. In some exposures fairly distinctive layers an inch or more in thickness are found which consist of typical resin-colored palagonite. There are also a few places where rather distinct layers of slightly granular, gray, ashy, material are to be seen which still further indicate its pyroclastic origin.

Finch has called attention to an unconformity near the top of this ash which is indicated by a dark humus layer and the remains of tree ferns.[23] No de-

21 Stone, John B., Op. cit., p. 25, 1926.

22 Stone, John B., The Products and Structure of Kilauea, Bishop Museum Bulletin 33, pp. 25-26, 1926.

Finch, R. H., Unconformity in the Ash Deposits near Glenwood, Hawaiian Volcano Research Association, Volcano Letter No. 21, May 21, 1925.

23 Finch, R. H., Loc. cit., 1925.

tailed study of sections in this tuff was made by the present writer, but if it is the equivalent of all or part of the Pahala ash series, as seems most likely, it is to be supposed that a number of separate ash falls are represented by it and, since it is located in a district of heavy rainfall, it is very likely that a number of humus bands will be found on more detailed study. Though the Glenwood tuff, because of its climatic situation, is much more weathered than the corresponding ash of the Pahala and Kalae districts, it is probable that even now, in spite of considerable alteration, it would show the character of fine powdery dust like that of the Pahala, Waikii or Humuula districts if the rainfall were reduced to a small fraction of its actual value in the Glenwood locality.

The Glenwood tuff in places rests on basalt flows, and in others rests on lenses and low mounds of "agglomerate." The latter was at first thought to be true pyroclastic agglomerate and is identical with the "agglomerate" which underlies considerable areas in the vicinity of Ferndale, Olaa, and along the Waiakea Plantation Railroad. The areas underlain by it are kipukas surrounded by subsequent flows and are characterized by an irregular topography which is only slightly dissected. In detail the topography consists of numerous mounds scattered over the country, the individual mounds being five to twenty-five feet in height, and irregularly spaced from fifty to two hundred feet apart. It was at first thought that these mounds of detrital material might represent individual volcanic vents fed by dikes and producing a detrital driblet lava which covered the entire terrane.

More extended study by H. A. Powers has, however, led to the conclusion that at least part of this material and its characteristic topography are in reality parts of a tremendous and very tumultuous aa flow.[24] In any case, the "agglomerate" terrane is the oldest surface in the southeast part of Hawaii and cannot be younger than early Pahala. More likely it is of pre-Pahala age and roughly correlatable with Ninole time. The Olaa "agglomerate" is overlain by the Glenwood tuff, the latter by Mauna Loa and Kilauea flows, and these in turn by the ash of the 1790 series. In places where the Glenwood ash lies on basalt flows it is not clear whether these flows are essentially contemporaneous with the Olaa "agglomerate" or if they are separated from the "agglomerate" by a considerable time interval and hence probably early Pahala in time. No sections were seen in which lava flows lie between ash beds of the Glenwood type in the district but this may be due to the lack of a dissection adequate to penetrate even surface flows to depths of more than a few feet. However, the general conformity between the top of the Olaa series and the surface flows of Mauna Loa and Kilauea, with the interlaminated Glenwood ash suggests that it is unlikely that an unconformable Pahala series of flows could exist in this district and nowhere be exposed in such a way as to show its relations.

[24] Powers, H. A., Personal communication, 1930.

The Waiau Formation

General Relations

As stated above, the Waiau formation includes all those pyroclastic materials which are believed to have been produced at the numerous secondary vents within the Mauna Kea summit areas, as well as at a few vents now marked by cinder cones some distance outside the summit area on the Mauna Kea dome. This formation may also include the tuff member of the Pahala formation of the Kalae, Pahala, Kilauea and Glenwood areas though these have been described in another section under the designation Pahala tuff.

With the exception of the above-mentioned areas of southeastern Hawaii, the Waiau formation is confined to six of the geomorphic divisions of Hawaii, the Mauna Kea summit area, the Northwest Mauna Kea slopes, the Hamakua and Keanakolu slopes, and the Waimea and Humuula saddles. Except for a few places where Mauna Kea cones have been surrounded by Mauna Loa flows in and northwest of the Humuula saddle province the Waiau formation is buried under more recent Mauna Loa flows along the entire Mauna Loa-Mauna Kea boundary from Hilo to Puako.

The Waiau formation shows two principal phases, though each is somewhat variable in its own area. The definite cones which surround vents are composed chiefly of coarser materials which, though much weathered, have not become palagonitized and indeed in part consist of lithic components. In places this type of material extends for considerable distances away from the cones and the non-palagonitic products of numerous vents form a mantle covering large areas. At greater distances from the source vents the Waiau formation consists mostly of palagonitic tuff, generally fine-grained and more or less consolidated, according to climatic and hydrologic conditions. In many places it is rather thinly laminated so as to indicate its derivation from a great number of eruptions within the same general area. In places the phase which is dominantly palagonitic and has generally been known as yellow ash, yellow dust, etc., shows layers of coarser material which still retain in part the glassy character of the original small basaltic lapilli. In other places the beds of non-palagonitic proximal material are locally altered to yellow or brown or lavender tuff of palagonitic character.

In some districts the two different phases are more or less irregularly or unconformably interbedded in a very local or provincial fashion, so as to suggest that in the one episode the source was nearby or more favorably to the windward, and in the other more remote or to the leeward. Because of this provincial character and the difficulty of identifying stratigraphic components over large areas, it has not been possible to find any generally applicable division of the Waiau formation into subordinate members.

In the past, the close relationship between the black ash and cinder phases of pyroclastic rocks and the yellow, buff and red palagonitic phases have not been generally recognized. Thus Stone implies that the summit cones of Mauna Kea could hardly have been the sources of the Pahala tuff because "they are not ash cones, as has often been supposed, but cinder cones quite like those at the sources of many Mauna Loa flows."[25] Stearns recognized the probability that the Pahala tuff was derived from Mauna Kea vents but points out that many of the cones on Mauna Kea are "true ash cones, differing from cinder cones in that they are the product of great explosions rather than of lava or fire fountains."[26] The present writer agrees that ash in large quantities is the product of highly explosive eruptions but doubts somewhat whether a sharp distinction between cinder cones from fountains and those which are the local product of eruptions producing much widely drifted ash can be made by inspection.

Study of the various phases of Hawaiian pyroclastics, such as those of southeast Oahu and much of Hawaii, in their various areal relationships show how complete a transition exists between all the seemingly divergent types. The essential fundamental differences are those of texture considered with due regard for geologic age. At one extreme the uniformly fine-grained product of a presumably highly explosive and probably phreato-magmatic eruption such as that of Diamond Head becomes quickly altered to palagonitic tuff. Because there was little coarse-grained material thrown out and the fine material was produced in enormous amounts, the cone itself is formed largely of palagonite, except for a very few lenses of only slightly altered glassy lapilli, which throw a light on the changes involved.

At the other extreme some littoral cones are almost wholly built of pellets and shattered fragments of basaltic glass and there is little to suggest that any appreciable part of the debris was sufficiently fine-grained or lay in sufficiently thick beds to become palagonitized. Combining the characters of these types are many of the cones of the Waiau formation, which are themselves largely composed of somewhat weathered but not greatly palagonitized basaltic cinders. These unquestionably constitute the locally deposited residuum of enormously larger amounts of finer ash, accumulated widely on lower slopes. This fine ash consisted of glass particles now generally altered either to a sticky, palagonitic tuff like the Glenwood phase in the rain belt, or to dry powdery palagonitic tuff like the yellow dust of the Kalae or Waikii districts in drier situations.

Various explanations have been proposed to account in particular for the yellow tuff in those parts of the island where drouth promotes the production of yellow dust and silt and where the relation to pyroclastic craters is not clear. Thus Dutton considered the Pahala soil to be essentially alluvial in origin.[27] Though Hitchcock recognized the pyroclastic origin of the Pahala

[25] Stone, John B., Op. cit., p. 26, 1926.
[26] Stearns, H. T., and Clark, W. O., Op. cit., p. 68, 1930.
[27] Dutton, C. E., Hawaiian Volcanoes, U. S. Geol. Survey, Fourth Ann. Report, pp. 97-98, 1884.

soil,[28] extension of the same interpretation to similar material on other parts of the island has been slow, and within the past few years alluvial, eolian and fluvio-glacial hypotheses have been put forward as possible explanations of the yellow dust of the Humuula and Waikii localities. In mentioning these as untenable it must not be supposed that the writer denies the presence of much secondary eolian tuff over parts of the surface, or of a considerable amount of alluvial transport continuing to the present day. It is merely in the search for the essential agent and the explanation of all the important occurrences of the yellow tuff that these must be rejected and the tuff pronouncd a primary aerial product of great numbers of explosive eruptions.

The Central Cone Phase

Time in the field permitted the study of only a few of the many cones in the central Mauna Kea district. A few were studied in some detail; others were merely visited, or seen from one side in passing.

Approximately 132 minor cones are shown on the U. S. Geological Survey maps of the Mauna Kea dome, of which the distribution in elevation is shown in the following table:

TABLE OF MAUNA KEA CONES BY ELEVATION

Elevation (feet)	Number of Cones
Above 11,000	34
9,000 – 11,000	22
7,000 – 9,000	31
5,000 – 7,000	27
3,000 – 5,000	11
0 – 3,000	7

Above 11,000 feet the cones average one to the square mile; below 3,000 feet the number is approximately one to each 40 square miles.

Many of the smaller cones are not over an eighth of a mile in diameter and one or two hundred feet in height, whereas at the opposite extreme are great cones like Makanaka, northeast of the summit, which is nearly a mile in diameter and rises to 600 or 700 feet above its average base.

Measurements of 34 cones, impartially selected, show 5 under 1000 feet and 5 over 3000 feet in diameter, with 11 and 13 respectively in the 1 to 2 and 2 to 3 thousand foot intervals. Of 39 cones 5 were under 100 feet high, and 1 each over 500, 600 and 700 feet in height. The average height was approximately 250 feet. Of 40 cones, the high points of 33 were in the south, southwest, west or northwest directions; a sector of 180 degrees centered at S67½°W, showing a fairly strong trade wind effect, but by no means dominance of such wind directions.

[28] Hitchcock, C. H., Volcanic Phenomena on Hawaii, Geol. Soc. Amer. Bull., Vol. 12, pp. 45-56, 1900.
————, Hawaii and Its Volcanoes, pp. 153-155, Honolulu, 1909.

On the eastern slope of Mauna Kea only very few cones are found at low elevations. Southwest of Hilo are two small cones, Halai and Puu Hono, which rise about 100 feet above their surroundings, of which the character is obscure. From a cursory examination it appeared that they are probably agglomerate mounds which are in part mantled by tuff of the Waiau formation. Their location is such that they may be a part of the terrane of the Olaa "agglomerate."

Inland from Pepeekeo are three small cones which were not examined in detail but which appear to be cinder cones. No other cinder cones are known at low elevations on the eastern slope of the Mauna Kea dome. The district which lies along the road from Waimea to Honokaa at elevations from 2900 to 2000 is characterized by numerous small eminences and mounds composed of agglomerate and sputter lava, and which have been described under the heading of Waimea formation. Certain of the mounds are fifty or more feet in height and are composed of purple-gray, bedded agglomerate which is clearly of aerial origin. In other cases the material, though detrital, may be part of a ragged aa flow. No detailed study of this terrane and no general discrimination between the true pyroclastic material and that due to disruption in the course of an aa flow was made. It is recognized that the unit cones of undoubted aerial formation may be due to phreatic explosions incidental to the emplacement of aa flows and not the product of deep-seated vents. The mode of emplacement of this material, like that of the Olaa agglomerate, and of other similar formations on the island is one of the important geologic problems for future study.

No pyroclastic cones are found on the northwest Mauna Kea slopes below 2000 feet. In the zone between 2000 feet and 7000 feet the chief cones are found to the northwest of the summit area and along the line joining Mauna Kea and Kohala, known as the Kea rift. The northwesternmost of these is Puu Pa, located three and a half miles southwest of Waimea. It is about half a mile in diameter and its summit consists of an irregular cluster of hills of which the highest reach about 200 feet above the surrounding parts of the Waimea plain. The cone is chiefly composed of medium-grained cinders but shows a small summit flow of basalt. The eruption of this cone was remarkable for the prodigious number of small crystals of augite which were thrown out. These are strewn over the surface and in many places form a lag formation from which lighter materials have been blown away. They range in size from 1 to 10 millimeters in diameter and are from 1 to 4 diameters long. A few bombs are intermingled with the cinders of the cone and there was probably originally a moderate amount of fine ash, which is now much weathered.

About four miles southeast of Puu Pa is the cone Holoholoku, of about the same diameter, but somewhat higher, its high westward peak being about 400 feet above the adjacent level of the plain. This cone has the form of a thick, massive crescent with only a very slight rim on the eastern side of the central depression. It is largely composed of rather coarse agglomerate and driblet lava. The entire mass is much weathered and patches of red and yellow "wash" are found on the sides. In places on the sides of the cone are masses of basalt probably derived from dikes in the cone.

Immediately to the east of the Kona Road, about six miles south of Waimea, is the cone Nohonaohaeiki, of which the main mass is somewhat elliptical and about one-third mile across in its longest diameter. It is slightly less than 200 feet high and consists of agglomerate and driblet lava with some beds of one centimeter cinders. The latter are glassy, vesicular basaltic droplets. A few ribbon and double-ended, almond-shaped bombs were seen at the top but the larger fragments here were mostly broken blocks of basalt. On the westward side of this cone are beds ten or twelve feet thick consisting of one-centimeter cinders, but no finer ash or tuff was seen in the vicinity.

Nohonaohae is a somewhat larger cone about one and one-half miles farther south which has a shallow depression at the top and a summit crescent with the opening to the north. The diameter at the base is slightly under a half-mile and the diameter of the rim crest is about 900 feet. The height is over 400 feet measured from the western base. The cone consists mainly of coarse cinders, with irregular masses of droplet lava and small and large bombs. In exposures not far from the base of the cone, cinders and yellow tuff are mingled in section but it is doubtful if the yellow tuff came from this cone.

The cone Mahaelua is located about two and a half miles northwest of Waikii. It is an irregular mound not over 100 feet high and consists of highly vesicular and scoriaceous cinders and driblet lava. The material is red and purple in color and is in part glassy and in part porphyritic with feldspar laths. The upper surface is mantled with two to three feet of yellow tuff of the sort common in the district and derived from more distant cones.

Puu Ka Pele is about two miles south of Keekee and southwest of the Waikii-Humuula Road. It is almost circular and is one of the most symmetrical cones of the island. The diameter at the base is 2300 feet and its rim is 1300 feet in diameter, the height ranging from 200 to 400 feet. The central bowl lies over 100 feet below the lowest part of the rim. Unfortunately this cone was not visited but its symmetry would suggest that it is composed of medium or fine-grained cinders or ash. Its highest point is on the northwest, suggesting its formation while dominant winds were driving through the Humuula saddle from the east. The Keamuku lava flow from Mauna Loa is closely flanked against its southwestern base.

Ahumoa lies on the western slopes of Mauna Kea, one and a half miles inland from the Waikii-Humuula road and four miles southeast of Waikii. It forms a conical protuberance on the slope of Mauna Kea and its base is half a mile in diameter. Between it and the Mauna Kea slope is an undrained depression of the type not uncommonly found in such situations. These appear due to a slight deflection of lava streams. The rim of Ahumoa is 800 feet in diameter and rounded at the crest. It rises to 400 feet above the adjacent saddle and nearly twice that height above the western base. The bowl is 100 feet deep.

Ahumoa is composed of black, glassy ash with some beds of cinders ranging to 1 centimeter. Progressively toward the top are larger numbers of lapilli ranging to 4 or 5 centimeters interbedded in the ash. In places on the western slope pronounced unconformity can be seen between the lower and thicker masses of black ash and the upper few feet of ash. Such an unconformity may mean merely local erosion and wind shifting in the course of a single eruption and no contrasts in degree of weathering were seen which seemed to indicate two periods of eruption. In common with many other cones the upper slopes and rim of Ahumoa are thickly strewn with large and small bombs. This is in accord with the common observation that the more explosive and violent, gas-yielding phase of an eruption produces finer ash and that the waning stages are those during which larger lava masses are slung into the air to form bombs.

The bombs are of three principal types: double-ended, almond-shaped bombs, ribbon bombs, and breadcrust bombs. The largest, mostly of the first type, are three or four feet in length. The central crater is as round and symmetrical as a bowl, strewn with a few bombs on its upper slopes and graded with wash on its more gentle lower slopes. Ahumoa has a nearly level rim and no pronounced asymmetry.

Along the Humuula road south of Ahumoa, are a number of small, pyroclastic vents, mostly without notable cones. The small cone showing a summit elevation of 5911 feet and a base diameter of less than a quarter mile is composed of black ash and cinders. Wind drift was probably from the west at the time of eruption. Puu Maau is chiefly composed of black ash and cinders and its height is about 200 feet above average base elevation. Its top and upper slopes are strewn with driblet lava and bombs.

Cone 7019,* east of Humuula is composed of two to five millimeter, glassy, gray cinders. Its upper surface is covered by secondary, washed, fine material together with vesicular, lithic lapilli. To the north are numbers of small driblet mounds five to ten feet in height and 50 to 150 feet in diameter. North of the road, cone 6981 is composed of two-centimeter cinders with bombs strewn on the surface. Omaokoili, the northwesternmost cone of the group, culminates in a crescent 400 feet in height which lies on the west side of the central depression. This cone is composed of one to two centimeter cinders. In places the cinders fell while still plastic and have been thus cemented to form masses of weak rock. Bombs are exceptionally well developed and are

*** In referring to unnamed cones the elevations as given on the U. S. G. S. topographic sheets will be used in this report as identification numbers, both in the text and in parenthetic form.**

found strewn over the surface and interbedded in the cinders. They include almond-shaped, bulbous ribbon, and plain ribbon bombs. The first type is characterized by two pulled, twisted ends, distinguishable front and back surfaces, a recurved, flow-formed rim between the two surfaces and a smooth front or top surface as contrasted with a rough, vesicular back or bottom surface. The ribbon bombs show a similar polygonal cross-section and may be curved or straight.

The most highly evolved type is the first, since this shows details of configuration developed during flight, whereas the others appear to take their form almost wholly at the time of separation from the plastic mass.

Two miles southeast of this group of cones and a mile south of Humuula is Puu Huluhulu, which rises 200 feet above the adjacent level of the Humuula saddle. It is 1000 feet in diameter, composed of very old cinders one centimeter in diameter. Its slopes are covered by a soft, brown soil and on the slopes and summit is a dense growth of large trees, including koa trees. On the north side there are small masses of driblet lava near the summit.

Northward from Humuula more than a dozen cones rise within a radius of four miles. Hookomo is a nearly circular crater 1600 feet in diameter with a crescentic rim highest on the northeast side. The height from the high side of the base is about 125 feet and that from the low side more than 400. The slopes are smooth, bare and little dissected. The mass is composed of fairly fine cinders or ash and few bombs are visible from the northeast side.

Northwest of Hookomo is a cone 3400 feet in diameter at the base with circular rim 1300 feet across. It has two high points, the westernmost standing at 8676 feet, whereas its base is under 8400 feet. The central bowl is more than 100 feet deep. This cone is composed of one to two centimeter cinders and the surface is strewn with bombs. On the south rim erosion has exposed beds which dip toward the center but elsewhere the rim consists of the original curved crest beds. Southeast there are several large mounds of driblet lava, 100 feet or more in height.

Cone 8123, which lies less than a mile southwestward, is composed of one- to two-centimeter cinders. From its southwestern side, several small aa flows have emerged and several 10 to 20 foot mounds of lava have been formed. Cone 8151, south of the last and two miles northwest of Hookomo, in its upper parts is composed of lapilli and bombs ranging from 2 to 15 centimeters and showing true, plastic aerial shapes. Lower down on the slopes are finer cinders and ash. Surrounding these cones for distances of two or three miles are fine cinders and black ash in parallel, uniform bedding determined by underlying surfaces.

Northeast of cone 8676 is one reaching an elevation of 9003 feet. This cone and Puu Kalepeamoa to the northwest are partly lava cones on the surface and show rough flows down the sides, though there may be a considerable amount of pyroclastic material in the mass of each. Puu Haiwahine is a large compound cone with two central bowls and crescentic rings showing excess accumulation on the east and northwest rims, respectively. It is over 400 feet in height and is 4000 feet in diameter from northwest to southeast. The material is mostly ash with numerous bombs on the rim and a few on the lower slopes.

Cones 7203 and 7315 southwest of Loaloa are each less than 1000 feet in diameter at the base and about 150 feet in height. Each has a tiny top crescent on the west side and a small central depression. They are cinder cones. Loaloa cone is composed of black ash and cinders and in places is strewn with large blocks of lava. On the inland side in the saddle is a mound of driblet and scoriaceous flow lava. The cone is over a half-mile in diameter and rises over 400 feet above the inland saddle and 600 feet above its southern base. The territory west and south is buried by black ash from this and other nearby cones.

Puu Kole is two miles north and east from Loaloa and shows brilliant red ash and cinders, the color the result of weathering. Near Puu Oo ranch are three small cones, including Puu Oo. This is a cone a quarter mile across and about 200 feet high which is seen from the southwest side to be composed of fine-grained cinders. Few bombs were seen. The summit is a slight crescent with its high point to the west. The 100-foot cone 6517, west of the ranch house, is composed of cinders.

Northeast of the summit of Mauna Kea, Puu Kanakaleonui and Puu Hole are parts of one great cone of black cinders. South of Umikoa are several cones at elevations between 7000 and 9000 feet. Puu Kihe is over 1000 feet in diameter with a low summit crescent which lies to the southwest of the central bowl. It is composed chiefly of one- to two-centimeter cinders and driblet lava and its rim is strewn with bombs from ten centimeters to a meter in diameter. Puu Kea, one and a half miles southwest, is interesting in the relationship of its ash to the surrounding aa lava terrane. This aa lava had its source near Puu Lehu and covered a circular area two and a half miles in diameter after the emplacement of the ash and cinders of the vicinity. Within this area Puu Kea forms a surrounded outlier a half mile in diameter. The cone is now not over 50 feet above the saddle inland from it. The central mass consists of five-centimeter driblet lava, grading to finer cinders and ash farther from the vent. The surface of Puu Kea is strewn with well-formed bombs from ten centimeters to a meter in diameter.

Between Kapula and Kaluamakani and over much of the surrounding country are thicknesses of black ash and cinders ranging from 25 to 100 feet. Southwest of Kapula the head of Huluhulu Gulch exemplifies remarkably the characteristic features of rill channels cut in slightly cemented porous material. (Extreme west edge of Mauna Kea quadrangle at southwest base of Kaikipauula.) The head of this channel commences abruptly in grassy ground and is cut in uniform beds of black ash and cinders to a depth of thirty feet practically at its head. The width at the top is from fifteen inches to five feet. In a few rods the depth has increased to a maximum of 100 feet with the top width at no place greater than eight feet and in places it is no more than two feet wide. Commonly the bottom is not directly under the top, because of the swinging of the channel as it was cut progressively deeper, and only in few places can a stone be dropped without striking the sides. At many places there has been not the slightest slumping or modification of the side walls and one comes abruptly on the two or three foot break in a grassy surface wholly unsuspecting its extraordinary depth.

The cone Kemole, some four or five miles southwest, is reported to consist of red cinders. In the vicinity of Makahalau Camp are several cones; the most distinctive of these have crescentic crests opening to the northeast. With this district the description of Mauna Kea cones below the general level of 9000 to 10,000 feet is concluded.

The summit group of cones on Mauna Kea is essentially included within the 13,000 foot contour. From this central cluster there extend three principal sectors of cinder cones, one to the south, one to the west-northwest and one to the northeast. The first and last of these groups of cones and the ash mantles which are associated with them have determined the two chief routes by which the summit is commonly reached, those from Humuula and Kukaiau, respectively. On the south, after passing the cones described earlier, inland from Humuula, one encounters at 11,500 feet the cone Puu Keonehehee with one or two subordinate cones on the east. This cone is a quarter-mile in diameter and has a circular, central bowl eight hundred feet across which is nearly 150 feet in depth. The cone consists of five-centimeter black cinders. In the bowl is a small, secondary cone and on one side of the inside slope of the principal crater of Puu Keonehehee are lava flows which may be part of the main lava structure of Mauna Kea. If this is the case, this crater was evidently developed by explosive perforation of the Mauna Kea dome at this point. The apex of the rim of this cone lies to the northwest, that of a small adjacent cone to the east.

Higher on this slope several small or imperfect cones are found in the vicinity of Keanakakoi, where the ancient Hawaiians formerly roughed out enormous numbers of adze heads from fine-grained dike basalt. Two of these cones show high points to the northwest and one to the northeast. All are of cinders so far as known. Puu Lilinoe is the highest of the cones which is detached from the summit cluster on this side and is a quarter-mile in diameter and 500 feet high from the downhill side. It has a small central depression and a rim showing high portions on two opposite sides.

The west-northwest group of cones lies mostly between the contours of 10,000 and 11,500 feet and corresponds to a considerable protuberance of the Mauna Kea dome along this radius, much greater than can be attributed solely to detrital accumulations. Some of the cones of this group are symmetrical and others irregular; the majority have crescentic rims with horns pointing to the northwest toward Kawaihae Bay. The highest rises to about 400 feet above its average base.

Approaching the summit of Mauna Kea from the northeast, only a few small cones are seen between 9,500 and 11,500 feet. Just above the latter elevation the trail passes through the gap known as Kaula Gulch which lies between the cones Red Hill and Puu Makanaka on the southeast and an unnamed cone on the northwest side. Puu Makanaka is 4000 feet in diameter and very symmetrical, with a high crescent on the northwest and a lesser crescent on the opposite side. The central bowl is 200 feet deep. The height of the rim above this is 700 feet. Red Hill is a crescent cone lying northwest of several small depressions with very little rim formation on the opposite side (Plate *2B*).

Cone 11988 on the opposite side of the trail is similar to Makanaka but smaller and suggests wind drift from the northeast. All these cones, including four more smaller ones which lie between them and the summit cluster, are of medium to coarse black, or black and red, cinders with some bombs strewn on the surface.

Four principal conic piles form the summit cluster of Mauna Kea. Of these the southernmost is the low cone which carries Lake Waiau in its central basin. This cone is less than a half-mile in diameter and shows a low crescentic rim on the south from which it slopes off steeply about four hundred feet. North and northwest the Waiau basin merges imperceptibly with adjacent low slopes and no conic sides are apparent. Lake Waiau is three hundred feet in diameter and has a surface elevation of 13,007 feet. It is thought to be the highest lake in the Pacific Region, between the high mountains of central Asia and the Cordillera of western America.

The lake is probably associated with a perched water table of exceptional elevation. It is not known with certainty whether this water is retained by impervious ash beds, by basaltic dikes of favorable configuration or by perennial masses of ground ice preserved by the low mean annual temperature of these summit elevations. The precipitation is here much less than at lower elevations but it is probable that a considerable share of it is the result of winter snowfall and that conditions for recharge of a body either of ground water or ground ice are quite favorable. On the west the head of Pohakuloa Gulch approaches the lake shore closely and at times carries water in a surface channel from the lake.[29]

Northeast of Lake Waiau is a very round cone with a basin 100 feet deep in its top. It is about 300 feet high. Northwest of the lake is a larger and more irregular cone, Puu Poliahu. This is 600 feet high and over 3000 feet in diameter from east to west and appears to have been formed from two

[29] Gregory, H. E., and Wentworth, C. K., General Features and Glacial Geology of Mauna Kea, Hawaii, Bull. Geol. Soc. Amer., Vol. 48, pp. 1719-1742, 1937.

vents, the high rim between them reaching 13,612 feet above sea level. All these cones are composed of medium-grained, red-brown and black, more or less weathered cinders, with a few bombs on their upper slopes. Northeast of these cones lies a complex conical heap of cinders formed from at least three vents and extending a mile and a quarter from southeast to northwest and less than a mile in the opposite direction. The westernmost vent produced a cone 300 feet high with a crescent open to the west. The crescent of the southern vent is open to the southwest and that of the central vent slightly more to the west. The northeast apex of the southern crescent reaches an elevation of 13,784 feet, top of what is believed to be the highest mountain in the Pacific oceanic area.

On the Mauna Kea topographic sheet, Edition of 1930, a small closed contour is shown one-fourth mile northwest of the summit, which implies an elevation over 13,800 feet. This is an error made in the course of preparing the map for publication, the highest point being actually 13,784 feet. (Letter from Director's Office, U. S. G. S., Jan. 9, 1931.)

With a few exceptions the cinder cones described above are located on the high, steeper portion of the Mauna Kea dome, which lies above elevation 6000 feet. Above this elevation very little yellow palagonite tuff is found and below it, except in the vicinity of local source cones, very little black ash sand or cinders are found in beds of appreciable thickness. No great part of the higher area of Mauna Kea was examined in detail but certain parts may be described briefly.

The sector which extends from Humuula and Puu Oo to the summit of Mauna Kea is largely ash-covered, the thickness of black ash or sand and cinders in this district varying from ten feet to a hundred feet on the slopes which are not actual parts of cones. Near the center of this district between the elevations of 7500 and 9000 is an aa lava terrane which covers four or five square miles.

At least a considerable part of this aa is more recent than much of the black ash and cinders of the Waiau formation since it is found in places to overlie 10 to 20 feet of pyroclastic material (Plate 3*C*). In other places ash overlies aa flows or mounds of driblet lava which may be associated with the aa. It seems most probable that the aa flows resulted from the same general epoch of eruptivity as did the Waiau formation but were in this locality so late as not to be generally covered by ash.

In several parts of the sector in question there are large quantities of lava blocks strewn over the surface and mingled with the surface ash. These are probably from small contemporaneous flows. Structurally, the ash and cinders have the slope of the general surface. The bedding is mostly the result of rather gradual transitions in the coarseness of the material and the coarse and fine phases are uniform and continuous for long distances parallel to the bedding. The variations from parallel bedding are those common in ash as a result of mantling previous irregularities in the surface, including those due to ash. Thus in places is noted a thickening or thinning of beds in long sweeping curves. In places abrupt unconformity may be seen where new ash has mantled the edges of an older, scoured series, or where an advancing talus of new ash or cinders has covered an older and more nearly horizontal series. In some places these relations may indicate a considerable lapse of time but unless the material shows marked contrasts in weathering or cementation one must recognize that new ash cones may be quickly scoured or slumped and then mantled discordantly by shifting ash accumulations and torrential rains with a lapse of only a few hours or days.

The sector bounded by radii drawn through Puu Oo and Keanakolu was not visited. From a detailed examination of the topography as shown on maps it is thought that the yellow tuff terrane may here reach 7000 feet or more and that above it there are probably local ash accumulations but also considerable areas of bare and only slightly weathered lava up to 11,000 feet.

From Keanakolu westward to a position north of the summit is a sector which, like that above Humuula, is quite generally ash covered. Here also is a small area of aa lava which is younger than the adjacent ash and surrounds the cone of Puu Kea. From the north line around the west side of Mauna Kea and back to the Humuula sector little is known of the Mauna Kea slopes between the 6000 and 10,000 foot levels. A few small aa flows are found which are probably to be correlated with those already mentioned. The surface over considerable areas is cut by closely spaced consequent channels fifteen to twenty-five feet deep. In certain parts of Hawaii such channels are nearly always indicative of an ash cover but it is more probable here that many of these are cut on a lava terrane. The presence of a number of large cones in this district suggests that there may once have been a considerable ash cover but it is probable that at present this cover is intact only in patches and that it has been stripped from a good many areas where it was once developed, owing to steep slopes which characterize this district.

The high summit area of Mauna Kea, within the 10,000 foot contour, while it carries a number of large ash and cinder cones, is not generally covered with a continuous mantle of these materials.

On the contrary, much of this area is strewn with heterogeneous accumulations of basalt blocks of all sizes. These spread out over lower country between the various cinder cones and extend somewhat down the outer slopes.

In places, associated with the accumulations of basalt blocks, some large dikes outcrop and these appear to be the principal source of the material of the debris piles. Plainly preserved grooves and striations on the dike outcrops are found in many places and show that the great tongue-like accumulations of rock debris which extend down the fairly gentle slopes of the summit plateau are really the moraines of Pleistocene glaciers which were fed from a small capping snowfield on the summit of Mauna Kea. A close search reveals also a small number of striated blocks but for the most part these are angular and unmodified (Plates *3D* and *4A*).

These evidences of a Pleistocene glacier on Mauna Kea were first described by R. A. Daly[30] and have been seen by a small number of geologists who have visited the top of Mauna Kea. They have since been described by Jaggar, who suggested that the extensive fans of alluvial gravel and sand which are found northwest of Humuula may be the product of glacial outwash.[31] As Jaggar and others have recognized, the moraines are younger than many of the cones near the summit, but apparently some of the cones farther from the top are of later date than the moraines. A more detailed account of glacial features and relation to volcanic features has recently been published elsewhere.[32]

The writer observed the fans of gravel and sand northwest of Humuula, which converge near the mouth of Pohakuloa Gulch. These consist of large boulders ranging to four or five feet in diameter, together with small boulders, cobbles and sand. A few well-shaped bombs were included in the beds and also a few lenses of black ash and yellow-tuff dust. According to residents of the district occasional rains at the present time send torrential streams across the Humuula-Waikii road and there is every evidence that new channels are cut and old ones filled and that the process of fan growth is continuing at the present time. The writer's observations were not sufficiently detailed to show whether a portion of the deposit is markedly older than the rest and indicative of more vigorous and competent transport than exists at persent. In the absence of such evidence and relying purely on the presence of this coarse piedmont fan, the writer does not feel that any agency more potent than modern stream wash is essential. It is quite possible, and perhaps even more likely than not, that this fan growth commenced during the time of glacial activity on Mauna Kea but it is not felt that these fan deposits can be regarded as evidence of glacial action. That the fresh basaltic blocks now rounded to boulders in these channelways have here been available in exceptional quantities through glacial erosion and plucking seems quite possible.

Mention should here be made of the suggestion which has been made, not only that some of the yellow-tuff masses might be slope-wash or mud-flow deposits but that they might possibly be primary fine-grained glacial outwash. All the details of bedding and positions in which such yellow ash masses occur seem now to militate against such an interpretation. Local alluvial tuffs are known and it is entirely likely that minor amounts of glacially outwashed derivatives exist, since the glacial and volcanic action appeared to overlap in

30 Daly, R. A., Amer. Jour. Sci., Fourth Series, Vol. XXX, p. 297, 1910. (Also Science Conspectus, p. 120, 1911, and Proc. Am. Acad. Arts and Sci., p. 158, 1915.)

31 Jaggar, T. A., The Daly Glacier on Mauna Kea, Volcano Letter 43, October 22, 1925. (Also Monthly Bulletin, Volcano Observatory, pp. 75-77, October, 1925.)

32 Gregory, H. E., and Wentworth, C. K., Op. cit., 1937. More extended observations in 1935 and 1937 indicate that most of the striated outcrops are lava flows and that dikes are less numerous than was his cursory impression in 1929.

time, but these are very unimportant in quantity and the main part of all the yellow tuffs appears to be aerially deposited. Further discussion of this question appears in the section on the yellow-tuff phase.

Before leaving the cinder cone phase of the Waiau formation it will be interesting to consider the volumes of some of the larger cones. Measurements of the volumes have been made roughly by planimeter. According to these the compound cone which forms the Mauna Kea summit has a volume, above 13,250 feet, of approximately 134 mile-feet.[33] The cone of Makanaka contains about 125 mile-feet. The two Mauna Kea summit cones are probably the largest of the Mauna Kea series. On the island of Hawaii, only one cone exceeds them greatly in size. This is the great cone of Puu Waawaa which will be described below. This cone is now partly buried by lava flows from Hualalai and possibly Mauna Loa, but even its exposed portion is still by far the largest secondary pile on Hawaii. Its volume as now exposed is of the order of 600 mile-feet and its whole volume is estimated roughly at 1700 mile-feet above the original slope on which it was formed. It should be recognized that this cone has not been studied carefully and it may contain some effusive material and in any event is probably the complex product of several eruptions.

Comparing these cones with others on the topographic maps it appears that in general the larger cones contain perhaps 50 mile-feet and many cones like Puu Huluhulu south of Humuula or Puu Hou west of Kalae, which are conspicuous locally, contain between 1 and 10 mile-feet. These are all comparatively small cones, the largest much smaller than Diamond Head on Oahu, which has been estimated at a volume of 243 mile-feet above sea level and a total volume of 766 mile-feet.[34] Several other craters on southeast Oahu have volumes comparable to Diamond Head.

It is recognized, of course, that great quantities of detrital material were thrown and drifted beyond the limits of the intermediate cone. A rough attempt may be made to determine the order of magnitude of the whole mass. If the cones of Mauna Kea, some 132 in number, be taken at an average volume of 20 mile-feet, which is probably liberal, the total volume will be 2640 mile-feet or exactly one-half a cubic mile. This value can easily be 50% in error in either direction but is sufficiently close for our purpose. The very slight magnitude of the individual eruptions of some of these cones as compared to that of Katmai near the Valley of Ten Thousand Smokes in Alaska is shown by the fact that the ash output of that volcano in 1912 is estimated at 4.75 cubic miles or 25,000 mile-feet.[35] This estimate is based on many measurements of ash thickness over wide areas.

[33] One foot thick on a base of one square mile. This unit equals 1,032,500 cubic yards and about 791,000 cubic meters.

[34] Wentworth, C. K., Pyroclastic Geology of Oahu, Bishop Museum Bulletin 30, p. 47, 1926.

[35] Griggs, R. F., The Valley of Ten Thousand Smokes, Nat. Geo. Soc., pp. 29-31, 1922.

The volumes of very large individual lava flows of historic time in various parts of the earth range from 100 to 50,000 million cubic meters, hence from 130 to 65,000 mile-feet. Most of those above 1,000 million cubic meters are fissure flows.[36] Of 25 lava flows for which volumes are given in numerical form by Sapper[37] the distribution of volumes is: over 10 cubic kilometers, 1 flow; 1 to 10 cubic kilometers, 3 flows; 100 million cubic meters to 1 cubic kilometer, 10 flows; 10 to 100 million cubic meters, 10 flows; under 10 million cubic meters, 1 flow. According to these data the most common volume for what may be called large flows is around 100,000,000 cubic meters or about 130 mile-feet. Several Mauna Loa flows have reached volumes between 100 and 500 million cubic meters or 130 to 650 mile-feet, and the flows of 1859 and 1868 have been computed at volumes of 2,700 and 1,670 million cubic meters respectively.

An estimate of the amount of pyroclastic material drifted far from the Mauna Kea vents must be very rough. The total area originally covered by this material, must, if the Pahala and Kalae materials are from this source, be a large fraction of the entire island, let us say 3000 square miles. Again, if this assumption is made, it would be difficult to postulate an average thickness of less than five feet, in fact, thicknesses known in most of the remoter remnants would suggest a total volume of 15,000 mile-feet or some three cubic miles. Perhaps we may conservatively estimate from three to ten cubic miles as a total on this assumption.

On the other hand, if the Pahala, Kalae, Kapukapu and Glenwood occurrences are eliminated and we deal simply with that area suggested by the contiguous areas of Waiau tuff there may be an area of possibly 1700 square miles to an average depth of not over five to ten feet, possibly a total of not over two to four cubic miles. These volumes are of course very rough approximations but they indicate orders of magnitude. From them it appears that perhaps from five to ten times as much fine-grained material was expelled from the various cinder cone vents as now lies in the cones themselves. If the largest of the cinder cones with volumes of the order of a fortieth of a cubic mile were the sites of eruptions in which this ratio obtained, the total volume expelled during the most prodigious eruptions must have been from an eighth to a quarter of a cubic mile or about 500,000,000 to 1,000,000,000 cubic meters. Considered as lava this material would have a volume perhaps half as great, 250,000,000 to 500,000,000 cubic meters. This volume corresponds very closely to the volume of several of the large historic Mauna Loa flows. The average volume of the more numerous explosive eruptions producing the Waiau formation apparently was of the order of 50,000,000 cubic meters.

[36] Geikie, A., Textbook of Geology, Vol. 1, pp. 300-301, 1903.
Daly, R. A., Igneous Rocks and Their Origin, pp. 120 and 290, 1914.
[37] Sapper, K., Vulkankunde, Stuttgart, 1927, pp. 264-311.

Several recent flows into the pit of Halemaumau since 1924 have had volumes computed as shown in the following table, which gives a record of reduction of depth and volume of the pit.[38]

Date of Eruption	Depth of Fill (feet)	Area of Floor (acres)	Volume of Fill (cubic meters)
May 1924 (after the great collapse)	0	1.6 (gravel)	cup talus
July 1924 (measured May, 1926)	93 (flow 25 ft.)	6.5 (partly landslip)	752,000 (flow and landslip)
July 1927–January 1928.....	92	26.3	2,983,000
February 1929	50	30	1,877,000
July 1929	50	40	2,830,000
November 1930	70	53	5,492,000
December 1931	110	73	9,765,000
September 1934	120	111	16,010,000
Volume remaining, November 1938	750	154	4,955,000,000

The figures are shrinkage results from contour maps made after the eruptions indicated. The floor left after the explosive eruption of May 1924 was a gravel cup. The floor prepared (May 1926) for the 1927-28 eruptions was *July 1924* lava, with 68 feet of landslip on top of it (survey by Beam).

The months of April 1926, December 1933, and December 1935 were times of Mauna Loa drainages of lava from the volcanic system, respectively 20 days, 15 days and 42 days long. As a cycle slightly exceeding 11 years, acceleration appears in both Mauna Loa and Kilauea, with Mauna Loa filling Kilauea quiet intervals and closing the cycle in 1935. The lack of lava eruption 1936-1938 inaugurates a new cycle, similar to the repose period 1924-1926.

In the range from ¾ to 16 millions of cubic meters there is an order of magnitude of approximately one-tenth that found for the greater number of explosive Waiau eruptions.

The Yellow Tuff Phase

The yellow tuff to varying depths covers the lower slopes of the Mauna Kea dome on the east and southeast sides, north of the Wailuku River and the margin of the more recent Mauna Loa flows and extends continuously around the northeast, north and northwest sides. The cover of yellow tuff is somewhat less continuous on the lower northwest slopes. The laminated yellow tuff of the Glenwood and Mountain View areas has commonly been identified with the Pahala tuff formation but, both by location and relation to the Mauna Loa lavas and by their petrographic character, this ash more closely resembles the yellow tuff of the Waiau formation. As mentioned elsewhere the present writer regards the Waiau and Pahala formations as equivalent.

