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GEOLOGY AND WATER RESOURCES OF THE KAU DISTRICT, HAWAII

(Including parts of Kilauea and Mauna Loa Volcanoes)

BY

HAROLD T. STEARNS AND WILLIAM O. CLARK

WITH A CHAPTER ON

GROUND WATER IN THE HAWAIIAN ISLANDS

BY

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Prepared in cooperation with the Territory of Hawaii

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By Oscar E. Meinzer

HISTORY OF THE KAU INVESTIGATION

On August 7, 1919, the Hon. Charles J. McCarthy, Governor of the Territory of Hawaii, addressed a letter to the Secretary of the Interior requesting that a geologic survey of the Territory be undertaken with special reference to its ground-water resources and proposing to finance the first unit of this survey with funds provided by C. Brewer & Co. This action was taken on the suggestion and advice of H. E. Gregory, professor of geology in Yale University and Director of the Bernice P. Bishop Museum, and the project was made possible through the influence of such public-spirited men as J. R. Galt, A. Gartley, and A. F. Judd.

Professor Gregory had previously made a visit to the island of Hawaii. With his capacity for grasping large problems and projects in their true perspective, he saw the opportunity presented by the Kau District, on this island, for a detailed geologic and hydrologic survey that would be of great scientific and economic value. Upon his recommendation the Kau District was therefore selected as the first unit area to be covered by a systematic geologic survey with special reference to the ground-water resources. The present is the final report on this survey. It is hoped that this may be the first of a series of areal reports that will describe in detail the geology and water resources of the Hawaiian Islands.

The project was placed under my direction as geologist in charge of the division of ground water in the United States Geological Survey. W. O. Clark and L. F. Noble, geologists in the Geological Survey, were assigned to the project. Mr. Clark was to carry out the complete investigation and to be responsible for the preparation of the water-supply paper. Mr. Noble, whose available time was limited, was selected, because of his experience and ability as a geologist, to spend several weeks in the field at the beginning of the work on the basic problems of the difficult and poorly understood geology of the area.

Messrs. Clark, Noble, and I reached the island of Hawaii early in February, 1920, and spent about three weeks in a reconnaissance of the Kau District. I then left for a reconnaissance of about a month in the islands of Oahu and Maui, after which I returned to the mainland. Mr. Noble devoted about six weeks to a study of the geology of Kau, ending his field work early in April. Soon thereafter he submitted several brief manuscript reports which outlined the geologic results that had been obtained and the problems that required further study. Mr. Clark devoted his time chiefly to detailed study of the high-level ground water and to methods of prospecting for it. He made a preliminary report in March, 1920, which was followed by several other brief unpublished reports on the ground-water conditions. On December 31, 1921, he resigned from the Geological Survey but remained in the Kau District to direct high-level water developments for the sugar plantations in the district.

The reports by Mr. Noble represent a long forward step in the unraveling of the geologic structure and history of the Kau District. In these reports he described the profound erosional and angular unconformity between the older and the younger lavas, concluded that the center of extrusion of the older lavas was located some distance southwest of the present summit crater of Mauna Loa, divided the lava rocks and associated ash beds into the three formations that were later used in mapping the geology of the district, and pointed out the great extent of the radial and peripheral fault systems and their effects on the structure and topography of the region. All these basic facts and concepts of the geology of the region were essentially developed in the present investigation. Early in the field work it was recognized that the extensive alluvial deposits mentioned by Dutton do not exist,[1] that there is no satisfactory evidence of elevated sea terraces in Kau, as Dutton had supposed,[2] and that the "Mohokea caldera," described by Hitchcock, should be differently interpreted.[3]

When the report by Whitman Cross on the lavas of the Hawaiian Islands was published, in 1915, it was still believed that no deep canyons had been cut into the mass of Mauna Loa and that probably the oldest lavas visible were those exposed in the walls of Mokuaweoweo, the summit caldera.[4] In the present investigation it soon

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[1] Mr. T. A. Jaggar suggests (1926) that future work on the ash member at the top of the formation here called Pahala basalt may link parts of it with the past glacial history of the island of Hawaii. Detailed interpretation of the stratigraphy in relation to other islands of the group is not possible until all are geologically mapped.