Distinguishing features of the yellow tuff phase of the Waiau formation are both lithologic and physiographic. In most of the Mauna Kea area any given section consists of numerous rather distinct bands ranging from one to six or more inches in thickness. These consist of several different sorts of

[38] T. A. Jaggar, Jr., Letter dated November 7, 1938.

material. Some bands, even in the most deeply weathered and obscure sections, show definite detrital ash characteristics when examined closely. Small grains and pellets are discernible, which are certainly not ordinary alluvial sand or gravel and which because of their continuity in beds conformable with the rest of the series are clearly aeriform. In less weathered sections these bands are nearly fresh, typical black ash.

In most districts many of the bands consist of material of yellow or buff color which is either water-soaked and of a somewhat cheese-like constitution or is soft, powdery dust, or of some intermediate character. Some of these bands, or very thin parts of bands, consist of reddish or resin-colored, translucent material which is recognized even with the hand lens as palagonite by its color, its cloudy translucency and its fracture into small, chunky, subconchoidal fragments. Along with these two types of material are many bands of less distinctive material. Some are quite dark and sticky, clayey material.

Individual layers have highly distinctive characteristics in water retention, and in the secondary textures, such as pellet-texture, vertical, columnar jointing, and the like, which result from water saturation and subsequent drying. The greatest proportion of dark, sticky, clayey material is found in the rainy districts.

Wherever the ash cover is thick it conditions a relatively homogeneous and perfect development of equal, non-branched, consequent drainage channels. This is due in part to the more youthful character of the ash slopes than of the adjacent Mauna Kea lava terranes, but it is mainly due to the more homogeneous and impervious character of the ash than of the lava flows. This type of drainage pattern is found on many parts of the eastern and northeastern Mauna Kea slopes. Ash-covered terranes, in general, show smooth, broadly curving contours, minutely notched by channels 10 to 25 feet deep. Lava terranes more commonly show either the conventionalized aa contours, or the wavy, irregular contours of pahoehoe, either with no stream valleys at all or with less regular and larger valleys.

Most of the yellow tuff of the Waiau formation is primary pyroclastic material deposited from the air during volcanic eruptions and mainly in localities far from the source vent. Secondary tuffs deposited by streams, or wind, following erosion of primary ash deposits, are known but as so far identified these do not comprise a large proportion of the entire bulk, either of the Waiau or of the Pahala tuff formations. Primary tuff and its secondary derivatives grade imperceptibly into one another, especially when the latter are eolian and it is not always easy to discriminate between the two. However, in their purer phases, true pyroclastic beds are marked by the following characteristics, owing to the conditions of formation:

1. Equivalent beds tend to decrease in coarseness systematically away from the vent in a given direction.
2. Equivalent beds tend to decrease in thickness systematically away from the vent in a given direction.
3. Near the source, bedding may be somewhat definite due to distinct and sudden changes in coarseness of the material; in the finer-grained beds farther from the source, bedding is much less definite, since the slower rates of drifting and fall tend to nullify initial pulsations in ejecting the material and to produce a generalized composition, not only for single eruptions but to some degree in the remoter material from successive distinctive eruptions.
4. The accumulation is marked by mantle-bedding, in which the beds are laid down with nearly uniform thickness on any pre-existing surface having slopes less than the angle of rest for the material. Where slopes are steeper, talus bedding is developed.
5. Beds have a remarkable continuity over all types of surface. No other sub-aerial agent is capable of placing thin layers of rock material over such wide sub-aerial areas, with essentially no regard for their relief, except as the slope exceeds the angle of rest. Resultant from this feature is a marked uniformity of section, where an identical alternation of coarser or finer beds with identical thicknesses may commonly be found over areas of many square miles. In non-marine beds, on slopes as steep as those of the Hawaii domes, such bedding is strong indication of pyroclastic deposition.
6. Absence of cut-and-fill structures, channeling, and local unconformities as well as cross-bedding are suggestive of pyroclastic deposition.
7. On slopes of several hundred feet to the mile, where coarse material is abundant, the absence of recognizable water-rounded material interbedded with finer material strongly suggests that the beds are not aqueous and if they are highly uniform in section and mantle-bedded over underlying irregularities, a pyroclastic origin is suggested.
8. In strata made up of fine material the intimate interlamination of markedly continuous and widespread thin layers of cinders, too coarse for eolian transport under ordinary conditions (2 to 8 millimeters) and too thin-bedded and homogeneous to be the result of water transport, are strong evidence of pyroclastic accumulation of the whole series.
9. Presence of bomb sags and cuspate tree trunk structures together with bombs and blocks, sporadically distributed, is good proof of pyroclastic accumulation.

All these features are abundantly and distinctively shown in the pyroclastic formations of southeast Oahu[39] and are also displayed in various of the formations of Hawaii which are so related to the vents as to leave no doubt as to their origin. The wider presence of most or all of these features in other parts of Hawaii where areal relations are more obscure leads the writer to the belief that no large or essential parts of the formations described are of sec-

[39] Wentworth, C. K., Op. cit., 1926.

ondary origin. Subordinate and chiefly superficial parts have been recognized as derived from pyroclastics and redeposited by eolian, fluvial or marine agencies, the most striking examples being at Kalae, Kemole Gulch and the northwest coast at Puako.

The southern edge of the yellow-tuff phase of the Waiau formation on the eastern slope of Mauna Kea follows the course of the Wailuku River where its extension farther south is buried by recent Mauna Loa flows. The yellow tuff was studied south and east of Puu Oo and near Hilo (Humuula and Hilo quadrangles). One-half mile south of Puu Oo ranch at 6125 feet is an exposure of eight feet of moist, brown, earthy material which could be traced laterally as palagonitic and ashy layers, only partially altered. Due south of this point at 5850 feet, nine to ten feet of much weathered, ashy tuff was seen, which also contained palagonitic layers and other layers in which a granular texture of one-half to two-millimeter coarseness could be detected. Several other exposures of five to ten feet of tuff were seen in this vicinity and the grassy character of the surrounding country indicates a widespread tuff or ash cover east and northeast of this locality.

Territory between this district and the coastal zone near Hilo was not examined by the writer. Along this whole line as shown on the topographic maps, the contrast between the topography and drainage on the north and south sides of the Wailuku River Channel is very striking and due in part to the tuff cover.

At an elevation of 1000 feet near Piihonua, there are two types of stream valleys. The larger are cut through the tuff cover into lava but the others, mostly not over 10 to 20 feet deep are cut mainly in tuff, though some may bottom on lava (Mauna Kea and Honomu quadrangles). A half mile northwest of Piihonua a fifteen-foot section of tuff was observed, which showed fourteen alternations between red-brown layers and gray, somewhat granular layers. Similar sections may be seen at other points in the vicinity and to the northward but none was found south of the Wailuku River, where the surface consists of hard, rugged and slightly weathered lava flows.

Below B. M. 380 on the Amauulu Road at Hilo the tuff section is about eight feet thick and underlain by weathered basalt. Near Kaimukanaka Falls two and a half miles from Hilo the tuff is thirteen or fourteen feet thick. On the main road north from Hilo and a fifth mile north of the Wailuku River bridge the following section was measured:

Top:	Feet	Inches
Red, ash tuff, weathered	4	
Gray, gumbo material, columnar jointing	1	
Red, ash tuff, granular ash when dry	2	6
Columnar, gumbo material		4
Red tuff	1	
Grayish, granular ash		1

	Feet	Inches
Red tuff		1
Drab, gumbo material grades downward into		6
Weathered, mottled basalt	4	6
Base: Concealed.		
Total	14 feet	

On the same road at Pukihae stream the following section was measured:

Top:	Feet	Inches
Red tuff, weathered	4	
Gumbo, columnar, gray		10
Gray-red ash, granular	1	11
Red, clay gumbo		4
Tuff, red, with darker red at base	1	
Gray granular material		1
Red material (tuff)		1
Red and drab gumbo material grade downward into	4	6
Basalt, weathered, soft but intact	4	6
Total	17 feet	3 inches

Similar sections ranging from 6 to 10 feet in thickness were measured at several other points in the north part of the town of Hilo and northward on the Honomu Road. On the road near Maili stream at 800 feet this section was measured:

Top:	Feet	Inches
Dried, pellety, ash-derived soil		4
Red soil, that in places dries to undoubted tuff	1	2
Red tuff		2
Gray, granular ash		1
Red tuff		2
Red-buff, sticky gumbo residuum, not clearly identifiable as tuff	5	
Gray, gritty, mottled, weathered basalt	1	
Base: Concealed.		
Total	7 feet	11 inches

A half mile northeast at 700 feet the following section was exposed in a road cut:

Top:	Feet	Inches
Dried, pellety, ash-derived soil		6–8
Reddish, uniform tuff	3	6
Red, granular tuff pellets with grayish, sandy cores		5
Columnar gumbo		2
Red and gray, ashy tuff		6
Gray, granular ash		2
Red tuff		2
Weathered basalt with basalt kernels in it	5	
Base of exposure.		
Total	10 feet	5 inches

The following section was exposed a few yards north of Pahoehoe Stream at 180 feet:

Top:	Feet	Inches
Resin-red tuff, rather uniform, moderately sticky	3	8
Columnar gumbo		3
Red-brown tuff	2	7
Columnar gumbo		3
Red and brown, ashy tuff		8
Red tuff		1
Gray-granular ash		1
Red tuff		1
Columnar gumbo		5
Sticky, uniform buff to drab, basaltic residuum	3	6
Base of exposure.		
Total	11 feet	3 inches

A similar section was measured at the top of the hill on the road north of Kawainui Stream:

Top:	Feet	Inches
Red tuff	4	
Yellow tuff		2
Drab tuff		3
Red tuff		4
Columnar gumbo		4
Red-brown tuff		8
Columnar gumbo		5
Columnar, sticky residuum, layers of basalt kernels	4	
Basalt, intact	5	6
Base of exposure.		
Total	15 feet	8 inches

At 325 feet, just south of Honomu Stream this section was measured:

Top:	Feet	Inches
Pellety, drab soil material	2	
Sticky, red-brown, loam-like material tuff	2	9
Columnar gumbo		2
Red palagonite		2
Columnar gumbo		2
Red, slightly granular, ashy tuff		5
Drab, sticky material		7
Red, ashy tuff		1
Grayish layer, more granular		1
Red tuff		1
Drab, sticky, somewhat columnar, basaltic residuum	3	6
Base of exposure.		
Total	10 feet	

Several similar sections were measured along the road south of this locality as well as at several points three or four miles inland. Similar but somewhat thinner sections are found as far north as Laupahoehoe. Though much of the district has not been examined in detail, there is little doubt that much of the sector north of Hilo is covered by this banded tuff complex up to elevations of five or six thousand feet.

The constancy of the section is of interest. Nearly all the sections measured showed approximately four feet of nearly uniform red tuff at or near the top. Below this are thinner layers which show local variations, most of which are believed to be due to progress of weathering rather than to original differences. Another sequence which is rather constant is that of the gray ashy tuff band between two red tuff bands near the base of the section. Commonly each component is not over one or two inches thick. On the whole the similarities of the section are more striking than the differences when one considers the rather large area involved. Purely apart from the clear lithologic evidence of pyroclastic origin, the stratigraphic uniformity of these beds over so large an area having a uniform steep slope to the east and their freedom from gravel lenses or other evidences of fluvial action constitutes strong evidence of aerial deposition.

Northwest from Laupahoehoe, the tuff cover thins rapidly along the coast (Hamakua quadrangle). At several places, sections of two or three feet of pellety, gray or red material were seen but in few places were these as clearly divided into zones or bands as similar material is farther south. Commencing a short distance northwest of Laupahoehoe, road cuts show occasional agglomerate mounds which are in places clearly of true pyroclastic origin and associated with beds of coarse gray ash, as well as lapilli layers with sizes ranging to 16 centimeters. These in turn are commonly overlaid by a few inches or a foot or two of the red tuff of the Waiau formation. This agglomerate complex extends northward to Waipio and west along the main road nearly to Waimea. It has been described above as the Waimea agglomerate.

One of the first prominent exposures is about a quarter mile west of Kalona church. Here four feet of gray ash and lapilli bands which are somewhat weathered and cemented are overlaid by about one foot of pellet soil that appears to be ash of the Waiau formation. A few rods farther west is a 12-foot section of coarse agglomerate with fragments ranging up to one foot in size which is rudely bedded. These bedded ash and lapilli masses are the product of local explosions and in places steeply dipping beds showing the structure of local cones may be seen. Whether these explosive eruptions are from deep-seated vents or are associated with local lava flows is not known since no detailed study was made of the agglomerate. At numerous points the agglomerate beds underlie the Waiau tuff and show clearly that the agglomerate is the older.

Inland from the coast in the Hamakua district the thickness of the tuff cover increases rapidly from one or two feet to ten feet or more. Nearly a mile south of Kukaiau at 1250 feet the following section was exposed:

Top:	Feet	Inches
Light brown, porous soil		5
Yellow to red tuff	1	8
Light, cream-colored tuff		4
Yellow to red tuff	1	4
Gumbo, probably agglomerate residuum		6
Weathered agglomerate, intact	1	3
Base of exposure.		
Total	5 feet	6 inches

At 2100 feet a total of about 60 inches of tuff is found with 4 inches of light, cream-colored tuff about 20 inches from the base and 2 inches of red palagonite dust 15 inches below the top. At 2600 feet on the Umikoa road the following section was measured:

Top:	Feet	Inches
Dark, drab gumbo (tuff?)	1	6
Reddish tuff		6
Gumbo-like, columnar material		9
Porous, gray-cream, ashy tuff		2
Gumbo-like, columnar material		9
Red-yellow, palagonite tuff		5
Red-brown tuff	1	6
Drab gumbo	2	6
Weathered agglomerate in place	?	?
Base of exposure.		
Total	8 feet	1 inch

Throughout this district the tuff lies on agglomerate mounds. On the tops it is thinner and in the hollows somewhat thicker than the average. The following section was measured at B. M. 3089 on the Umikoa Road:

Top:	Feet	Inches
Crimson to wine-red, powdery ash		6
Semicolumnar gumbo	3	
Agglomerate lapilli (alluvial?)		6
Yellow, porous, indurated tuff		4
Gumbo		2
Yellow, indurated tuff		4
Dark, drab gumbo	1	6
Yellow, palagonite tuff		1
Gumbo	1	4
Yellow palagonite		2
Gumbo	1	
Base, agglomerate		
Total	8 feet	6 inches

This section shows considerable secondary and slope-washed material but the tuff layers appear to be primary.

One of the thickest sections measured is the following from a half mile east of Umikoa:

Top:	Feet	Inches
Soil and bright red, upper ash		6
Drab, semicolumnar material		7
Yellow-buff palagonitic tuff		4
Dark drab tuff		4
Yellow-black, porous, indurated tuff		2
Drab, powdery tuff		6
Yellowish tuff		2
Dark brown, powdery tuff		6
Yellow-cream-colored, somewhat indurated tuff		2
Yellow-brown, slightly moist tuff	1	6
Yellow indurated tuff		2
Drab tuff		3
Yellow, porous, somewhat gritty tuff		5
Dark drab, columnar gumbo	1	
Yellow palagonite tuff		1
Gumbo		2
Yellow palagonite tuff		1
Drab gumbo	2	2
Alternate yellow tuff and gumbo layers	1	1
Dark tuff		6
Columnar gumbo	2	1
Yellow tuff		4
Base: Irregular porphyritic basalt.		
Total	13 feet	1 inch

Inland from Umikoa for several miles, there is a thick cover of banded tuff which closely resembles the sections previously described. It lies on a rugged, hummocky agglomerate terrane and carries the persistent, six-inch top layer of crimson red ash mentioned above. Eastward of Keanakolu, in the land district known as Laupahoehoe and adjacent territory, it is reported that little or no ash covers the surface and this seems likely from the general aspect of the topography as mapped.

Inland from the Waimea-Keanakolu trail the tuff cover thins and becomes more irregular. The proportion of cinders and black ash increases as Puu Kihe and other cones are approached, and above the elevation of 6000 to 7000 feet practically no yellow tuff is found. Farther west along Kahawailiilii Gulch there are only moderate thicknesses of yellow, banded tuff inland from the trail and it here likewise gives way to black ash and cinders below 6000 feet.

On the road from Honokaa to Waimea a few thin beds of yellow tuff were seen overlying mounds of agglomerate and lapilli from local vents (Waipio quadrangle). The tuff is rarely so much as a foot thick. At the roadside at about 2500 feet the following section was measured:

Top:	Feet	Inches
Dark, drab soil	2	6
Yellow, palagonitic tuff		2
Drab material		4
Yellow-red, sticky material		4
Drab, sticky soil	1	
Drab soil with basalt fragments	2	
Base of exposure.		
Total	4 feet	4 inches

At the crossing of Inoino Gulch the road cuts through three agglomerate cones approximating fifty feet in height. These consist of irregularly bedded coarse agglomerate ranging to fragments 1 or 2 feet in diameter and associated with masses of driblet lava. The agglomerate formation is a purplish gray in color and the thin, yellow, palagonite layer of the section described above lies mantled over the top of the cones. For several miles westward the topographic details are dominated by similar agglomerate mounds, and similar thin but persistent bands of yellow and red tuff are found in the soil cover.

In the vicinity of Makahalau the soil cover is composed to a considerable extent of weathered, yellow tuff but exposures showing well-defined sections are comparatively rare. In Puu Huluhulu Gulch at 4070 feet, a five-foot section of banded yellow and black tuff and ash was seen. This appeared to be a primary aerial section. In other exposures along this gulch there are sections which consist largely of alluvial gravel and tuff. A generalized section from this gulch would show agglomerate mounds at the base, a rather massive yellow tuff lying on it in places, and above these, in places on one and at other places on the other, a complex consisting partly of primary and partly of alluvial, gray ashy tuff containing numerous, current-bedded pebble-bands. It is possible that the finer wash from the gray ash at the top is largely palagonitized and forms the top soil. At any rate it seems somewhat doubtful if the top, yellow-tuff soil is derived from the older yellow tuff.

A remarkable series of pyroclastic materials is found in exposures along Kemole Gulch, which follows a course northwestward from Kemole cone and crosses the Kona road about four and a half miles south of Waimea. Somewhat similar sections are found in Kamakoa Gulch which lies a short distance farther southwest. It is probable that much of the material in these sections is from local episodes but the materials found are of much interest because of the light they throw on different forms which may be taken by pyroclastic materials.

The following section was measured at the crossings of the Kona road:

	Feet	Inches
Recent alluvium, with possibly some pyroclastic material, contains basalt cobbles up to 20 centimeters in diameter	1	
Buff-brown fine-grained silt (tuff-derived).............	2	
Conglomerate of pebbles of gray, ashy tuff, pebbles to 8 cm., cemented with calcareous material...............	1	
Gray cemented tuff, showing deep, filled channels, curved bedding planes, sharp changes in coarseness. Varies from fine gray "dust-rock" to tuff with fragments 4 or 5 millimeters in diameter. The finer material lies at the base, the bedding is more irregular toward the top. In part is undoubtedly alluvial.........................	2	
Yellow-buff tuff	2	
Basalt flows and driblet lava..........................	1	
Base: Concealed.		
Total	9 feet	

Upstream from this point for about three miles the Kemole watercourse is very imperfectly defined and no exposures were examined in detail. At approximately 2950 feet and for short distances up or downstream four formations are seen in the walls of the gulch. The basal member consists of gray, irregular basalt flows of which one to three feet are exposed. Above this is from three to nine feet of yellow tuff, followed by a gray ashy tuff complex and this in turn is capped by modern gravelly alluvium (Plates 5*A* and 4*B*).

The upper half of the basal, tuff member is powdery, buff to grayish, silty material. The lower half is more compact, yellow to red to pinkish-lavender tuff which contains calcareous plant-stem casts and resembles the basal tuff of the Kalae district. The color and other characteristics vary with local moisture conditions. Among the several contacts shown in this gulch that between this tuff and the gray ash which lies above is most nearly regular and conformable. Whether this can be interpreted to mean that the time interval between the expulsion of the yellow tuff and the gray ash tuff was short is rather doubtful.

The gray-ash complex is highly variable; lower in the course of the stream this consists largely of very slightly cemented ash in beds one to three inches thick, with calcareous crusts between the beds. Much of the material consists of black and reddish pellets of one and two millimeter sizes. Parts of the material are buff and yellow, and seem to have undergone a certain amount of alteration to palagonite. Farther upstream the beds are coarser and contain more material believed to be alluvial. Here the primary ash in thin lenses of uniform, laminated tuff is subordinate to pebble beds that are clearly alluvial. The latter are too lensy and too much marked by cut-and-fill structure to be primary lapilli falls. Very rapid transitions take place between the different types, due in part to the fact that the present channel is cut in winding fashion back and forth across the positions of previous channels (Plate 4*C*).

The upper gravel is mostly even-bedded and contains a large proportion of pebbles ranging from 8 to 64 millimeters. There is a moderate amount of cut-and-fill structure within the mass and it cross-cuts the present gulch in various places. This material appears to have no close relationship to the pyroclastic episodes. Varied exposures of one or several of the members of this series are found up to about 3300 feet. In places the entire series of detrital formations lying on agglomerate or on flows amounts to a thickness as great as fifty feet and is exposed in vertical or over-hanging walls.

At approximately 3300 feet the rock floor of the gulch rises somewhat abruptly and on it lies a thickness of two or three feet of yellow-red tuff with an eroded upper surface. Abutting against this from the downstream side are the beds of the basal eight or ten feet of the gray tuff, the contact being one of marked unconformity. For a considerable distance above this point the channel is not over fifteen feet in depth and shows numerous exposures of the red tuff at the bottom, the formation in places rising to five or six feet above the bottom of the channel and in other places disappearing altogether. Above it the gray tuff is coarse and carries much alluvial material but also shows lenses of fine, black or gray, primary ash. Within the next two or three miles the depth of the gulch increases and the cut-and-fill unconformities between pure, aerial, gray tuff of several types and several phases of mixed, alluvial tuff become more numerous and more rugged. The base of this detrital material is marked by numerous agglomerate mounds. Some of these are 20 to 40 feet high and are high enough to pinch out much or all of the overlying section. In places, small masses of red tuff lie in hollows adjacent to the agglomerate mounds. In the upstream part of this section of the channel, the basal, red tuff becomes more persistent and commonly reaches seven or eight feet in thickness.

So far as could be observed in a traverse of part of the adjacent Kamakoa gulch the basal, red and yellow tuff grades into the common banded surface yellow tuff of the western upper slope of Mauna Kea. It is thought that the heavy mantle of primary and alluvial gray ash and tuff which is found along the channels of a number of streams from Makahalau around to Kamakoa and which extends down to elevations of 3000 feet or less is due to an eruption of some cone on the north side of Mauna Kea at a time when there was an unusual air drift to the north and east and which was accompanied by torrential falls of rain which swept great amounts of alluvial material out over the lower slopes (Plate 5*B*). It is quite possible that more than one such eruption occurred. Because of the remarkable development of these formations in Kemole and Kamakoa gulches it seems that Kemole cone may have been the source of one of these eruptions. No other alluvial ash and tuff complex even approaching the magnitude and complexity of the Kemole series was seen by the writer, though one would suppose that in the course of the pyroclastic history of Mauna Kea several such might have been produced. Only more detailed study of this complex and of others which may yet be found in other areas will reveal the exact relations of the different sorts of materials and the history which they portray.

In the district around Waikii, especially toward the east and southeast, there is a notable thickness of banded, yellow tuff of the Waiau formation (Waikii quadrangle). It has long been known as the source of the thick yellow dust which forms the soil in this vicinity and which offers serious impediment to travel in places where the grass cover is broken. The following section was measured in Auwaiakeakua Gulch a half mile southeast of Waikii:

Top:	Feet	Inches
Dark, drab material with small, basalt fragments at the base	2	
Powdery, soil material, carbonaceous at top and grades to dark brown at base, contains numerous snail shells		10
Yellow-drab, fine-grained, ashy material with very little grit	2	1
Dark brown, carbonaceous, slightly gritty material		6
Slightly gritty, yellow-brown tuff		8
Drab material, fine grain		3
Yellow-brown material		3
Dark purple, gray and black dust, with a few coarser grains		1
Yellow-brown dust		4
Fine, purple-gray dust		1
Yellow-brown tuff		3
Slightly coarser, pinkish-brown tuff		2
Gray-drab, medium grained ash		2
Yellow-brown tuff with slightly cemented, speckled black layers		3
Yellow-brown material with gray-black layers	1	3
Compact, blocky purple-black material		3
Yellow-brown tuff	1	3
Purple-black, blocky material		2
Yellow-brown tuff		2
Purple-black material		3
Dark, salmon-colored, porous tuff with plant stems		10
Alternating, dry, fine-grained yellow layers with moist, fine-grained purple gray layers		4
Dark, cream-yellow porous tuff grades into next below	2	
Lighter, cream-colored, fine, powdery ash		6
Yellow-buff tuff, medium to fine grain, whiter below, with coarser ashy layers, ranging to 2 millimeter sizes	2	
Base: Concealed.		
Total thickness	11 feet	6 inches

A thickness of ash and tuff ranging from 15 to 20 feet is exposed along this gulch for a mile or more and it is generally composed of similar thin bands of pyroclastic material, undoubtedly the product of forty or fifty distinct ash falls, some of the above-described layers being the combined product of several eruptions described as one alternating series in the interest of brevity.

In this district the tuff series is underlain by agglomerate of local origin and in places the products of agglomerate eruptions have been transported alluvially and deposited unconformably over at least a part of the tuff series. Beds of lapilli ranging to 64 millimeter sizes in places appear to have been alluvially deposited almost contemporaneously with their eruption and it is thought that the agglomerate-forming eruptions commenced earlier than those producing ash but here at least lasted well into the epoch of ash expulsion. The tuff section carries larger amounts of gray and black, glassy, and more or less unaltered ash particles at progressively higher elevations and with greater proximity to the parent cinder cones.

In the other direction the series of banded, alternating yellow tuff and gray ashy layers undergoes a transition into a more nearly homogeneous, compact red-brown palagonitic tuff. At 4000 feet, due west of Waikii, an exposure shows five feet of banded yellow tuff. A half mile farther west is a twelve-foot section showing very little banding. On this slope Popoo Gulch forms a boundary between a terrane covered by yellow tuff which lies on the northeast and one in which the yellow ash has been mostly covered by 3 to 20 feet of dike and driblet lava. At 2900 feet, in the gulch just below the upper trail road, four feet of the yellow tuff is seen to underlie the lava of a small dike flow which extends 200 to 300 feet toward the sea. At 2700 feet several mounds of agglomerate with associated lava flows lie on the yellow tuff, though other similar mounds seem to occur below the tuff. The latter is three to four feet thick and shows a bright red color immediately beneath the overlying lava, apparently a result of baking. Below, the tuff is cream-buff in color. Similar relations are shown at 2450 feet, at a point in the gulch about a half mile northwest of the main Kona road. The tuff is not over five feet thick and the agglomerate is gray-purple in color, with fragments ranging from one centimeter to one meter in size, and is associated with trickle flows. The agglomerate was not closely studied and it is not known whether it is the product of deep seated local vents or if it is the secondary product of lava flows or possibly of largely detrital aa material.

The relations between the cinders of cones of the summit area of Mauna Kea north of Humuula, the gradually thinning surface cover of black ash which lies to the northwest of Humuula, the banded tuff section and the yellow dust of the Waikii area and the non-banded yellow-buff tuff of the area north and northwest of Keamuku are sufficiently clear to show the essential unity of all these phases of the Waiau formation. Two additional occurrences should be mentioned as belonging to this series. In the vicinity of Puako on the west coast and extending for about two miles southwest from Puako Bay the shore flats are covered by deposits of fine-grained, brown to yellow dust and slightly coarser gray-brown ashy material (Puako quadrangle). On the beach this material is washed out to fine, brown sand. These materials are evidently parts of an alluvial fan built by streams from Popoo Gulch which drains the southwest margin of the ash-covered terrane and from Kemole and Kamakoa Gulches which flow down the north slope of Mauna Kea. No primary yellow tuff was seen along the shore though it is quite evident that the materials of the fan are alluvially transported pyroclastics. At one or two places along the shore between Puako and Kawaihae a reddish, calcareous rock was seen which is thought to be subaqueous tuff, mingled with marine sediments.

The Waawaa Pyroclastic Materials

This formation is restricted to the Puu Waawaa cone and to certain strata exposed in the face of the Anahulu cliff, north of the Puu Waawaa cone (Puako quadrangle). The Waawaa cone is the largest cone on the island and is located on the northeast slope of the Hualalai dome a short distance west of the line along which Mauna Loa and Hualalai flows merge. Its summit elevation is 3971 feet and the saddle between it and the Hualalai slope has an elevation of 3514 feet. As Jaggar has pointed out, Puu Waawaa is a large and complex mass probably the product of many eruptions and scarcely comparable to most of the other secondary cones.[40]

The cone is surrounded and partly buried by Hualalai flows. The exposed portion is one mile in diameter and is deeply trenched by deep and somewhat mature gullies. The crest has the form of a blunt, U-shaped crescent open to the southeast. Only a very brief examination of the structure and petrography of the cone was made and the resulting data are presented here in pursuance of the plan of assembling all available information concerning pyroclastic cones and formations.

So far as could be observed in a gulch on the southwest side of the cone the main mass is composed of light gray beds of pumiceous lapilli, beds of glassy fragments showing prominent flow structure interbedded with much larger amounts of lithic volcanic rubble, which in places is well cemented. The pumiceous and glassy fragments as well as the lithic debris are quite evidently not of basaltic composition, being much less basic, and the products of the vent have long been known to represent the most marked departure from basaltic composition of any rocks on the island. According to Cross[41] the material is all of trachytic composition and it was his view that the Puu Waawaa eruptions must have occurred during the building of Hualalai.

Petrographic descriptions based on the specimens collected in 1929 will be presented in the section on petrography. On the western flank of Puu Waawaa above the ranch house, several gulch exposures show a mantle of 0 to 5 feet of basaltic cinders and somewhat palagonitized ash and cinders overlying

[40] Jaggar, T. A., Personal communication, March, 1934.

[41] Cross, W., the Lavas of Hawaii and Their Relations, U. S. Geol. Survey, Prof. Paper 88, pp. 35-36, 1915.

a 20 to 30 foot section of pyroclastic materials, largely pumiceous cinders of the intermediate series. The vent from which the later basaltic cinders were expelled is not known.

In the face of the Anahulu pali north of Puu Waawaa a section is exposed which consists of a basal coarse talus of lava with agglomerate beds, both of trachytic composition. Next above is 1 to 6 feet of pumiceous cinder and ash beds and this series is in turn overlain by basalt flows which have come down over the slope. The trachytic cinder and ash beds are also disposed in mantle bedding down over the slope and thus these pyroclastics appear, at least in part, to postdate the faulting which produced the pali. More complete correlation and accurate dating of the trachytic materials, together with discussion of the petrographic relations of these rocks must await more detailed field studies.

The Uwekahuna Formation

The writer made no study of this tuff formation and this description is based wholly on the work of others. The following statement is quoted from Stone[42] (Kilauea quadrangle).

"The only ash bed in the walls of Kilauea is exposed at the base of the Uwekahuna cliff northeast of the fault terraces. Another ash section was formerly exposed southwest of the fault terraces (31, p. 230) but was buried by the lava flow of 1919 from Halemaumau. A careful examination of the walls showed no other beds, but ash layers only a few inches thick might escape observation.

"The exposed ash beds extend along the base of the cliff for about 3000 feet from the niche at the northeast end of the fault terraces to the point where it dips below the level of the crater floor. At the northeast end of the exposure the bed is three feet thick and consists of gravel, a few lava-coated bombs, and rock fragments commonly 6 or 8 inches across but reaching a maximum size of about 16 inches. Beneath the Uwekahuna intrusive body is 6½ feet of ash having a basal layer of medium-coarse, black ash overlain by 2 feet of gravel and cobbles, then another ash layer overlain by a second gravel stratum, and at the top about 8 inches of yellow ash with glass droplets and crushed thread-lace scoriae (11, pp. 163-166). At the southwest end of the exposure the ash bed lies on the surface of an unformity in the lavas.

"According to Powers (Sidney), the incomplete section formerly exposed at the locality (i.e., that buried by the flow of 1919) was 17 feet thick and was composed of yellow ash containing rock fragments 1 or 2 inches across."

According to Finch, the ash at the latter locality lies under nearly 500 feet of lava flows which separate it from the ash of 1790 and of earlier episodes which lies on the present surface.[43] This formation is evidently the product of explosive eruptions occurring considerably earlier than the date of forma-

[42] Stone, John B., The Products and Structure of Kilauea, Bishop Museum Bulletin 33, pp. 27-28, 1926.

[43] Finch, R. H., The Ash Deposits at Kilauea Volcano, Volcano Letter No. 17, April 23, 1925.

tion of the Kilauea caldera. Since the long series of distinct explosive episodes resulting in the formation of the Keanakakoi formation took place after the caldera was formed and is now known to have been quite complex, it is probable that the caldera was formed at least several hundreds of years ago. Stone estimated the age of the oldest members of the surface ash as not over 300 to 500 years.[44]

Stearns has estimated post-Pahala time as possibly 30,000 years, ascribing a maximum thickness to the Kamehame basalt of over 800 feet. Since the Uwekahuna formation lies under more than half of this thickness the latter formation may be 15,000 or more years old, assuming the approximate correctness of the original estimate.

The suggestion made by T. A. Jaggar to Stone, to the effect that the Uwekahuna ash might be the equivalent of the Pahala ash, seems to the present writer subject to rejection on the ground that the lithologic character as described by Sidney Powers shows more differences than similarities to the known Pahala sections of the Pahala, Kalae, Kapukapu localities and of the kipukas northwest of Kilauea even after allowance has been made for the effect of different degrees of sorting and climatal differences. The lithology described for the Uwekahuna formation accords much more closely with that of the Keanakakoi series in view of the abundance of accidental constituents than with that of the known Pahala or Waiau ash formations.

Hualalai Pyroclastic Materials

The ash and cinder formations of the Hualalai Rift province constitute an important subject for future investigation. A total of some fifty or sixty cones, ranging in diameter from 500 feet to one half mile and in height above their surroundings from 50 to 300 feet, are found in this province. The larger number are found above the 5000 foot level but a few extend in a long line about 15 miles to the northwest coast (Kailua quadrangle).

At a point near Huehue Ranch on the main road from Kona to Waimea are several cones consisting of cinders and glassy driblet fragments ranging to 10 centimeters in size. The whole mass was evenly mantle-bedded and accordant with the present surface.

Very little information is available concerning the summit craters of Hualalai. Brigham has described briefly some of the general features of the Hualalai dome.[45] According to his account there are numerous pit craters at the summit in which flows of solid gray lava are exposed. Two views of the Hualalai summit, accompanying Dr. Brigham's account, together with the recently issued U. S. Geological Survey maps, show clearly the presence of

[44] Stone, J. B., Op. cit., p. 35, 1926.

[45] Brigham, W. T., The Volcanoes of Kilauea and Mauna Loa, Bishop Museum Memoirs, Vol. II, No. 4, pp. 8-15, 1909.

numerous cinder cones. So far as known these are probably composed of basaltic material but no detailed observations have been made.

MAUNA LOA PYROCLASTIC MATERIALS

There is no record of an exclusively pyroclastic eruption in historic times, though cones of detrital material have been built at the sources of many of the recent lava flows. Thus in the eruption of 1852 as reported by Titus Coan a ring cone about a thousand feet in diameter and 150 feet high was formed and he reports an unusual amount of limu or basaltic pumice.[46] This was recognizable ten miles from the crater and increased to depths of 5 to 10 feet at the margins of the cone proper.[47] During this eruption ash and Pele's hair fell thick on the streets and roofs of houses in Hilo, at a distance of about 25 miles.

Similar falls of pumiceous lapilli and Pele's hair are reported by H. M. Whitney, as quoted by Brigham, to have taken place during the eruption of 1868,[48] and these appear from all accounts to accompany in greater or lesser amount practically all the effusive eruptions.

On recent topographic maps of the dome of Mauna Loa numerous small cones are shown which consist either of lapilli or other detrital material or of adherent driblet material. The most common form of these cones is that of a crescent, commonly breached on the down-slope side. Heights range from 50 to 200 feet and diameters from 200 to 500 feet. At about 7500 feet on the Mauna Loa southwest rift zone is a crescentic cone, open to the north, known as the Alika cone (Mauna Loa, Honaunau and Hoopuloa quadrangles). West of this cone a small area of sand is mapped and the cone doubtless consists of ash and lapilli. Farther southwest, on the same rift zone at about 6700 feet is the conspicuous cone of Puu Keokeo, rising over 200 feet above the surrounding slope and source of large amounts of detrital material (mapped as sand) which are strewn to the southwest. Several other cones, probably of similar character, such as Ohohia at 5400 feet, and an unnamed cone southeast of it, lie at somewhat lower elevations.

According to Finch many of the cones on the southwestern rift zone at about 10,000 feet are cinder cones, some being quite old and others quite fresh.[49] In the same report Finch states that the Mauna Loa flows appear to be either very old, or quite recent, with none of transitional age. Jaggar has described various cones formed in 1926 near the source of the flow which entered the sea at Hoopuloa. These are mostly heapings of light, basaltic pumice, reaching heights of 75 to 100 feet.[50]

46 Limu is the Hawaiian word for seaweed and was also applied to light, attenuate pumice.

47 Brigham, W. T., The Volcanoes of Kilauea and Mauna Loa, Bishop Museum, Memoirs, Vol. II, No. 4, pp. 67-68, 1909.

48 Brigham, W. T., Op. cit., p. 105, 1909.

49 Finch, R. H., Expedition to the Southwest Rift of Mauna Loa, Bulletin Hawaiian Volcano Observatory, Vol. XIII, No. 12, p. 90, 1925.

50 Jaggar, T. A., Journal of Mauna Loa, Bulletin Hawaiian Volcano Observatory, Vol. XIV, No. 5, pp. 55-56, 1926.

A number of cones are found along the Mauna Loa east rift zone but so far as known are of the flow type and were not the producers of stratigraphically significant amounts of pyroclastic material (Kaohe and Humuula quadrangle).

Stearns lists Puu o Keokeo, Keau, Kapoalaala, Ihuanu Halepohaha, Pahualalu, Akihi, Puu o Lokuana, Ohohia, Ohialele, Laula, Homaha, Pualehua, Puu Kuhua, Leau, Kulani, Kiipu, Ulaula as being composed of cinders and states that there are about 200 more unnamed cones of this class on the two rift zones of Mauna Loa.[51] The largest of these is Puu o Keokeo, which is a compound cone, in one pit of which a lava lake once existed, and the southern side of this cone was the source of the lava flow of 1907.

The Kona Tuff Formation

In the course of a reconnaissance through the Kona district in the summer of 1929 no ash formations were noted between the vicinity of Kahuku and the Hualalai Rift division. Later, in connection with a detailed study of parts of the Kona district, Dr. H. A. Powers, of the Volcano Observatory, found several areas mantled by a yellow-brown palagonite ash.[52] The following summary of characteristics of this formation has been written by Dr. Powers for this report (Kailua quadrangle):

"A roughly triangular section of the southwest slope of Hualalai, its apex at the summit and its base about 6 miles of the coast line south from Kailua, is covered with a mantle of pyroclastic material. The ash is more or less interbedded with lavas of different age. On the lower slope, the mantle is pockety, occupying small depressions in the surface, and probably would make a continuous mantle not more than 1 or 2 inches thick. It thickens gradually from a few inches to 5 feet, and forms a continuous mantle, up the mountain slope, grading finally into the cinder cones of the summit. At 4000 feet it has a maximum thickness of 3 feet. All of the material, except the cinders of the cones, is very fine-grained palagonite with an inconspicuous amount of minute fragments of olivine and feldspar crystals. The texture of the mantle and the physical characteristics of the palagonite indicate that the material is completely altered fine, vitric ash. No pronounced bedding is found on the lower slopes, but as the summit cones are approached, definite bedding of coarser and finer layers in the ash mantle becomes evident. The size of grains also increases near the summit cones. It is quite clear, therefore, that the ash mantle is made up of the finer ash produced during the summit cinder-cone eruptions which was drifted some distance down the mountain slope.

"Several strips of the Mauna Loa slope are covered with a palagonite mantle of variable thickness. The most important areas are: a strip about 3 miles wide along the southern edge of North Kona extending from sea level to between 4500 and 5500 feet; several small strips less than a mile long and relatively narrow in the northern part of South Kona lying between 1000 and

[51] Stearns, H. T., and Clark, W. O., Op. cit., p. 124, 1930.

[52] Powers, H. A., Ripperton, J. C., and Goto, Y. B., Survey of the Physical Features That Affect the Agriculture of the Kona District of Hawaii, Hawaii Agricultural Experiment Station, Bulletin 66, 1932.

2500 feet elevation; an area about a mile wide and 2 miles up and down the slope above Honaunau; and several small strips 2 or 3 miles south of Honaunau. These areas are all parts of an ash-covered terrane which have not been buried by the lava flows of Kamehame age from Mauna Loa. As yet there is no direct evidence on which this ash may be correlated with the Pahala tuffs, but the general relationship to the Kamehame basalts permit such a correlation. The mantle is made up of fine grains of palagonite and traces of broken olivine and feldspar crystals. On the lower slopes, the thickness averages about 6 inches, and this increases to 4 or 5 feet at about 2500 feet elevation. Above this level, the thickness stays about constant, or even decreases slightly, except in one locality where the mantle grades into a small ash cone at 5490 feet elevation (Kikiaeae). The palagonite of the mantle has been formed by the decomposition of an unconsolidated deposit of fine vitric ash. No traces of bedding are found, so either the original ash showed no bedding, or such bedding has been lost in the process of alteration. Puu Kikiaeae is obviously the source of part of this ash. Possibly a number of other similar cones may have been buried by the Kamehame basalts. It is probable, also, that a limited amount of fine ash may have been drifted south from the Hualalai ash portions from the rest of the deposit."

In the preceding paragraphs Powers has suggested the possibility that this tuff may be the equivalent of the Pahala tuff. Though there is no clear evidence either to prove or disprove this view the present writer is disposed to believe that the thin Kona tuff is a product of the post-Pahala eruptions of the Hualalai and Mauna Loa vents. The exposed thickness is nowhere great enough to indicate equivalence with the larger part of the Pahala tuff and it seems more likely that the entire Kona surface is composed of post-Pahala flows from Mauna Loa and Hualalai.

The Kapoho Pyroclastic Materials

Two types of pyroclastic formations are to be found in the Puna district, the first resulting from primary eruptions from vents along the Kilauea east rift zone, and the second consisting of littoral cinder and ash cones formed by lava flows at the points of their contact with sea water. The craters of the western end of the Kilauea east rift zone are mostly pit craters and few cones are found in this district. At the eastern end of this zone, however, there are a number of ash and cinder cones. The principal ones from east to west are Puu Kukae, Kapoho Crater, Kaholua o Kahawali Crater, Puu Kii, Puu Honuaula, Puu Kaliu, Puu Kepaka and Ilewa Crater (Puna, Kalapana and Makuu quadrangles).

Puu Kukae is about 150 feet in height, a V-shaped crescent with its points facing northward and covering an area about 2000 feet in diameter. It consists of black and red cinders 2 centimeters in diameter. The material is exposed in a large pit from which road ballast is being dug (Plate 5*C*). A few layers contain cinders coarser than 2 centimeters but no beds finer than this were seen. On all sides the dip of the layers of cinders is practically parallel with the topographic surface. This cone is uncommonly homogeneous and its coarser texture adapts it particularly well for commercial use.

Kapoho Crater is about ¾ mile in diameter and is a somewhat complex crescent with the breached side facing northeast. Its highest point on the rim stands about 400 feet above the adjacent surface. Green Lake and one other small pond occupy positions within the crescentic rim. The successive events in the history of this crater have been interpreted by Stearns.[53] According to him the crater is thought to have been first formed by a submarine explosion of the magmatic type which resulted in a crescentic accumulation of cinders and pumice, which contains also numerous accessory blocks weighing a ton or more. This interpretation is based on the general relation of the cone to the east cape, though no actual structural evidence is known. The eruption was followed by a long interval during which erosion and accumulation of a soil layer took place, and which came to a close with an eruption of 4 lava fountains which played from a fissure in the center of the crater and which formed layers of cinders 5 to 15 feet in thickness. Accessory masses of baked clay suggest the presence of a lake and lake clay beds prior to this eruption. In one of the sinks formed during this second eruption Green Lake now lies. This lake appears to be perched on relatively impervious clay layers that have been washed into the basin.

To the present writer it appears to be an entirely open question whether Kapoho Crater was formed before the island had been extended to its site or slightly thereafter. The relationship of the lava flows on the two sides of the rift zone to the crater is such as to indicate that the surface formations are subsequent to the formation of the cone, but farther than this, existing data are inconclusive. The present crater bottom lies so little above sea level that it seems likely that the crater bottom extended below sea level immediately after the eruption, but this suggestion does not particularly favor either interpretation, nor would the presence of calcareous marine accessory blocks show whether these were brought directly from the sea bottom or from material previously buried by pre-eruption lavas encroaching on the sea.

Puukea is a subordinate cinder cone lying on the northwest flank of Kapoho Crater and the result of an eruption subsequent to the first Kapoho eruption. Kaholua o Kahawali Crater and Puu Kii are two small crescentic cones with points facing east. Each is about 1000 feet in diameter and though they were not visited, they are presumed to be cinder or ash cones because of the orientation of the high sides to the leeward. All the small craters mentioned above, Puu Honuaula, Puu Kaliu, Puu Kepaka and Ilewa Crater show crescentic forms with the points facing either to the northeast or toward the southeast coast.

The Keanakakoi Formation

For many years this complex of ash formations has been loosely referred to as the 1790 ash, since it is clear that a part of it was expelled during the great explosive eruption of Kilauea in 1790. However, many geologists and others

53 Stearns, H. T., and Clark, W. O., Op. cit., 1930 (pp. 146-148).

have recognized that the products of several eruptions are included in the series and that these were separated by sufficient time intervals to allow considerable amounts of erosion and the growth of a heavy forest cover.[54] In view of the complex character of the series and the evident error in applying the term 1790 ash to the whole, it is here suggested that the name Keanakakoi formation be used to apply to the whole series of surface ash layers which appear to have resulted from successive explosions of Kilauea during the present physiographic epoch. This formation, thus defined, includes not only the 1790 ash but also that of 1924 as component members.

The Keanakakoi formation forms a thin surface cover over the region closely surrounding the Kilauea caldera (Kilauea quadrangle). Within the caldera only that portion of the Keanakakoi formation which was expelled during the 1924 eruption lies on the present surface, the larger part being interbedded between lava flows which have overrun the floor of Kilauea and form the dome of Halemaumau. The Keanakakoi formation has a maximum thickness over 30 feet on the tongue of the caldera rim which extends westward from Keanakakoi Crater (Plate 5*D*). Similar thicknesses of ash were originally thrown over a larger area south and southwest of Halemaumau but these are now buried. According to computations made in estimating the whole volume of the formation the maximum thickness deposited in the central area was probably about 80 to 90 feet. Thicknesses of five feet or over are exposed in a crescent-shaped area lying close to the caldera rim on the east, south and west sides. Not over 30 square miles is covered by more than four inches in this ash. Measurements of thickness have been compiled by Stone and also by Stearns.[55] A contour map first published by the latter is redrawn in Figure 10.

The Keanakakoi formation includes beds of material of considerable variety. Parts of it seem to be largely composed of lapilli and dust, produced by phreatic explosions and trituration of the wall rocks of the Kilauea vent, but other parts, especially the layers of reticulite[56] (the "thread-lace scoria" of Dana) indicate important magmatic explosions during which much essential

[54] Stone, John B., The Products and Structure of Kilauea, Bishop Museum Bulletin 33, pp. 33-35, 1926.

Powers, Sidney, Explosive Ejectamenta of Kilauea, Amer. Jour. Science, Fourth Series, Vol. 41, pp. 238-239, 1916.

Stearns, H. T., Geology and Water Resources of the Kau District, Hawaii, U. S. Geol. Survey, Water Supply Paper 616, pp. 149-152, 1930.

[55] Stearns, H. T., Geology and Water Resources of the Kau District, Hawaii, U. S. Geol. Survey, Water Supply Paper 616, pp. 149-152, 1930.

Stone, J. B., The Products and Structure of Kilauea, Bishop Museum Bulletin 33, pp. 28-29, 1926.

[56] Because of the objections elsewhere stated to the term scoria as applied to the "thread-lace scoria" of Dana and the distinct difference between this material and true pumice the term reticulite has been proposed for this extremely attenuate rock formed of glass threads. Wentworth, C. K., and Williams, Howel, the Classification and Terminology of the Pyroclastic Rocks, National Research Council, Bulletin No. 89, pp. 41, 47-50, 1932.

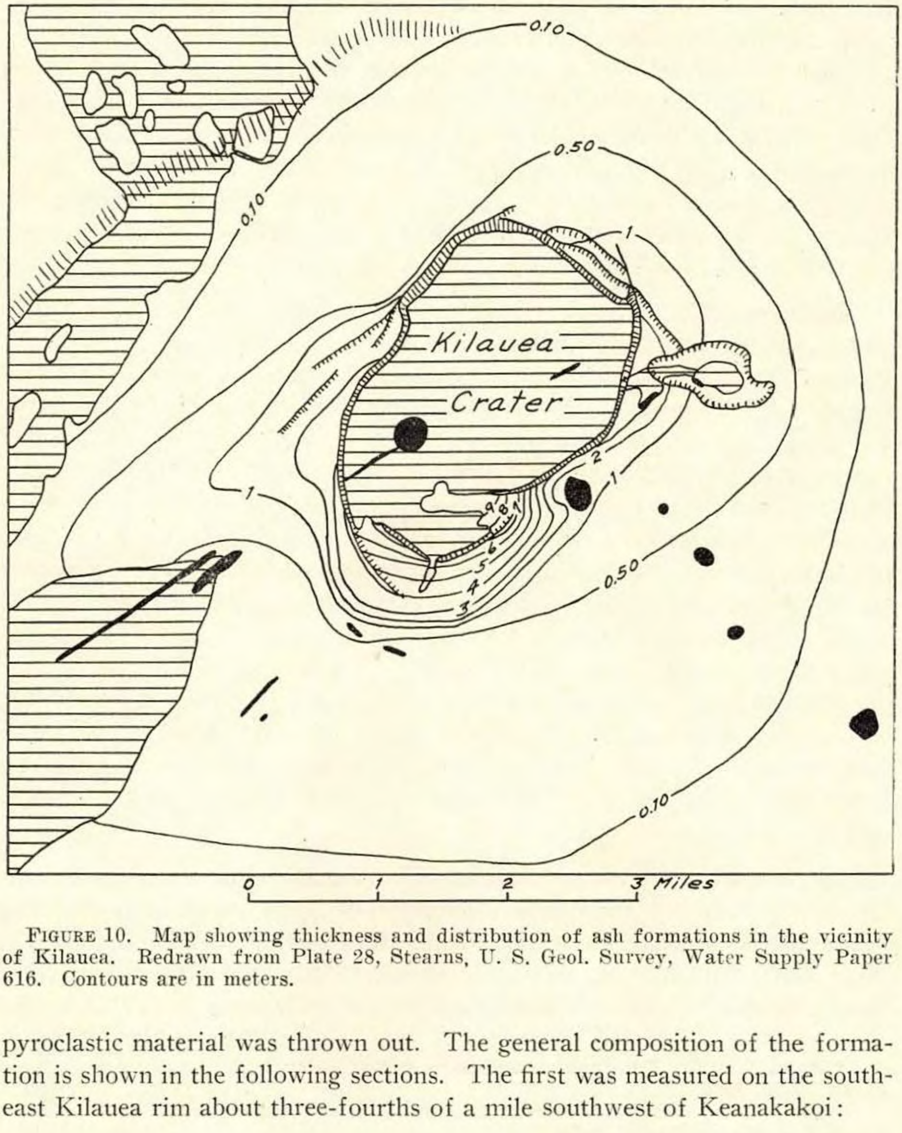


FIGURE 10. Map showing thickness and distribution of ash formations in the vicinity of Kilauea. Redrawn from Plate 28, Stearns, U. S. Geol. Survey, Water Supply Paper 616. Contours are in meters.

pyroclastic material was thrown out. The general composition of the formation is shown in the following sections. The first was measured on the southeast Kilauea rim about three-fourths of a mile southwest of Keanakakoi:

Top:	Feet	Inches
Gray-lavender, fine sand-sized ash......................		3
Gray and black, granular lapilli ranging to 4 mm.		3
Slight unconformity.		
Banded gray sandy to pebbly textured ash ranging to 16 mm.	1	6
Olive gray sandy to pebbly textured ash................	1	
Discontinuous layer of blocks up to 12" producing "bomb sags" in subjacent beds.		
Olive brown sandy to pebbly textured ash ranging to 8 mm.	2	8

	Feet	Inches
Purple, cemented, clayey ash		6
Black cinders		6
Nearly uniform beds of olivine-bearing sandy ash	10	
Finely laminated, rapidly varying beds of olivine sandy ash, glass grains, cinders ranging to 4 mm. Bedding very uniform and averaging one inch thick	13	
Base: Basalt.		
Total	29 feet	8 inches

At a point immediately west of Keanakakoi, another section was measured which consisted of the upper six feet of the foregoing section down to the black cinders, with almost identical thicknesses.

The following section is exposed on the trail south of Lua Manu Crater, east of Keanakakoi:

Top:	Feet	Inches
Lithic, accessory debris (1790 ash?)		6
Lavender, clayey powder		2
Gray-brown sandy textured ash		4
Brown, earthy layer		6
Black, 8 millimeter cinders		5
Olive and black sandy textured ash		6
Yellow-brown reticulite		4
Base: Basalt.		
Total	3 feet	9 inches

Top:	Feet	Inches
Earthy, weathered, pyroclastic material ranging to 64 millimeter lapilli	1	10
Porous, moist layer of 2 to 8 mm. lapilli		3
Lavender-gray, clayey dust		1
Gray, sandy textured ash		8
Brown, laminated earthy and sand textured ash		10
Lavender to purple, sandy-textured ash		4
Reticulite		10
Base: Basalt.		
Total	4 feet	8 inches

A few rods farther west a similar but less clearly exposed section was measured as follows:

	Feet	Inches
Weathered, earthy material carrying lapilli and blocks ranging to 64 millimeters, sandy-textured layers at base	2	3
Earthy, sticky brown material		10
Reticulite	1	1
Base: Basalt.		
Total	4 feet	2 inches

Another section was measured at the edge of Waldron Ledge about 2000 feet south of the Volcano House:

	Feet	Inches
Coarse, lithic debris ranging to 15 centimeters, poorly bedded and sorted		9
Even-bedded, sandy-textured material carrying lapilli ranging to 4 mm. Black and red "sand" at base		9
Olive-brown, sandy-textured material ranging to 2 millimeters		9
Weathered reticulite		?
Base: Concealed.		
Total	2 feet	3 inches

Farther east the ash cover thins rapidly (Puna quadrangle). In places a part of the formation may be buried under later flows. A thousand feet southeast of Heake Crater the section consists of five inches of lithic lapilli lying on four inches of black cinders, with basalt flows beneath. A mile and a half east of this point and nearly south of Aloi Crater the total ash section is not over five inches in thickness. On the Keauhou trail south of Ainahou Ranch at 2400 feet the total thickness of the Keanakakoi formation is about eight inches and no trace was noted south of Poliokeawe Pali.

On the Volcano Road about three miles east of Volcano House and at 3600 feet elevation the average thickness of Keanakakoi ash was estimated at ten to fifteen inches. Three miles farther east at 2850 feet not over three inches was recognizable. On the west side of Volcano House about 1500 feet west of the Military Camp, the following section is exposed (Kilauea quadrangle):

	Feet	Inches
Coarse, red and black lapilli layers ranging to 64 millimeter fragments	1	
Lithic, red and black ash with grains to 2 millimeters	1	2
Yellow reticulite	1	4
Total	3 feet	6 inches

A mile and a half farther southwest on the road the section shows the following:

	Feet	Inches
Lithic lapilli ranging to 32 millimeters	1	3
Red and black ash of sandy texture with black cinder layer at base	1	
Sandy-textured, olive-colored ash with lavender-gray layer at base	1	2
Reticulite		6
Base: Concealed.		
Total	3 feet	11 inches

At the intersection of the Kau Road and the 3900 foot contour the Keanakakoi ash is at least four feet thick and the thickness increases southeastward toward Uwekahuna Bluff. At a point due west of Keanakakoi and at the edge of the bluff the following section was measured:

	Feet	Inches
Lavender-gray ash (1924)		4
Reticulite, in part coarser and more pumiceous than typical variety	3	4
Banded detritus, mainly accessory lapilli to 1 centimeter but with some fragments ranging to 50 cm............	5	
Olive-green sandy textured detritus ranging to 4 millimeters	3	
Olive-green detritus like above only 1 mm. coarseness.....	3	
Olive-green sand-to-silt-textured debris under ½ mm......	3	
Base: Basalt.		
Total	17 feet	8 inches

Near the Halfway House, about seven miles southwest of Kilauea, at the roadside the following section was measured:

	Feet	Inches
Dark soil		3
Variable gray-black, sandy-textured ash, probably of 1790		6
Yellow dust	2	
Pockets of gray ash ranging to 1 mm..................		2
Yellow tuff dust, probably secondary..................	6	
Pockets of gray cinders ranging to 4 mm................		6
Slope-washed debris with fragments of yellow tuff.......	4	
Base: Concealed.		
Total	13 feet	5 inches

This section is near the base of the Kaoiki Pali which marks the southeast margin of the Mauna Loa surface in this vicinity and the material appears to consist of layers from the Keanakakoi ash interbedded with secondary eolian and slope-washed material from the Pahala tuff which is exposed at a number of places along this escarpment.

About a mile and a half farther southwest ash of the 1790 type covers the surface to a depth of about eight inches. Similar sections to those given above have been measured by Stone and by Powers.[57] No one has yet made a sufficiently detailed study of these sections to trace the several component beds for any considerable distance, or to describe the sequence of events in greater detail than merely to recognize the multiplicity of eruptions by which the Keanakakoi formation was deposited.

It is probable that both phreatic explosions like those of 1924 and true magmatic explosions have taken place during the Keanakakoi epoch. On the basis of existing knowledge only certain general conclusions can be stated. All observers agree that the eruption of 1924 was phreatic and wholly non-

[57] Stone, J. B., The Products and Structure of Kilauea, Bishop Museum Bulletin 33, pp. 30-33, 1926.

Powers, S., Explosive Ejectamenta of Kilauea, Amer. Jour. Sci., Fourth Series, Vol. 41, pp. 234-236, 1916.

magmatic.[58] The mechanism of this eruption has been ably interpreted in the paper by Jaggar and only a brief statement need be made here. Commencement of the explosive phase had been preceded by an extreme withdrawal of the lava column from Halemaumau. Thus deepened and its walls unsupported, the pit was greatly enlarged by progressive engulfment. Huge talus cones flanked its lower walls and merged in the center at the deepest part of the pit, which showed a depth below the rim of 1330 feet shortly after the eruption. This exceptionally deep withdrawal of the lava column permitted ground water, ordinarily kept back by steam pressure, to invade the heated rocks under Halemaumau and to be converted into steam in enormous quantities. Seemingly the talus materials over the vent acted as a great plug and a geyser mechanism of a crude sort. Periodic, spasmodic steam explosions took place, which on the one hand sent tremors through the surrounding rocks and on the other gave rise to tremendous columnar and cauliflower-shaped dust clouds and to the expulsion of large quantities of coarser debris onto the adjacent surface of the Halemaumau dome (Plate 6*A*).

The largest block thrown out during the eruption was estimated to weigh 14 tons and lay for several years near the east rim of Halemaumau. On September 10, 1930, it fell into the pit with an avalanche. Another block weighing about 8 tons was thrown 3500 feet from the center of Halemaumau. Thousands of smaller blocks ranging down to two or three inches in diameter are strewn around the Kilauea floor for several hundred feet from the rim of Halemaumau. None of these show any sign of fusion and all are broken pieces of wall rock. Some, which were observed to be incandescent at the time they were ejected, doubtless came from large, newly-exposed intrusive and as yet uncooled bodies encountered in the wall of the pit as engulfment proceeded.

Finer material in large quantities was deposited over the surrounding country. Its lithologic character will be described in the section on petrography. During the rain showers which were induced by some of the dust clouds, accretionary lapilli were formed by the falling of rain drops through the dust. Some of these were still further increased in size by rolling on the ground after they fell. No pumice, cinders, Pele's hair or any other kind of juvenile or essential ejecta were thrown out during the explosions. This not only indicates that these explosions were not magmatic in character but also that liquid lava did not produce, and was not exposed by them. The ordinary Kilauean fountaining produces pea-sized cinders and Pele's hair and during the eruption of 1929 such materials were observed by the writer to be carried out of the 1000 foot pit in the hot updraft. The thickness of the 1924 ash

[58] Jaggar, T. A., Volcanic Phenomena of the Eruption, Bulletin of the Hawaiian Volcano Observatory, Vol. XII, No. 5, pp. 31-37, 1924.
Stearns, H. T., The Explosive Phase of Kilauea Volcano, Hawaii, in 1924, Bulletin Volcanologique, No. 5, and 6, 3rd and 4th Trimester, p. 14, 1925.
Stone, J. B., Op. cit., p. 35, 1925.
Stearns H. T., Op. cit., pp. 145-146, 1930.

formation on the rim of Halemaumau was reported by H. T. Stearns to have been from 6 to 17 inches.[59] If the thickness of 17 inches be compared with the thickness of 35 feet which is about the maximum rim thickness for the Keanakakoi formation it is seen that the 1924 formation comprises approximately 1/25 of the whole series in this locality. Since the maximum thicknesses of the Keanakakoi formation components are not all found in one place and the maximum aggregate still exposed is probably somewhat less than at some more central locality where the ash has been buried, it is probable that the true ratio is somewhat higher than this, possibly 1 to 50 or 1 to 100. It is clear from data given in the measured sections, that certain component members of the Keanakakoi formation are considerably greater in volume than the 1924 member, possibly amounting to as much as one-fourth or one-third of the whole. In order to learn the general significance of the whole group of Keanakakoi eruptions, the thickness map published by Stearns and here reproduced in Figure 10, has been used as the basis of planimeter measurements from which the total volume of visible Keanakakoi formation has been computed. This amounts to 160 mile-feet, or about 126,000,000 cubic meters. Because the present Kilauea caldera is three miles in diameter, it is evident that a large part of the original volume of ash has been buried by incorporation in the Halemaumau dome. In the case of the Waiau formation it has been estimated in an earlier section that possibly not over ten to twenty percent of the total volume of expelled material lies in the central cones and that a larger part has been carried out over the surrounding country. In somewhat feebler eruptions, like those of the Keanakakoi epoch, it is probable that more of the whole mass was deposited in the central area. An attempt has been made to calculate the amount of the ash lost in the caldera and lying outside the contoured area.[60] This appears to be about one-half as much as the known volume. The total volume of the Keanakakoi formation may therefore be as much as 240 mile-feet or 190,000,000 cubic meters, and thus seems to be comparable as a whole with the smaller of the cone forming eruptions of the Mauna Kea series. Its individual eruptions were therefore mostly quite insignificant volumetrically. The volume, as ash, of the material ejected in 1924 has been computed by Jaggar as 55,420,000 cubic feet (1,570,000 cubic meters) or very close to 2 mile-feet. This is 1/120 of the total determined above for the Keanakakoi formation.

[59] In June 1924, Jaggar found dust thicknesses from the 1924 eruption of 8 to 16 millimeters at 4 miles, 2 to 7 millimeters at 11 miles, 3 to 4 millimeters at 14 miles, and a mere film under ¼ millimeter at 20 miles at Pahala, all points in a leeward direction. (Hawaiian Volcano Observatory Bulletin, Vol. XII, No. 6, p. 67, 1924.)

[60] The areas enclosed respectively within the 1/10, 1 and 10 meter thickness contours were used to determine the probable area within the 1/100 meter contour and also the probable height of the central cone had none of the formation been engulfed in the caldera. The determination was made on the assumption that the diametrical profile of total accumulation is a probability curve of the form $\log_e Y = h^2x^2 K$, where Y is the thickness, x the radius from the mode of the curve, e the base of the Napierian natural logarithms (2.718) and h and K are constants.

If it be assumed that the largest of the single magmatic eruptions included in the Keanakakoi formation amounted to a third of the whole, or 80 mile-feet, this volume may be compared to the volume of lava poured into the Kilauea caldera from 1823 to 1921 which has been estimated by Jaggar. This amounts to 1,708,000,000 cubic meters or about 2150 mile-feet. Thus the larger magmatic explosions amount only to about 4 years quota of the crater filling and the lesser eruptions to very much less.[61] Several small flows into the Halemaumau pit since 1924 have averaged under 5,000,000 cubic meters of basalt (about 6 mile-feet) for each and very closely one flow and the same volume per year. This is less than one-third the average rate for the last century.

Next earlier than the 1924 explosive eruption was that of 1790. This occurred before Europeans were permanently settled in any part of the Hawaiian group but was recalled by many natives living at the time of the arrival of the missionaries and was vividly, if not accurately impressed on their minds because of the destruction of a part of the army of Keoua, which was advancing to attack the forces of Kamehameha. It is not necessary to repeat the story, which has been reported by numerous writers from the original account by Dibble.[62] It seems clear from the various facts reported, including the condition of the bodies of the natives who were killed, that this eruption was a magmatic one and that hot sulfurous gases were emitted which caused suffocation of the members of the native party. Additional evidence of the juvenile character of this explosive eruption is afforded by the lava bombs found in the 1790 ash which have been described by Perret,[63] and observed and mentioned by various other students. Though moderate amounts of juvenile material are found in the 1790 member of the Keanakakoi formation, the larger part of that member consists of fragments of the pre-existing wall rock, which, at certain localities not far from the Kilauea caldera, range to 50 or 100 millimeters in diameter. Sections in which the 1924 ash consisted of a fine dust almost devoid of sand-sized grains in many cases show the 1790 detritus as containing fragments of the size of peas or hickory nuts, testifying to the far greater violence of the earlier eruption. The total amount of material thrown out during the 1790 eruption was several times as great as was expelled in 1924.

The upper part of the 1790 member appears chiefly to be accessory material, which suggests the likelihood that the 1790 eruption may have commenced

[61] Jaggar, T. A., Volume Relations of the Explosive Eruption 1924, Bull. Haw. Volc. Obsy., Vol. XII, No. 12, 120, 1934.

[62] Dibble, Rev. Sheldon, History of the Sandwich Islands, Lahainaluna, 1843, p. 65.

Brigham, W. T., The Volcanoes of Kilauea and Mauna Loa, Bishop Museum Memoirs, Vol. II, pp. 36-39, 1909.

Dana, J. D., Characteristics of Volcanoes, New York, 1891, pp. 41-45.

Powers, S., Explosive Ejectamenta of Kilauea, Amer. Jour. of Science, Fourth Series, Vol. XLI, pp. 227-230, 1916.

[63] Perret, F. A., Some Kilauean Ejectamenta, Amer. Jour. of Science, Fourth Series, Vol. XXXV, pp. 611-613, 1913.

with a magmatic phase which resulted in the expulsion of much juvenile material. Following this there was probably a withdrawal of the lava column, as in 1924, with resulting collapse of the walls of the pit by engulfment. This in turn was probably followed by a series of phreatic explosions caused by the admission of ground water to the heated rocks adjacent to the pit. It does not seem likely to the present writer that explosions which were exclusively magmatic in origin could have expelled so large quantities of accessory lapilli, or that such material could have been distributed with such apparent periodicity without the engulfment and rock geyser mechanism described above as characteristic of the 1924 eruption.

Below the base of the 1790 ash the component members have not been identified and separated in detail. Between the base of the 1790 ash and the thread-lace "scoria" or reticulite, as it is called in this report, is a series of beds ranging from one to ten or more feet in thickness and consisting largely of juvenile material. This latter is of rather variable character and includes layers of black cinders; yellow, olivine-bearing sandy-textured ash; layers consisting largely of glass grains, and the like. The thickest part of this section is not developed in the places where the reticulite is best developed but, according to Stone, thin remnants of the reticulite can be found at the base of some of the thickest sections of the Keanakakoi formation west and southwest of Keanakakoi.[64] In this section there is no thick layer of coarse-grained, accessory material and present evidence does not indicate any earlier phreatic explosions with violence approaching that of 1790. On the other hand, there appears to have been a much more vigorous series of magmatic explosive eruptions prior to 1790 than any which took place at that time. The strata which megascopically most strongly suggest accessory phreatic explosions are the comparatively thin layers of lavender, clay-like ash.

It is worth speculating as to whether the phreatic explosions could operate so effectively and ideally from a vent at the bottom of a much shallower pit stoped in a much lower Halemaumau dome than existed in 1924. It appears plausible that with the much lower elevation of the Kilauea floor in 1823 (according to Jaggar, the bottom of the Kilauea Crater in 1823 was 1400 feet lower than the level of Kilauea overflow in 1921)[65] and probably all the prior time back to the time of formation of the caldera and with a ground water table similar in elevation to that of the present time, the phreatic type of explosion may not have been so well developed or so effective in expulsion of accidental debris. Contrariwise magmatic explosions might quite reasonably have been more imminent and more effective under these conditions. If these surmises are correct the 1790 in part and the 1924 eruptions as a whole may be regarded as the culminating phreatic type eruptions under conditions either at or approaching an optimum phase.

[64] Stone, J. B., The Products and Structure of Kilauea, Bishop Museum Bulletin 33, pp. 31-32, 1926.

[65] Jaggar, T. A., Op. cit., pp. 119-120, 1924.

In an artificial cut near the Volcano Observatory are six carbonaceous layers indicating an equal number of epochs when plants grew on the surface following ash falls. These are all in material which underlies the 1790 ash. In other places two or three such soil layers have been found. Stone,[66] and Stearns,[67] as well as others, have suggested that special conditions of wind direction combined with local topography have produced special local concentrations of the materials from certain eruptions. It has also been recognized that directed blasts may account for asymmetrical distribution. These were observed in 1924 as a product of changes in the directions of the pipe due to changes in plugging. Attention should also be directed to the fact that the directions of air currents in different strata of the atmosphere up to fifteen thousand feet or more show considerable differences at any given time and the type of eruption and the height to which the greater bulk of the material was thrown would thus be an important factor in determining its ultimate distribution. It appears that a considerable part of the whole Keanakakoi formation is sufficiently fine in texture to be subject to appreciable drift of the sort implied.

Nearly all students have agreed that the Kilauea caldera had assumed essentially its present form by the time Keanakakoi eruptions commenced, and there appears no reason to dissent from this view. Stone attempted on the basis of the forest and the ages of trees to estimate the age of the older Keanakakoi ash members, and concluded that the oldest ash is not over 300 to 500 years old.

Mauna Loa Littoral Cone Materials

Formation of littoral pyroclastic cones where lava flows reach the sea has been common in the geologic history of Hawaii. Such cones are usually soon cut away by the sea, and only few examples remain.

None is known along the Mauna Loa shore southward from Hilo, but several are found on the southern and western Mauna Loa shores. At Punaluu, two miles east of Hilea is a beach of coarse black glass fragments, which were formed by a littoral explosion when a lava flow reached the sea but the cone has been destroyed. South of Punaluu, two littoral cones, Puehu and Waipouli, are listed by Stearns, but only the latter was identified by the writer.[68] Puu o Mahana has already been described in an earlier section. Puu o Haupu, also listed by Stearns as on the Kalae coast is not known to the writer by name. Puu Lohena lies a mile west of Pali o Kulani, and consists of a low mound of cinder and ash beds. The upper part is gray-green and contains much olivine; the lower beds are mostly red. This cone may have been formed from lava of a flow prior to that of 1868, though it is surrounded by 1868 lava. (On the Kalae topographic sheet the name "Lava

66 Stone, J. B., Op. cit., p. 29, 1926.
67 Stearns, H. T., Op. cit., pp. 149-152, 1930.
68 Stearns, H. T., and Clark, W. O., Op. cit., p. 126, 1930.

Flow of 1868" is misplaced and should lie on the terranes both east and west.)

A mile and a half farther northwest is the best known and largest of the littoral cones on the island, Puu Hou, which was built in April, 1868 (Plate *6B*). This cone is 1500 feet in diameter and 273 feet high. Its seaward slope has been cut away until the center of the cone is nearly exposed in the present sea cliff. The chief mass of Puu Hou is composed of vesicular coarse, red-weathered cinders. To the southeast and a few feet above sea level is a lava flow (itself older than the chief tongue of the 1868 flow) which overlies 10 to 15 feet of fine-grained gray cinders and ash like that of Puu Lohena. This suggests the formation of Puu Lohena and the westward dispersal of its gray ash prior to the formation of Puu Hou. It appears, though it is not clearly proved, that this event took place some years before 1868 rather than as a part of the same eruption.[69] Puu Waimanalo and Puu Kaimuuwala are prehistoric littoral cones mapped by Stearns. He does not state their composition. In addition he lists Puu Ki and Na Puu a Pele which are shown on the Hoopuloa topographic sheet as rising to elevations of 143 and 243 feet respectively, but does not describe their material.

Kilauea Littoral Cone Materials

The northernmost of the littoral cones of Kilauea is known as Sand Hill and is about five miles northwest of the east cape. This is 118 feet high and is surrounded by a small area of drifting sand. It is the remnant of one of three cones formed where the lava flow of 1840 reached the sea. This flow extended the coast a quarter mile and lava continued to enter the sea for about three weeks, commencing on the evening of June 3, 1840. The three hills of scoria and sand which were formed ranged from two hundred to three hundred feet in height but have now been largely destroyed. The eruption and the shattering of the lava into sand on entering the sea have been vividly described by the Reverend Titus Coan.[70] According to Brigham the cones were one hundred and fifty to two hundred and fifty feet high eight months after their formation and in 1865 were less than a third of their original height.

Kaakepa is a small cinder and scoria cone which rises to 125 feet on the south coast nearly midway between Cape Kumukahi and Kalapana. It is probably the result of littoral explosions from a flow somewhat antedating the most recent on this coast. Fairly large lava fragments were found in the material which dips radially outward throughout most of the hill. A remnant of another cinder cone lies five miles farther southwest on the north side of the coastal indentation at Kehana. Here about 20 feet of black cinders ranging from 1 to 8 millimeter sizes overlies a low lava dome.

69 Puu Lohena has been mapped by Stearns as a product of the 1868 flow. However, the writer got a contrary impression during a very brief visit on June 15, 1929.

70 Brigham, W. T., The Volcanoes Kilauea and Mauna Loa, Bishop Museum Memoirs, Vol. II, No. 4, pp. 50-54, 1909.

Notable quantities of medium to coarse black sand are found in the beaches and shore flats for a distance of somewhat over a mile at Kaimu (Plate 6*C*). The coarser fragments consist of fine-grained basalt and are well rounded by the waves. The finer material is vesicular basaltic glass and the whole was undoubtedly derived from an important littoral eruption, though the location of the resulting cone and the date of this prehistoric event are unknown.

Na Puu o na Elemakule, nearly ten miles east of Pahala, is a littoral cone rising 106 feet above sea level. Puu Moo, Puu Pili and Kamehame Hile are also littoral cones on the Kau portion of the Kilauea coast but their composition is not known.

PETROGRAPHY

Physical and Chemical Properties

Mechanical Composition

Regional features. Fragments included in pyroclastic formations on Hawaii range in size from blocks or bombs having diameters of two meters and weighing ten to fifteen tons down to the finest dust particles. The larger pyroclasts are restricted to the immediate vicinity of the volcanic vent; the finest material is found both near the crater and to leeward on the most remote parts of the island. The majority of the pyroclastic cones on Hawaii are composed of material in the lapilli (32 to 4 mm.) or coarse ash (4 to ¼ mm.) sizes. Cones largely formed of fine ash (¼ mm. or less) and now gone over to palagonite like those of southeast Oahu are unknown on Hawaii, but ash of this type is widespread in thin deposits formed beyond the immediate vicinity of the sites of eruption.

In various districts pyroclastic derivatives are transitional in composition between the pyroclastic debris and the materials normally accumulated by the process which has transported it. On beaches where wave action is effective the pyroclastic material is soon resorted to a composition typical of mature beach materials. (See Figures *12a* to *12d*, *12h* to *12j*, *12l*, *12o*, and *13a*, especially.) Fluvial transportation on such islands as Hawaii is mostly too ephemeral and of too torrential a character to effect mature sorting of any sediments, whatever their source. Eolian transportation is also extremely variable, though some fairly well-sorted fine-grained materials are in places accumulated by the wind at considerable distances from the source of materials.[1]

Pyroclastic sediments. The analyses shown in Figures 11-13 were made by sifting in a mechanical shaker for a period of five minutes, using the 1-2-4-8 mm. scale of sieve sizes described elsewhere.[2] The analyses of pyroclastics deal mainly with finer lapilli and coarser ash and cannot in any sense be regarded as a representative sampling of the pyroclastic accumulations on Hawaii. The mechanical compositions of the most typical samples shown are very similar to those previously found to be characteristic of pyroclastic materials on the island of Oahu. This composition is characterized by a maximum nearest the coarse end of the range, and a series of progressively smaller

[1] Wentworth, C. K., and Ladd, H. S., Pacific Island Sediments, U. of Iowa, Studies in Natural History, Vol. XIII, No. 2, pp. 7-9, 1931.

[2] Wentworth, C. K., Methods of Mechanical Analysis, Univ. of Iowa, Studies in Natural History, Vol. XI, pp. 3-52, 1926.

———, Methods of Computing Mechanical Composition Types of Sediments, Bull. Geol. Soc. Amer., Vol. 40, pp. 771-790, 1929.

———, The Mechanical Composition of Sediments in Graphic Form, Univ. of Iowa, Studies in Natural History, Vol. XIV, No. 3, 127 pages, 1931.

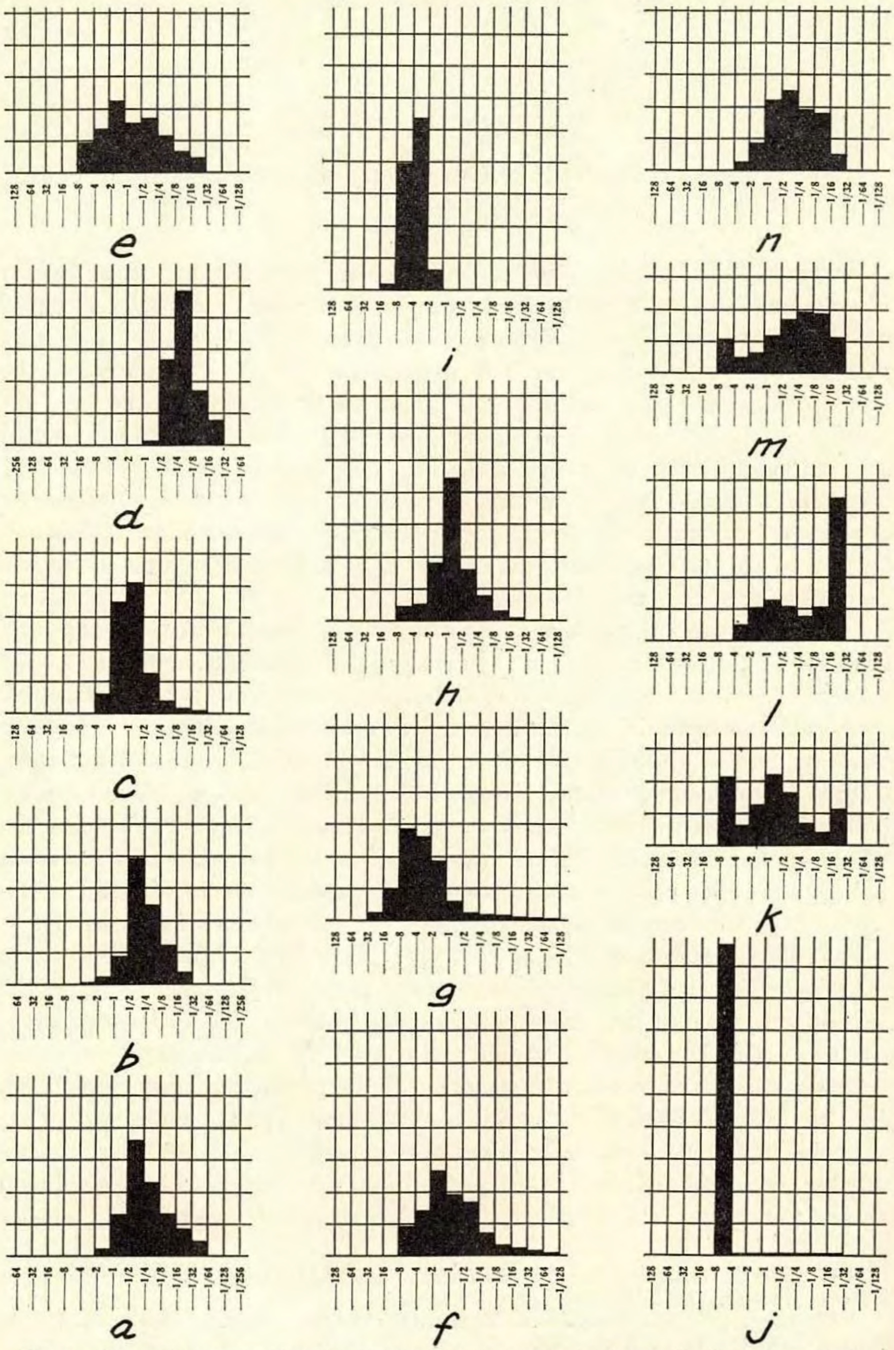


FIGURE 11. Histograms showing mechanical composition of pyroclastic sediments from the Island of Hawaii. (*a*) Sample 18, black ash north of Kalae lighthouse. (*b*) Sample 19, black ash north of Kalae lighthouse. (*c*) Sample 410, gray ash from north of Humuula. (*d*) Sample 509, greenish, sandy ash southwest of Military Camp, Kilauea. (*e*) Sample 549, lapilli and dust from one-half mile northeast of Keanakakoi Crater. (*f*) Sample 619, ash from littoral cone at Kehena, northeast of Kalapana. (*g*) Sample 744, basaltic cinders from west base of Puu Waawaa. (*h*) Sample 183*b*, lapilli and ash from Pohakuloa Gulch on Kohala road. (*i*) Sample 544*a*, cinders from eruption of Kilauea, July, 1929. (*j*) Sample 555, cinders from east of Kilauea on Chain of Craters road. (*k*) Sample 2357, lapilli and dust, 1924 eruption of Kilauea from near Volcano Observatory. (*l*) Sample 2356, (*m*) Sample 2358, and (*n*) Sample 2359, the same.

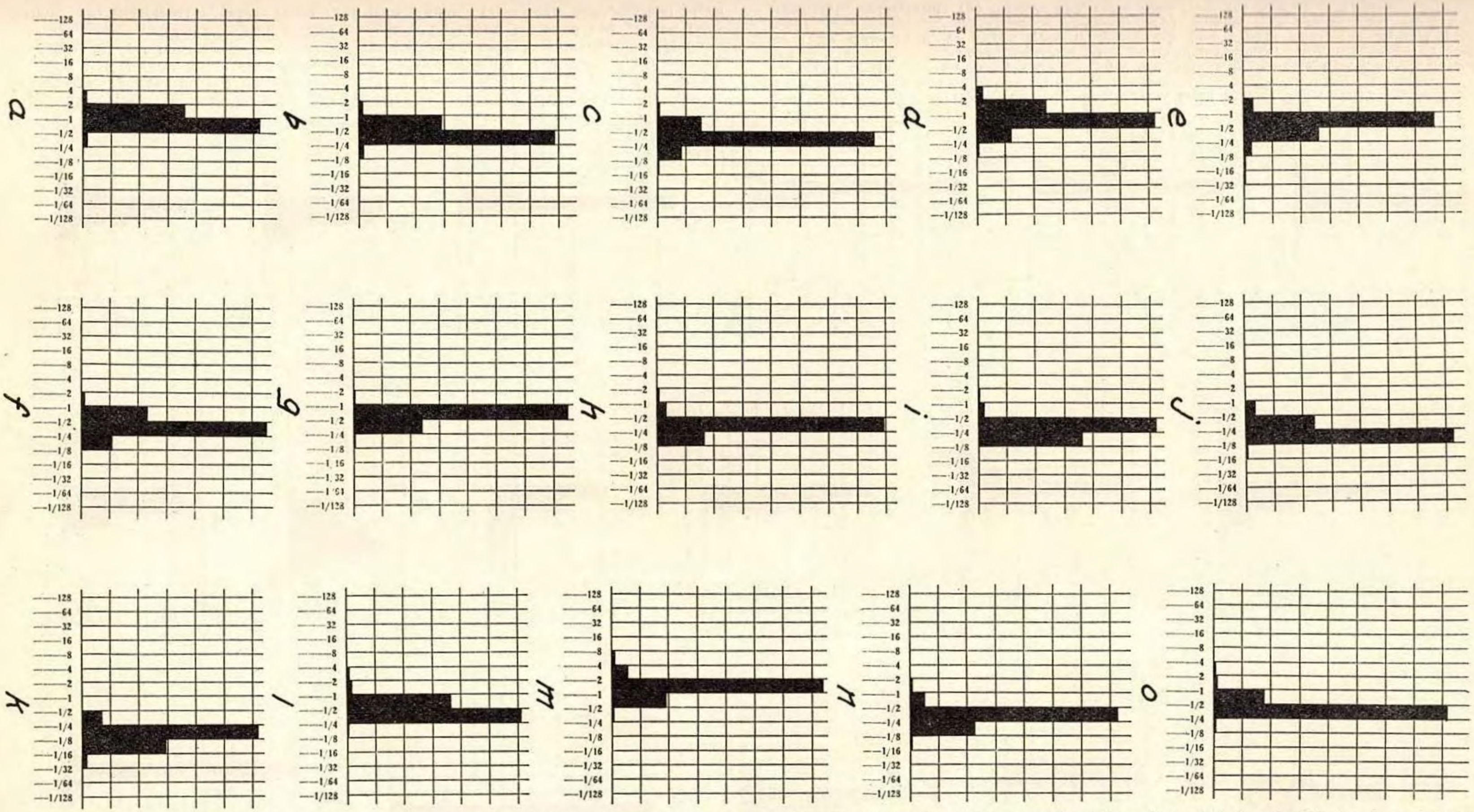


FIGURE 12. Histograms showing mechanical composition of sedimentary derivatives. Beach sediments. (*a*) Sample 10*b*, olivine sand east of Kalae. (*b*) Sample 27*a*, normal beach sand east of Kalae lighthouse. (*c*) Sample 27*b*, olivine sand from same locality. (*d*) Sample 51*c*, beach sand from near Puu Lohena ash cone. (*e*) Sample 77, olivine beach sand from northeast of Kalae lighthouse. (*f*) Sample 112, beach sand from Puu o Mahana. (*g*) Sample 202, beach sand from south of Kawaihae. (*h*) Sample 203, beach sand from near Kawaihae lighthouse. (*i*) Sample 499, beach sand from Hookena. (*j*) Sample 502, beach sand near Napoopoo. (*k*) Sample 602, beach sand from near Keaau. (*l*) Sample 617*a*, normal beach sand from Kaimu. (*m*) Sample 650*a*, coarse surface sand and pebbles from Keauhou. (*n*) Sample 737, beach sand from Kailua. (*o*) Sample 755, beach sand from south of Kawaihae.