[2] Dutton, C. E., Hawaiian volcanoes: U. S. Geol. Survey Fourth Ann. Rept., pp. 97–98, 1884.

[3] Hitchcock, C. H., Mohokea caldera (Hawaii): Geol. Soc. America Bull., vol. 17, pp. 485–496, 1906.

[4] Cross, Whitman, Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, p. 38, 1915.

became evident that a very extensive geologic section representing a long period is exposed on Mauna Loa, affording a hitherto unrealized opportunity to study the petrography of the rocks that make up this volcano. Moreover, it was hoped that distinct petrographic differences would be found which would serve to identify the rocks of different ages. A considerable number of rock samples were collected by Mr. Noble, and later an additional collection was made by Mr. Clark. Mr. Cross manifested much interest in these collections and made petrographic examinations and descriptions of them.

Owing to the resignation of Mr. Clark the investigation was interrupted when little detailed work had been accomplished except on the occurrence of the high-level water. H. T. Stearns was assigned to carry on the investigation, including the detailed geologic mapping of the district, and to prepare a final report for publication as a water-supply paper. Mr. Stearns brought to this work three years of experience in the investigation of ground water in the lava rocks of the Snake River Plains in Idaho. He reached the Kau District in May, 1924, and carried on field work, with some office work, until November 20. Mr. Stearns's salary and traveling expenses were paid by the United States Geological Survey, but the field work was greatly expedited through the generous cooperation of Mr. James Campsie, manager of the Pahala plantation, Mr. William Campsie, manager of the Hutchinson plantation, and others mentioned by Mr. Stearns on page 34. Mr. Stearns returned to Washington by way of the Orient in order to visit the volcanic areas of Japan, Chosen, the Philippine Islands, Java, and Italy. This trip added greatly to his understanding of volcanic processes. The present report was submitted by Messrs. Stearns and Clark in February, 1926.

When the first work was done on this project no adequate base map was available. In 1920, however, topographic mapping of the Kau District was begun by the Geological Survey through financial cooperation by the Territory of Hawaii. Consequently, accurate 10-foot contour maps of most of the district, on the scale of 1:31,680, were available for Mr. Stearns's field work and were used by him in mapping the geology. The field data of the topographers under A. O. Burkland were of exceptional value in preparing the way for the geologic mapping of this rough country, parts of which are almost inaccessible.

Acknowledgment should especially be made of the helpful cooperation of T. A. Jaggar, Director of the Hawaiian Volcano Observatory, which has since been made a part of the United States Geological Survey. The scientific work of this observatory, as reported in numerous published papers (p. 38) furnished a cornerstone, as it were, for the present investigation.

UTILIZATION OF WATER IN THE HAWAIIAN ISLANDS

In the Hawaiian Islands water is needed for domestic and public supplies, irrigation, fluming sugar cane, and watering livestock. One of the most essential supplies is the public supply for the city of Honolulu, to which a large amount of investigation and discussion has been given for many years. The water supplies for the naval and military establishments have also presented many problems. Some of the smaller communities are situated where water is extremely scarce and the supply from even an insignificant seep is highly prized. In a few places, as at the Volcano House, on Kilauea, and in the Kona District, it is necessary to depend on rain water that is obtained from the roofs of buildings or from specially constructed rain catches and is stored in cisterns, wooden tanks, or concrete reservoirs. A unique method of obtaining water for drinking and domestic use on the island of Lanai is described by Emory.[5] This consists of collecting dew from the shrubbery and from oiled cloths spread out for the purpose.

The wealth of the Hawaiian Islands is derived chiefly from sugar cane, and in most places this crop requires irrigation. As sugar cane consumes much water, heavy irrigation is generally necessary, but the crop is so valuable that where water is to be had at all, large costs can be borne to place it on the land. Thus well water is pumped to heights of more than 600 feet for use in irrigating sugarcane. In the aggregate very large supplies of water, developed at great cost, are utilized for this purpose. Water has long been used, especially in low places, to irrigate rice and taro, but these crops are now of minor importance.