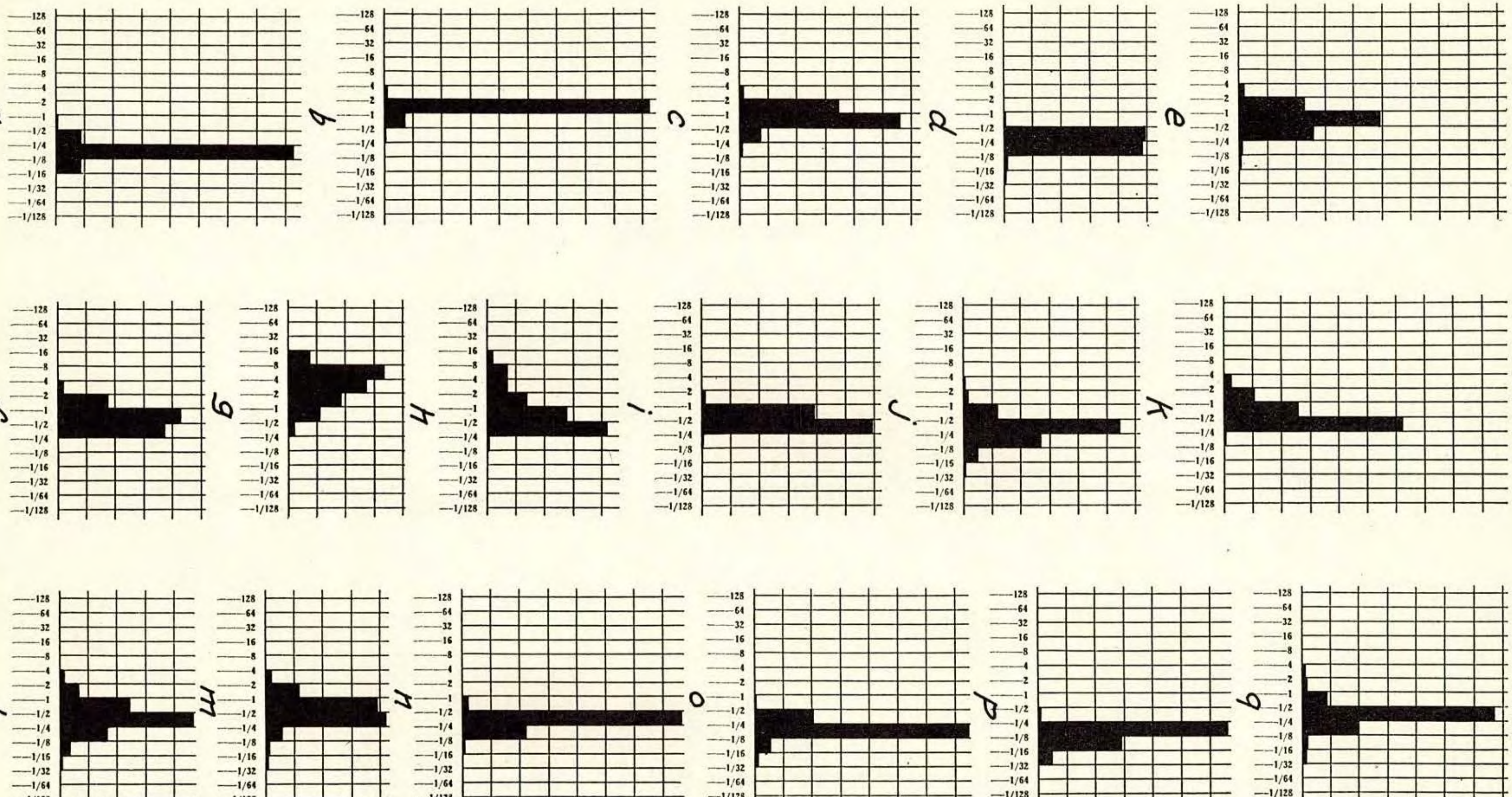


FIGURE 13. Histograms showing mechanical composition of sedimentary derivatives. (*a*) Sample 756, beach sand from same locality. (*b*) Sample 813, beach sand from Punaluu. (*c*) Sample 10*a*, beach sand from east of Kalae lighthouse. (*d*) Sample 158*a*, beach sand from Waipiò (see Figure 66). (*e*) Sample 495, beach sand from Hoopuloa. (*f*) Sample 501, beach sand from Napoopoo. (*g*) Sample 617*b*, coarse lag sand and pebbles from Kaimu. (*h*) Sample 617*c*, pebble beach sand from Kaimu. (*i*) Sample 650*b*, normal beach sand from Keauhou. (*j*) Sample 722, beach sand from east of Hilo. (*k*) Sample 738*a*, beach sand from south of Kailua.

Fluvial sediments: (*l*) Sample 285, sand from pothole in Kemole Gulch. (*m*) Sample 764, fluvial sand from local agglomerate rocks south of Kawaihae. Eolian sands: (*n*) Sample 158*b*, dune sand, 75 yards from Waipio beach (see Figure 56). (*o*) Sample 217*b*, eolian sand from ash northwest of Ahumoa. (*p*) Sample 569, eolian sand from near Maunaiki. Talus sand: (*q*) Sample 113, talus sand from ash of Puu o Mahana.

amounts of finer grades.[3] This distribution of particle sizes is apparently due to a winnowing process taking place in air currents which move horizontally past the site of deposition.

The chief difference between the pyroclastics from Oahu and the selected group from Hawaii is that the latter are somewhat less well-sorted. As shown in Table 1, these features are displayed by standard size ratio deviations ranging from 1.59 to 3.97 and by a very characteristic positive skewness ranging from 0.46 to 1.13.[4]

Sample 555, Figure 11*j*, is remarkable for the high degree of sorting shown, nearly 98% of the fragments lying between the limits of 4 and 8 millimeters in diameter. From its location it is thought to be the winnowed product of a

TABLE 1

MECHANICAL COMPOSITION CONSTANTS FOR SELECTED SAMPLES OF VOLCANIC ASH

Sample Numbers	Standard Deviation (class ratio = 2)	Standard Size—Ratio Deviation	Skewness (all positive)
Island of Hawaii:			
18	1.36	2.57	0.82
19	1.04	2.06	0.46
410	1.06	2.08	1.04
509	0.87	1.83	0.80
549	1.99	3.97	0.82
619	1.86	3.63	0.94
744	1.79	3.46	1.11
Average	1.42	2.80	0.86
Island of Oahu:*			
14	0.68	1.60	0.79
50	0.78	1.72	1.05
85	0.67	1.59	1.04
161	0.86	1.80	0.78
515*b*	1.88	3.68	1.02
535	0.67	1.59	0.55
559	1.91	3.76	1.13
588	0.95	1.93	0.90
1854	0.93	1.90	1.26
Average	1.04	2.19	0.95

* Wentworth, C. K., Pyroclastic Geology of Oahu, Bishop Museum Bulletin 30, pp. 96-98, 1926.

[3] Wentworth, C. K., Pyroclastic Geology of Oahu, Bishop Museum Bulletin 30, pp. 96-98, 1926.

[4] These terms refer to the shape of the frequency curve which shows the distribution of particle sizes as described in the paper on computing methods cited above. The standard size ratio deviation is the ratio by which the diameter of the most representative particle deviates from that of the mean particle. It is a measure of sorting, the value 1.00 would indicate perfect sorting and uniform sized grains. The value 2.00 would indicate that the most representative particle encountered at random would be ½ the size or twice the size of the mean for the whole number. Skewness is a measure of asymmetry and may be either positive or negative. Positive skewness indicates that the frequency or weight of particles falls off more abruptly at the coarse-grained end of the analysis.

brief episode of a nearby eruption. The mechanical compositions of four samples of detritus deposited near the Volcano Observatory during the 1924 eruption of Kilauea, shown in Figures 11*k* to 11*n*, show only crude sorting and are probably due to the mixing of materials thrown out in numerous spasmodic explosions of greatly different intensity.

Beach sediments. The mechanical compositions of beach sands and gravels composed in part of pyroclastic constituents are shown in Figure 12, and Figure 13*a* to 13*k*. The distribution constants for those samples in which more than sixty per cent is found in one grade are shown in Table 2. This point of separation was adopted arbitrarily to restrict the computation to those samples in which the sorting had been most perfect and in which the composition is presumably most ideal (Figure 12 and 13*a* and 13*b*). Further descriptions of these sediments are given on pages 154 to 156, inclusive:

TABLE 2
MECHANICAL COMPOSITION CONSTANTS FOR SELECTED BEACH DERIVATIVES

Sample Numbers	Standard Deviation	Standard Size Ratio Deviation	Skewness
10*b*	0.52	1.434	—0.83
27*a*	0.50	1.414	—0.96
27*b*	0.55	1.464	—0.32
51*c*	0.67	1.591	—0.32
77	0.71	1.636	1.18
112	0.60	1.516	—0.65
202	0.47	1.385	1.06
203	0.48	1.395	—0.71
499	0.71	1.636	—0.58
502	0.54	1.454	—1.05
602	0.61	1.526	1.47
617*a*	0.58	1.495	—1.05
650*a*	0.55	1.464	0.39
737	0.56	1.474	0.31
755	0.51	1.424	—1.37
756	0.46	1.376	—0.94
813	0.32	1.248	1.48
Average	0.55	1.464	

It will be noted in the table that the standard size-ratio-deviations vary from 1.24 to 1.64, and the skewness values from +1.48 to —1.37. The characteristic high degree of sorting is shown by the low standard size-ratio-deviations. Of seventeen analyses computed, eleven show negative skewnesses ranging from —0.32 to —1.37. The average of these is —0.80, and over half of the whole series of skewnesses fall within 0.50 of this average. This skewness appears to be the approximate typical position for these beach sands. Variations from it are quite erratic, ranging far over to the positive side of the scale and indicating either a very incomplete aqueous sorting or an inclusion of finer-grained tailings, perhaps of different density from the principal constituents.

Fluvial, eolian and talus sediments. The mechanical composition of two fluvial sands derived largely from pyroclastic materials is shown in Figures 64 and 65. Similar data for eolian and talus derivatives are shown in Figures 66 to 69. Size distribution constants for these samples are shown in Table 3.

TABLE 3

MECHANICAL COMPOSITION CONSTANTS FOR FLUVIAL, EOLIAN AND TALUS DERIVATIVES

Sample Number	Origin	Standard Deviation	Standard Size Ratio Deviation	Skewness
285............	Fluvial	1.05	2.07	—0.42
764............	"	0.93	1.905	0.68
158*b*...........	Eolian	0.48	1.395	1.02
217*b*...........	"	0.55	1.464	0.00
569............	"	0.60	1.511	0.83
113............	Talus	0.73	1.658	—0.56

The number of fluvial, eolian or talus sediments analyzed is insufficient to justify any general conclusions in regard to their composition characteristics. Apart from the imperfect sorting of some of them, their size composition is subject to considerable departure from that of ideal sediments because of the presence in them of materials of markedly different densities.

Shapes and Structures of Fragments

Larger fragments: Bombs. Bombs in general owe their shapes either to the conditions under which they were separated from the liquid or plastic parent material; to the forces of rotation, air resistance, or cooling during flight through the air; or to the conditions of their landing after flight.[5] Most of the Hawaiian bombs noted had shapes primarily determined by the conditions of separation (ribbon bombs) or by the forces operating during flight (almond-shaped bombs). A few of the latter showed broken ends or a slight crushing due to the force of landing but most of them apparently had become quite solid before reaching the ground. The almond-shaped bombs seen on Hawaii range in size from about one-half inch long to as much as six feet in length. Ribbon bombs were mostly from one inch to two feet in length.

Detailed study of the shapes and structures of the two types of bombs mentioned reveals a number of very interesting features which throw light on the conditions of flight. The bi-polar or almond-shaped bombs are most abundant and seem to be most characteristic in form and will be described first, since most of the other types appear to be less perfect, more primitive relatives of these. Reck recognizes three types of bombs, types two and three being those formed around a gas bubble core or a foreign (accidental or acces-

[5] The most extensive published work on the types and shapes of bombs is that by Hans Reck, Physiographische Studie Über Vulkanische Bomben, Friedlaender, Neapel, 1915.

sory) core, respectively.[6] No bombs of these latter types were noted by the writer on Hawaii. The fundamental feature of the bi-polar bombs consists of two projections at opposite ends. These projections are commonly broken so as to show the vesicular cross-section and the evidence of elongation while plastic.

Between the two ends, the typical bomb is bulbous, with a middle diameter three to ten times that of the end section (Plate *7A*). The middle diameters vary from 1/5 to 4/5 of the lengths. Much of the surface of many bombs is ribbed, parallel to the axis through the projections, and the central cross-section and profile are closely similar to those of the ends. The general form of the central profile ranges from a moderately eccentric ellipse to a circle, most having minor diameters 3/5 to 4/5 of the major diameter. There is thus a close general similarity to the shape of an almond or to the seeds of various fruits. Here the similarity stops. The two flatter or less convex surfaces of most bombs are distinctly different; there is seen to be a "top" and a "bottom" surface (Plate *7B*), (Figure 14). Separating the two and

FIGURE 14. Drawing showing ideal features of bi-polar, almond-shaped bomb, viewed from the side and showing parts of both stoss and lee surfaces.

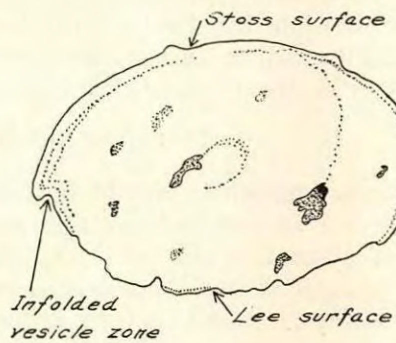


FIGURE 15. Drawing of mid-section through an almond-shaped bomb. Attention is called especially to the infolding of the vesicle zone at the annular rim and the irregular arrangement of vesicular spots through the interior. Slightly conventionalized from an actual bomb.

running from end to end along the most convex part of the surface is a fairly distinct edge or rim. In many instances this is a sharp, feather edge, from which plastic material appears to have been pulled and which has been sufficiently plastic to have been sharply turned, commonly toward the surface which will here be called the "lee" or ribbed surface.

The most striking difference between the two surfaces is that one is commonly marked by distinct and little-modified ribs or flutings extending between the ends, and the other shows either no ribs or else somewhat modified, indis-

[6] Reck, Hans, Op. cit., pp. 36-37, 1915.

tinct corrugations. These surfaces will here be referred to as the ribbed surface and the smooth surface. The smooth surface of some bombs is marked by slight, usually smooth protuberances, or pustules, which on breaking are seen to be due to slight distensions of the surface by bubbles. Occasionally these are broken open, but most appear to have been due to mechanical accident rather than to plastic bursting. In addition to the pronounced ribs on the side opposite the smooth side, that side is also commonly rough, and openly vesicular. In general the vesicular structure shown in this surface is finer, showing larger numbers of smaller cavities than are indicated by the pustules of the smooth side.

The various features shown point strongly to an effect of fluid drag on the bomb during its flight and when the surface was still capable of response by flowing. It is thought that the smooth surface was the front surface, or the bottom surface in case the bomb was falling. However, to avoid confusion it appears best to refer to this surface as the stoss surface; that is, the surface which moved against the fluid resistance of the atmosphere and volcanic gases. Correspondingly, the opposite surface will be regarded as the lee surface, or that facing opposite to the direction of motion. Thus the stoss, smooth, bottom and front sides are usually one and the same side; whereas the other side may be named either the lee, ribbed, top or back side depending on momentary interest.

The internal structure of the bombs shows only a moderate diversity. The material of most is slightly vesicular throughout. The most common differentiation is that of a slight zone of vesicles a few millimeters inside the relatively dense skin and most prominent adjacent to the smooth side. This zone is best seen in cut and polished sections. One of the best evidences of drag flowage of the surface material of the smooth side is found in the in-folding of the vesicle zone in the overhanging wrinkle of material which forms the lateral rim separating the two faces. In numerous examples this phenomenon was shown and in addition some show elongation of the vesicles by flow (Figure 15).

Reck, in the work previously cited (p. 37) considers the perfection of development of bombs to be marked by the extent to which the internal structure has become adjusted to the external form. To the present writer it seems more correct to say that both external form and internal structure tend, so long as high temperature permits deformation, toward adjustment to the resultant of various forces, surface tension, differential surface pressures and differential drags, centrifugal forces, gas expansion, and the like.

A few of the bombs of this type show small areas of skin-cracking on the smooth side similar to typical bread-crust bombs. There is great variety in the cross-sections and attitude of the two ends of the bombs. Many are triangular in section, even though the thicker portion of the bomb is quite rounded and elliptical. Some are straight and broken squarely off; others are somewhat recurved, usually but not invariably toward the lee side, and some are mashed or quite markedly twisted. The foregoing features are characteristic of a well-formed, mature bi-polar bomb, and each can be readily observed in a collection of a dozen or two of bombs. However, not all bombs show all the features and there are all intermediate types ranging from ribbon bombs to the more perfectly formed ones.

The more typical ribbon bombs are elongate masses of basalt having a nearly uniform cross-section, usually of rudely flat or triangular section. The entire lateral surface is commonly ribbed and the structure is vesicular and the vesicles elongated by flow. The whole strongly resembles a segment of pulled taffy. Many are curved, twisted or otherwise deformed (Plate *7C*).

The writer observed on Hawaii very few bombs of types other than the two mentioned. A few bread-crust bombs showing surface cracking due to the expansion of the interior gases after a surface skin has congealed were seen but these were not numerous.

Stearns has described "rotational or spiral" bombs which he considers to be due to the hurling of viscous lava masses "through the air with a spiral motion. The spiral motion causes the bomb to develop earlike projections on the ends of its axis of rotation." He found that these bombs were comparatively rare in the Kau district.[7]

The present writer is unable to visualize the mechanics which Stearns attempts to describe. It seems very unlikely that rotation of a viscous mass would cause protuberance at "the ends of its axis of rotation." If such protuberances were due to rotational forces they would be in an equatorial plane and as remote as possible from the axis of rotation. Stearns also explains the parallel lines (ribs) on the surface of the bombs as "the result of its motion." In the view of the present writer after examining some hundreds of bombs of this type, both the projecting ends and the parallel ribs are due chiefly to the pulling of the viscous mass away from the parent magmatic material. This view is supported by the fact that in the somewhat bulbous ribbon bombs, and in the related, incompletely bulbous bi-polar bombs, the ribbed surface is well-preserved and is seen on both sides of the bomb. In those bombs which are most rotund, the ribbed configuration of the ends and of the lee side is retained, whereas that of the stoss side is largely smoothed and modified, though such fluting as remains is seen to be in perfect continuity with the ribbing of the ends.

It is difficult to picture a rotational or flight mechanism which would develop a continuous ribbed surface from end to end, and the writer doubts if most of the bombs show any evidence of rotation rapid enough to be of consequence in deforming the bomb. On the contrary, the chief modification which appears to have taken place during flight is a rounding and increase of

[7] Stearns, H. T., and Clark, W. O., Geology and Water Resources of the Kau District, U. S. G. S. Water Supply Paper 616, p. 115, 1930.

bulbousness due to surface tension, a drag of the material of the stoss surface toward its margins, and a differential effect of pressure on the stoss and lee sides. On the stoss side a fairly dense skin was formed with a few large closed vesicles. On the lee side the lesser pressure and perhaps slower cooling induced the formation of a more finely vesicular structure.

It should be recognized that the writer is drawing conclusions from a study only of a comparatively restricted series of bombs formed under similar conditions from one type of lava, though these are essentially the same as those studied by Stearns. Reck, after a careful study of a large collection of bombs from many regions and of varied composition, discusses the factors responsible for the shape of volcanic bombs.[8] While he recognizes that a few bombs owe their shape largely to rotational forces, and that some others show minor traces of rotational effects, he concludes in general that the factor of rotation during flight is subordinate to other factors and that its importance has been greatly overestimated by the majority of writers. He lists the following factors in shape genesis in the order of importance:

1. The original shape and conditions of commencement at the source.
2. The relative fluidity of the magma.
3. The active forces operating in the direction of flight (air resistance, gravity).
4. The expansive force of included gases.
5. The axial rotation.

He states that the first three of these factors are most important and of universal operation, while the last two depend on the nature of the bomb and may be lacking or only supplementary to the first three (p. 61).

Conclusions reached by the present writer after a study of the bombs described above are practically identical with those of Reck. The great variety in the shapes of the Hawaiian bi-polar and less mature ribbon bombs are attributable chiefly to differences in the sizes and shapes of the original masses of plastic magma, to differences in liquidity and rate of cooling and to the proportionate effects of surface tension, fluid drag, differential cooling and pressure effects on vesiculation. Clear evidences of rotational effects are rare, if they exist at all.

Blocks. The larger blocks, broken fragments of wall rock, have their shapes mainly determined by the fracture characteristics of the material. Most of them seem to be rudely polyhedral in outline and show a slight development of parallel upper and lower surfaces determined by the limiting surfaces or flow structures of the parent lava rocks. Most of the blocks are chunky and nearly equidimensional (Plate 6*A*).

Medium fragments: Essential lapilli. The most important shape characteristics of essential lapilli are due to the expansive force of the contained gas after the pellets of liquid material have been separated from the magma

[8] Reck, Hans, Op. cit., pp. 39-61, 1915.

and before solidification takes place. A few lapilli exhibit the shapes of bombs, showing two pulled ends and consisting of an expanded knot between these ends. Such droplike masses with either one or two pulled ends are found down to very small sizes and include the bulbous portions not uncommon in Pele's hair.

Most of the essential lapilli of Hawaii are of the cinder type. These particles are moderately porous with spherical or elongate vesicles commonly 1/10 to 1/20 of the diameter of the lapillus. The external surfaces are of two types; the smooth but somewhat ribbed, warty or pustulate surface formed by the pulling or bubbly expansion of the pellet while it was still plastic, and the ragged, usually glassy surfaces due to breaks after the material solidified. Cinders vary greatly in their porosity. Some are glassy with a moderate number of distinct vesicles and others are highly pumiceous. Many show a few large vesicles surrounded by a highly porous, finely pumiceous glass; a sort of porphyritic texture wrought in vesicles instead of phenocrysts. Lapilli much more porous than the general type described above are the reticulite pellets (thread-lace scoria of Dana) found at Kilauea[9] (Plates 9*D* and 9*E*).

This material was originally deposited in foam-like masses ranging up to two inches or more in diameter. Like other lapilli, these are bounded in part by a skin formed during the liquid stage and in part by a broken surface. The external skin of the reticulite pellets is the most dense and continuous part of the mass. The internal part, in the most attenuate sorts, consists of a delicate three-dimensional network of glass threads. These threads run in various directions connecting solid angles to which from three to six threads are attached. In any given plane the threads are arranged in more or less regular polygons and these polygons are somewhat irregularly arranged in space to form the bounding lines of polyhedral voids. In a few places the polygonal faces are represented by thin glass membranes.

It is evident on inspection that the reticulite is the result of extreme attenuation of the liquid glass by gas pressure. After the rock foam had been expanded to a mass of bubbles, the pressure evidently continued to stretch the bubble walls until the central portions of the walls separating any two bubbles were caused to burst and the material was immediately retracted into the thread structure. It is evident that in any system of closely packed, subequal, sub-spherical bubbles the least amount of inter-bubble space would be immediately between any two bubbles, that a greater amount of inter-bubble space would lie in a triangular cross-section between three bubbles and that the largest amount of space would remain in those solid angles bounded by more than three bubbles.

In the formation of the reticulite the solidification of the glass after the bursting of the bubble walls must have been very rapid, for the glass threads which form the network all have triangular cross-sections corresponding to

9 Dana, J. D., Characteristics of Volcanoes, Dodd, Mead & Co., 1891, pp. 163-167.

the cross-section of the space between three spherical bubbles. The liquid glass was retracted to a fairly compact triangular form with concave curved sides and exceedingly sharp angles, but did not remain liquid long enough to assume a circular cross-section. The details of the solid angles where the threads meet and which remind one of jack-stones all indicate an instantaneous freezing before the process of retraction of the liquid and its adjustment to the effect of surface tension was complete. At the solid angles the triangular edges of adjacent threads are expanded to form a sort of web and the threads themselves are expanded and joined in a beautifully buttressed fashion, all reentrant angles being rounded by smooth fillets of the glass.

Textures showing all degrees of transition from ordinary pumice to reticulite are found. Certain essential lapilli are less porous than those common in the cinder cones. A special example is found in the glassy pellets thrown up in some littoral eruptions due to the contact of a lava flow with sea water. These are commonly composed of rather dense, clear glass with a few large vesicles but no generally pumiceous texture. Here the liquid glass was shattered by the steam explosion but was not so intimately penetrated by the gas as happens in most magmatic eruptions where more intimate foaming takes place.

Accessory and accidental lapilli. Shapes of fragments broken from previously solidified rock, whether of consanguineous origin or other igneous or any country rock are chiefly determined by the fracture characteristics of the rock. These lapilli have conchoidal, hackly or other surfaces according to the structure of the parent rock. Most of the larger accidental lapilli found in the Keanakakoi formation at Kilauea are composed of fairly dense basalt and are chunky cuboidal or polyhedral shapes with nearly plane faces. Smaller grains are more irregular in shape, except as these consist of grains of olivine or augite with crystal faces or cleavage boundaries. Lapilli formed by vesicular rock show ragged fracture surfaces. Those composed of soft, friable rock are subject to attrition in the process of expulsion, and in some instances lapilli of even the harder rocks show a recognizable rounding due to mutual grinding in the vent.

Smaller fragments: Essential ash particles. In describing the shapes of essential particles of lapilli size (32 to 4 mm.) it was stated that these were largely due to the process of gas expansion, modified in some by breakage after solidification. In the finer particles it appears that the breakage becomes more important and that the shapes are more commonly those produced by the breakage of particles previously given a vesicular texture by the action of gas. Probably the impression of breakage is somewhat accentuated by observation in thin section under the microscope where incomplete vesicular sections are more prominent and where some breakage occurs in preparing the section.

The most common form of fragment observed in thin sections is rather markedly vesicular and exhibits margins notched by arcs of the circular boundaries of the large and small vesicles. Small fragments are commonly rudely triangular and bounded chiefly by the concave perimeters of three or more vesicles. The concave margins of the typical shards and lunar shapes are due not only to the vesicular structure of the glass but also in part to the conchoidal fracture. A few of the finer ash particles show strongly elongate forms with marked flow structure and elongation of vesicles. These structure elements are preserved in the subsequent alteration and palagonitization. Many of the ash particles consist of an olivine crystal surrounded or partially surrounded by adherent glass.

Viewed under a binocular microscope certain ash deposits are seen to consist mainly of small, sub-spherical, vesicular glass pellets which have not been generally broken, but such material is probably subordinate in general in the ash sizes. Other ash beds consist of lithic, rounded pellets one or two millimeters in diameter, which in cross-section show a finely crystalline structure.

Accessory ash particles. These fragments consist largely of particles of single minerals or of glass and are all angular. The larger part of the fine material of the 1924 ash is a very fine, lavender-gray powder which covers and colors the surfaces of the larger fragments as well.

Induration

The pyroclastic accumulations of Hawaii range from wholly unindurated, loose lapilli, ash or dust beds to fairly strongly cemented rocks. A few are sufficiently hard and compact to take a fair polish or to dress into a good hand specimen. However, most of the indurated tuffs are somewhat friable, easily carved with a knife and equivalent to a shale or a weak sandstone. Many of the older tuffs have an induration and strength similar to loess and probably attributable to a somewhat similar texture and mode of cementation.

Many of the finer ash deposits, especially the more recent ones, do not appear to be held by any actual cement. Their induration appears to be due chiefly to the mutual adherence of fine particles. Where these have been at one time saturated with water, the process of induration by adhesion may have been greatly aided by the compaction wrought by surface tension of the contained water in the course of progressive drying. Where palagonitization or other alteration has taken place, the process has usually affected margins of grains and has contributed in considerable measure to the induration of the mass.

There are three chief modes of cementation. The first consists of an agglutination of pyroclastic particles which are still hot enough to be plastic when they fall and form somewhat adherent masses in driblet cones. The second is a cementation through the formation of palagonite. The third is by means of secondary calcium carbonate in the form of calcite or aragonite.

Cementing is also accomplished by the formation of colloidal or gelatinous silica compounds and a subsequent dehydration, a process related to those involved in the setting of Portland cement. This was found to have taken place in the 1790 ash in various places around Kilauea.[10]

Some of the older palagonite tuffs, especially the so-called lavender tuffs, are highly calcareous and are quite markedly cemented by the calcareous material. The calcite is present both in megascopically visible veins and patches and as minute fillings of vesicles and interstitial spaces. The so-called lavender color, described in the section on colors, is due to the admixture of the white calcite with the buff and drab of the palagonite mass.

Calcite cementation is also found in some of the coarser and less altered pyroclastic deposits of the cinder cones and elsewhere. This is shown both in the form of local cementation by calcite deposits in vertical joints, along plant stems or along certain beds of a favorable coarseness, and also as a general induration of the entire mass. In some of the more altered yellow tuffs there is a considerable amount of palagonite which appears to be secondarily deposited and which contributes to the induration of the mass. In such tuffs there is commonly also a considerable amount of calcite and in some there are fillings of zeolite. It is impossible to say what relative part is played by these various materials in cementing the whole into a somewhat indurated mass.

Tuff beds in parts of the Pahala or Ninole formations, which have been buried under a considerable thickness of lava, have probably suffered some compaction through the weight of the superincumbent load. Some of the structures usually attributed to the process of mantle-bedding may be due in part to subsequent modification by differential compaction. An air-deposited tuff is an exceedingly porous mass, due to at least two causes. The rock particles fall from the air directly into place; the shuffling and readjustment into more stable position which commonly takes place in the deposition of eolian, fluviatile or marine materials is lacking. Moreover, the individual particles are generally irregular or attenuate as well as vesicular and mechanically weak. Such materials are more likely to assume unstable positions and high angles of rest and are subsequently especially susceptible to readjustment by turning and by the crushing and failure of corners and other irregularities of the particles. For these reasons pyroclastic accumulations are more susceptible to pressure compaction and more likely to exhibit its effects at comparatively slight depths than most other sedimentary materials.

Porosity

Porosity of fragments. Certain pyroclastic fragments are practically non-porous, such for example, as olivine crystals thrown out of a vent explosively, or fragments of dense dike rock triturated by a subsequent eruption.

[10] Finch, R. H., Volcano Letter No. 15, April 9, 1925.

In general, however, the fragments in pyroclastic rocks are somewhat porous, and many are notably so. The internal porosity of vesicular lapilli having partially broken surfaces is difficult to determine accurately. Such fragments cannot be coated with paraffin without a large error due to penetration of the paraffin into the exposed vesicles and in determining gross porosity of the aggregate of such lapilli the inter-grain porosity cannot be distinguished from the intra-grain porosity. From examination of the exposed interior of vesicular lapilli under the microscope it has been estimated that the porosities of grains range from 20% to 75%. These figures agree roughly with those obatined by comparing estimated volumes of fragments with their weights and their picnometer specific gravities.

The most porous rock on the island of Hawaii and, indeed, probably the most porous rock in the world is the reticulite of Kilauea. The specific gravity of this rock was determined by dressing out of it a rectangular mass of which the volume was determined by measurement of the sides. The grain density of the glass contained in this reticulite was also determined. From these two values the sample of reticulite used was found to have a porosity of 98 per cent. Dana found a porosity of about 98.3 per cent for this material.[11]

Porosity of aggregates. Several determinations of porosity of pyroclastic rocks were made by comparing the specific gravity of fragments with those of grains contained in the fragments. A number of tuff specimens thus treated were found to have porosities ranging from 24 to 58 per cent. These were chosen to represent the most dense and the most porous of the specimens collected. (See Table 5.)

Several specimens of cinders were found to have gross porosities of from 40 per cent to 88 per cent. The sample exhibiting a gross porosity of 88 per cent when poured and jarred in a cylinder was found to have a porosity within the grains of 81 per cent. The porosity between the grains was thus about 38 per cent.

Similar measurements made on the Oahuan tuffs from the vicinity of Honolulu showed variations from 13 to 38 per cent with an average value of about 22 per cent. It is evident that the tuffs of the island of Hawaii are extremely light and porous by comparison. The grain densities of the latter tuffs average approximately 7 per cent less than those of the Oahuan tuffs.[12]

Specific Gravity

Specific gravity of glass and palagonite. Accurate determinations of the specific gravity of fresh or altered natural glasses are difficult to make.[13] Minute inclusions of magnetite or other minerals tend to increase the specific gravity and fine pores tend to decrease it. Since both mineral inclusions and

[11] Dana, J. D., Op. cit., pp. 163-167, 1891.

[12] Wentworth, C. K., Op. cit., p. 104.

[13] George, W. O., The Relation of the Physical Properties of Natural Glasses to Their Chemical Composition, Journal of Geology, Vol. XXXII, pp. 361-362, 1924.

pores in some glasses appear to extend down to sub-microscopic dimensions, preparation of powders fine enough to eliminate errors due to their presence is in some samples quite impossible.

For the purposes of this study the writer found the method of balancing powders in a test tube of diluted bromoform somewhat more convenient than the picnometer method, though the latter was used to some extent and is undoubtedly more accurate when water temperature and other conditions are carefully standardized. The bromoform method had the advantage that for palagonite, which probably does not have a definite specific gravity, the manipulator gets an impression of the upper and lower limits as well as of the mean value. The bromoform was adjusted by adding ethyl alcohol to reduce its gravity and pure (S. G. = 2.89) or nearly pure bromoform to increase its gravity. One or more measurements of the specific gravity of the bromoform was made for each sample by means of a small brass plummet, having a volume of 1.000 cubic centimeter, which was weighed suspended in the liquid. The difference between this weight and the known weight in air gives the specific gravity directly.[14] The plummet method is convenient for use with small amounts of liquid and entails a minimum of weighing or cleaning of vessels. The results of several measurements are shown in the following table:

TABLE 4

SPECIFIC GRAVITY OF PYROCLASTIC MATERIALS

Name	Specimen Number	Specific Gravity
Vesicular Pele's hair glass....................	534	2.04 average
Basaltic glass from cinders of 1929 eruption...	544*b*	2.562
Trachytic glass from Puu Waawaa............	743*b*	2.435
Basaltic glass with some inclusion and vesicles, from beach sand at Punaluu	813	2.84 average
Palagonite from Ninole tuff..................	819*b*	2.026

The specific gravity of the glass of sample 544*b* is 2.562. According to data compiled by W. O. George,[15] this corresponds to a silica content of about 59 per cent or considerably higher than any known Kilauean rocks. According to analyses by H. S. Washington and others the range in silica content for the basaltic lavas of Kilauea is from 46 to 52 per cent.[16] The correspondence here is not satisfactory and may be due to errors both in the determination of the specific gravity of the glass and in the graph of George. The specific gravity of one specimen of palagonite was 2.026. Those reported by Peacock from Iceland ranged from 1.91 to 2.4.[17] The specific gravity of the single

14 As stated, this process gives the density, strictly speaking; the two, however, are for practical purposes the same.

15 George, W. O., Op. cit., p. 362, 1924.

16 Washington, H. S., Petrology of the Hawaiian Islands, A. J. S., Vol. VI, pp. 338-367, 1923.

17 Peacock, M. A., Op. cit., p. 73, 1926.

specimen of trachytic glass was 2.435, which on George's graph corresponds to 67 per cent silica. The actual silica content found by Cross[18] for the Puu Waawaa trachyte obsidian was 62 per cent. Thus in both these cases the graph by George gives silica values several per cent too large.

Specific gravity of pyroclastic fragments. The grain specific gravity of grains from several pyroclastic rocks was determined by the picnometer method as well as that of fragments of the same. The values thus determined are shown in detail in the following table, as well as the resulting computed porosities. The first four were chosen as light and very porous, the last four as heavy and least porous.

TABLE 5

SPECIFIC GRAVITY AND POROSITY OF PYROCLASTIC FRAGMENTS

Formation	Specimen Number	Specific Gravity of Fragments	Specific Gravity of Grains, as Crushed	Porosity (per cent)
Ninole tuff	820*b*	.92	1.887	51.3
Pahala tuff	817	.99	2.332	57.6
Pahala tuff (Kalae)	129	1.03	2.118	51.3
Waiau yellow tuff	242	1.05	2.235	53.0
Waiau gray tuff	261	2.07	2.738	24.4
Waiau gray tuff	275*b*	1.90	2.560	25.8
Keanakakoi tuff	550	1.86	2.510	25.9
Waiau gray tuff	237	1.81	2.584	30.0
Average		1.45	2.37	39.9

Specific gravity of pyroclastic rocks. Specific gravities of a number of specimens of indurated tuffs were determined by coating them with paraffin, using essentially the method described by Melcher.[19] From a few check determinations which were made it is believed that the specific gravities are accurate to within 1 or 2 per cent. Many of the tuffs are so porous and of such irregular and ragged fracture that it appears impracticable to attempt closer measurements. The values obtained are shown in the following table:

[18] Cross, Whitman, Op. cit., p. 64, 1915.

[19] Melcher, A. F., Determination of Pore Space of Oil and Gas Sands, Mining and Metallurgy Number 160, Section 5, April 1920, pp. 1-8.

TABLE 6

SPECIFIC GRAVITIES OF TUFF

Specimen Number	Character of Tuff	Formation	Specific Gravity	Lbs. per Cu. Ft.
93*b*	Gray, ashy	Pahala	1.18	73.8
110	Gray-green	Littoral	1.46	91.2
129	Red, earthy	Pahala	1.03	64.3
177	Calcareous	Waiau	1.30	81.1
217*a*	Black, ashy	"	1.51	94.2
237	Gray	"	1.81	112.8
242	Buff, crumbly	"	1.05	65.5
261	Hard, stony	"	2.07	129.2
275*b*	Gray	"	1.90	118.5
323	Yellow	"	1.60	100.0
486	Yellow	Pahala	1.64	102.5
487*a*	Lavender tuff	"	1.54	96.1
550	Purplish, clayey	Keanakakoi	1.86	116.1
552	Greenish, granular	"	1.40	87.5
639*b*	Red, crumbly	Pahala	1.21	75.5
648	Yellow tuff	"	1.19	74.3
747	Gray, crystal tuff	Waawaa	1.92	120.0
817*b*	Yellow tuff	Pahala	1.23	76.9
820*b*	Red tuff	"	.92	57.4
822*b*	Red-brown, nodular	"	1.34	83.7
817*a*	Yellow, nodular	"	.99	61.9
Average			1.44	90.0

It will be noted that the specific gravities cover a large range and that the average is low, indicating a rock of about half the specific gravity of basalt derived from the same magmas. There appears to be no very systematic relation between the type of tuff and its specific gravity. Several of the buff or yellow tuffs are very light in weight but the same is true of the gray and black varieties and both appear among the heavier specimens as well. These tuffs from Hawaii are much more variable in specific gravity than those of southeast Oahu and average about 25 per cent lighter than the latter.[20] The variations are largely due to variable porosity as is shown by the greater uniformity of specific gravity of the component grains. The latter was determined by the picnometer method for four of the lightest and four of the densest specimens, and is shown in the preceding table together with the corresponding porosity (Table 5).

Many of the cinder formations are extremely light as they lie in natural bedding and the specific gravities of several were determined (Table 7). A sample of cinders carried out of the Kilauean pit during the eruption of July 1929 showed a bulk specific gravity of .2875. Individual fragments from the same have a gravity of .467 and the grain specific gravity for the same material is 2.562.

[20] Wentworth, C. K., Pyroclastic Geology of Oahu, Bishop Museum Bulletin, No. 30, pp. 102-104, 1926.

TABLE 7

SPECIFIC GRAVITY AND POROSITY OF CINDERS

Specimen Number	Spec. Gravity (gross)	Spec. Gravity (of lapilli)	Spec. Gravity (of powder)	Porosity (gross)	Porosity (aggregate)	Porosity of Lapilli
544*a*	.287	.467	2.562	89%	39%	82%
626	.548	1.00	2.58	79	45	61
623	1.29	2.07	2.99	57	38	31
744	.306	.919	2.435	87.5	67%	63%
813	1.533	....	2.84	46%	....	....