In the Kau District most of the sugar cane is raised without irrigation, but water is used to flume the cane to the mills. To one not familiar with the conditions this might seem to be a low use of water. In fact, however, it is almost the only practicable method of transporting the cane from the difficultly accessible fields at the higher levels. Moreover, with the great fall available, very moderate quantities of water suffice to transport large quantities of cane. Thus it is that in this district high-level water has an almost incredible value for fluming. Moreover, much of this water that is used for fluming has a double value because it is an essential supply for the mill on the lower ground, where it is used in the boilers and for extracting the sugar. Even at Pahala, to which it is possible to haul some cane on the railroad, the mill can not be operated without the flume water.

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[5] Emory, K. P., The island of Lanai, a survey of native culture: B. P. Bishop Museum Bull. 12, p. 46, 1924.

On much of the land devoted to stock raising water is very scarce. On parts of the range there are no streams, springs, or wells, and cattle live for weeks and months without any ordinary water supplies, obtaining moisture only from the dew and the rain. In these areas, watering places for stock are highly prized.

Water is also valuable for developing power where there are streams of sufficient discharge and the flow is not too variable.

PRINCIPLES OF OCCURRENCE OF WATER IN THE HAWAIIAN ISLANDS

CONTROLLING CONDITIONS

RAINFALL

To a person who is familiar only with the mainland, the hydrologic conditions in the Hawaiian Islands seem to be freakish in every respect. These unusual conditions in regard to the water are due to peculiarities in the two controlling conditions, namely, the rainfall and the geology.

The rainfall differs from anything found on the mainland in both intensity and areal variability. As is pointed out in this report, the rainfall in some places averages more than 400 inches a year and throughout considerable areas it averages more than 100 inches; also, more than 30 inches has been known to fall in 24 hours and as much as 24 inches in four hours.[6] The heavy rainfall in the humid parts of the islands produces a quantity of water per unit area far in excess of that found anywhere on the mainland.

Though the rainfall in some parts of the Hawaiian Islands is excessive, many parts are, nevertheless, arid or semiarid, and the change from aridity to excessive humidity may occur within a very short distance. Thus, the authors cite a change in average annual rainfall on Kauai from nearly 500 inches to only about 15 inches within a distance of 15 miles, and on Maui from about 400 inches to only about 8 inches within a distance of 7 miles. When we were engaged in field work in the Kau District we could virtually choose each morning on starting out from Pahala whether to go "mauka" (mountainward), where we would be working in mist, rain, and dripping vegetation, or to go "makai" (seaward), where the day would be as bright and the land as dry as if we were in the desert of Arizona.

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[6] See also Day, P. C., Summary of the climatological data for the United States, Hawaii section, U. S. Weather Bureau.

GEOLOGY

The other controlling factor in the occurrence of water supplies in the Hawaiian Islands is the geology. The islands consist mainly of great volcanoes, active or extinct, made up of an almost endless succession of flows of basaltic lava, with some ash and cinders and intrusive bodies, and only very minor amounts of sedimentary deposits. Generally speaking, the lava rock is like a sieve. The water percolates through this rock as it would through a pile of stones. In respect to permeability the extrusive basalt of the Hawaiian Islands is in a class with the cavernous limestone of a karst region. For the mass as a whole the coefficient of permeability is very great. Very large bodies of extrusive basalt also occur in the western part of the United States proper, especially in Washington, Oregon, California, and Idaho, and much of this basalt is as permeable as that in the Hawaiian Islands. In most parts of the country, however, there is no rock that compares in permeability with the Hawaiian basalt.

The causes of the permeability of the basalt are well explained in this report by Messrs. Stearns and Clark. Probably the principal cause is the extensive jointing that occurs when the lava cools rapidly. When I was at the lava flow of 1920 I indulged in the popular pastime of poking out gobs of liquid lava from the edge of the flow and molding them around coins. I found, however, that after these lumps of lava had solidified and cooled they were not only extremely brittle but almost explosive, for they would break apart on the slightest jar until I had nothing left except fragments. Mr. Clark states that after the flow had ceased and the lava had solidified there was from time to time a loud noise like the report of a gun, due to the sudden cracking of the basalt. Obviously in a very copious flow in which the lava accumulates to considerable depth the lower part of the lava may re-fuse and cool slowly, thus forming a more compact and less jointed mass comparable to an intrusive body. So far as has been observed, the lava flows from the Hawaiian volcanoes have, however, been small, like those of historic times, and have therefore built land masses of extreme permeability.

The hydrologic consequences of the widespread occurrence of this very permeable rock are obvious—rapid absorption and downward percolation of the rain water; small and flashy run-off; scarcity of tight reservoir sites; great ground-water recharge and large supply of ground water; very low and flat water table with great depths to ground water in most places; copious springs in the low valleys, along the coasts, and on the adjacent sea bottom; and salt water at no great depth below the water table. On account of the great surface relief most of the land where water is needed lies high above sea level, where the depth to the water table is great. Therefore the abundant supply of ground water is largely either not available for economic use or recoverable only at heavy cost.

This is, in outline, the story of water in the Hawaiian Islands. But it is not the whole story; from the economic standpoint it is far from being the whole story. There are some impermeable materials and materials of relatively low permeability. These include surface or buried soils and residual clays, clayey alluvial and marine deposits, beds of compact ash, igneous dikes and sills, and perhaps the dense lower parts of lava flows. They form only a small part of the total mass of rock and they control the ground water in only small degree; yet that small control is of great economic consequence and involves difficult geologic problems that are of great practical moment.

Anyone who reads the present report will, I believe, realize that these geologic problems have been effectively attacked but not yet adequately solved. It is my conviction that the foundation has been laid for more definite application of geologic methods to the ground-water problems of the islands and that the science of geology will render increasing service in the development of the water resources of the islands as fuller understanding is gained of the volcanic processes and products and of the peculiarities of the subsequent processes of erosion and deformation.

RESULTING CONDITIONS

SURFACE WATER

RUN-OFF

Systematic gaging of the streams in the Hawaiian Islands was begun in 1909 by the Geological Survey, through financial cooperation by the Territorial Government, and has been continued to the present time, the chief hydrographer of the Territory being also a district engineer in the Geological Survey. As a result of this work a series of water-supply papers has been published which give the daily discharge of numerous streams, many of them for periods of several years.[7] These records provide a large amount of reliable information on the character of the streams in the islands. If they are studied in connection with the rainfall records and the geology they will give much information as to the ground-water conditions.

Most of the streams are very irregular in their flow, rising suddenly to great volume during heavy rains and then during periods of fair weather dwindling to insignificant streamlets or drying up entirely. The water-supply papers cited above afford abundant

[7] U. S. Geol. Survey Water-Supply Papers 318, 336, 373, 430, 445, 465, 485, 515, 516, 535.

examples of streams that are characterized by these violent fluctuations. A typical example is the Kalihi Stream, near Honolulu. In the year ending June 30, 1921, this stream had a maximum discharge of 1,250,000,000 gallons a day, a minimum of less than 1,000,000 gallons a day, and an average, exclusive of the month of January, of about 3,000,000 gallons a day.[8]

The high stages are not difficult to understand. They result from excessive rainfall and from the steep gradients of the stream channels and occur in spite of heavy seepage losses into the permeable rocks. The low stages have a more complex explanation. Many streams are very ephemeral, drying up soon after the rain ceases on their drainage basins. Many of the larger streams, however, including a large proportion of those that have been gaged, continue to have a small flow during long periods and may be perennial or may dry up only after prolonged droughts. The Kalihi Stream is an example of a perennial stream of this kind. In the eight years of record, from 1913 to 1921, its flow has not been less than 500,000 gallons a day.