Among all the pyroclastic materials the most remarkable in point of density as well as in some other aspects is the reticulite which has been described above in detail. A fragment of this material carefully cut to plane surfaces and having a volume of 25.57 cubic centimeters weighed 1.095 grams and thus had a specific gravity of .0428. This material thus weighs somewhat less than 3 pounds to the cubic foot and original surface accumulations must originally have weighed even less than this. There is little doubt that this is one of the lightest known rocks of the earth.

Color

Color of fragments and constituents. Colors of rocks depend in differing degrees on the wave-length of light transmitted and reflected by the component grains, on the condition of the surface and character of the light in which they are viewed, and on the color and transparency of the cement. The basaltic glass in thin section or in small fragments ranges in color from yellow to light green (Ridgway 23‴ to 35″d).[21] In large masses where reflected light is dominant the glass appears nearly jet black. The general distribution of the recorded colors of basaltic glass in thin section is shown in Figure 16. Here it will be noticed that the yellow colors are nearly full spectral hues, whereas the greens are tints considerably lighter than the spectral values. There is a moderate admixture of gray throughout the range.

The colors of palagonite seen in thin section range from yellow to slightly reddish orange and also tend toward tints in the shorter wave-length hues and shades in the longer wave-length hues (Ridgway 21d to 9k). (See Figure 72.) These are nearly pure colors with little or no admixture of gray. Aside from the glass and the palagonite which results from its alteration, the most

[21] All colors mentioned in the following descriptions have been referred to the Ridgway system set forth in Color Standards and Color Nomenclature (Washington, 1912). According to this system the spectral hues are represented by the numbers from 1 to 71, running from Red 1, Orange 11, Yellow 23, Green 35, Blue 49, Violet 59, back to Red 72, or 1. The letters a, b, c, d, e, f, g, designate increasing lightness of tint ranging from the pure spectral hue to white, and the letters h, i, j, k, l, m, n, designate increasing darkness of shade in a similar fashion. About half of this arrangement is shown graphically in Figure 72. Increasing admixtures of gray, producing dirty, or less pure colors, are indicated by the symbols ′, ″, ‴, ⁗, or ″‴, which follow the Arabic number.

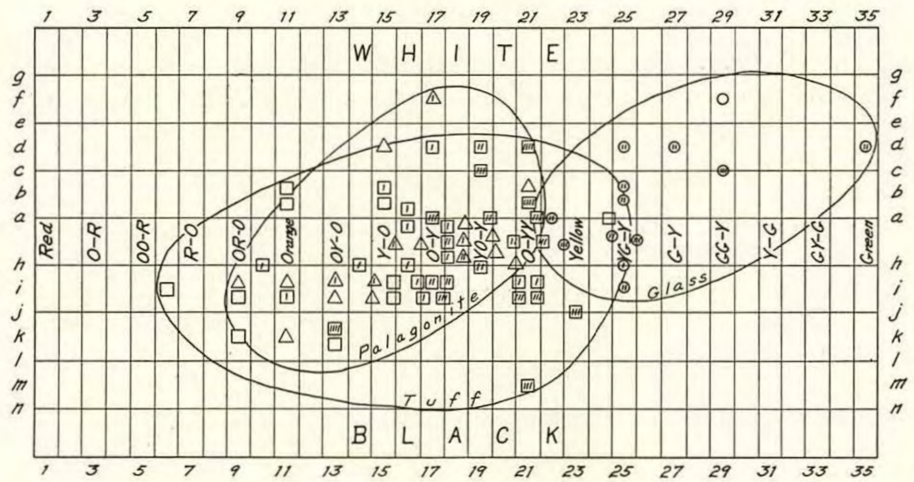


FIGURE 16. Diagram showing the range of colors of glass, palagonite and tuff, as recorded from specimens examined in the laboratory. The diagram corresponds to about half the spectral range of the Ridgway color book. The admixture of gray is shown by marks within the symbols, corresponding to those used in the Ridgway book.

conspicuous constituent of the Hawaiian pyroclastics is olivine. When fresh this shows a light, yellowish-green color (Ridgway 27′b).

Colors of rocks. Fresh, fairly coarse ash beds and cinders are usually black or dark gray. Finer-grained ash beds tend to be lighter in general color, usually gray, but in some instances yellowish or lavender tints are discernible according to the dominant hue transmitted through minute fragments. Weathered materials display a great variety of colors due to the superficial effect of the weathered and tarnished surfaces. Highly vesicular material such as pumiceous cinders or reticulite commonly shows a light color approaching that of the same material in thin section.

Cemented tuffs on Hawaii range in color from gray to yellow, buff, brown and dark red. The yellow may be due to glass or to palagonite; the darker browns and reds are due to palagonite. The lighter colors are due in part to finer grain and in part to the presence of calcareous cement. Deep red and brown tuffs are almost invariably palagonitic but many gray or lavender tuffs contain far more palagonite than the color suggests. The distribution of color comparisons made in the course of laboratory study is shown in Figure 16. It will be noted that these are most numerous in the range from yellow to orange-yellow and that tints and shades are about equally numerous. A considerable admixture of gray is usual. It is probable that because of the interest attaching to the process of palagonitization and the finer tuffs, the yellow colors are somewhat more abundant in the diagram than in nature. The grays and browns are more mottled and more irregular and less inviting for comparison with standards than the characteristic yellow-orange due to palagonite.

Optical Properties

Basaltic glass. The refractive indices of a number of samples of black glass and palagonite are given in the following table. All values are probably correct to the nearest .003, of the more tractable specimens to .002.

TABLE 8

REFRACTIVE INDICES OF BASALTIC GLASS, TRACHYTE GLASS, AND PALAGONITE

Sample Number	Basaltic Glass	Palagonite	Trachyte Glass
129		1.542	
275*a*		1.540	
487*c*		1.541	
534	1.612		
544*b*	1.614		
546	1.595		
744			1.523
813	1.590		
819*b*		1.542	
820*c*		1.550	
Average	1.603	1.543	1.523

Black glass or sideromelane from Iceland, studied by Peacock[22] showed an average refractive index of 1.61, which is in accordance with the lower average silica content of the Icelandic glasses than of the Hawaii lavas. According to studies made by W. O. George basaltic glasses having the range of composition known to occur in the basalts of the island of Hawaii should show a range of refractive index from 1.57 to 1.63. The mean of 56 analyses of Hawaii basalts corresponds to a value of about 1.59, a much more satisfactory relationship than was found in the case of specific gravities. Similarly, the analysis cited by Cross, of trachyte obsidian applied to W. O. George's graph, Figure 3 of his paper, corresponds to a refractive index of 1.524 which agrees extremely well with the present writer's determination of 1.523.

Palagonite. Samples of palagonite from Iceland, studied by Peacock, have refractive indices of 1.50, 1.50 and 1.52.[23] Those reported here (see Table 8) vary in refractive index from 1.540 to 1.550, with an average of 1.543. If the somewhat aberrant example of 1.550 be omitted, the average is 1.541. These values are notably higher than those found by Peacock, who considers the refractive index to have a linear relationship to the water content. Palagonite from samples 129 and 819*b* were analyzed as shown below and carried 16 and 26 per cent water. Though the two have identical refractive index and do not by themselves indicate such a trend, they fall as closely to the line of Peacock's graph as do his own samples. Until analyses of many more samples of palagonite from known glasses are available, his hypothesis seems open to question.

[22] Peacock, M. A., Op. cit., p. 70, 1926.
[23] Peacock, M. A., Op. cit., pp. 60-70, 1926.

Chemical Composition

History of the term palagonite. The material palagonite was first named by von Waltershausen in 1845, from Palagonia in Sicily.[24] It has recently been described and its relationship to basaltic glass (sideromelane) and to chlorophaeite discussed by Peacock and Fuller.[25] It is defined as a gel produced by the hydration of basaltic glass. Field relations and petrographic character of the palagonite tuffs of Hawaii and also of those of southeast Oahu previously studied by the writer afford abundant evidence of this derivation of the palagonite from finely divided basaltic glass thrown out in pyroclastic eruptions.

Palagonite is not a mineral but rather a mineraloid as recognized by Peacock, following Niedzwiedzki.[26] Its composition is therefore not at all constant, though certain general points of similarity may be observed in the analyses shown below. Moreover, palagonite is unstable and tends to pass through stages of decomposition and alteration similar to those followed in the weathering of basalt. Since the variable optical characters of palagonite grade with little break into those shown by the material of fine-grained laterite soils, it is difficult to distinguish sharply between palagonite and its derived soils. Moreover, only a part of the materials thrown out in many pyroclastic eruptions are glassy and many of the tuffs are a mixture of partly palagonitized glass and of more or less weathered lithic materials.

Composition of Hawaiian palagonitic rocks. Seven chemical analyses were made possible through the courtesy of the U. S. Geological Survey and the results are shown in Table 9 below.[27] It was hoped that these analyses would not only show features sufficiently distinctive to help in determining if the red-brown tuff belongs to one formation or several, but also that they would yield useful information on the nature of palagonite.

Samples 129 and 819*b* were prepared by crushing the nearly pure palagonite rock so as to pass a 1/16 mm. screen and separating the palagonite by suspension in bromoform. Examination of the separated powder, mounted in balsam, shows an appreciable contamination by small grains of feldspar and other minerals, but it was considerably purer than the original sample.

In Table 10 the analyses of palagonites and palagonite tuffs have been recalculated on a water-free basis for comparison with the average of 56 analyses of basalts of the island of Hawaii.[28] In Table 11 these analyses have

[24] von Waltershausen, S., Über die submarinen Ausbruche in der Tertiär-Formation des Val di Noto in Vergleich mit verwandten Erscheinungen an Aetna, Gott. Stud., I, pp. 371-431, 1845.

[25] Peacock, M. A., and Fuller, R. E., Chlorophaeite, Sideromelane and Palagonite from the Columbia River Plateau, American Mineralogist, Vol. 13, pp. 360-382, 1928.

[26] Peacock, M. A., The Petrology of Iceland, The Basic Tuffs, Trans. Royal Soc. Edinburgh, Vol. LV, Part I, No. 3, pp. 51-76, 1926.

[27] U. S. Geol. Survey, Bulletin 878, Analyses M-S, p. 26, 1937.

[28] Washington, H. S., Petrology of the Hawaiian Islands, III, Kilauea and General Petrology of Hawaii, Amer. Jour. Sci., 5th Series, Vol. VI, p. 361, 1923.

been further recalculated on an assumption of no loss of Al_2O_3 and an original composition identical with the average basalt of Hawaii.

TABLE 9

ANALYSES OF PALAGONITE AND PALAGONITE TUFF

	A	*B*	*C*	*D*	*E*	*F*	*G*
SiO_2	45.34	33.33	37.16	50.73	55.58	46.03	3.39
TiO_2	3.54	3.92	3.51	1.79	1.46	2.93	5.01
Al_2O_3	12.56	16.36	18.94	19.06	19.13	13.38	31.72
Fe_2O_3	12.20	16.32	7.37	7.48	6.40	9.28	24.90
FeO	1.14	0.54	5.93	1.03	0.50	4.22	0.84
MnO	0.12	0.20	0.12	0.11	0.31	0.34	0.13
MgO	2.72	2.36	3.72	1.55	0.52	3.45	0.12
CaO	2.10	0.82	5.58	1.92	0.44	5.67	0.03
Na_2O	2.44	0.12	2.67	1.79	4.59	1.04	0.44
K_2O	1.27	0.04	1.00	1.98	2.84	0.38	0.30
H_2O-	7.02	14.20	6.51	5.14	2.74	6.05	8.22
H_2O	9.20	11.94	6.33	6.60	5.58	6.62	24.27
P_2O_5	0.12	0.10	1.02	0.13	0.10	0.58	1.15
Total	99.77	100.25	99.86	99.31	100.19	99.97	100.52

A.—Prepared sample of palagonite from specimen No. 129, tuff from Kalae shore ½ mile east of lighthouse. J. G. Fairchild, analyst.

B.—Prepared sample of palagonite from specimen No. 819*b*, red Ninole tuff from 850 feet elevation, a few rods north of Kepue, Hilea. J. G. Fairchild, analyst.

C.—Yellow-brown tuff, No. 242, from 5175 feet in Auwaiakeakua Gulch, southeast of Waikii. J. G. Fairchild, analyst.

D.—Red tuff, No. 275*a*, from 3500 feet in Kemole Gulch. J. J. Fahey, analyst.

E.—Yellow tuff, No. 323, from beneath lava flow at 2900 feet in Popoo Gulch, north of Keomuku. J. J. Fahey, analyst.

F.—Yellow tuff, No. 648, from about 600 feet elevation in face of Puu Kapukapu, one-half mile east of summit. Charles Milton, analyst.

G.—Red, palagonite tuff, No. 707, five feet below top of road cut, one-fourth mile south of Pepeekeo. Charles Milton, analyst.

TABLE 10

PALAGONITE ANALYSES RECOMPUTED ON WATER-FREE BASIS

	H 129	*I* 819*b*	*J* 242	*K* 275*a*	*L* 323	*M* 648	*N* 707	*O* *Hawaii Lavas*	*P* *Iceland Palagonite Rock*
SiO_2	54.28	44.96	42.77	57.90	60.51	52.74	4.98	49.73	47.04
TiO_2	4.22	5.29	4.03	2.05	1.59	3.36	7.36	2.84	2.78
Al_2O_3	15.04	22.11	21.75	21.79	20.82	15.31	46.64	13.71	14.74
Fe_2O_3	14.61	22.01	8.46	8.54	6.96	10.63	36.60	2.92	13.59
FeO	1.36	0.73	6.81	1.18	0.54	4.84	1.23	8.64	2.90
MnO	0.14	0.27	0.14	0.13	0.34	0.39	0.19	0.13	0.29
MgO	3.26	3.18	4.27	1.76	0.57	3.95	0.18	8.27	8.62
CaO	2.51	1.11	6.38	2.19	0.48	6.50	0.04	9.10	9.26
Na_2O	2.92	0.16	3.07	2.05	4.99	1.19	0.65	3.16	0.21
K_2O	1.52	0.05	1.15	2.26	3.09	0.44	0.44	1.02	0.25
P_2O_5	0.14	0.13	1.17	0.15	0.11	0.65	1.69	0.48	0.32
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

O.—Average of 56 analyses of lavas of Island of Hawaii. Washington, H. S., Op. cit., p. 361, 1923.

P.—Palagonite rock, Iceland. Peacock, M. A., Op. cit., p. 66, 1926. 0.07% of sulphur determined.

TABLE 11

ANALYSES CALCULATED ON A CONSTANT Al_2O_3

	Q 129	*R* 819*b*	*S* 242	*T* 275*a*	*U* 323	*V* 648	*W* 707
SiO_2	49.50	27.88	26.88	36.42	39.80	47.25	1.46
TiO_2	3.85	3.28	2.54	1.29	1.05	3.01	2.16
Al_2O_3	13.71	13.71	13.71	13.71	13.71	13.71	13.71
Fe_2O_3	13.32	13.65	5.33	5.38	4.58	9.52	10.75
FeO	1.24	0.45	4.29	0.74	0.36	4.34	0.36
MnO	0.13	0.17	0.09	0.08	0.22	0.35	0.06
MgO	2.97	1.97	2.69	1.11	0.38	3.54	0.05
CaO	2.29	0.69	4.02	1.38	0.31	5.82	0.01
Na_2O	2.66	0.10	1.93	1.29	3.28	1.07	0.19
K_2O	1.38	0.03	0.72	1.42	2.03	0.39	0.13
P_2O_5	0.13	0.08	0.74	0.09	0.07	0.58	0.50
Total	91.18	62.01	62.94	62.91	65.79	89.58	29.38

TABLE 12

PERCENTAGES OF CONSTITUENTS REMAINING

	AA 129	*BB* 819*b*	*CC* 242	*DD* 275*a*	*EE* 323	*FF* 648	*GG* 707
SiO_2	99.6	56.0	54.0	73.2	80.0	95.0	2.9
TiO_2	135.5	115.5	88.4	45.4	37.0	106.0	76.1
Al_2O_3	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Fe_2O_3	456.1	467.5	182.5	184.2	156.9	326.0	368.1
FeO	14.4	5.2	49.7	8.6	4.2	50.2	4.2
MnO	100.0	130.7	69.2	61.5	169.2	269.2	46.1
MgO	35.9	23.8	32.5	13.4	4.6	42.8	0.6
CaO	25.2	7.6	44.2	15.2	3.4	64.0	0.1
Na_2O	84.2	3.2	61.1	44.0	103.8	33.8	6.0
K_2O	135.0	0.0	73.4	138.3	199.0	38.2	12.7
P_2O_5	27.1	16.7	154.1	18.7	14.6	120.8	104.2

In Table 12 are shown the percentages which each of the constituents of the palagonite rocks bears to the original amount of that material on the assumption of no loss of alumina and an original composition identical with that of the average of analyses of lavas of the island of Hawaii. This assumption in some instances is doubtless only a crude approximation to the truth, but no better basis for comparison is known. In Table 11 it will be noted that two samples, Nos. 129 and 648, appear to have suffered losses of only about ten per cent each. Four others have lost from thirty-four to thirty-eight per cent and one has lost seventy-one per cent. The first two mentioned are samples of palagonite from the Pahala tuff formation of the Kalae district and of palagonite tuff from the same formation of the Kapukapu district. The four samples mentioned above include a sample of Ninole tuff, and three samples of Waiau tuff from the Waikii, Kemole and Keomuku localities, respectively. The last sample mentioned is supposed Waiau tuff from Pepeekeo.

Differences in these groups of samples in the amount of total losses, largely silica, can be interpreted in two ways. The three groups can be regarded as belonging to three different formations having different original compositions. The fact that the two known Pahala samples are thus quite distinct might lend validity to this view. On the other hand, except for the two Pahala samples, the silica content and that of some other constituents has been reduced below that normal for any Hawaiian lavas and the reduction and a considerable part of the difference must certainly be due to alteration. The alternative interpretation lies in the different climatic and soil moisture situations in which the materials have lain and the length of time elapsed since they were so placed. The Kalae and Kapukapu localities are among the most arid of all the localities from which the analyzed samples were taken. On the other hand, sample No. 707 was taken from a locality where the annual rainfall averages 130 inches and is certainly the most moist of all the localities. In Table 13 the samples and the total remaining percentages as shown in Table 10 are arranged in the order of mean annual rainfall at their sites of deposition. There is a slight suggestion of an inverse relationship but the evidence is not conclusive.

TABLE 13
RELATION BETWEEN RAINFALL AND CHEMICAL COMPOSITION OF PALAGONITE SAMPLES

Sample No.	Locality	Annual Rainfall	Residual Percentage
129	Kalae	15″	91.18
323	Keomuku	22	65.79
648	Kapukapu	26	89.58
242	Waikii	30	62.94
819*b*	Kilea	38	62.01
275*a*	Kemole	40	62.91
707	Pepeekeo	130″	28.94

The analyses of palagonite here reported may be interpreted in comparison with those reported and discussed by Peacock.[29] The chief features these have in common are (columns H, I, and P, Table 10) an amount of ferric iron nearly or quite equal to that of alumina, a moderate loss of silica, and partial losses of the lime, soda and magnesia. Sample 819*b* (column I), though carefully prepared as a representative sample of palagonite, probably does not represent the ideal composition as closely as sample 648 (column M), which is a palagonitic tuff containing some glass. Sample 819*b* is known from its field relations to be from a very old tuff of the Ninole formation and from its present ground-water relations, it appears that it may have suffered a considerable amount of leaching which cannot properly be regarded as a part of the palagonitization proper.

Sample 129 (column H), judging both by its microscopic character and its similarity in composition to the analysis of column P, is probably the most nearly pure and unweathered palagonite. Sample 648, column M, as stated

[29] Peacock, M. A., Op. cit., pp. 66, 73, 1926.

above, contains a considerable amount of unaltered glass, shown in the analysis by incomplete oxidation of the iron and by large content of lime and magnesia. Sample 242, columns J and S, carries a considerable content of microlitic material. Though the color is yellow-brown and much palagonitic material is present there has apparently been less palagonitization, even of the glass present, and more true weathering of the silicate minerals. Sample 275*a*, columns K and T, Tables 10 and 11, is more generally palagonitized, but has also suffered considerable loss of silica and soluble alkalis and alkali earths by weathering. Sample 323, columns L and V, Tables 10 and 11, is quite similar to the preceding. Sample 707, columns N and W, Tables 10 and 11, has been so completely weathered that it is difficult to tell what degree of palagonitization was originally attained.

Nature and origin of palagonite. That palagonite is an alteration product of basaltic glass has long been known in a general way, but the nature of the process has not been understood in detail. According to Peacock, who has made the most recent and critical studies, the chief chemical changes involved in the formation of palagonite from basaltic glass are nearly complete oxidation of the iron and a partial loss of lime and soda. These changes are accompanied by a pronounced hydration.[30] Specimens analyzed by Peacock indicated a water content ranging from 18.5 to 28 per cent. The first product of alteration of the glass is either a clear, yellow gel-palagonite, or an obscurely fibrous and birefringent material called fibropalagonite, both names having been applied by Peacock. Further alteration results in the formation of chlorite and zeolites.

The gross water content of the seven samples analyzed from Hawaii ranges from 8 to 32 per cent. Since some of these samples contain a considerable amount of non-palagonitic material, the amount of water cannot be regarded strictly as a measure of the hydration of palagonite. Samples 129 and 819*b* contain approximately 16 and 26 per cent of water respectively, the two being as nearly representative of palagonite as it was practicable to prepare. Percentages of the various oxides in the several analyses disclose some features due to palagonite and some others probably due to weathering of lithic material. These are perhaps best shown in Table 10.

Samples 129 and 648 show percentages of silica which indicate little, if any, loss of silica through weathering. Sample 129 also shows nearly complete oxidation of the iron but retains fairly large amounts of MgO, CaO, Na_2O, and K_2O. This sample is probably nearly pure, unaltered palagonite. Sample 648 contains larger amounts of unpalagonitized glass than 129. Samples 819*b* and 707 were probably nearly completely palagonitized but have suffered further alteration by weathering, the former having lost nearly half its silica and the latter probably about ninety-seven per cent of the original silica con-

[30] Peacock, M. A., Op. cit., pp. 67-74, 1926.
Peacock, M. A., and Fuller, R. E., Chlorophaeite, Sideromelane and Palagonite from the Columbia River Plateau, Amer. Mineralogist, Vol. 13, pp. 360-383, 1928.

tent. Both have been extensively leached of the alkali and alkaline earth radicals. The remainder of the samples appear to be either only partly palagonitized, to consist only in part of glass susceptible of that alteration, or to have been somewhat weathered subsequent to the palagonitization. It appears from a comparison of the microscopic character of the specimens and of the chemical composition of the samples that we are here dealing with two fairly distinct processes which operate on material which originally contained variable proportions of glass and crystal or lithic material. The contained original glass may be more or less altered to palagonite and the associated lithic pellets or included microlites as well as the palagonite and (or) glass may be more or less weathered. The former process cannot be regarded as weathering proper and from its field relations and evidence in thin sections, it is believed to take place essentially at the time of the eruption and only subordinately *in situ* after the deposition of the pyroclastic material.

Since the palagonitization invariably proceeds from the outer surfaces of grains inward and is enormously more common in fine-grained materials, it seems to be a fair assumption that it may be a hydrothermal and oxidizing process taking place chiefly at the time of eruption in the presence of heat, moisture and some admixed oxygen from the atmosphere.

In the palagonitization there is no change in the relative proportions of alumina and silica, and weathering, either of palagonite or of glass or basalt minerals, must be invoked to explain the more pronounced changes of composition. Since the original compositions are not known and can only be estimated, and since palagonitization and weathering have affected different specimens to different degrees, it appears impossible in the present state of knowledge to use the analyses to throw any light on the correlation of various ash formations.

In several of the thin sections of palagonite tuffs and obscurely palagonitic rocks, certain material occurs which appears to be secondarily deposited palagonite. This forms an interstitial filling and appears to lack the vesicular and other structures usually inherited from the glass. No critical study of this material was made and the manner of its formation, if it be secondarily deposited palagonite, is unknown.

Alteration. The weathering of pyroclastic materials takes place in a manner similar to that of other igneous rocks of the same composition. Medium and fine-grained pyroclastic rocks under favorable moisture conditions weather with exceptional rapidity and in many parts of the island of Hawaii this process has produced a fertile soil for sugar cane, in what is probably a small fraction of the time necessary to produce a commensurate weathering and preparation of soil from lava flows. It should be noted, however, that arability and fineness of grain favoring water retention are as important as availability of chemical compounds in a soil. In these two former respects, volcanic ash is immediately ready for the growth of plants. On the other hand, except for the alteration to palagonite which probably takes place at the time of eruption, many of the yellow tuff formations of the drier parts of Hawaii show remarkably little change which can be ascribed to weathering processes.

The general weathering of basalts in Hawaii has recently been discussed by Palmer.[31] His treatment is based on four pairs of analyses of the fresh cores and the weathered shells of spheroidal boulders from the Wahiawa region of Oahu. On the basis of assuming no loss of alumina, it was found that in these weathered shells about 67 per cent of the total had been lost by solution, and 6 per cent had been gained by hydration and 1 per cent gained by oxidation of the ferrous iron. Titania, contrary to the findings in other soil studies, appears here to be less stable than alumina.

Iron suffered a net loss of about 30 per cent of its original total, due apparently to the presence of reducing conditions during part of the weathering process. About 80 per cent of the original silica is lost and about 88 per cent of the manganese oxide. Of lime and magnesia only 1 per cent each of the original amounts remain. Of potash 13 per cent and of soda 7 per cent remain. Of SO_3, P_2O_5 and MnO, the amounts remaining are 54, 32, and 12 per cent respectively. Only one of the analyzed samples from Hawaii has been sufficiently weathered to make comparison with Palmer's results intelligible; this is sample 707, of which the residual percentages of presumed original amounts are shown in column GG of Table 12. The two are compared in Table 14.

TABLE 14

PERCENTAGES OF CONSTITUENTS REMAINING

	HH Palmer Weathered Shells	*II* Tuff 707
SiO_2	19.8	2.9
TiO_2	49.8	76.1
Al_2O_3	100.0	100.0
Fe_2O_3	170.3	368.1
FeO	16.8	4.2
MnO	12.1	46.1
MgO	1.0	0.6
CaO	1.1	0.1
Na_2O	6.9	6.9
K_2O	13.5	12.7
P_2O_5	32.0	104.2
SO_3	54.3	n.d
H_2O	728.1	*

* Exact indication of the water increase is impracticable. Hawaiian lavas commonly show water content under 1 per cent, many show less than 25%. Compared to the alumina standard this sample may be presumed to have suffered a water increase of 1400 to 5000 per cent of its original amount.

HH.—Average of four analyses of weathered shells, referred to average of analyses of four fresh shells.

II.—Palagonite tuff, sample 707.

31 Palmer, H. S., Soil-Forming Processes in the Hawaiian Islands from the Chemical and Mineralogical Points of View, Soil Science, Vol. XXXI, pp. 253-265, 1931.

It is evident that sample 707 represents a much more advanced stage of weathering than the four samples studied by Palmer. In the sample, 707, the relative increase of ferric iron is more than twice as great, and less than a sixth as much silica remains. Less lime and magnesia remain and ferrous iron has been reduced to a much greater extent. In view of uncertainties in regard to the original amounts of the less abundant oxides in the Hawaii material, it is not clear what significance attaches to the variations in titania, manganese oxide or phosphorus pentoxide.

In the study reported from Oahu, the mineralogical composition of the fresh and weathered rocks was calculated from the chemical composition. Only a summary of results can be given here. Of amounts of minerals calculated in the norm for the fresh rock, there remain in the weathered rocks only the following approximate percentages: quartz, 82; ilmenite, 44; orthoclase, 14; albite, 4. Anorthite, wollastonite, clinoenstatite, iron minerals and rhodonite are all completely destroyed. The chief new minerals are limonite, which forms 16.95 per cent of the weathered rock, and gibbsite and bauxite which together form nearly half of the weathered rock, as computed by the method of norms. There is thus a complete destruction of the feldspars, the survival being progressively greater toward the soda and potash end of the series.

The relative rates of weathering of a basaltic glass and a crystalline basalt are not known. Natural glasses are regarded as less stable than crystalline rocks. Whether this generalization holds for rocks of basaltic composition is not known with certainty. No doubt a fine-grained, detrital material such as most glassy pyroclastics are, with a great surficial area exposed, weathers more rapidly than basaltic lavas. Large compact masses of basaltic glass are not known in Hawaii. In the vitric tuffs the minerals which have crystallized first as microlites are magnetite, olivine and feldspars, in the order named. The glass which remains is doubtless more silicic in composition than the magma from which the whole came. It is probably more resistant to weathering than a glass of the composition of the magma. Whether the fact that this glass surrounds many of the mineral grains indicates slightly greater resistance to weathering on the part of partially vitric tuffs as compared to lithic tuffs of the same mean composition is not clear. From the comparatively fresh appearance of most of the olivine crystals and felspar microlite in the tuffs studied, many of which have been long exposed to weathering, the writer is inclined to believe this is the case.

Petrographic Descriptions of Formations

Ninole Tuff

General features. Undoubted Ninole tuff was seen only at a few localities. The specimens studied were collected at localities 819 and 820, in a gulch three-fourths mile northwest of Hilea. As described by Stearns and

Clark,[32] the "ash bed" of the Ninole formation is a compact, dark red or brown, palagonitic material which stands for long periods and retains pick marks in tunnels for many years. They also state that, in general, it is somewhat finer in grain than the Pahala tuff. In view of the fact that most of the occurrences of the Ninole tuff are outcrops in the faces of steep bluffs, whereas, much of the Pahala tuff is exposed on very old land surfaces, where it has never been deeply buried, it is clear that the Ninole would appear megascopically to be more compact and to display less grain than would the Pahala. So far as microscopic examination goes, the specimens of 819 and 820 do not differ systematically in coarseness from the Pahala samples collected.

Like others of the palagonite tuff formations studied, the samples from localities 819 and 820 show that considerable differences exist in different parts of the section, even of a single tuff bed, in the degree of palagonitization, and of deposition of calcite. A sample of palagonite separated from material collected at location 819 was chemically analyzed and found to have suffered a considerably greater amount of weathering and removal of silica and other oxides than a similarly prepared sample of palagonite from Pahala tuff collected at Kalae. This may be due in part to greater age but may also be due to the greater activity of ground water associated with the deeper burial of the Ninole tuff at Hilea.

DESCRIPTION OF SPECIMENS

No. 819*a* Earthy tuff from near top of section in ravine three-fourths mile northwest of Hilea.

Megascopically, this is an earthy, porous red tuff. Under the microscope it appears as a yellow, brown and black, cloudy mass of fine-grained palagonite. A few small and somewhat weathered olivine crystals and plagioclase laths are included in the palagonite, and there are also a few separate pellets of lithic material with feldspar microlites.

No. 819*b* Red tuff lower in section, same locality as above.

In the hand specimen, this is a medium-grained, porous, red-brown, non-laminated rock. The color is Ridgway 10'h. In thin section, the rock appears as a porous mass of highly vesicular and stringy palagonite fragments. Individual masses are very irregular in structure with prominent cuspate forms and zonal palagonitization around the margins. Numerous fresh olivine phenocrysts 0.3 to 1.5 millimeters across are present. The palagonite shows a compound banding parallel to free surfaces, to vesicles and also to contacts with olivine. The width of the zone of banding is .05 mm. and in places it shows a tangential extinction, though in the main it is quite opaque between crossed nicols. The deepest color of homogeneous palagonite is tawny (13'i) and many parts are much lighter, an extreme being lemon chrome (21). The olivine crystals and palagonite both include a few magnetite grains which range to 0.1 mm., mostly chunky but a few are euhedral. One or two dark microlitic pellets are present, but the dominant palagonite is free from inclusions other than magnetite and small olivines. (See Plate 8*A*.)

[32] Stearns, H. T., and Clark, W. O., Geology and Water Resources of the Kau District, Hawaii, U. S. G. S., Water Supply Paper 616, pp. 61-65, 1930.

No. 819*c* Tuff from near base of exposure at same locality.

Megascopically this is a fine-grained chalky, crumbly rock of buff color (17'd), which contains much secondary calcite. Under the microscope it shows a mixture of fresh, light-gray pellets and darker, irregular, brown, cloudy masses. The light pellets under higher powers appear to consist largely of shreddy secondary calcite. The entire rock is fine-grained and the whole much weathered. Green grains 0.25 mm. across appear at first to be mineral grains but under high power and crossed nicols seem to have a chloritic structure. Some of the pellets carry feldspar grains .01 to .02 mm. across. Much interstitial spherulitic secondary calcite is present.

No. 820*a* Tuff from lower formation in gulch below exposure of 819, northwest of Hilea.

This is a fine-grained, chalky-textured rock of pinkish-brown color. The color ranges from 11b to 9i. The thin section shows a much altered palagonite tuff of average grain about .05 mm. There is much secondary calcite and numerous small feldspar fragments. An abundant low birefringent, secondary mineral arranged in fans and roses was thought to be a zeolite. Certain light green areas may be chloritized glass areas, with secondary zeolites.

No. 820*b* Tuff from same locality as 820*a*.

This is a yellow-cream, fine-grained rock with 2 to 10 mm. pellets of palagonitic material. The color of the rock is 11b; that of the pellets is 9k. The grain specific gravity is 1.887 and that of the rock 0.92, the porosity being 51.3 per cent. In thin section there appear two chief constituents: deep orange to opaque palagonite, highly vesicular and showing typical glass structures, and surrounding areas and matrix of secondary calcite slightly colored by what appears to be secondary palagonite. (See Plate 8*B*.) The largest single palagonite masses are about 2 mm. in diameter, and the largest vesicles about 0.1 mm. with a range down to .01 mm. A few granular aggregates of olivine 0.5 to 1.0 mm. across are present. In the lightest and clearest palagonite the interior masses show a color about primuline yellow (10') and the bands marginal to the vesicles are about mars yellow (15i). The latter show a fine parallel banding with lighter and darker laminae. (See Plate 8*C*.) Total thickness of marginal zone about .02 to .03 mm. and of laminae about .001 to .003 mm. Under crossed nicols these laminae show a slight differential illumination normal to the vibration of the lower nicol which appears to be due to a kind of Becke line effect rather than true extinction. In some places the banded palagonite lies inside another zone of opaque material which appears to have been derived from the banded material and to be in a more advanced stage of alteration.

The following additional specimen was collected and studied:

No. 820*c* Tuff from same locality as 820*a*.

Kohala Pyroclastic Formations

General features. So far as could be observed in the short time devoted to the north end of the island, the pyroclastic materials of the cones of the Kohala Summit division consist chiefly of only slightly altered cinders. Only the coarser material in and near to the central cones is known at present; if a more distant, finer-grained, palagonitized tuff formation analogous to the yellow-tuff phase of the Waiau formation exists, it must be nearly everywhere buried or covered by the sea. Until detailed studies have been made it does not seem advisable to apply a definite formation name. The term Kohala is here used only in a regional and descriptive sense.

DESCRIPTION OF SPECIMENS

No. 181 Gray cinders from an exposure on Kohala road west of Puu Honu.

These are light, yellowish-gray, vesicular cinders. Under the microscope they are seen to consist of olive-buff glass (21‴), showing much flow structure and numerous microlites of feldspar. A small fraction is partially palagonitized.

No. 183*a* Lapilli tuff from elevation 3120 on Kohala road at Pohakuloa Gulch crossing.

This rock is a porous mass of 3 to 5 mm. pellets of tawny olive color (17″i). Microscopically the rock is composed of rounded, irregularly vesicular pellets. Many of these are opaque, others nearly so, and a few are light yellow and transparent. By incident light the opaque grains are orange to cream colored (15′ to 17′f). Around the margins of the opaque grains and filling the pore space is golden yellow palagonite (17 to 19), some of which appears to be secondary. The dark pellets contain numerous feldspar microlites and show the growth of much fibrous, dark-brown palagonite.

Pahala Tuff

General features. In various situations the Pahala tuff varies from a moderately compact, chalky or earthy-textured rock to an almost wholly unindurated dust. The colors of these phases are red-brown and light yellow-buff, respectively. These differences in appearance are due more to moisture content under existing climatic and topographic conditions than to any inherent difference in degree of cementation or petrographic character. Nearly all exposures contain some zones of coarser material in which at least small amounts of only slightly altered basaltic glass may be identified with the hand lens and many of the pebble zones which have been reported and considered to be evidence of fluviatile deposition are believed to be lapilli zones. The present writer did not recognize any general or widespread incorporation of stream-borne detritus in the Pahala tuff or any considerable part thereof which did not seem to be primary, aerially-deposited pyroclastic material, except for variable and not clearly differentiated lenses of the upper part of the Pahala formation of the Kalae region which are due to recent and modern eolian deposition.

Many of the exposures of Pahala tuff show a striking similarity in appearance and structure to loess and this is probably the result of a similar porosity and texture.[33] By itself, however, this similarity should not be taken as evidence of deposition of materials by the wind. Since primary volcanic ash derived directly from a volcanic vent is deposited out of the atmosphere, it also shows, when of similar texture, some features similar to those of the loess.

Most of the Pahala tuff is massive and without close lamination. In many exposures several distinct beds or members occur, marked by fairly distinct

[33] The problem of eolian origin and use of the term loess has been discussed in an earlier section of this paper, p. 43. See also Palmer, H. S., Volcano Letter 350, 1931.

differences in the character of the material, by sharp differences in water content, calcareous veinlets or other secondary features. Some of the contacts within the Pahala are marked by a secondary crust of calcareous material a fraction of an inch in thickness, which weathers out as a resistant lamina in the outcrop.

Pahala region: General characteristics. The Pahala tuff of the Pahala region is characteristically non-laminated, powdery, red or yellow material, with some interbedded layers of coarser, granular, grayish, ashy material. In a few places near steep slopes, it is associated with layers of slope-washed ash and other debris. Where it lies on the present surface, it grades upward to layers of wind-blown palagonitic dust interbedded with black or gray sandy ash laminae probably belonging to the Keanakakoi series.

DESCRIPTION OF SPECIMENS

No. 817 Tuff from highway cut one mile southwest of Pahala.

This specimen is a dull yellow (19''h), crumbly rock with no lamination and an earthy texture. The specific gravity of the grains is 2.332, that of the rock 0.99, and the porosity 57.6 per cent. Under the microscope it appears a mass of light and dark, yellow to black pellets and phenocrysts. Lighter material is mostly small, cloudy, yellow-brown palagonite with darker included magnetite. Plagioclase among phenocrysts is andesine. Granular masses of augite contain irregularly-oriented feldspar laths. The olivines are commonly broken fragments.

No. 822*a* Tuff from 2000-foot elevation in Keaiwa Gulch.

This is a yellow-orange, crumbly palagonitic rock which carries some black glass grains and some darker red palagonite pellets. The general color is mars yellow. Microscopically this rock is composed of somewhat cloudy and obscure palagonite masses with a few clear, vesicular glass-structured palagonite pellets. The palagonite shows marginal banding similar to but less clear than in Ninole No. 820*b*. A few olivine crystals and a few microlitic pellets are present.

No. 822*b* Tuff from darker nodules at same locality as above.

This is a moderately compact, non-laminated material of amber brown color (13k). The specific gravity of the rock is 1.34. Under the microscope this is seen to be a fine-grained aggregation of palagonitic shards and small crystals, nearly all .5 mm. or less in diameter. Most of the material is in small, nearly clear yellow, fragments of palagonite. A few very cloudy and opaque pieces are present. Occasional plagioclase laths are seen, but the palagonite contains few microlites.

No. 827 Glassy surface of lava flow north of Pahala.

This is a finely-vesicular, basaltic rock with a ¼-inch exterior of red-brown color. The interior is gray. In thin section the main rock shows a ground mass surrounding the vesicles, which is nearly opaque. In this part are scattered microlites of feldspar and olivine. Toward the edge of the brown selvage the mass becomes lighter brown in color and progressively the inner parts show clear, light green isotropic glass. Near the extreme outer parts the main mass is clear isotropic glass, still with numerous microlites, and on the margins of vesicles there is a band of clear yellow palagonite about .04 mm. in width. Penetration of the palagonitization seems to have been very feeble, though the glass seems to have been progressively devitrified in the interior.

The following additional specimens were collected:

No. 510 Yellow tuff from section at Halfway House southwest of Kilauea.

No. 822*c* Weathered tuff from same locality.

No. 823*a* Tuff from an exposure in Keaiwa Gulch.

No. 823*b* Tuff from same locality as above.

Kalae region: General characteristics. Usually the Pahala tuff at the base is a dark, red-brown, earthy material which contains small branching calcareous thread-like masses. Above it lighter-colored, more friable tuff is found. At the top is a variable section showing in places several feet of probable wind-deposited dust interlaminated with thin layers of ill-assorted black ash belonging either to the Keanakakoi series or to some local littoral pyroclastic formation. Calcareous secondary crusts occur above the darker, basal material and in some places between other members of the variable section. A distinctive member of the tuff cover in the Kalae region is the so-called lavender tuff. This is a rather hard, but somewhat crumbly and shattered rock which lies at the base of the section wherever it occurs. Whether it should be regarded as a component part of the Pahala tuff or as a local product of an ancient littoral or other eruption peculiar to the Kalae region, is not known.

DESCRIPTION OF SPECIMENS

No. 93*b* Tuff from gray, granular beds associated with "lavender" tuff. From 300′ contour in Kahawai Kolono, Kalae.

This is a porous, friable rock of somewhat mealy texture. The color is yellow ocher (17′) with some darker glass grains. The gross specific gravity is 1.18. Microscopically the rock is composed of poorly-sorted glass fragments (.01-1.0 mm.); many are highly vesicular (.03-.25). The larger fragments of glass are clear and unaltered in interior, color green-yellow (25″b). In smaller fragments much of substance is altered to palagonite. Strong flow structure appears in many fragments. Some fragments carry numerous feldspar microlites (.01 by 0.5 mm.). Only a few olivine grains (.12 mm.) are present. A few small magnetite grains are present in the olivine and in the glass. The palagonite occurs as zones (.01-.02 mm.) around margins and in vesicles of glass fragments and as an irregular cloudy alteration of the entire mass of smaller fragments. Zones are composed chiefly of yellow-orange, sub-parallel, fibrous material showing partial extinction parallel to margin. The more distinct zones appear to be secondary. Much shreddy calcite is seen in vesicles surrounded by the palagonite of the vesicle margins. In places the fibro-palagonite zone is now apparently broken apart from the glass and a parallel, clear space intervenes. Some fragments of glass carry numerous laths of a plagioclase determined as andesine.

No. 100 Lavender tuff from lens under buff tuff at Puu o Mahana.

This specimen is a fine-grained, drab tuff. The color is 18‴c. Microscopically this is a greenish-black, speckled rock with original grains .5 mm. to .02 mm. in diameter. It also contains large masses of shreddy, secondary calcite and shows a few small masses of palagonitized glass. It is chiefly a fine-grained mosaic of small glass fragments so loaded with microlites as to nearly obscure its isotropic character. Feldspar occurs as large, irregular masses (.5 mm.) and small plagioclase laths showing albite twinning.

The olivine is in chunky grains 0.2 mm. in diameter. The color of the glass is light green (29'''c). Most of the grains are densely riddled with microlites. A few clear grains show sub-parallel, wavy extinction which appears to be due to a form of devitrification. Some grains are so devitrified as to be nearly opaque. The section carries large grains of a delicately fibrous mineral of light yellowish-green color and slightly pleochroic, nearly parallel wavy extinction.

No. 116 Basal red Pahala tuff, west of Puu o Mahana.

Megascopically this is a ragged, red-brown, earthy material, showing darker grains. It consists of large, dark grains of glassy, somewhat altered material loosely cemented together in a mealy, palagonitic matrix. In this section the rock shows large grains (2 mm.) of somewhat altered glass which include olivine crystals ranging to 2 mm. The glass is light to dark yellowish-green and contains numerous vesicles ranging from 1/10 to ¼ mm. in diameter. Even in larger grains only a few nuclear patches show complete isotropic extinction. Most of the area under crossed nicols is dull brownish-green with light transmitted by probable microlites. The margins of the vesicles show shreddy secondary calcite and some are filled solid with spherulitic calcite. The olivine crystals are mostly fresh, with a few large euhedral magnetite crystals included. The palagonite appears as a general, yellow cloudiness over most of glass and becoming thicker near margins. Many of the vesicles are lined with yellow material showing spherulitic extinction. From the revelations shown in coarser-grained parts of the rock, these are believed to be due to a growth of fine-grained, radially-oriented calcite or aragonite in gel-palagonite.

No. 129 Red, basal tuff from shore one-half mile east of Kalae.

Megascopically this is a slightly coherent, powdery yellowish-orange rock with small thread-like markings of secondary calcite. The color is 16'. The grain specific gravity is 2.118, the specific gravity of the rock 1.03 and the porosity 51.3 per cent. In thin section the rock is fine-grained mass of palagonite with minor amounts of olivine and plagioclase. The material prepared from this rock for chemical analysis as palagonite shows much spherulitic arrangement of calcite or zeolites with secondary palagonite in vesicles now forming balls. A fair number of large, weathered olivines and a sprinkling of plagioclase microlites appear.

The following additional specimens were collected:

No. 34 Calcareous tuff from edge of Kulani Pali at 700-foot contour north of Kalae lighthouse.

No. 63 Red tuff from beneath basalt flows at Awawaloa southwest of Kaalualu.

No. 93*a* Lavender tuff from base of section at 300-foot elevation in Kahawai Kolono at Kalae.

No. 119 Red Pahala tuff from Kalae district.

No. 486 Yellow tuff from rim of pit crater Lua Puali, south of Kahuku Ranch.

No. 487*a* Lavender tuff from rim to pit crater Lua Poa south of Kahuku Ranch.

No. 487*c* Rose-colored tuff from section at same locality (Plate 8*D*).

Kilauea region: General characteristics. The Pahala tuff of the Kilauea-Kapukapu region differs from that of the Pahala and Kalae regions in the greater proportion and prominence of the grayish layers of detrital, glassy ash. The bulk of the total thickness of about 40 feet is palagonite tuff, here as elsewhere, but occasional gray ash layers are more prevalent throughout the section from bottom to top than in any other locality of undoubted Pahala tuff.

DESCRIPTION OF SPECIMENS

No. 639*b* Tuff from top of Kapukapu.

Megascopically this is a coarse, crumbly rock of orange color (14'h) with some darker grains. A sample nearly identical with this has a gross specific gravity of 1.21. In thin section this rock shows greenish-brown (19"), highly vesicular, partially palagonitized masses of glass. It contains a few lithic pellets and numerous large olivine crystals. Some of the vesicles have a fringe of tangential calcite.

No. 639*c* Tuff from the top of Kapukapu.

The hand specimen is a coarse, crumbly mass of grayish-green and buff grains and lapilli. It shows only crude bedding. Under the microscope it is seen to be a mixture of glass, porphyritic glass and olivine. The glass is greenish-brown, and only very slightly altered.

No. 648 Yellow tuff from about 600-foot elevation in face of Kapukapu.

The hand specimen is an irregularly-fracturing, crumbly mass of fine ash and palagonitized material. The finer part has a yellowish-orange color (16'a) and the coarser has an olive color (21'i). The gross specific gravity is 1.19. The thin section shows a fine-grained aggregate (0.03 to 0.1 mm.) of glass shards and other cuspate shapes, the glass moderately vesicular and only slightly altered.

No. 839*a* Tuff from top of Kapukapu.

Glenwood region: General characteristics. The surface tuff of the Glenwood region is a moist, sticky, red-brown to gray-drab material with thin bands of resin-colored palagonite. In places it shows a granularity due to original ash pellets but these are subordinate to granules developed in the course of weathering. The lamination or banding of the Glenwood tuff is intermediate in its distinctness between the Pahala tuff of the Kapukapu and Kilauea region and the Waiau yellow tuff found along the coast north of Hilo.

DESCRIPTION OF SPECIMENS

No. 581*a* Weathered ash from road out 8 miles northeast of Kilauea on Hilo Road.

When dry this is a light cream-yellow, granular, very slightly calcareous, crumbly material. Under the microscope it is seen to consist of 2 to 3 mm. pellets of opaque material with lath-shaped microlites up to 0.5 mm. long. The matrix is largely white in incident light. Around the margins of the pellets is a fringe of adherent yellow, somewhat palagonitized glass, which is only slightly vesicular and almost perfectly isotropic. (See Plate 8*E*.)

No. 581*b* Gray ash from section in road 8 miles northeast of Kilauea.

This specimen is a mealy-textured, crumbly rock of mottled cream color (19"d) with dark grains. In thin section it conists of black and gray pellets (1.0 to 0.5 mm.) of lath-filled porphyry. These pellets are irregularly surrounded by yellow palagonite, which appears to be secondarily deposited.

Waiau Formation

Central cone phase: General features. The materials composing the numerous large and small pyroclastic cones of the summit area of Mauna Kea vary in grain from coarse ash to large bombs. Few of the cones in their steeper portions exhibit any large amount of material finer in grain than about 4 millimeters. On the other hand, of the thirty or forty cones visited, none were seen which consisted dominantly of fragments larger than 10 or 15 centimeters in diameter. Many of the cones consist of cinders or denser lapilli mostly in the 4 to 16 millimeter grades but have a few coarser fragments and bombs up to a meter in diameter strewn over their upper surfaces. Only a few adequate exposures were seen but it is believed that the coarser material is mainly confined to the upper surfaces and represents the product of lava sputtering during waning phases of the eruptions.

Pyroclasts in the central cones coarser than 8 millimeters in diameter are mainly lithic with a very fine grain in the smaller sizes. Much of the material smaller than this size is glassy or consists of abundant microlites in a glassy matrix. In a few instances almost wholly lithic material as fine in grain as 1 millimeter occurs. Very little palagonitization is megascopically evident in the central cone phase of the Waiau formation. In thin section some of the tuff specimens from near the central cones show small amounts of palagonite but in general these coarser materials have only been slightly affected by this type of alteration. As a consequence the dominant colors are black and gray, or dark hematite red as a result of weathering of the exposed surfaces.

DESCRIPTION OF SPECIMENS

No. 174 Lithic tuff from point on Kona road south of Waimea, elevation 2490, at Kamakoa Gulch crossing.

The hand specimen is a rather finely cemented, granular rock of gray-drab color (19''''c) with a few minute flecks of orange palagonite. Under the microscope the rock appears as a porous mass of irregular to somewhat rounded fragments which consist mostly of numerous slender feldspar microlites imbedded in an opaque ground mass. Fragments range from 0.25 mm. to 1.5 mm. in diameter and feldspar laths range up to 1 millimeter long by 1/10 to 1/5 as broad as long. The ground mass of fragments in incident light ranges from light yellow to red to black in color. Much of the fine-grained material which surrounds the larger grains is a mixture of yellow palagonite and secondary calcite. A very few pieces of light yellow, transparent, only slightly palagonitized porphyritic glass are present, showing the same texture as those with the opaque matrix. A few olivine grains, 0.03 mm. in size are present with a moderate amount of magnetite in grains 0.02 mm. in diameter. The bulk of the microlitic material is oligoclase near andesine (Plate 8*F*).

No. 237 Gray tuff from elevation 5850 feet in gully west of Puu Maau, south of Ahumoa.

The hand specimen is a porous, friable rock composed of dark brown grains with a few lighter grains. The gross specific gravity is 1.81. The grain specific gravity is 2.584 and thus the porosity is 30 per cent. The rock shows a very rude lamination visible in the hand specimen. Microscopically it is a porous mass of rounded, brown or black, opaque grains (0.5 to 1.0 mm.) carrying numerous clear microlites, together with abundant shards of opaque material (0.25 to 0.50 mm.) and of only slightly cloudy, yellow basaltic glass. The glass is only slightly palagonitized and carries numerous microlites.

No. 261 Tuff from upper layer at elevation 3025 feet in Kamakoa Gulch north of Waikii.

This is a hard, stony tuff of light gray color (2.''''d). The gross specific gravity is 2.07, and that of the grains 2.738, the porosity being only 24.4 per cent. It contains a few rusty plant and leaf impressions. Under the microscope this rock is a compact mosaic of poorly-sorted ash pellets (0.01 to 3.0 mm.). These all show structure shreddy with feldspar laths, the matrices varying from yellow to opaque. One large pellet is 1.5 mm. by 3.0 mm.; one-half its area is opaque, black matrix, the remainder is a series of sub-parallel oligoclase laths 0.20 mm. long by 0.02 mm. wide. There are also a few olivine grains which range to 0.15 mm. Other ash pellets are lighter in color due to less complete alteration of the glass. Some show clouds of small magnetite grains and greater amounts of olivine. A few scattered olivine crystals up to 0.5 mm. are seen in the matrix. Feldspars up to 1.0 mm. are present. Average composition is An 45: Ab 55. A few small fragments of augite were seen.

No. *275b* Gray tuff above unconformity at elevation of about 3500 feet in Kemole Gulch.

This rock is a fairly well cemented, poorly-sorted mass of pellets (1-4 mm.) of gray color. The gross specific gravity is 1.90 and the grain specific gravity is 2.560. The porosity is therefore 26 per cent. Under the microscope pellets of several types are seen. Most numerous are opaque grains carrying few or many feldspar laths. These are either brown or gray by incident light. Next in order are glassy, usually much palagonitized grains showing numerous vesicles. A few olivine grains (0.3 mm.) and augite grains (0.5 to 1.0 mm.) are present as phenocrysts. One millimeter grains of plagioclase are present.

The following additional specimens were collected:

No. *217a* Black tuff from beds northwest of Ahumoa, elevation 5600 feet, Humuula road. (See No. *217b*, p. 157.)

No. 236 Black tuff from elevation 5750 feet at the west base of cone 5911, south of Ahumoa.

No. *331a* Crystal lapilli from east slope of Puu Pa.

No. 383 Fine-grained tuff from elevation 5700 feet on north slope of Puu Huluhulu southeast of Makahalau camp.

No. 410 Gray ash from 7650 feet in gulch one mile northwest of Hookomo north of Humuula. (See Figure 11*c*.)

Yellow tuff phase: General features. Considering the wide area over which it occurs, the yellow-tuff phase of the Waiau formation shows a much greater uniformity in lithologic character than does the central cone phase. The yellow tuff is everywhere characterized by a prominent degree of palagonitization of the original glass. Since the ash particles which drifted far from the source cones were everywhere of small size, they consisted of quickly cooled glass. Not only the glassy condition, but also the fine grain with its large ratio of surface area to volume permitted an effective reaction with associated moisture of the eruption and favored a prompt conversion of notable parts of the material into palagonite.

A second feature is the common banding of the Waiau yellow tuff. In many exposures brighter, yellower bands alternate three or four to the foot in thickness, with darker, moister, stickier bands. In general the yellower bands show a coarser texture, either original or secondary. Since the yellow tuff phase in its main areas is remote from most of the cones and must be the product of many eruptions, it is reasonable to suppose that the banding represents successive ash falls. It is believed also that the finer bands represent the finer-grained, later products of a given eruption, possibly modified by weathering before it was covered by the ash from the next eruption.

DESCRIPTION OF SPECIMENS

No. 167 Palagonite tuff from two-inch layer three feet below surface at elevation 2550 feet on Waimea road southwest of Honokaa.

This is a soft, orange-brown material associated with darker brown beds. Under the microscope it appears as chiefly red-brown palagonite (9i) with subordinate yellow palagonite (25d). Fragments are cuspate-margined shards, vesicular, and clearly derived from glass. Except for a very few small crystals, probably feldspar, and moderate amounts of secondary calcite, the entire mass is isotropic.

No. 242 Tuff from elevation 5175 feet in Auwaiakeakua Gulch, southeast of Waikii.

The hand specimen is an earthy, porous tuff of yellow-brown color (17'i). The gross specific gravity was determined as 1.05; that of the grains is 2.235 and the porosity is 53.0 per cent. Under the microscope the rock appears as equal proportions of gray, rounded grains 0.5 to 1.5 mm. in diameter and light yellow, vesicular grains 1 to 2 mm. in diameter (Plate 9*A*). The gray grains show a few openings filled with palagonitic material but consist chiefly of a thick mat of feldspar microlites which almost completely obscure the matrix in which they lie. Around the margins of these grains is a brown palagonite fringe. The yellow grains consisted of slightly palagonitized glass, in which are some microlites but an insufficient number to produce the gray aspect. Considerable numbers of small magnetite grains are seen in some of the pellets. A few small olivine grains are present.

No. 274*a* Red tuff from below unconformity at elevation of about 3500 feet in Kemole Gulch.

This rock is a fine-grained, powdery mass of buff color (15'b) and showing a few small root tubes stained possibly with manganese oxide. In thin section it is composed of irregular masses and aggregates of palagonitized glass particles (0.05 to 0.10 mm.) which are chiefly dark, cloudy brown in color. The general color is 15'i. The most conspicuous pellets are round or oval masses largely filled with feldspar microlites and magnetite crystals in a felted configuration. Some of these appear to have been coherent aggregates of crystals around which a coating of glass, now palagonitized, has adhered.

No. 323 Yellow tuff from beneath lava flow at elevation of 2900 feet in Popoo Gulch north of Keamuku.

This is a compact, fine-grained fairly hard tuff of tawny olive color (17''i). The gross specific gravity is 1.601. A few small calcitic root casts are present. The thin section shows a few microlitic pellets 0.5 to 1.0 millimeters in diameter in a matrix of palagonitized finer fragments ranging down to 0.02 mm. A large number of 0.25 mm. plagioclase laths are in the matrix. Little or no olivine was seen.

No. 680*a* Weathered "gumbo" from highway crossing over Pukihae Stream north of Hilo.

This material is a dark brown, slightly mottled, dense, fine-grained, somewhat clayey, mass with veins and fillings of secondary calcite. It is probably partly palagonitic but does not show convincing primary ash structures.

No. 769*a* Red, powdery ash from surface layer east of Umikoa.

Megascopically this is a fine, powdery, somewhat gritty, material. The color is nearly mahogany red (6i). Under the microscope it is seen to contain a few small masses of secondary calcite. The remainder is fine, nearly lateritic, ferruginous material.

The following additional specimens were collected:

No. 168 Yellow palagonite tuff from a two-inch layer three feet below the surface at elevation of 2450 feet on Waimea Road south of Honokaa.

No. 177 Basal lavender tuff from elevation 2670 feet at southwestern base of Nohonaohaeiki, south of Waimea.

No. 668 Weathered palagonite tuff from elevation 700 feet, west of Honolii Cove.

No. 672*a* Red "gumbo" from section on the highway a half mile north of Hilo.

No. 680*c* Gray-red ash from section at crossing of Pukihae Stream north of Hilo.

No. 700*b* Red-brown gumbo tuff from highway cut north of Pahoehoe Stream, north of Hilo.

No. 700*c* Red sticky tuff from section in road cut north of Pahoehoe Stream, north of Hilo.

No. 707 Firm red palagonite tuff from highway cut ¼ mile south of Pepeekeo.

No. 710 Red granular tuff from highway cut south of Honomu Stream.

Waawaa Pyroclastic Material

General features. The Puu Waawaa cone is composed of well-statified beds of pumiceous and dense, trachytic lapilli and ash. As seen in a gulch on the north side of the cone the fragments range mostly from 4 to 128 millimeters in diameter. Here perhaps 10 to 15 per cent of the whole section exposed consisted of light gray pumiceous fragments mixed with denser glass lapilli. The remainder was a well-sorted accumulation of lithic lapilli, in places cemented with calcite. On the southwest side of Puu Waawaa, near the base, the trachytic cinder beds are overlain by about five feet of basaltic cinders. Neither the source of the basaltic cinders nor the relationship between them and the trachytic ejecta which appear to form the main cone are known at present.

Cross has described the materials of Puu Waawaa and the nearby Anahulu terrace as "tracyte rich in soda and containing only about 10 per cent of mafic minerals."[34] He considered from its relations that the cone of Puu Waawaa must have been formed by a trachytic eruption during the period of formation of the basaltic dome of Hualalai and pointed out the very great petrographic interest attaching to such a history, but as yet no one has made a detailed study of the petrography in the light of field relations.

DESCRIPTION OF SPECIMENS

No. *734a* Trachytic glass from lapilli deposit on north flank of Puu Waawaa.

The specimen is a 30 millimeter fragment of a dark, flow-lined glass. In thin section it is a clear, perfectly isotropic, colorless glass containing slender microlites (0.2 mm. long by 0.01 to 0.02 mm. wide) arranged in parallel flow bands 0.1 to 0.5 mm. across and spaced by roughly similar amounts from each other. The microlites show a slight preference for parallel positions, especially when isolated, but to a considerable extent the bands are felty masses of non-oriented microlites. A few vesicles are visible. Quadratic and granular sections of an opaque mineral are fairly numerous and are probably magnetite. A mineral of hexagonal section and prismatic form is present sparingly in crystals 0.03 mm. in diameter. (Acmite?) Microlites are parallel extinguishing, gray to slightly yellow in birefringence color, somewhat cloudy wisps. No distinct albite twinning was seen. A few small nuclei of more completely crystallized microlitic material are present.

No. *743b* Vesicular trachyte glass from north flank of Puu Waawaa.

These are somewhat rounded, pumiceous lapilli, in sizes from 4 mm. to 32 mm. A few denser, glassy fragments are present. In thin section the lapilli consist of flow-oriented glass with vesicles 0.05 to 0.5 mm. in diameter and carrying numerous microlites mostly 0.05 to 0.1 mm. in size. The glass is very cloudy. (See Plate *9B*.) The grain specific gravity of the glass is 2.435.

No. *744* Basaltic cinders from surface beds, near west base of Puu Waawaa.

These consist of buff-colored, broken vesicular lapilli. These mostly show several surfaces of blown or pulled shapes with other broken surfaces showing the cross-sections of vesicles. The pulled surfaces are mostly unbroken by vesicles. Under the microscope the material is mostly brown-black glass. The mesh of vesicles is about 1/16 to ¼ mm.

No. *747* Crystal tuff from point on road west of 1859 flow and north of Puu Waawaa.

This is a light gray (23''''d), medium granular rock. The specific gravity of the rock is 1.92. Under the microscope practically the entire rock consists of feldspar debris in which are included microlites.

Uwekahuna Formation

The Uwekahuna formation, so far as known, is accessible for examination only at one point, since an exposure previously known was buried by the lava flow of 1919 from Halemaumau. Of the two exposures, the one now buried

34 Cross, Whitman, Lavas of Hawaii and Their Relation, U. S. Geol. Survey, Professional Paper 88, pp. 35-36, 1915.

was reported by Powers[35] as 17 feet thick and consisting of yellow ash with rock fragments 1 or 2 inches across. The remaining exposure consists of blocks and lapilli, with a few lava-coated bombs, ranging to 16 inches across, at the northeast end. At another point the section includes medium coarse black ash, "gravel and cobble" beds, and yellow ash with glass droplets and crushed reticulite lapilli.[36] So far as can be judged from these meager data, the Uwekahuna formation is very similar in character to the Keanakakoi formation in its mixed content of coarse and fine essential ejecta with coarse and fine accessory material, all probably the product of Kilauean eruptions. No specimens were collected.

Hualalai and Mauna Loa Pyroclastic Materials

Reports by the few parties which have ascended Hualalai as well as inspection of the topographic maps show the presence of numerous cinder cones in the summit area of the mountain but little is known of the petrographic character of the materials. They are probably chiefly of basaltic composition.[37] Some pyroclastic cones in the Hualalai rift zone where it is crossed by the Kona road are composed of coarse, moderately vesicular cinders and driblet lava, of basaltic composition.

The lavas of Mauna Loa are well known and their composition has been studied by Washington, Cross, and others. No separate study has been made of the petrographic character of the pyroclastic materials in various cones at the sources of flows. That they are chiefly of basaltic composition is quite certain, though they doubtless show considerable chemical diversity. The Kona ash formation,[38] described below, may be derived from Hualalai or Mauna Loa vents, or both.

Kona Tuff Formation

General features. This formation consists of fine-grained palagonitic ash with small amounts of olivine and feldspar crystals. It is somewhat coarser near the summit cones of Hualalai and Mauna Loa and shows definite sorting into coarse and fine beds. On the lower slopes no trace of bedding is apparent.

DESCRIPTION OF SPECIMEN

No. 500*c* Yellow tuff from surface of unconformity where later flows have come down over cliff at Napoopoo.

In thin section this is a fine-grained, dark red-brown to opaque palagonite rock. The color in incident light is the same. It shows a few small areas of secondary calcite.

[35] Powers, Sidney, Explosive Ejectaments of Kilauea, Amer. Jour. Sci., 4th Series, Vol. 41, p. 230, 1916.

[36] Stone, J. B., The Products and Structure of Kilauea, Bishop Museum Bulletin 33, pp. 27-28, 1926.

[37] Cross, Whitman, Op. cit., pp. 34-35.

[38] The writer is indebted to Dr. H. A. Powers for information relating to the Kona ash formation, which was recognized by Dr. Powers after the writer's return from Hawaii.

Kapoho Pyroclastic Materials

General features. From the few observations made on pyroclastic craters of this district, it appears that the materials are petrographically similar to those of Mauna Kea and Hualalai. The cinders of Puu Kakae are remarkable for their uniform sizes between 1 and 2 centimeters. Basaltic, vesicular cinders were seen in exposures of several other cones. Kapoho crater is composed of cinders and finer ash beds, now somewhat cemented, together with a few bombs and accessory blocks.[39]

DESCRIPTION OF SPECIMEN

No. 628 Cinders from Puu Kakae, Puna.

These consist of red and black, rusty fragments of finely vesicular pumice. The original free surfaces show a light brown glaze. The sizes range from 4 mm. to 32 mm. Under the microscope the lapilli are seen to range from light pumice to a crude, irregular reticulite, all consisting of dark, red-brown glass, which appears to be weathered but not palagonitized.

Keanakakoi Formation

General features. The general petrographic character of this complex series of pyroclastic beds is best shown in the measured sections described below. Some of the beds consist wholly of essential pyroclastic material derived directly by explosion from the magma. Others, like the ash and lapilli of 1924, consist wholly of accessory material resulting from disruption or collapse of the walls of the vent. Still others contain both essential and accessory material in intimate mixture. The finer-grained essential pyroclastics of this formation consist of greenish yellow, sandy textured mixtures of glass fragments and olivine grains. Coarser essential pyroclastics include yellow, pumiceous cinders or dark to black, less vesicular cinders, and extremely light, reticulite lapilli.

The finer accessory materials take the form of gray or pinkish gray dust or clayey beds. The coarser beds of accessory material, much mingled with the gray dust, consist of mottled red and black, angular lapilli ranging to blocks one or two feet in diameter. In a number of places around Kilauea, small pellets formed by the falling of rain drops through dust clouds during an eruption are found. These have previously been called pisolites but are here called accretionary lapilli, following Williams.[40] These materials occur in all sequences in section and it has not yet proved practicable to work out a general sequence of eruption types prior to 1790.

39 Stearns, H. T., and Clark, W. O., Op. cit., pp. 146-148, 1930.

40 Perret, F. A., Some Kilauean Ejectaments, Amer. Jour. Science, 4th Series, Vol. 35, p. 612 (figured in Figure 2), 1913.

See also Bul. Hawaiian Volcano Observatory, June 1921, and July 1921, and Volcano Letter, Nos. 157 and 182.

Williams, Howel, Notes on the Characters and Classification of Pyroclastic Rocks, Proc. Liverpool Geol. Soc., Vol. XIV, pp. 231-232, 1926.

DESCRIPTION OF SPECIMENS

No. 534 Pele's hair from the Kau desert southwest of Kilauea.

This consists of wisps and mats of light, olive-yellow glass threads with occasional larger bulbous sections, included magnetites and vesicles. Fragments mostly one to three inches long. The grain specific gravity is 2.631. Under the microscope the filaments are seen to consist of green glass. Smaller ones are commonly clear (1/100 to 1/15 mm. in diameter); larger threads up to ¼ mm. contain elongate vesicles and microlites. A few have enlarged glass bulbs with numerous vesicles and inclusions. There is much microlitic material scattered within the glass threads. Threads show a pulled, minutely-striated configuration and structure and a pseudoanisotropic appearance under crossed nicols. (See Plate 9*C*.)

No. 544*a* and 544*b* Pumiceous cinders from Kilauea eruption of July, 1929.

These are small, broken, pustulate, irregular masses of finely vesicular glassy material mostly 4 to 16 mm. in diameter. The broken surfaces are brownish olive (19″m); the glazed, unbroken surface is iridescent purplish or bluish black. Sample 544*b* differs from sample 544*a* in being coarser. Some lapilli range to 25 mm. Microscopically these cinders are intermediate between pumice and reticulite in structure. Many of the vesicle walls have burst but in many the glass has not completely retracted to form a typical reticulite thread but remains as a partial membrane. (See Plate 9*D*.) The grain specific gravity of glass from these cinders was determined as 2.562.

No. 546 Reticulite from surface bed three-fourths mile southeast of Volcano Observatory.

This consists of irregularly-rounded masses of glass net work on the outer surface of which is a more or less complete tarnished and iridescent glass skin. Internally the network consists of a three dimensional system of polygonal rings of glass thread. (See Plate 9*E*.) A mass of reticulite was carefully squared by dressing with a hacksaw blade and the sides measured. The 25.57 cubic centimeters weighed 1.095 grams, the fragment thus having a gross specific gravity of .0428 and weighing less than 3 pounds per cubic foot. The porosity is about 98 per cent.

The glass is clear, isotropic, and light yellow in color, practically without vesicles or microlites. Each ring corresponds to the periphery of the surface of contact of two bubbles in an expanding pumice. Each angle of a polygon is a point where another thread branches off as part of the perimeter of another ring. The threads may be conceived as having the shape which would be assumed by a complete system of interstitial material in a close-packed mass of sub-equal, spherical grains in which close packing and mutual flattening had proceeded so far as to restrict the spaces between grains to the triangular tubes between three adjacent grains and to the corresponding solid angle junctions where these meet.

The cross-sections of the threads are beautifully triangular, the sides of the triangles being concave and the angles thereby exceedingly sharp and attenuate. The solid angles consist of gracefully curved junctions of the threads to form jack-stone-like masses. The thicker parts of threads are 1/50 mm. across, the whole triangular section about 1/20 mm. across. The diameters of the polygonal rings range from .25 to 2.00 mm. The form of this material suggests an explosive expansion of foaming lava particles to the point where the thin walls of vesicles burst and allowed the material to retract into the thread lattice. At this juncture solidification was so rapid as to prevent the forming of a rounded thread but preserved the attenuate and momentary triangular cross-section. In places the thin walls of vesicles are intact or are only partly withdrawn into the triangular threads.

No. 550 Gray tuff from near base of section on Halemaumau road west of Keanakakoi Crater.

This is a medium fine-grained, rather compact rock composed of gray grains with much calcareous cement in coarser parts. The color of the finer parts is gray olive (21''''b), other parts approach 59''''b. The specific gravity of the grains is 2.510, that of the rock, 1.86, and the porosity, 25.9 per cent. In thin section this rock consists of glass, palagonite, olivine and feldspar grains, mostly 0.02 to 0.2 mm. in diameter. Much of the material is probably of accessory origin.

No. 552*a* Basal green sandy ash from section three-fourths mile southwest of Keanakakoi Crater.

The hand specimen is a thin-bedded rock (2-4 mm.) in which the finer-grained layers are yellow-green; the coarser are dark green (21''' and 21'''m). The rock is only moderately cemented, and somewhat crumbly. The gross specific gravity is 1.400. In thin section the rock shows clear green (25'h) glass, boldly vesicular, with grains up to 1.5 mm., broken to shards and other ideal glass shapes. There are very few microlites in the glass, and a few olivines. No alteration is apparent. Small amounts of secondary calcite are found in some of the vesicles. (See Plate 9*F*.)

No. 571 Accretionary lapilli (pisolites) from Kau Desert three miles southwest of Halemaumau.

These are lavender gray (21''''d) pellets 5 to 10 mm. in diameter. They consist of fine-grained material on outside and progressively somewhat coarser material on inside. The shapes are nearly spherical, some are slightly flattened, and they carry small protuberant points apparently resulting from the accretion of small pellets of dust. Plate 10*A* shows a section of an accretionary lapillus about 12 mm. in diameter. In the central portions it consists of angular fragments mostly from 1/32 to ¼ mm. across. The outer part, a millimeter thick, consists of much finer material (.002 to .02 mm.) in concentric layers. The bulk of the fragments are of crystalline lithic material, feldspar, olivine, and the like. A few larger glass and palagonite fragments are present.

No. 1579*b* Volcanic detritus from 1924 eruption collected near the Volcano Observatory.

Megascopically this is a varicolored, coarse, angular sand. The mechanical composition is 16.2% plus 2, 45.4% plus 1, 29.6% plus ½, 7.2% plus ¼, and 1.6% plus ⅛ mm. grains. The coarser grades consist of rough, angular red and black basalt fragments with a few olivine grains. Finer grades show more glass in smoother grains, olivine, and considerable feldspar and short segments of Pele's hair.

The following additional specimens were collected:

No. 508*a* Gray ash from bed apparently mantled down over pali one mile north of Halfway House on Peter Lee Road.

No. 549 Lapilli and dust from one-half mile northeast of Keanakakoi Crater.

No. 551 Sandy green ash from base of section a few yards southwest of Keanakakoi Crater.

No. 522*b* Basal green sandy ash from the section three-fourths mile southwest of Keanakakoi Crater.

No. 2356 Accessory dust from 1924 Kilauea eruption.

No. 2357 Lapilli and dust from 1924 Kilauea eruption.

No. 2358 Accessory "sandy" ash from 1924 Kilauea eruption.
No. 2359 Accessory "sandy" ash from 1924 Kilauea eruption.

Kilauea Littoral Cone Materials

General features. So far as known all littoral pyroclastic formations consist of fairly dense, only moderately vesicular glass grains ranging to fine-grained basalt in the coarser grades. In addition to the specimen described below see descriptions of beach sands.

DESCRIPTION OF SPECIMEN

No. 619 Ash from littoral cone at Kehena, five miles northeast of Kalapana.

This ash consists of angular, poorly-sorted black basalt and glass fragments. The mechanical composition is 9.2% plus 4, 14.2% plus 2, 26.4% plus 1, 19.2% plus ½, 16.7% plus ¼, 7.0% plus ⅛, 3.1% plus $\frac{1}{16}$, 2.1% plus 1/32, 1.4% plus 1/64, 7% minus 1/64 mm grains. The fractions show: (plus 4) angular fragments of fine-grained vesicular basalt with glassy exterior; (plus 2, plus 1) increasingly glassy fragments; (plus ½, plus ¼, plus ⅛) similar to above, more brown glass; (plus $\frac{1}{16}$, minus $\frac{1}{16}$) similar to above, possibly 1% of feldspar, all very angular.

Mauna Loa Littoral Cone Materials

General features. Several types of material are included in this series. At Kalae a fine-grained black ash is found in thin layers a few inches below the surface of the ground. Whether this has been derived from a littoral eruption along the coast to the northeast or from Kilauea is not known, though the former explanation seems more plausible. A littoral cone, Puu Lohena, west of the fault scarp at Kalae is composed of gray-green vitric tuff and Puu Hou, farther west, is composed more largely of lithic, coarser ejecta.

The dissected littoral cone at Puu o Mahana, the formation of which antedates at least a part of the Pahala tuff, is composed of poorly-assorted gray agglomerate overlain by green, vitric ash and tuff. A similar tuff (Nos. 122*a* and 123) whose exact source is unknown is described here because of its similarity to some of the nearby littoral tuffs and the lack of any other near relatives.

DESCRIPTION OF SPECIMENS

No. 51*a* Gray-green, partially-cemented ash from low cone at Puu Lohena northwest of Kalae lighthouse.

This is a porous, greenish-black rock made up of angular grains of basaltic glass. In thin section it shows a very porous mass of green glass fragments in which are imbedded large olivine crystals and smaller magnetite grains. Very slight alteration is shown. A Rosiwal analysis showed 43.5% pore space, 34% glass, 21.8% olivine and 0.7% magnetite. The glass color is olive-green (23‴). The fragments are 1 to 2 millimeters across. Vesicles are 0.05 to 0.25 mm. in diameter and circular. They show shard shapes with cuspate, re-entrant margins, in part bounded by large adherent olivine crystals. The glass is perfectly isotropic and contains numerous small microlites. Olivine occurs as large, clear, unaltered, euhedral crystals, ranging mostly from 0.08 to 1.0 mm. in diameter. It carries inclusions of magnetite and glass. The magnetite grains range in size from .25 to less than .003 mm. Shapes are both irregular and euhedral. Most of the magnetite is in the glass but it is not uncommon in the olivine. Numerous clear microlites .005 to .05 mm. are found in all the glass fragments. These are chiefly oligoclase (An25-Ab75). Practically no alteration of the glass is shown. Occasionally grains of deep blue color, high index and showing considerable pleochroism are probably carborundum introduced in the process of grinding the thin section. In places in the section cracks parallel or oblique to its plane are marked by orange dendritic growths which appear to be iron oxide. The width of penetration of the dendrites is commonly .02 or .03 millimeters.

No. 51*b* Altered ash from cone Puu Lohena northwest of Kalae lighthouse.

This rock is similar to 51*a* except for its brownish-purple color. It is a somewhat porous, ferruginous, almost clinkery mass containing megascopic olivines and glass fragments. It appears to have a fairly high specific gravity. The thin section shows a very porous mass of clear, shark-shaped and vesicular glass fragments containing large olivine crystals and showing marginal alteration. Numerous short lath-shaped feldspar microlites are included in the glass. Euhedral magnetite grains are common. Vesicles are 0.05 to 0.3 mm. across. The glass is mostly quite fresh internally and of yellow-green (27″d) color. Olivine crystals range up to 2 millimeters in diameter. In places they show a marginal alteration which consists of a progressive invasion by iron oxide. The outer edge is almost opaque, dark brown iron oxide which becomes slightly lighter toward the inside. Extending inward from the inner edge of continuous iron oxide is a root-like system of minute, iron oxide filaments which extend into the clear, unchanged olivine. Some of these filaments are as much as 0.2 mm. in length and mostly are not over 0.002 mm. in diameter. Some olivine grains show a rounding and occasionally the development of a deep re-entrant by corrosion while within the magma. In other grains what appears at first to be a marginal alteration of the olivine proves in reality to be a ferruginous alteration of a thin film of glass which adhered to the olivine crystal as it was expelled from the vent.

Nearly all the margins of the glass fragments carry a uniform light cadmium-yellow band (19) of clear palagonite which is commonly 0.01 to 0.02 mm. wide. The yellow palagonite bands show no true extinction and the only structure exhibited is a minute tangential zoning made apparent by the variable refractive index of the zones which produces a zonal illumination due to the Becke line effect. Considerable parts of the space interstitial to the glass fragments and of space in the marginal vesicles is filled with a ferruginous material. By transmitted light this material is a deep, reddish-brown. In incident light it appears as a cream-colored mass rather uniformly speckled with small ferruginous dots. No anisotropism is visible.

A moderate number of magnetite grains are present, ranging in size from 0.1 mm. down. The majority are chunky, sharply or roughly euhedral and are contained both in the glass and in the olivine. A number of vesicles are filled with a secondary mineral in a mosaic pattern. The mineral is probably calcite. A few cavities and margins of the secondary iron deposits show shreddy, fine-grained masses of anisotropic material of low relief and birefringence which is thought to be a zeolite.

The following additional specimens were collected:

No. 18 Gray ash from thin layer in yellow tuff five feet above base of section at edge of cliff three-fourths mile north of Kalae lighthouse.

No. 19 Impure black ash from point three-fourths mile north of Kalae lighthouse.

No. 99 Red tuff altered from gray tuff by heat from overlying basalt flow. East shore of bay at Puu o Mahana at elevation of 15 feet.

No. 110 Gray-green ashy tuff from Puu o Mahana.

No. 122*a* Vitric tuff from point south of Kaalualu road at 450 feet elevation.

No. 122*b* Buff tuff, same locality as above.

No. 123 Vitric tuff from point south of Kaalualu road at 400 feet.

Derivatives of Pyroclastic Materials

General statement. In the normal course of weathering of basaltic rocks the sedimentary products are mostly fine-grained or carried in solution. There is no mineral of this region resistant both to physical and chemical weathering, that plays the important role almost invariably played by quartz in continental regions. Well-sorted, chemically stable fluviatile sands are practically unknown in Hawaii.[41] In a few places in the Hawaiian group, like parts of the north coast of Molokai, where strong wave action makes and remakes coarse boulder beaches at the feet of actively eroded cliffs, there lie adjacent to the boulder beaches, beaches of sand which is largely composed of unweathered fragments of practically all the constituent minerals of the basalt. Such beaches and such sands are quite exceptional and local in their occurrence.

In coastal localities favorable for the growth of marine organisms, beach gravels and sands are not infrequently composed largely of shell debris, fragments of coral, and the like. In other places where a vesicular, olivine-rich basalt fringes the shore, olivine may form conspicuous beaches. Lack of a single dominantly resistant and ubiquitous mineral like quartz paves the way for a sporadic, local dominance of a variety of materials in beaches, in stream deposits and in the material handled by the wind and built into dunes. Pyroclastic eruptions not infrequently furnish materials ready-broken for handling by wind or water and in quantities sufficient to dominate locally the composition of nearby sedimentary accumulations. It is this condition which makes the pyroclastic materials and derived sediments somewhat more conspicuous and significant than they would be in many continental regions.

The sediments described below were chiefly collected from localities where pyroclastic materials were prominent and mostly contain a considerable proportion of constituents of pyroclastic origin, as will be evident from the descriptions.

[41] Wentworth, C. K., Diamond Head Black Ash, Jour. Sed. Petrol., Vol. 7, pp. 97-102, 1937.

DESCRIPTION OF BEACH SEDIMENTS

No. 10*b* Olivine sand from beach one mile east of Kalae.

This sand is composed of coarse olivine fragments flecked with shell debris. The mechanical composition is 1.1% plus 2, 35.6% plus 1, 61.9% plus ½, and 1.4% plus ¼ mm. grains. The separates show: (+2) estimated olivine 50%, shell debris 30% and glass 20%. The grains are thoroughly frosted; (+1) olivine 63%, glass and a few grains of fine basalt 13%, shell debris 24%; (+½) more olivine, less glass and shell debris; (+¼) 90% olivine, rest glass, shell debris and palagonite pellets.

No. 14 Calcareous beach sandstone; a rounded cobble of sandstone from beach east of Kalae lighthouse.

A firmly cemented, granular rock composed of cream-colored grains with subordinate pink grains, dark gray grains, and olivine crystals. A few grains reach 2 millimeters in diameter. In places very small grains of palagonite are included. The thin section shows a granular texture, grains are nearly equidimensional and range from ½ to 1 millimeter in diameter. The grains are barely in contact, in places open-textured. Nearly half of area is gray-olive, calcite cement (21'''') of very fine grain. Phenoclasts are mostly calcareous fragments of foraminifera or other marine shells. Three per cent is olivine crystals; two percent fine-grained, basalt fragments with random-oriented, minute laths of feldspar. The most conspicuous shell form is a transverse section of certain discoid foraminifera in nearly all shells; the calcite shows pronounced radial or tangential orientation of extinction with resulting spherulitic aspect. Numerous shard-shaped cavities show secondary radial growth of calcite crystals extending inward. The grain of the matrix is smaller than 0.002 millimeter and mostly less than 0.0005 millimeter.

No. 77 Olivine beach sand from Kaahua, northeast of Kalae.

This sand is composed of coarse olivine grains with shell debris. The mechanical composition is 3.5%+1, 67%+½, 26.6%+¼, 2.2%+⅛, 0.5%+$\frac{1}{16}$, and 0.2%—$\frac{1}{16}$ mm. grains. The fractions are composed of: (+1) olivine 61%, shell debris 24%, basalt and glass 15%, with grains much battered, some olivines well frosted; (+½) olivine 94%, basalt and glass 4%, shell fragments 2%; (+¼) estimated less shells, more glass than coarser grades, 90% olivine; (+⅛) roughly one-third olivine, one-third glass and one-third palagonite pellets; (+$\frac{1}{16}$) over 90% palagonite pellets with a few clear, organic spicules, (—$\frac{1}{16}$) same as coarser grade.

No. 112 Beach sand from Puu o Mahana.

This is a clean, black and green coarse sand. The mechanical composition is 1.1% of +1, 23.1% of +½, 65.2% of +¼, and 10.6% of +⅛ mm. grains. The composition of the various grades is: (+1) olivine 64%, glass 25%, olivine and glass fragments 6%, shell fragments 5%. Olivine grains range from much rounded to slightly rounded; many are frosted to a matt surface. Some grains show regularly pitted surface, pits 0.05 to 0.1 mm. across and half as deep. Many grains carry included magnetite. The glass fragments irregular, vesicular. Shells are smooth and frosted. (+½) similar to coarser grade, olivines slightly less rounded, euhedral shapes more evident; (+¼) similar to above, more abundant broken and little-abraded olivines, similar proportion shells and glass; (+⅛) similar, except more shells and glass and less olivine. A few feldspar prisms are found in this grade.

No. 617*a* Normal beach sand from Kaimu, near Kalapana.

Megascopically this is a mixture of black, glassy sand grains with a few gray, rounded, basalt pebbles. The mechanical composition is 0.8%+2, 1.7%+1, 36.5%+¢, 60.9%+¼, and 0.1%+⅛ mm. grains. The fractions show: (+2) gray basalt granules; (+1) black, vesicular, abraded glass 78%, gray rounded basalt 21%, shell debris

1%. Protected surfaces of vesicles clear, jet black glass; (+½) glass 99%, shell debris and olivine 1%; (+¼, +⅛) similar to coarser grades; (trace —⅛) palagonite pellets, glass, olivine, feldspar, shell debris.

No. 617*b* Coarse lag sand and pebbles from beach at Kaimu, near Kalapana.

This is a gravel composed of gray basalt pebbles 16 mm. to 2 mm. with a subordinate amount of more angular black glass debris ranging down to ¼ mm. The basalt pebbles are slightly vesicular, well rounded and smooth. The mechanical composition is 7.6%+8, 33.2%+4, 27.9%+2, 18.8%+1, 10.7%+½, 1.8%+¼ mm. grains. The fractions show: (+8, +4) all basalt pebbles; (2) contains 7% glass, remainder basalt; (+1, +½, +¼) progressively larger percentages of glass.

No. 617*c* Black pebbly sand from beach at Kaimu, near Kalapana.

The coarser grains are gray-black, the finer grains jet black. The mechanical composition is 1.9%+8, 7.2%+4, 7.4%+2, 14.0%+1, 27.6%+½, 41.7%+¼, and 0.2%+⅛ mm. grains. The composition of the fractions is as follows: (8, 4) moderately well rounded, smooth pebbles of fine-grained, slightly vesicular basalt; (+2) consists of 76% gray, finely vesicular basalt fragments, somewhat rounded, and 24% black, vesicular glass fragments. The basalt fragments are mostly over 3 mm. in diameter, the glass mostly under; (+1) not over 2 or 3% basalt, remainder vesicular glass grains, some fairly well rounded, mostly angular; (+½) glass grains with 1% or less of olivine and shell fragments; (+¼, +⅛) increasing amounts of olivine and shell debris. (See Plate 10*B*.)

No. 738*b* Pebble of calcareous sandstone from beach one-half mile south of Kailua.

This specimen is a calcareous sandstone, mostly ⅛ to ¼ mm. grains, speckled cream, red black. It consists chiefly of grains of shell debris, black glass, palagonite and olivine named in order of abundance. It is well cemented with calcite.

No. 759 Calcareous rock from coast south of Kawaihae.

This specimen is a fine-grained reddish drab rock, well cemented, with a few small irregular voids. The color is 15″j. Under the microscope it appears as a fine-grained, light yellow and white rock showing much secondary calcite. Larger units are apparently rounded or oval masses of clear colorless glass containing feldspar microlites similar to those of 743*a* and 743*b*. Smaller isotropic, orange-yellow palagonite fragments are present and give the yellow tint to the rock. A few large feldspar phenocrysts are present also.

No. 762 Beach rock near Puako.

This is a hard, conchoidally fracturing rock of fine-grained, structureless appearance. The color is 17‴h. The rock is pitted and cut into lapis on the surface from rain wash.

No. 763 Beach sand from coast south of Puako.

This is a fine-grained red-brown sand. Under the microscope it is seen to be mostly of ¼ mm. grain or finer. Probably 80% or more of these grains are small, rounded palagonite pellets.

No. 813 Black ash sand from beach at Punaluu.

This sample consists of coal-black, coarse, somewhat angular sand, which consists chiefly of black glass fragments. The mechanical composition is 0.7%+2, 92.0%+1, 7.1%+½, and 0.2%+¼ mm. grains. Most grains show some surfaces external to rounded cinders and some broken surfaces. The broken surfaces commonly cut across a coarsely vesicular mass. All the edges are somewhat rounded. The porosity of this littoral ash-sand after moderate jarring was found to be 43.7%. The fractions show:

(+2) glass 98%, gray basalt grains 2%; (+1) similar, mostly glass; a few basalt grains and olivine grains attached to glass: (+½) similar to next coarser grade: (+¼).

The following additional specimens were collected:

No. *27a* Normal beach sand at Kaulani, one mile east of Kalae lighthouse.

No. *27b* Olivine sand concentrate from beach at Kaulani, one mile east of Kalae lighthouse.

No. 51*c* Beach sand from point near Puu Lohena ash cone, northwest of Kalae lighthouse.

No. 56 Gravel from coast at Puu Hou, west of Kalae.

No. 158*a* Beach sand from near south end of Waipio beach. (See No. 158*b*, p. 157.)

No. 192 Beach sand from shore east of Kauhola Point, Kohala.

No. 201 Beach sand from Kawaihae shore west of Puukohola Heiau.

No. 202 Beach sand from 1½ miles south of Kawaihae.

No. 203 Beach sand from near Kawaihae lighthouse.

No. 495 Beach sand from Hoopuloa.

No. 499 Beach sand from Hookena on west coast.

No. 501 Beach sand from Napoopoo.

No. 502 Beach sand from Napoopoo.

No. 602 Beach sand from Keaau.

No. 650*a* Coarse surface beach sand from Keauhou.

No. 650*b* Normal beach sand from Keauhou.

No. 722 Beach sand from beach east of Hilo, on Hilo Bay.

No. 737 Sand from beach at Kailua.

No. 738*a* Beach sand from beach one-half mile south of Kailua.

No. 755 Beach sand from Ohaiula Beach south of Kawaihae.

No. 756 Beach sand from same locality as above.

DESCRIPTION OF FLUVIAL SEDIMENTS

No. 285 Channel sand from pothole in rock at elevation of about 3750 feet in Kemole Gulch.

This is a medium sand of angular, gray particles. The mechanical composition is 1.4%+2, 6.2%+1, 24.5%+½, 47.0%+¼, 16.9%+⅛, 3.5%+$\frac{1}{16}$, 0.5%—$\frac{1}{16}$ mm. grains. The fractions show: (+2) gray, vesicular lithic grains; (+1) chiefly gray lithic grains, with lesser amounts of olivine and glass; (+½) estimated 75% lithic grains, 10% olivine, 10% glass, 5% feldspar; (+¼) similar to above; (+⅛) similar to above.

No. 764 Fluvial sand derived from agglomerate terrane, three miles south of Kawaihae.

This sand consists of both black and brown fragments, all more or less altered augite and olivine. The mechanical composition is 1.9%+2, 11.2%+1, 39.0%+½, 41.7%+¼, 5.2%+⅛, 0.7%+$\frac{1}{16}$, and 0.3%—$\frac{1}{16}$ mm. grains. The fractions consist of: (+2) grains and aggregates of olivine and augite; (+1, +½, +¼, +⅛) olivine and augite nearly equal, partly euhedral; (+$\frac{1}{16}$) possibly a fourth is palagonite in pellets, the rest mostly augite; (—$\frac{1}{16}$) mostly palagonite.

The following additional specimens were collected:

No. 209*b* Gray ash sand from about 2700 feet in Kemole Gulch.

No. 209*c* Finer, gray ash sand from same locality.

DESCRIPTION OF EOLIAN AND TALUS SEDIMENTS

No. 32 Dune sand from point east of road and on 500-foot contour north of Kalae lighthouse.

This sand consists of a poorly-sorted mixture of coarser black grains with finer brown grains, probably palagonite dust.

No. 158*b* Dune sand, 75 yards from the Waipio Beach. (See No. 158*a*, p. 156.)

This is a fine black sand. The mechanical composition is 1.7%+½, 76.4%+¼, 21.4%+⅛, and 0.5%+$\frac{1}{16}$ mm. grains. The coarser grades (+½, +¼) consist of about 90% dark grains of basalt and glass. In the remaining 10%, plagioclase feldspar is dominant. Finer grades are similar but show more mineral fragments.

No. 569 Sand from drifting sand southwest of Kilauea and east of Mauna-iki.

This sample is a fine, black sand. The mechanical composition is 0.6%+¼, 66.0% +⅛, 29.0%+$\frac{1}{16}$, and 4.4%—$\frac{1}{16}$ mm. grains. The fractions show: (+¼) fresh and partly palagonitized glass 78%, olivine 14%, feldspar 8%. About half of the feldspar is a fine aggregate enclosing much magnetite, the remainder is clear; (+⅛, +$\frac{1}{16}$, —$\frac{1}{16}$) relatively more olivine and feldspar.

No. 217*b* Eolian ash sand from northwest of Ahumoa, at 5600 feet, Humuula road. (See No. 217*a*, p.143.)

This sample consists of a dark, red and black sand. The mechanical composition is 0.1%+½, 20.2%+¼, 74.3%+⅛, 5.1%+$\frac{1}{16}$, and 0.3%—$\frac{1}{16}$ mm. grains. The composition of the fractions is as follows: (+½) roughly equal amounts of basalt, glass, shell fragments, and olivine; (+¼) chiefly glass; (+⅛, +$\frac{1}{16}$) similar, with increasing amounts of pellets of palagonite; (—$\frac{1}{16}$) increasing amounts of feldspar.

No. 113 Talus sand from 30-foot elevation on sand slope at Puu o Mahana.

This is a black and green medium sand. The mechanical composition is 0.6%+2, 1.1%+1, 8.9%+½, 67.3%+¼, 20.0%+⅛, 1.3%+$\frac{1}{16}$, and 0.8%—$\frac{1}{16}$ mm. grains. The fractions show: 9 (+1) 75% glass, 23% olivine, with about one or two per cent shell fragments; (+½) similar to coarser grade; (+¼) olivine 75%, glass 12%, shell fragments 7%, palagonite 6%; some grains well frosted, mostly little-abraded; (+⅛) similar composition, with a few feldspar grains.

The following additional specimen was collected:

No. 239 Eolian ash sand from 6000 feet northwest of fence near Puu Maau.

PYROCLASTIC HISTORY AND ORIGIN OF FORMATIONS

Pre-Pahala Time

The history of pyroclastic activity on Hawaii is closely related to the general geologic history. The following discussion is based largely on the work of Jaggar[1] and on a summary published by Stearns and Clark.[2]

It has generally been supposed that of the component domes, the Kohala dome is the most ancient, as suggested by pronounced erosion and deep weathering of those parts of Kohala exposed to abundant rainfall. One other dome, however, not now extensively exposed, appears to be older than Kohala. This is the ancient Ninole dome, now buried under the southwest Mauna Loa rift zone and believed to have been formed around a vent located on the Mauna Loa ridge about eight miles southwest of Mokuaweoweo. This dome is believed to have reached a maximum elevation of about 10,000 feet.[3] According to Stearns and Clark the valleys which were cut in the Ninole dome were deeper than any now cut in the Kohala dome. If Kilauea was less high or did not then exist, rainfall and erosion on the windward slopes of the Ninole dome may have been comparable to that on the Kohala dome. However, since the deep cutting of the Ninole valleys was completed by Pahala time, it is most probable that the Ninole dome had been built, and with the cessation of its volcanic growth, was subjected to erosion at an earlier date than that of the formation of Kohala.

With decline of volcanic activity first at the Ninole center and later at the Kohala center, activity is believed to have shifted to the Mauna Kea center and to have resulted in the building of Mauna Kea. Kilauea is believed to have been next in order of formation and Hualalai probably commenced its growth shortly after. Some time later a new vent became active on the northeast slope of the Ninole dome and on the line of the Loa rift and round it was built the great dome of modern Mauna Loa with Mokuaweoweo at its summit. Stearns and Clark have summarized this history as follows:[4]

(1) Formation of two major rift systems;

(2) Development of Kea and Loa Ridges over these rifts;

(3) Growth of Ninole land mass on the Loa Ridge;

(4) Growth of Kohala cone on the Kea Ridge;

(5) Shifting of vigorous activity to the intersection of Kea and Loa rifts with the subsequent erosion and faulting on the two ridges;

1 Jaggar, T. A., Seismometric Investigation of Hawaiian Lava Column, Seismological Society of America Bulletin, Vol. 10, pp. 155-275, 1920.

2 Stearns, H. T., and Clark, W. O., Op. cit., pp. 101-107, 1930.

3 Stearns, H. T., and Clark, W. O., Op. cit., p. 102, 1930.

4 Stearns, H. T., and Clark, W. O., Op. cit., p. 104, 1930.

(6) Arrival at its prime and then decadence of Mauna Kea;
(7) Birth of Kilauea on Kea Ridge at point of intersection of Loa faults;
(8) Birth of Hualalai at or about the same time as Kilauea;
(9) Renewed activity on southwest rift of Loa Ridge below 7000 feet;
(10) Birth of Mokuaweoweo vent;
(11) Decadence of Hualalai;
(12) Maturity of Mokuaweoweo and Kilauea.

The earliest known pyroclastic event is the emplacement of the Ninole tuff. This tuff occurs over many square miles with subequal thicknesses. It is not part of a central cone but is a mantle of far-drifted, fine-grained, palagonitic debris. The nature of other such tuffs on Hawaii, as well as the variable interbedding of the Ninole tuff with the Ninole lavas, indicate that it is the product of many distinct explosive eruptions. According to the above history only two possible centers could have furnished the ash, the Ninole center or the Kohala center.

As suggested above, the Kohala dome is probably considerably younger than the Ninole dome. If pyroclastic activity in the Kohala area was confined to the closing stages when the summit configuration of cones now exposed was formed, it seems unlikely that this activity could have been early enough to have furnished the material of tuff beds buried deeply under Ninole lavas. Though not entirely evident, the derivation of the Ninole tuff from summit craters on the Ninole dome seems more likely than any alternative interpretation we can now offer.

It is believed that the next pyroclastic activity on the island was that of the summit cinder cones of Kohala. There are upwards of fifty of these cones, and, in view of the probable slower rate of expulsion of magmatic material during pyroclastic than during effusive episodes, it seems probable that this pyroclastic activity may have included a span of not less than a thousand, perhaps three or four thousand, years. It is quite possible that this activity did not closely follow the completion of the lava dome of Kohala but may have followed much later and been in part contemporaneous with events described below.

If a yellow tuff formation, formed from the widespread finer products of the Kohala explosive eruptions, exists, it must be largely buried beneath late lavas or under the sea. If any remnants are still accessible, they have not yet been discovered. The nature of the material in the central cones suggests that such a formation must once have existed.

The Pahala Problem

The most important single problem of the pyroclastic history of Hawaii is the determination of the origin and source of the Pahala tuff in its several localities and its possible relation to the Waiau formation. The former has long been known and there has been much speculation concerning its source and mode of origin. The latter has received practically no mention in the literature and its extent and character are here first described. The nature, origin and source of the latter are comparatively clear, and will be summarized here prior to discussing the problem of the Pahala tuff.

The Waiau Formation

For convenience of description the Waiau formation was considered under two heads, the central cone phase and the yellow tuff phase. The two were formed in the same series of eruption and represent the central and peripheral parts of a single unit. They grade into one another in the zone just outside the area of abundant cinder cones. The yellow tuff phase occurs chiefly to the east, north and northwest of the Mauna Kea summit which was its source. On the west, south and southwest, it is buried beneath later Mauna Loa lavas, and hence, its more distant phases in these directions are hidden from view. In some places, the Waiau yellow tuff is massive and without banding; more commonly it is divided into bands one to four inches thick, which appear to represent successive ash falls. In several places on the north and northwest flanks of Mauna Kea, an old, red or yellow, massive tuff is found underneath either Mauna Loa lava flows, or the more usual banded Waiau tuff. This basal tuff more closely resembles the Pahala tuff than much of the banded tuff, but there is too much variation in both formations to attach great significance to the close resemblance shown by an older and more deeply buried and hence naturally more compact and less clearly banded tuff at a few localities. There is also, at a single locality near Nahonaohaeiki northwest of Mauna Kea, a basal lavender tuff which is quite similar to the characteristic basal lavender tuff of several localities at Kalae. That the main body of Waiau yellow tuff, as well as the black ash, cinders and coarser ejecta of the scores of cones in the summit region of Mauna Kea, is a product of the long series of explosive eruptions which dominated the close of Mauna Kea activity, seems clear.

To one who has seen the great variation which exists in the yellow tuff from place to place and the common dependence of the clarity of banding on the mode of weathering and character of the exposure, it is not difficult to conceive the massive red and yellow tuff of Kemole, Kamakoa, and Popoo Gulches as merely a variant of the Waiau formation. It is true that in Kemole and Kamakoa Gulches the basal red and yellow tuff is overlain unconformably by gray ash beds and by alluvial tuffaceous derivatives, but it should be recalled that the entire Kemole and Kamakoa series, undoubtedly a part of the central cone phase of the Waiau formation, was derived from a cone quite near to the contacts in question and was deposited in association with rains and unusual torrential stream action. Under such conditions and allowing also for some hundreds, if not thousands, of years, which the Waiau epoch probably spanned, it is not at all strange that pronounced channel cutting should separate the red basal tuff from the younger gray tuff from the nearby Kemole cone. It is possible that the resemblance between the basal tuff and the Pahala tuff, together with the unconformity mentioned, are indications that the red tuff is a correlative of the Pahala tuff, and not of the Waiau tuff, but the evidences mentioned seem to the writer to fall far short of proving such a correlation and he considers the red tuff more likely to be a part of the Waiau formation as defined in an earlier section.

The Pahala Formation

The Pahala tuff consists of all those tuff members included in the Pahala lava flows as defined by Stearns and Clark.[5] The Pahala formation includes all lava flows (in the Mauna Loa and Kilauea domes) which are unconformable on the Ninole basalt and which were extruded before the formation of the topmost ash bed. It is evident that neither the definition of the Pahala tuff nor that of the Pahala formation as given are definite, since each refers to the other. The Kamehame formation of Stearns and Clark, which overlies the Pahala formation is defined by them as consisting of the lava beds which overlie the topmost Pahala ash member. Wherever the upper Pahala ash member is present and can be identified, it is a satisfactory horizon marker and a means of separating the Pahala from the Kamehame formation. Since there must be large areas where the ash is not present and where the two series have not been distinguished, this is not an entirely satisfactory criterion. It is not known whether the final pyroclastic episode of Pahala time is in any way related to tectonic or major volcanic changes which give real discrimination between the Pahala and Kamehame lavas. However, in the greater part of the area in which the Pahala and Kamehame lavas are readily separated, the Pahala tuff is exposed at the surfaces of relatively high fault blocks around which are lower blocks, whose surfaces are buried by Kamehame flows. The only exceptions are cliffs, due also to faulting where both the Pahala and part of the Kamehame basalts are exposed in section, or where the former is now exposed in a cliff over the edge of which Kamehame flows have fallen.

Since some of the thick sections of Pahala tuff which are believed to correspond to the combined thicknesses of ash beds elsewhere interbedded with Pahala lavas occur at the tops of fault blocks, which were not subject to overflow by lava, it appears that part of the faulting must have occurred long before the end of Pahala time. On the other hand, subsequent faulting has exposed those sections of the Pahala where the tuff is interbedded with flows. It does not seem possible to establish a precise date or dates for the faulting. It is quite likely that repeated slips may have occurred and occupied a considerable span of time.

The close petrographic similarity and closely homologous character of the yellow tuff of the Pahala, Kalae, Kilauea, and Kapukapu areas leave little

[5] Stearns, H. T., and Clark, W. O., Op. cit., p. 65, 1930.

doubt as to the identity of the Pahala tuff throughout this region. Moreover, there is very close similarity between the petrography of the Pahala tuff northeast of Kilauea and of the Glenwood tuff east of Kilauea. Both are on the surfaces of older lava terranes (Pahala), which have been surrounded by younger lavas (Kamehame). Any slight differences in present lithologic character, most of which disappear on the complete drying of the Glenwood tuff, are readily explained by the marked increase of rainfall eastward. The Glenwood tuff has therefore been included in the Pahala formation by this writer, as by others.[6]

Relative Ages of the Pahala and Waiau Tuff Formations

The problem now narrows to the determination of the relative age and relations of the Waiau formation and the Pahala tuff and the source of the latter. The Waiau and Pahala tuffs appear to be of essentially the same age. Both are overlain by thin Kamehame flows on the east flank of Mauna Loa, the Pahala tuff in the Glenwood area and the Waiau tuff along the course of the Wailuku River, where the Mauna Loa lavas overlap the older slopes of Mauna Kea with its tuff mantle. At Glenwood it is probable that the Kamehame lavas are not more than a score or two feet thick in the near vicinity of the exposed Pahala tuff. Owing to the discordance in slope between the two cones, it is inevitable that the overlying flows of the invading cone would appear thin at the margin at any stage of advance but the discordance in slope between the Mauna Kea dome and the Mauna Loa dome near Hilo is not great, and it is most probable that the thickness of Kamehame lavas is not great at any point between the exposed Mauna Kea slopes and the Glenwood inlier.

Similar relations exist along the northwestern boundary of Mauna Loa lavas northwest of Humuula and at various points in the Kalae and Kahuku regions. At the first of these regions the Kamehame lavas overlie Waiau tuff; at the second they overlie Pahala tuff. All of the four regions mentioned, with the exception of Glenwood, have been the scene of Kamehame flows within historic time. Thus there appears between the Pahala and Waiau tuffs no basis on which an age distinction can be made.

Origin of the Pahala Formation

A number of views have been held regarding the origin of the Pahala tuff.[7] Suggested sources include Mohokea "caldera,"[8] Mokuaweoweo,[9] Puu o Keo-

[6] Stone, J. B., Op. cit., p. 26, 1926.
[7] Palmer, H. S., Loess at Kalae, Hawaii, Volcano Letter No. 350, Sept. 10, 1931.
[8] Emerson, J. S., Some Characteristics of Kau, A. J. S., 4th Series, Vol. 14, p. 435, 1902.
[9] Hitchcock, C. H., Hawaii and Its Volcanoes, p. 155, 1909.

keo,[10] a line of craters in lower Kau,[11] Mauna Kea,[12] Kilauea.[13] Mohokea is not a true vent; Puu o Keokeo is inadequate in size and not located favorably to have been the source of the Pahala tuff. There is no evidence, in the light of modern studies, of the existence of a line of ash-producing craters in Kau as Baldwin postulated. There is practically no pyroclastic material in the walls of Mokuaweoweo and it is clear that Mauna Loa could not have been the source. It has been suggested that the absence of detrital material in the summit area of Mauna Loa was to be explained by the violence of the supposed explosions which blew all the erupted material to great distances from the vent. This is scarcely plausible, nor does it accord with the clear evidence on Mauna Kea that the eruptions which produced the far-flung Waiau tuff formed the cinder cones at the same time.

In the absence of clear evidence to the contrary, it seems to the writer that we must postulate explosive eruptions of the type which are known to have taken place in the Hawaiian group. These are chiefly three in number; the southeast Oahu type, the Mauna Kea type and the Kilauea 1790 and 1924 types. The first produced a wide, sharp-crested saucer of material mainly fine enough to undergo almost complete palagonitization; the second produced typically a higher cone, with a smaller bowl at the apex, consisting chiefly of coarse ash or cinders, and the third produced comparatively trivial amounts of accessory debris insufficient to build a topographically significant cone. From all these types large amounts of fine material were drifted over areas remote from the vent, but in none was the thickness of ash at remote points more than a very slight fraction of that near the vent.

Stearns refers to Hualalai as a possible source of the Pahala tuff but dismisses it as a source of more than a trivial part of the Pahala tuff on the basis that the Hualalai cones "are chiefly cinder cones."[14] In another place Stearns refers to "true ash cones, differing from cinder cones in that they are the product of great explosions rather than of lava or fire fountains." The present writer recognizes the difference between cones produced by great explosions and those due to lava fountains but does not regard this distinction as a sharp one. There is probably no persistent difference in the medium-grained lapilli produced by the two types of eruption, and study of the Waiau formation has shown that a far-flung "ash" deposit does not necessarily come from an "ash" cone. The pumiceous cinders drifted out of Halemaumau from the lava fountains of the eruption of July, 1929, are indistinguishable from the material of many cinder cones which were produced by lava fountain eruptions. Returning to Hualalai, it is believed that its summit eruptions have produced small amounts of palagonitic ash, now part of the Kona tuff, but its location seems hardly favorable as a source for the Pahala accumulations.

[10] Hitchcock, C. H., Hawaii and Its Volcanoes, p. 148, 1909.

[11] Baldwin, E. D., reported by Hitchcock, C. H., (9) above, pp. 169-171, 1909.

[12] Stone, J. B., The Products and Structure of Kilauea, Bishop Museum Bulletin 33, pp. 26-27, 1926.

[13] Stone, J. B., Op. cit., p. 27, 1926.

[14] Stearns, H. T., and Clark, W. O., Op. cit., p. 68, 1930.

The location of the Pahala occurrences chiefly to the leeward of Kilauea, invites serious consideration of Kilauea as the source of the Pahala tuff. The distribution, ranging from the more remote Kalae locality almost continuously to the nearer, single leeward locality at Glenwood, together with the greater thicknesses not far from Kilauea, constitute the chief arguments in favor of Kilauea as the Pahala source. Stone mentions also the Kilauea ash (Keanakakoi formation) as the thickest deposit of ash on Hawaii with the exception of the Pahala ash,[15] and finds in this fact an indication of the "potency of Kilauea as an ash-producer." There are two fallacies in this suggestion. One is that potency as an ash-producer would be indicated by deposits of ash close to the vent. The Mauna Kea pyroclastics show that this is not necessarily the case, since we find at the source, not ash, but cinders and coarser ejecta. The other is that the thickness of ash seen in the vicinity of Kilauea indicates large productivity of fragmental material. Observation on Oahu[16] and Hawaii show that exceedingly large thicknesses of ejected material near the vent corresponds to very small thicknesses of deposited material at moderate distances from the vent. This is shown by the very large aggregate thicknesses in the Mauna Kea central cones as compared with the very slight thicknesses, ten or twenty feet, of the main areas of Waiau yellow tuff. Measurements based on ash thicknesses compiled by Stearns show that the area covered by more than 4 inches of Keanakakoi ash is less than thirty square miles. Moreover the ash at the periphery of this area is chiefly fine dust. This fact, together with regularity of decline of thickness away from Halemaumau, render it quite unthinkable that any large body of ash from the Keanakakoi eruptions, remotely comparable in volume with the Pahala ash, lies outside the thicker accumulations which lies immediately adjacent to Halemaumau. Indeed, the total volume of the Keanakakoi formation has been found to approximate 240 mile-feet and, hence, to be comparable with a single one of the larger cone-forming eruptions on Mauna Kea. So far as we may judge by thickness in the Kilauea area, the same reasoning applies to the Uwehakuna formations, the only two known ash formations of Kilauean origin, are insufficient in amount to carry great weight as inferred proximal correlatives of the widespread Pahala mantle, or even as evidence of the adequate vigor of Kilauea as an ash former. As actual correlatives, both formations are further invalidated by the large proportion of accessory debris they carry. Stone has speculated on the occurrence of a regular sequence of events—pit collapse caused by withdrawal of lava, explosive eruptions, return of lava, overflows —in connection with Kilauean pyroclastic action.[17] Such a sequence seems highly probable for some of the Uwekahuna and Keanakakoi episodes, including those of 1790 and 1924. But such a sequence has no known bearing

[15] Stone, J. B., Op. cit., p. 27, 1926.
[16] Wentworth, C. K., Pyroclastic Geology of Oahu, Bishop Museum Bulletin 30, 1926.
[17] Stone, J. B., Op. cit., p. 52, 1926.

on a magmatic eruption of the type which must have been repeated many times to form the Pahala tuff.

The main body of Pahala tuff shows very little variation in coarseness from place to place. It is interbedded in its upper parts with gray ash and lapilli beds, some of which are probably of Kilauean origin, but much of the section at Glenwood, or at Kapukapu, or Kaone, is not appreciably coarser than the Pahala tuff at Pahala or Kalae. Judging from the distance one must go from the Mauna Kea summit outward to reach a fine-grained, not markedly banded phase of Waiau formation, it is believed that the character of the Pahala tuff at Kapukapu, or Glenwood, or on the Mauna Loa slopes northwest of Kilauea, precludes the possibility of its being derived from Kilauea. Indeed, it is the writer's belief that the comparatively slight textural variation, including lack of banding, which is characteristic of the Pahala tuff, is not only perhaps in part due to the dry climate over much of its distribution, but also the result of its deposition, in most localities, at a much greater distance from its source than the distance at which the Waiau yellow tuff was deposited. This is consistent with the common observation that fine-grained sediments deposited either from air or water are less variable in texture than coarser ones.

If the textural argument be disregarded, it may be postulated in favor of the Kilauean origin of the Pahala tuff that its source cones, similar to those of Mauna Kea, may be buried by lava flows belonging to the Kamehame formation. This, however, does not seem very likely, since the known thickness of the Kamehame, except in the immediate walls of Kilauea, does not exceed 200 feet.[18] This is insufficient to bury any cones comparable to those of any of the important pyroclastic groups of Hawaii. If any such burial has taken place, it must have been of a single great cone in the immediate caldera of Kilauea, where the Kamehame formation is much thicker, or the repeated foundering and reassimilation of a succession of cones on this exact site. Such a history is highly improbable and does not accord with any known in the Hawaiian group.

These difficulties in the way of a Kilauean origin seem to the writer insuperable. More exhaustive field studies or more complete understanding of the pyroclastic process may throw new light on the problem, but in the light of facts now in hand, the writer believes that the Mauna Kea cones were the source not only of the Waiau formation, but of the Pahala tuff as well.

The possibility suggested by Stearns[19] that the Kohala cones may have been a source of part of the Pahala tuff does not now seem probable, the lack of pyroclastic materials in quantity beyond the immediate cones on the Kohala dome itself militating against such an interpretation. The facts favoring the Mauna Kea summit cones as a source of the Pahala tuff, which have been indirectly indicated in the preceding discussion, are listed below:

[18] Stearns, H. T., and Clark, W. O., Op. cit., p. 69, 1930.
[19] Stearns, H. T., and Clark, W. O., Op. cit., p. 68, 1930.

Facts Indicating a Mauna Kea Origin for the Pahala Formation

(1) The homologous and very similar relations of the Waiau and Pahala tuffs beneath the edges of Kamehame lava flows west of Hilo, at Glenwood, in the Pahala and Kalae regions and in Popoo Gulch northwest of Keamuku.

(2) The lithologic similarity of the Hilo and Glenwood exposures of Waiau and Glenwood tuffs in particular and the similarity of lithology and mode of occurrence of the Waiau and Pahala tuffs in general.

(3) The appropriate fineness of grain and lack of banding in the Pahala tuff as befitting the more remote end-member of a series beginning with the cinders of the Mauna Kea cones, and passing through the generally banded Waiau tuff, with its clear transition from the central cone member.

(4) The presence in Popoo Gulch, under Kamehame lavas of a massive red tuff, similar to Pahala tuff and sufficiently remote, remembering its not directly leeward position, to be plausibly representative of the peripheral end-member mentioned above.

(5) The probability that a drier climate may in part also be responsible, together with the remoteness mentioned in (3) above, for the prevailing massiveness of the Pahala tuff as distinguished from the banding of the Waiau tuff.

The foregoing facts, based largely on the writer's field studies, lead him to regard the major parts of the Waiau and Pahala tuffs as one formation, and to believe that the Pahala tuff was derived from the summit eruptions which formed the Mauna Kea cones. To say that the interpretation favored is proven, in the present state of knowledge, would be too dogmatic.

Unfortunately, in the present state of knowledge of the petrography of pyroclastic rocks, the microscopic study of thin sections of these tuffs has not yielded data permitting a definite answer, pro or con, to the question of the equivalence of the Pahala and Waiau tuffs. Both are prominently palagonitic and both originally consisted largely of black glass. A larger amount of lithic material and a greater variety of crystalized products are shown in the Waiau tuff but this diversity and prominence of crystallized material is only to be expected in ejecta coarser in grain and probably nearer on the average to the source.

Likewise, the chemical analyses reported in another section have thrown more light on the composition of palagonitic tuffs in general and the various stages in their alteration from basaltic glass and their breakdown through weathering, than on the genetic likeness or unlikeness of the two main bodies of tuff on Hawaii.

The island of Hawaii is insufficiently large to determine the degree of asymmetry of the finer-grained and more remote parts of the Pahala-Waiau tuff, with reference to Mauna Kea as a postulated source. The Kalae locality is more than sixty miles distant from Mauna Kea in a direction a little west of south; in the opposite direction, the Kukaiau shore is only about eighteen miles away. Moreover, the cover of Mauna Loa lavas on the south and west sides prevents any attempt to trace similar thickness or degrees of coarseness around the Mauna Kea center. The fine-grained, massive, non-laminated yellow tuff of the Pahala-Waiau series at Kalae, Pahala, and Kapukapu on the south side of Hawaii, and the Popoo locality on the northwest slope, are all as remote or more remote from the Mauna Kea center than the bulk of the banded Waiau formation and lie within the leeward semicircular sector with reference to trade winds. They thus accord with the hypothesis of wider dispersal to leeward of the fine-grained products of pyroclastic eruptions.

On the other hand, it has been suggested that trade-wind drift is much feebler, if not at times absent, in the higher atmosphere at the Mauna Kea summit or in the zones to which the finer material from summit eruptions would be thrown.[20] Thus we should not necessarily expect to find the trade-wind type of asymmetry in the distribution of the Mauna Kea ash. The present writer believes that neither the trade wind drift nor any systematic drift of the upper atmosphere can be used in a simple explanation of the distribution of these ash beds. It is thought rather, that since many were involved, taking place at various elevations, with varying violence and height of explosion cloud, and located on different sides of the Mauna Kea dome, the resultant thicknesses of ash would not show a pronounced asymmetry according with any single set of conditions but would more probably show a generalized character, much less asymmetrical than the thickness distribution of many of the individual ash-falls, and approximating a simple circular form. Further, as has been stated elsewhere, the distribution of the finer-grained dust is in larger measure determined by the action of the accidental and kinetic factors which the writer has called "dispersal" (page 28) than by a definite drift. Though this dispersal is itself everywhere superposed on the movement by drift, it is by definition a radially symmetrical process and would tend in some degree to soften and mask a pronounced asymmetry due to any strong directional factor.

For the present we must regard the Pahala and Waiau tuffs as deposited through a long epoch of late Pahala time which we may properly call Waiau time. The total number of cones on Mauna Kea is about 132. Earlier in this report, the total volume in the combined Pahala and Waiau tuffs was estimated at from three to ten cubic miles. The largest Mauna Loa flow of historic time amounted to about two-thirds of a cubic mile. The total output of Mauna Loa within the past century has been estimated by Jaggar as about one cubic mile.[21] If we count one eruption for each cone and with intervals of nine years, the total period would be slightly under 1200 years. If, on the other hand, we estimate by the Mauna Loa output and the larger

[20] Stone, J. B., Op. cit., p. 27, 1926.
[21] Jaggar, T. A., Letter dated March 11, 1933.

of the volume estimates for the pyroclastics, the total period required would be 1000 years. It seems doubtful if the waning activity of Mauna Kea could have been nearly so productive in volume of ejected material as the last century of Mauna Loa activity. A period of five to ten thousand years of fairly steady recurrence of explosive eruptions during the Waiau epoch seems to the writer a much more probable figure and a period several times longer than this would not appear unreasonable.

By way of indicating roughly the most probable geologic age of lava formations in the Kau district, Stearns has listed the Ninole formation as "Tertiary or older" and the Pahala formation as "Pleistocene (?)."[22] The only contribution the writer can make to the problem of geologic age of the Pahala formation is to point out that the glaciation of the Mauna Kea summit area took place, at least in part, after the major cones of the summit area had been formed. On this basis, it is justifiable to assume that most of the Waiau activity took place in pre-Wisconsin time.[23] Some pyroclastic activity has postdated the glacial action, but the details are not yet known.

Post-Pahala Time

All post-Pahala lava formations have been included in the Kamehame formation by Stearns, and Kamehame time has been considered to include "late Pleistocene (?)" and recent time. The remaining pyroclastic events fall in this time division. The lower member of the Kamehame basalt at Kilauea contains the Uwekahuna ash. This is the oldest post-Pahala ash in the Kilauea region. In the remainder of Hawaii, the great cone of Puu Waawaa is the oldest post-Pahala formation. No direct evidence is known to show that Puu Waawaa is younger than the Waiau eruptions, but since it stands on the slope of Hualalai, which has continued activity into historic times and has been considered to be much younger than Mauna Kea, Puu Waawaa may be presumed to be post-Waiau in age.

No means is at hand for determining the relative ages of the Puu Waawaa cone and the Uwekahuna formation. The latter is deeply buried and exposed in section only and has been described first. The Uwekahuna eruptions were similar in character to those of 1790 and 1924. If we may judge from the 1924 eruption, they are evidence of Kilauean activity of a character similar to that of today, the alternate rising and falling of a lava column. Overflow and building of the Kilauea dome took place at the higher stages. At intervening times a lava lake like that which has occupied Halemaumau during most of the historic period rose and fell. At fairly long intervals, extreme withdrawal of the lava column and invasion of adjacent ground-water pro-

22 Stearns, H. T., Op. cit., p. 61, 1930.

23 Daly has suggested that the Mauna Kea eruptions may in part have been phreatic explosions due to water and ice from glaciers. (Jaggar, T. A., Op. cit., pp. 186-187, 1920.) To the present writer this seems unlikely because of the absence or rarity of accessory material in the cones.

duced phreatic explosions like those of 1924, rendered spasmodic by the intermittent collapse of the walls and choking of the vent by the falling debris. Explosions of this type were probably responsible for the great amounts of accessory debris found in the Uwekahuna formation.

The exact nature of the explosive eruptions which yielded mostly juvenile ejecta is not known. Eruptions of the ordinary effusive type, accompanied by much gas and attendant lava fountains, were doubtless responsible for such juvenile material as the reticulite beds and other, slightly less attenuate, cindery material. Even such a small eruption as that of July 1929, confined at the bottom of a 1000-foot pit, produced a thin sprinkling of pumiceous, glassy cinders over the floor of Kilauea adjacent to Halemaumau. No estimate of the thickness of this material was made in the field and it possibly did not amount to so much as one millimeter at the Halemaumau rim. The maximum height of the lava fountain during this eruption did not exceed 300 feet and thus fell short of the Kilauea floor by 700 feet. If such a fountain could place in three days, one millimeter of cinders on the Kilauea floor, it seems by no means unreasonable to suppose that over the entire area of the pit bottom at the level of its base, it may have placed a foot or more of pumiceous cinders. A more vigorous eruption, taking place nearly at the level of the Kilauea floor, might well be capable of placing beds a foot or more in thickness at the distance of the present Uwekahuna bluff.

On the other hand, it seems probable that some of the juvenile material was thrown out in connection with more violent magmatic or phreato-magmatic eruptions in which magmatic material was involved. The fairly thick beds of sandy-textured glass and olivine debris were probably formed by eruptions of this type.

The Puu Waawaa cone was probably formed by several great magmatic eruptions. These took place after the Hualalai dome had reached practically its present size but while the outpouring of the lava flows was still active, since these have surrounded the base of the Puu Waawaa to a considerable depth. The trachytic material of the Waawaa cone is also mantled over the Anahulu terrace and fault scarp and at least part of the eruption took place after the Anahulu faulting, possibly immediately after. The source of the basaltic cinders which lie on the southwest base of the Waawaa cone is unknown.

Three groups of pyroclastic events have been associated with flows of lava in three regions which are still active in historic times. The first group consists of eruptions which have formed the central cinder cones of Hualalai, the rift cones of Mauna Loa, and the Kona ash formation; the second group includes the cone eruptions of eastern Puna and the third has given rise to the Keanakakoi formation. No inland explosive eruption has taken place in historic times in the Puna group.[24] An explosive eruption near the summit

[24] There are native traditions of an eruption at Kapoho Crater in Puna in the 14th century.

of Mauna Loa is known from bombs strewn over summit lavas.[25] The 1790 and 1924 explosive eruptions at Kilauea belonging to the Keanakakoi series are the most recent events of this type.

Each of the three groups has produced a number of cones or a number of distinct beds of pyroclastic materials, and each probably spans a period which can hardly be estimated at less than a thousand years and may be considerably longer. No means is at hand for determining which of these groups of events commenced first.

The eruptions which formed the summit cones of Hualalai and may have formed part of the Kona ash were probably violent magmatic eruptions of the Mauna Kea type. They have produced, however, much smaller amounts of yellow tuff than those attributable to the Waiau eruptions of Mauna Kea. This is partly due to the smaller number of eruptions, but it is probably largely due to the continuance of effusive eruptions, and much of the finer ash is probably buried on the lava-covered slopes of Hualalai. The same is probably true of Mauna Loa, where the summit has not been invaded by cinder cone eruptions and where the effusive eruptions continue in even greater vigor.

Pyroclastic eruptions along the Kilauea rift zone have taken place at intervals through a long period of time. Stearns has reported phreatic explosion eruptions at two points on the Great Crack of the southwest rift zone, which took place in March, 1823. All the ejected material is accessory, with the exception of a few accidental fragments of reef limestone. Stearns concludes that the explosions originated at least 280 feet below the surface, at or below sea level and that the limestone came from a reef buried by the invasion of lava flows. The explosions took place after the lava had withdrawn below sea level following the effusive eruption of 1823 from the Great Crack.[26] A still earlier phreatic eruption at Alae Crater, Puna, is also described by Stearns.

The probable sequence of events in the production of the Kapoho Crater has been listed by Stearns.[27] The first event is considered by him to have been a submarine eruption which probably formed an island off the east point of Hawaii before the present Cape Kumukahi was built. After a considerable erosion interval and the formation of a soil layer 6 to 10 inches thick, there was a new eruption during which four lava fountains played from a fissure in the bottom of the old crater. Cinder beds 5 to 15 feet thick were formed and a small lava flow issued from the northeast jet. Collapse following cessation of the pyro-explosions produced three well-marked pits. Green Lake now occupies one of these depressions.

The series of eruptions which gave rise to the Keanakakoi formation commenced after the epoch of great collapse when the present Kilauea crater was

[25] Jaggar, T. A., Personal communication, 1933.
[26] Stearns, H. T., and Clark, W. O., Op. cit., pp. 143-145, 1930.
[27] Stearns, H. T., and Clark, W. O., Op. cit., pp. 146-148, 1930.

formed,[28] and have continued down to the present time. Like the eruptions which produced the Uwekahuna ash, they have been of two chief types, phreatic explosions producing only accessory ejecta, and magmatic explosions expelling juvenile material. Both types are thought to be associated with, or to follow falling of the lava column or decline in its thermal output. In the phreatic explosions such as that of 1924, the eruptions followed extreme withdrawal of the lava so that great deepening, collapse and engulfment took place. On the other hand, the magmatic explosions probably herald the rush of new volcanic energy after a period of congealing and partial sealing up of previously active vents.

Detailed accounts of the 1790 eruption (pp. 4, 100) and the 1924 eruption have been referred to elsewhere (pp. 97-100). The following table is based largely on the published summaries of Jaggar, Stearns and Clark and others, and to it are added the pyroclastic events recognized in the present study.

Summary of Geologic History of Hawaii

"Tertiary (?) Time"

(1) Formation of two major rift systems.
(2) Development of Kea and Loa ridges over these rifts.
(3) Early growth of Ninole land mass on the Loa ridge.
(4) Pyroclastic eruptions (from Ninole or from unknown source?) and formation of Ninole tuff.
(5) Later growth of Ninole land mass.
(6) Early growth of Kohala dome. (May have been as early as (3) or as late as (8).)
(7) Cessation of volcanic activity on Ninole dome and erosion of deep canyons.
(8) Beginning of faulting on southeast side of Loa ridge.
(9) Decline of growth of Kohala dome and formation of summit cones by pyroclastic action.
(10) Faulting in the Waipio area of Kohala and erosion of deep canyons. (May have been, but probably was not, as early as (7).)

"Pleistocene (?) Time"

(11) Shifting of vigorous activity to the intersection of the Kea and Loa rifts, possibly in connection with events 8, 9, and 10. Formation of Mauna Kea vent.
(12) Growth of the lava dome of Mauna Kea.
(13) Birth of the Kilauea vent.
(14) Birth of the Hualalai vent.

[28] Stone, J. B., Op. cit., p. 51, 1926.

Beginning of Pahala Time

(15) Renewed activity on the southwest rift of the Loa ridge below 7000 feet. Outpouring of lava from these rift vents and from Kilauea.

(16) Commencement of faulting of Pahala series.

(17) Cessation of effusive activity of Mauna Kea and commencement of pyroclastic action, formation of summit cones, and of Pahala-Waiau formation.

(18) Growth of Hualalai continued.

(19) Cessation of Mauna Kea pyroclastic action, additional faulting of Pahala series in Loa and Kilauea domes.

End of Pahala Time and Beginning of Kamehame Time

(20) Birth of Mokuaweoweo vent.

(21) Decline in first active period of building of Kilauea, collapse of lava column and pyroclastic eruptions producing the Uwekahuna formation.

(22) Decadence of Hualalai, feeble activity continues.

(23) Eruption of trachytic material on north flank of Hualalai and formation of Puu Waawaa, with associated faulting.

(24) Continued faulting along Kilauea rift zones and parallel to them, with division of Kilauean activity between the central vent (not yet Halemaumau) and the rift vents.

"Recent and Late Pleistocene (?) Time," "Prehistoric Time"

(25) Commencement of rapid growth of Mauna Loa around the Mokuaweoweo vent.

(26) Succession of great collapses resulting in formation of present Kilauea caldera. Commencement of functioning of Halemaumau and of formation of its dome within Kilauea. Similar collapses and pit formations at various points along the Kilauean rift zones.

(27) Pyroclastic activity at summit of Hualalai and formation of summit cones and the Hualalai component of the Kona tuff.

(28) Pyroclastic activity along Mauna Loa southwest rift zone, formation of cones and (?) contribution of ash to the Mauna Loa component of the Kona tuff.

(29) Beginning of explosive episodes of Kilauea which formed the Keanakakoi formation. (May have been as early as (26).)

(30) Pyroclastic activity along southeast rift zone of Kilauea and formation of cones in Puna. (May have commenced as early as (26).)

"Historic Time"[29]

(31) Complete dormancy (probably are extinct) of Kohala and Mauna Kea.

(32) Continued feeble effusive activity of Hualalai. Recent seismic activity (1929).

(33) Continued lava flows from central and lateral vents on Kilauea with less frequent phreatic explosions due to withdrawal of lava column. Decline of effusive activity and active dome building.

(34) Continued effusive activity at both central and lateral vents of Mauna Loa. Slow building of dome. Existence of well-formed caldera at summit presaging decline of over-flow from central vent.

(35) Continued normal faulting at various points along southern coast from Puna to Kalae.

(36) Continued drifting and resorting by wind of upper layers of yellow dust formation at Kalae and elsewhere.

The events of the 1924 eruption of Kilauea bring the pyroclastic history of Hawaii up to date. Since that date, successive flows of lava have taken place into the deep pit of Halemaumau which was formed at that time. The floor has been built up a total of nearly 600 feet, partly by talus from the walls and partly by lava, reducing the depth of the pit from a maximum of 1335 feet to about 750 feet after the activity of September and October, 1934. It is estimated that in 14 years from 1924 to 1938, about ¼ of the total volume of the pit had been refilled. Many years will probably elapse before the pit is so filled as to be the site of the readily accessible lake of molten lava for which Kilauea was famous before 1924, but the filling is evidently proceeding at an accelerated rate.

29 Summaries of the volcanic and tectonic events which have taken place on Hawaii in historic time have been published by Brigham (Op. cit., pp. 1-222), Dana (Op. cit., pp. 41-123, 180-219), Hitchcock (Op. cit., pp. 56-143, 162-261, 270-280), and Stearns (Op. cit., pp. 70-81, 143-157).

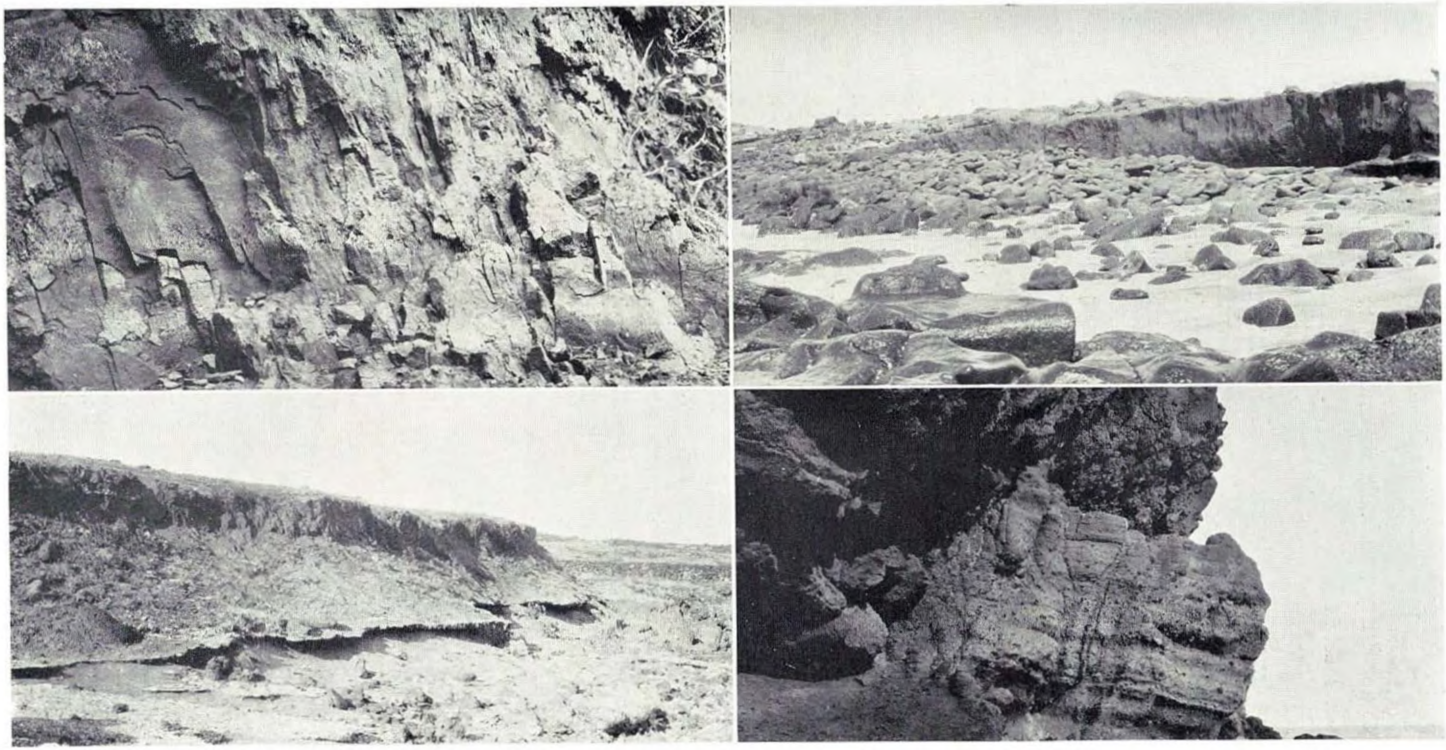


PLATE 1*A* (*upper left*).—Showing structure of Ninole tuff at tunnel entrance, north of Hilea. The tuff is compact, shows a subconchoidal fracture, and is marked by somewhat irregular vertical joints. A short pencil at right shows scale. *B* (*upper right*).—Showing banks of yellow tuff stripped back from surface of lava flows and also various beach features, east of Kalae Point. *C* (*lower left*).—Bank of yellow tuff on coast east of Kalae, showing secondary calcareous crust etched out by wave action. *D* (*lower right*).—Unconformity on east shore of Puu o Mahana bay. In center is small remnant of gray agglomerate. At top and at left is seen the under surface of a driblet flow of basalt which has flowed down the eroded surface of the agglomerate. Originally the sea surrounded the Mahana cone. Now, the larger part of the central cone has been cut away by waves and the shore lies on the side of the mass of gray agglomerate opposite to its former position.

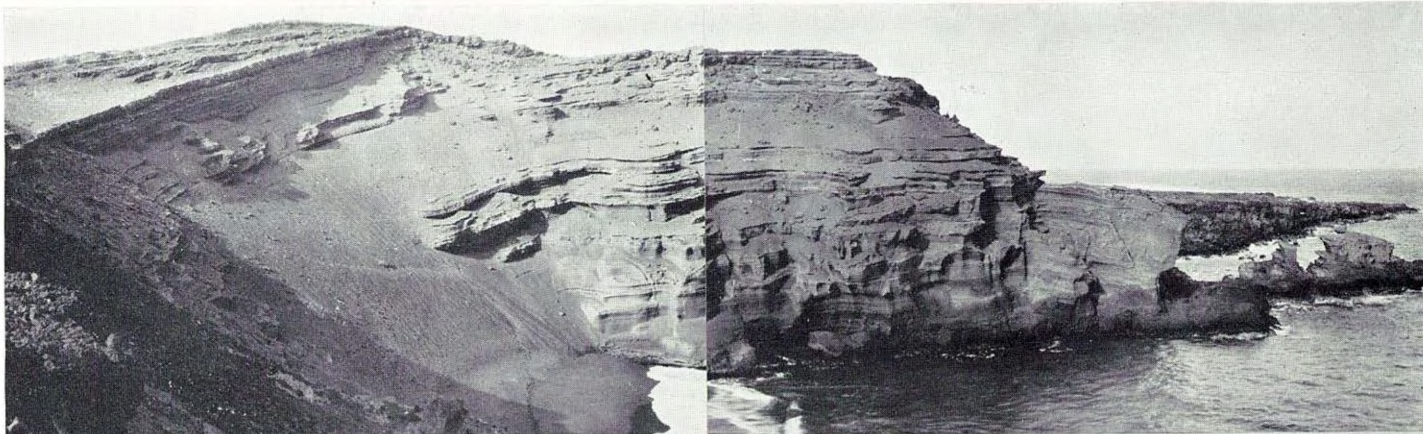


PLATE 24 (*above*).—Panorama of gray tuff beds and features of wave erosion at Puu o Mahana, east of Kalae. At left is smooth talus of gray sand loosened from the tuff by winds and other agencies. The extreme high point and the surface of the coastward slope at the right are mantled with Pahala yellow tuff. *B* (*below*).—Cinder cones near Mauna Kea summit, looking southwest from the northwest slope of Puu Makanaka. Much of the lighter colored material in areas between cones is glacially transported morainic material.

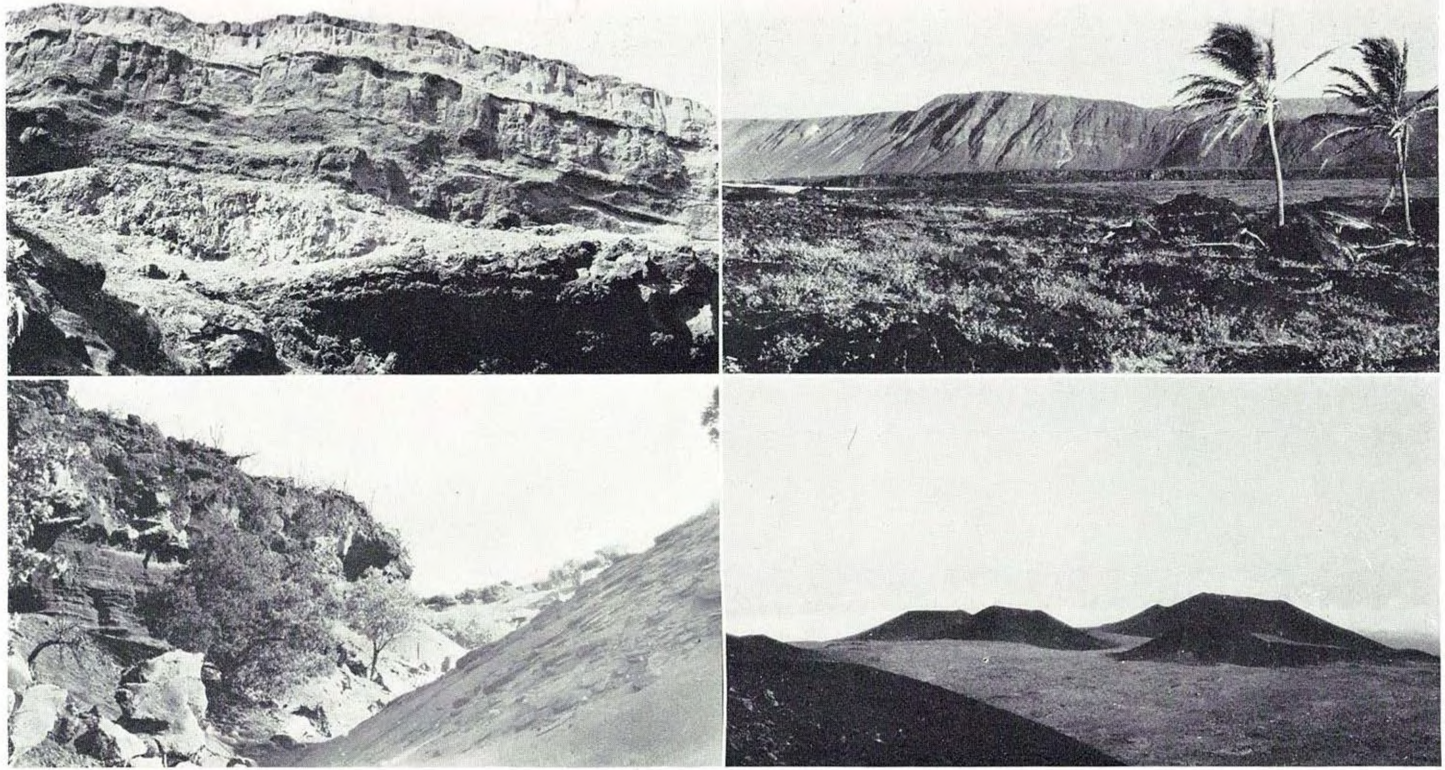


PLATE 3*A* (*upper left*).—Exposure on east side of Puu o Mahana. View looking northeast. At top is 10-foot mass of yellow tuff the upper part of which is possibly eolian. Lens in left center is lavender tuff. Under this at right is basalt flow which in turn lies on talus beds of gray tuff. At lower left is primary gray tuff. *B* (*upper right*).—Seaward face of Puu Kapukapu from Keauhou, in Puna. The cliff is a fault scarp and the post-Pahala lava series which lies in the foreground has been cut by another fault, the scarp of which is plainly seen at the foot of the Kapukapu cliff. *C* (*lower left*).—View southwestward at point north of Hookomo cone on south slope of Mauna Kea, showing ash section on left overlain by flow of aa lava. *D* (*lower right*).—View of summit cinder cones on Mauna Kea from the northeast. The lighter areas surrounding the cones are largely mantled with angular blocks, forming the moraines of former glaciers.

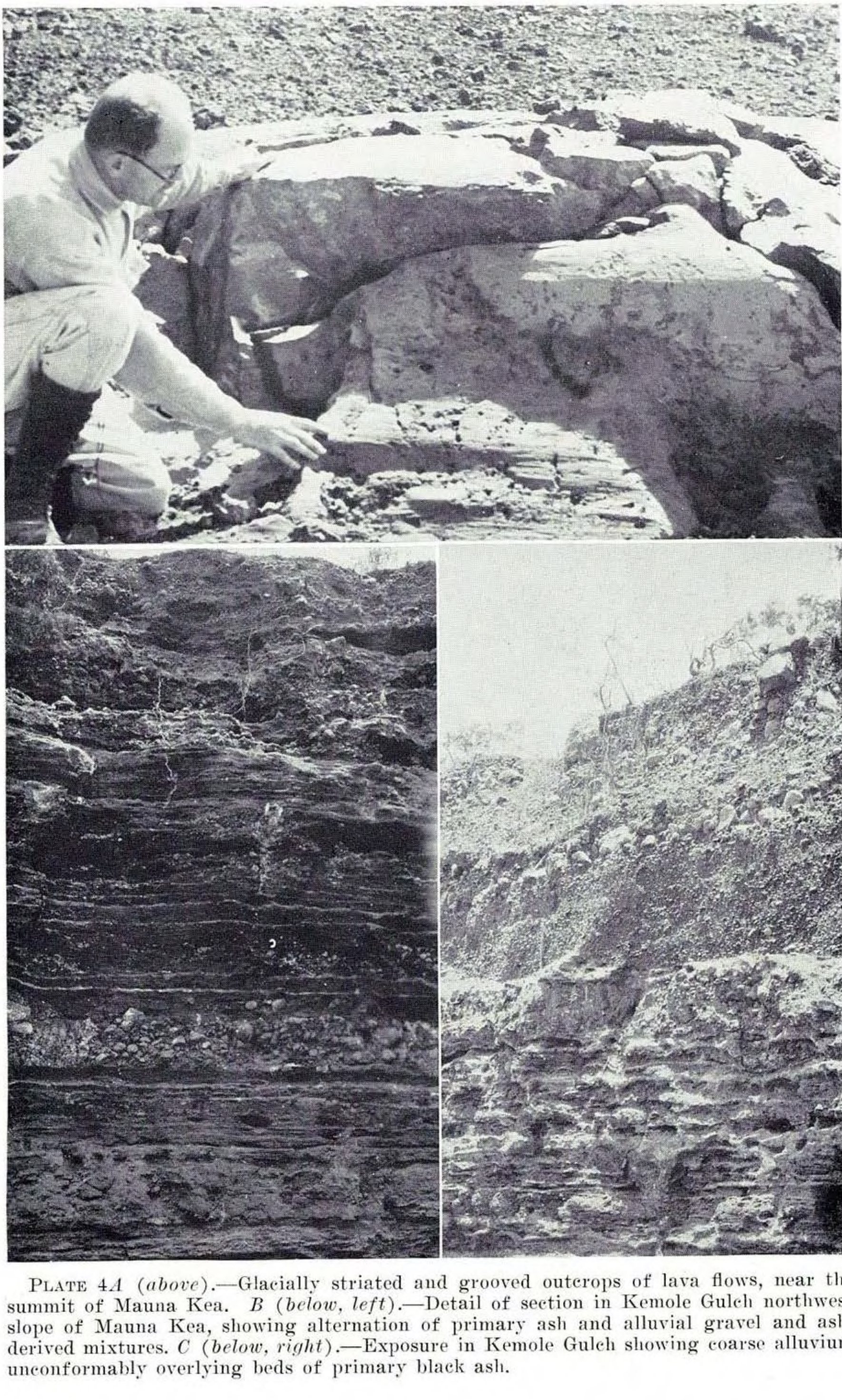


PLATE 4*A* (*above*).—Glacially striated and grooved outcrops of lava flows, near the summit of Mauna Kea. *B* (*below, left*).—Detail of section in Kemole Gulch northwest slope of Mauna Kea, showing alternation of primary ash and alluvial gravel and ash-derived mixtures. *C* (*below, right*).—Exposure in Kemole Gulch showing coarse alluvium unconformably overlying beds of primary black ash.

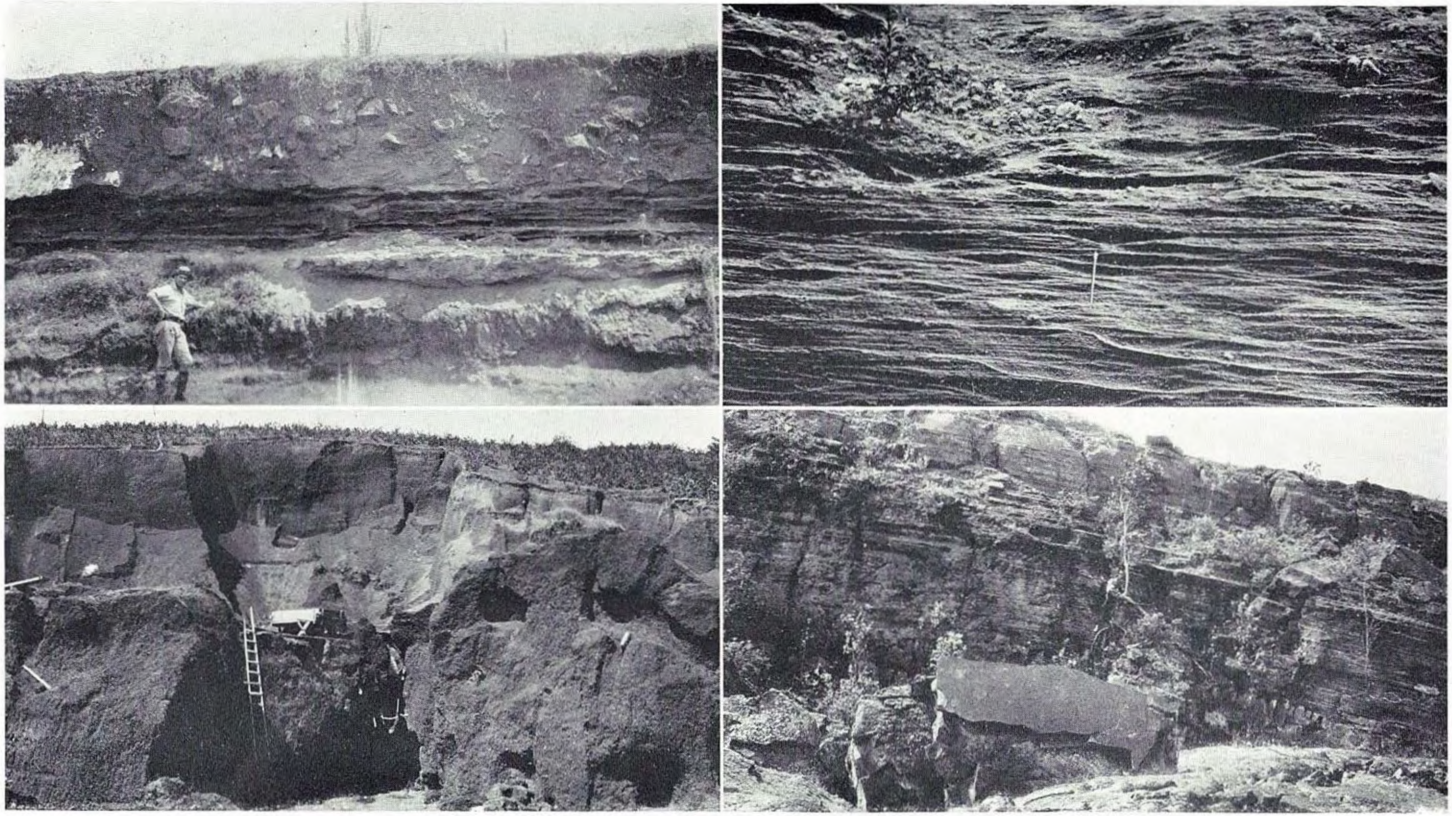


PLATE 5*A* (*upper left*).—Section showing red-brown tuff at base, overlain by primary and alluvial gray ash, and the latter in turn by coarse bouldery alluvium, in Kemole Gulch. *B* (*upper right*).—Detail of current bedding in ash-derived alluvium, Kemole Gulch. *C* (*lower left*).—Commercial cinder pit in Puu Kukae cone, Kapoho. Shows coherence of cinder beds. *D* (*lower right*).—Section of Keanakakoi formation on southeast side of Kilauea crater. The large block in the foreground shows the fairly firmly cemented crust which has been formed at certain horizons and also that the formation is sufficiently coherent to fall in large blocks.

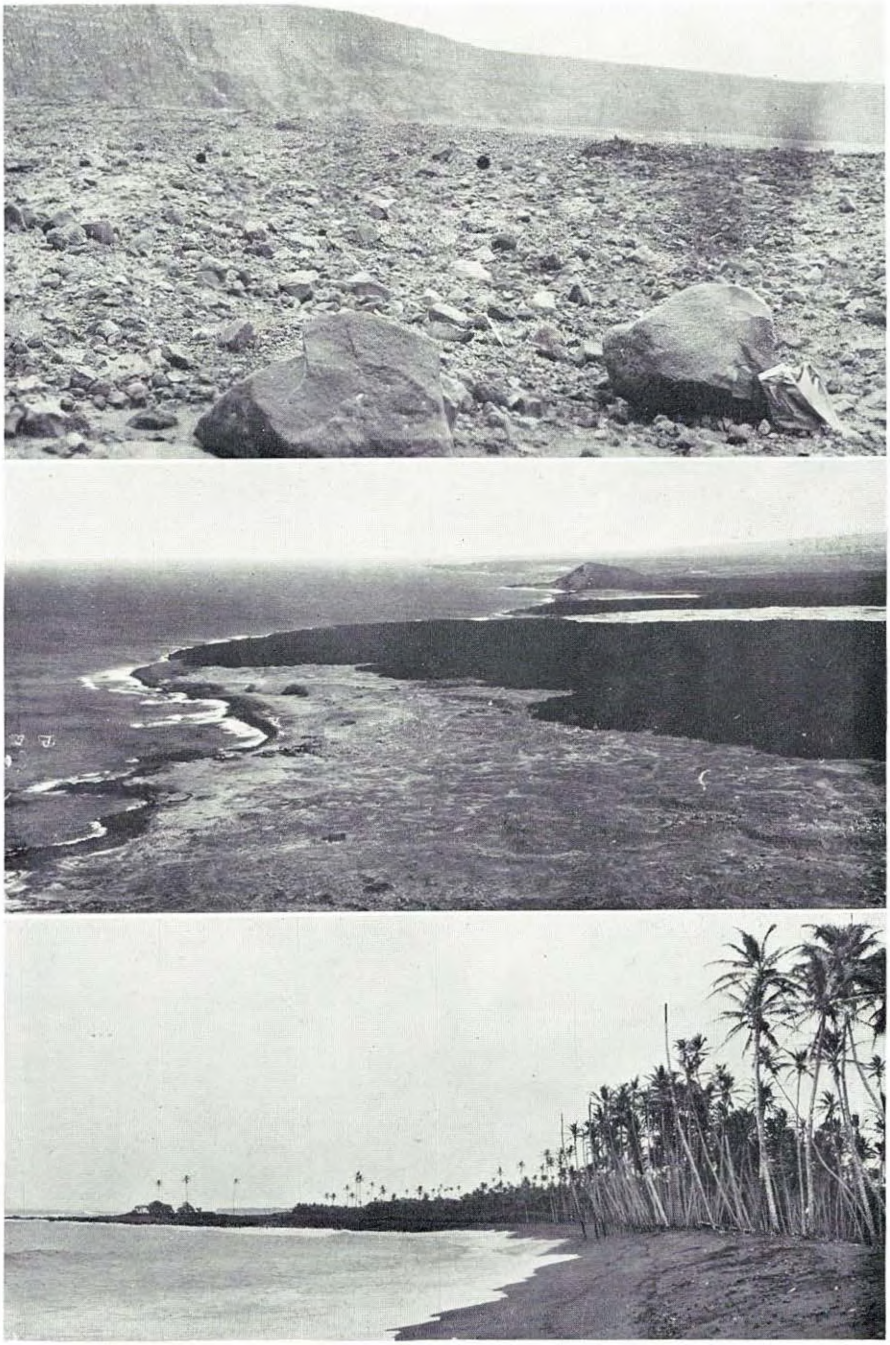


PLATE 6*A* (*top*).—Block strewn surface of Halemaumau dome, west of the Halemaumau pit in Kilauea crater. All this debris was thrown out during the 1924 eruption of Kilauea volcano. *B* (*center*).—View westward from brink of Pali o Kulani south end of Island of Hawaii, toward Puu Hou and showing the several tongues of aa lava formed during the Mauna Loa eruption of 1868. The lighter areas are covered with a small amount of vegetation and show a thin veneer of wind-drifted Pahala tuff. *C* (*bottom*).—Black sand beach at Kaimu. This sand was derived from some littoral pyroclastic cones which are now destroyed.

PLATE 7*A* (*upper left*).—Almond-shaped bomb, viewed from stoss side. Note the smoothing of this side in the more globular, middle section by obscuring of the once continuous pull-ribs or flutings, and the numerous, unbroken pustules. This particular bomb was broken off rather short at both ends. Length is 11½ inches. *B* (*upper right*).—Almond-shaped bomb, viewed from the side, showing stoss surface above and lee surface below. The contrast between the two surfaces is well shown as are also the twisted ends and the overhanging edges along the boundary between the two surfaces. Length is 7 inches. *C* (*left*).—Several small bombs. In the center are four well-formed, almond-shaped bombs. Around the margin are five others, ranging from ribbon bombs to semi-almond-shaped bombs. Length of specimen at the right is 5¼ inches.

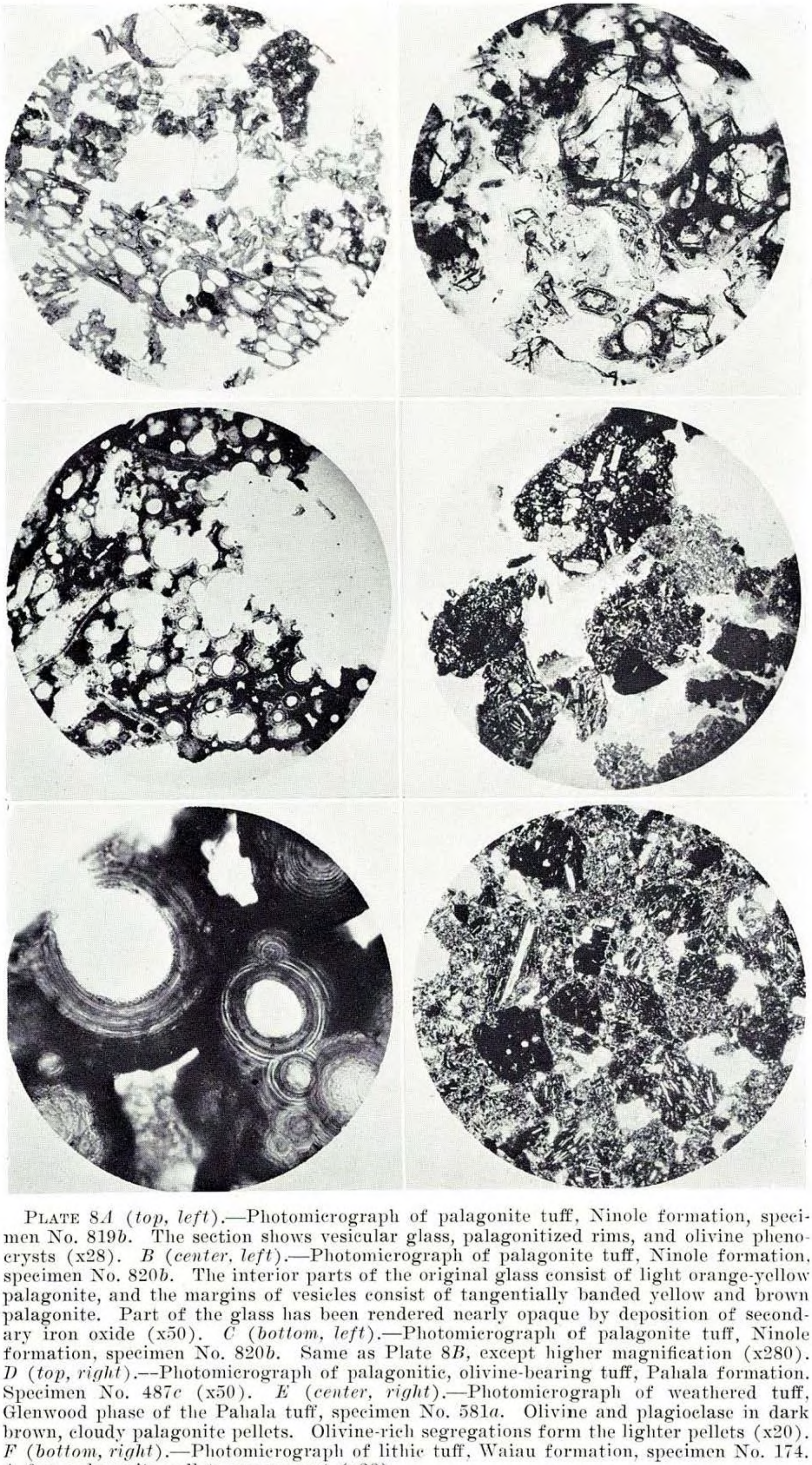


PLATE 8*A* (*top, left*).—Photomicrograph of palagonite tuff, Ninole formation, specimen No. 819*b*. The section shows vesicular glass, palagonitized rims, and olivine phenocrysts (x28). *B* (*center, left*).—Photomicrograph of palagonite tuff, Ninole formation, specimen No. 820*b*. The interior parts of the original glass consist of light orange-yellow palagonite, and the margins of vesicles consist of tangentially banded yellow and brown palagonite. Part of the glass has been rendered nearly opaque by deposition of secondary iron oxide (x50). *C* (*bottom, left*).—Photomicrograph of palagonite tuff, Ninole formation, specimen No. 820*b*. Same as Plate 8*B*, except higher magnification (x280). *D* (*top, right*).—Photomicrograph of palagonitic, olivine-bearing tuff, Pahala formation. Specimen No. 487*c* (x50). *E* (*center, right*).—Photomicrograph of weathered tuff, Glenwood phase of the Pahala tuff, specimen No. 581*a*. Olivine and plagioclase in dark brown, cloudy palagonite pellets. Olivine-rich segregations form the lighter pellets (x20). *F* (*bottom, right*).—Photomicrograph of lithic tuff, Waiau formation, specimen No. 174. A few palagonite pellets are present (x28).

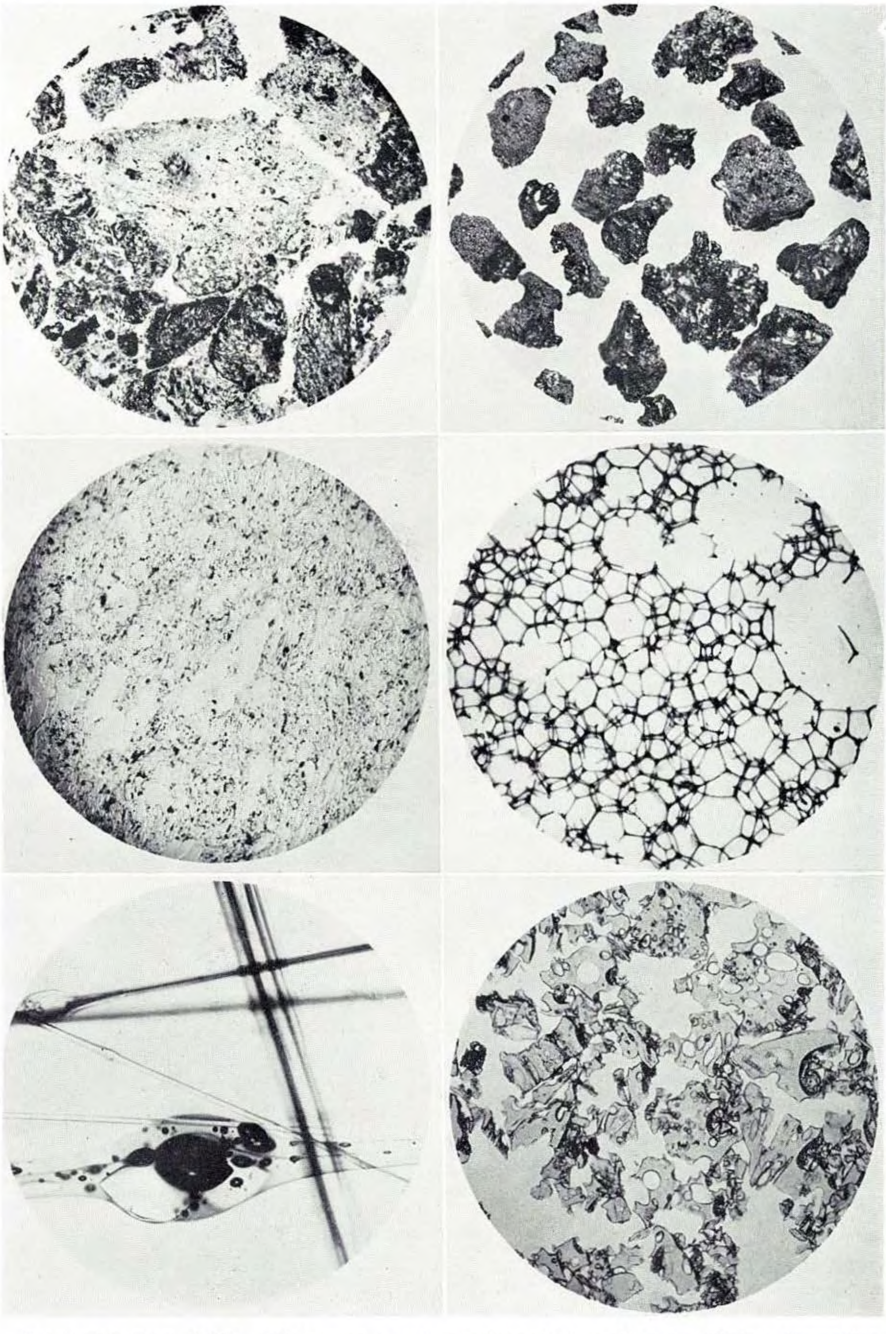
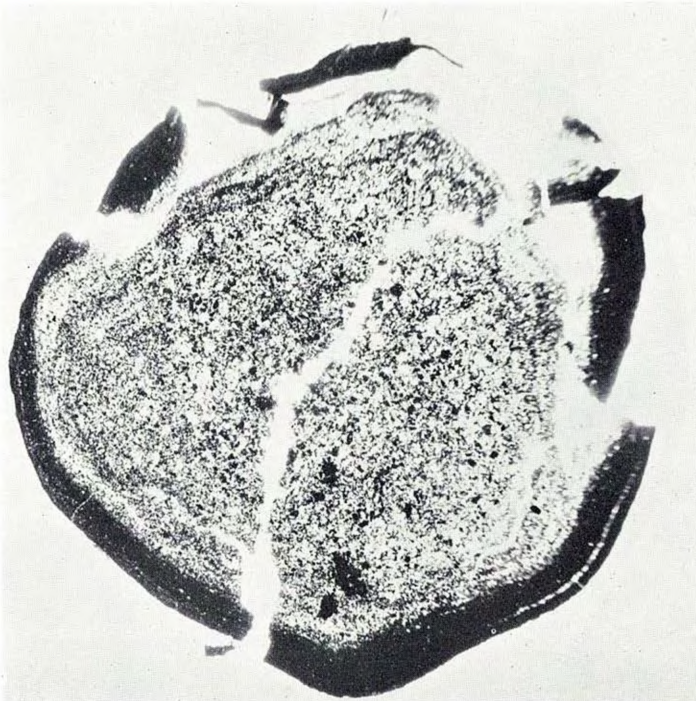


Plate 9*A* (*top, left*).—Photomicrograph of litho-vitric tuff from Waiau formation, specimen No. 242 (x58). *B* (*center, left*).—Photomicrograph of vesicular trachyte glass from Waawaa formation, specimen No. 743*b*. Becke line effect by oblique illumination (x20). *C* (*bottom, left*).—Photomicrograph of Pele's hair, Keanakakoi formation, specimen No. 534 (x50). *D* (*top, right*).—Photomicrograph of pumiceous cinders, July, 1929, member of Keanakakoi formation, specimen No. 544*b*. (x2). *E* (*center, right*).—Photomicrograph of reticulite, Keanakakoi formation, specimen No. 546 (x24). *F* (*bottom, right*).—Photomicrograph of vitric tuff, Keanakakoi formation, specimen No. 522*a* (x24).



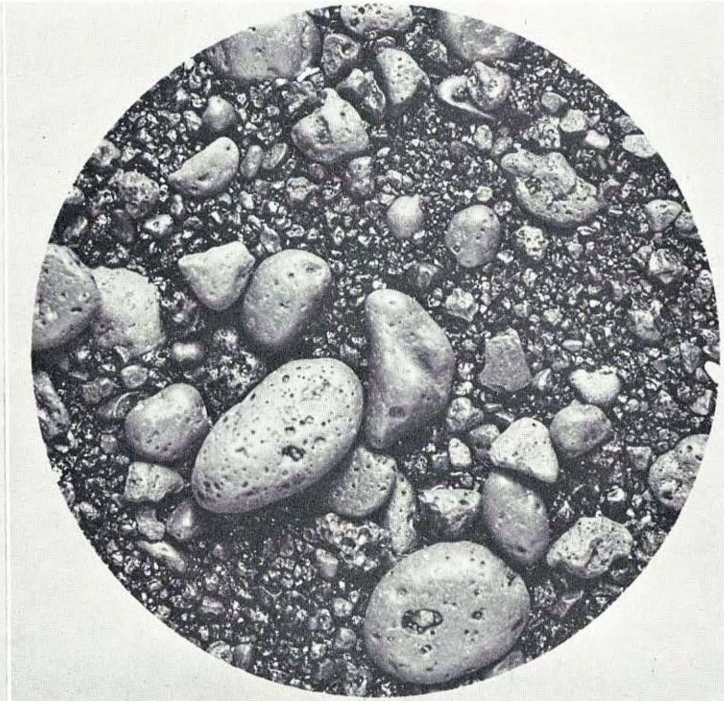


PLATE 10*A* (*left*).—Photomicrograph of section of accretionary lapillus, Keanakakoi formation, specimen No. 571 (x28). *B* (*right*). —Photograph of pebbly sand derived from Kilauea littoral formation, specimen No. 617*c*. The larger gray pebbles are basalt; the smaller black grains are glass (x2).

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