An excellent subject for investigation would be the sources of the water of the Hawaiian streams during their low stages. The sustained flow of some of the streams is doubtless due mainly to the frequency of the rains in some parts of the islands. Thus, before all the direct run-off of a stream in a humid area is discharged some rain is likely to fall on some part of its drainage basin. If it were not for this frequency of the rains, the surface-water supplies would be still more irregular and unreliable. In many drainage basins the retarding influence of the vegetation, forest litter, and soil is also an important factor in sustaining the flow. Many of the streams, however—the Kalihi Stream, for example—owe their sustained flow to the presence of springs or seeps. Wherever the flow is maintained by springs, ground water obviously occurs, and if the springs are at any considerable height above sea level, they are almost certainly fed by some perched body of ground water. Thus, any survey of the distribution of springs and seeps will throw light on the occurrence of high-level ground water.

Although most of the streams in the islands are of the extremely irregular type, there are some striking exceptions. Thus the Waiahole Stream, on the island of Oahu, during the year 1912, before the Waiahole tunnel was constructed, ranged only between 17,000,000 and 52,000,000 gallons a day, the water being derived mainly from large perennial springs at altitudes of several hundred feet.[9] Such

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[8] Grover, N. C., and Stewart, J. E., Surface water supply of Hawaii, July 1, 1920, to June 30, 1921: U. S. Geol. Survey Water-Supply Paper 535, pp. 52–53, 1924.

[9] Pierce, C. H., and Larrison, G. K., Water resources of Hawaii, 1912: U. S. Geol. Survey Water-Supply Paper 336, p. 121, 1914.

a large, steady flow obviously indicates a large and well-supplied ground-water reservoir. The stream-flow records seem to indicate that large perennial springs occur at high levels in some other localities, as in the Kohala District, on Hawaii, and on the windward side of Molokai. Apparently they occur in places where faulting and erosion have exposed rocks that were once far in the interior of the volcanic masses.

The Wailuku River, the most southerly stream in the Hilo group, on the east side of Hawaii, is regarded as the largest stream on the islands. From March 21 to December 31, 1911, its flow ranged from 26,000,000 to 3,430,000,000 gallons a day and averaged about 355,000,000 gallons a day,[10] and from February 20 to December 31, 1912, its flow ranged from 21,000,000 to 4,080,000,000 gallons a day and averaged about 370,000,000 gallons a day.[11] This stream is fed by 48 tributaries which head in a very humid zone on the flank of Mauna Kea. Its drainage basin is not well known, but the character of its flow does not indicate large perennial springs but rather the direct run-off and seepage from a large area of exceptional rainfall, with vegetation and soil to hold the water and to equalize the flow.

In the large area comprising the south and west sides of the island of Hawaii, there are no perennial streams but only very feeble and short-lived streams that flow in response to heavy and prolonged rainfall (p. 173). This is the area of the most recent lava flows, a fact which doubtless accounts chiefly for the extreme scarcity of surface water. In other parts of the islands where there has been no recent volcanic activity the surface has been extensively modified by weathering and erosion. Weathering has produced residual and alluvial materials that tend to hold up the surface water and thus to maintain the stream flow to some extent. Erosion has exposed structural features within the volcanic masses, some of which hold up ground water and feed it to the surface streams.

STORAGE

In order to use advantageously the very irregular flow of most of the streams, whether for irrigation, power, or any other purpose, large storage reservoirs would obviously be required. Unfortunately the natural conditions are unfavorable for the construction of reservoirs. The streams generally have steep gradients, with few basins in which much water could be stored except by the construction of very high dams. Moreover, the permeable character of the rocks in most localities precludes the possibility of constructing reservoirs

[10] Leighton, M. O., Martin, W. F., and Pierce, C. H., Water resources of Hawaii, 1909–1911: U. S. Geol. Survey Water-Supply Paper 318, p. 340, 1913.

[11] Pierce, C. H., and Larrison, G. K., Water resources of Hawaii, 1912: U. S. Geol. Survey Water-Supply Paper 336, p. 213, 1914.

that will not leak excessively. In several places small reservoirs have been built, some of which are constructed partly or wholly of concrete. Concrete reservoirs in the Kau District are used to conserve the night flow for fluming the next day during dry weather. All these reservoirs give considerable trouble because of the cracks caused by the numerous earthquakes that occur in the area. Any large dam or reservoir would be constructed at great hazard because of the earthquake shocks. In most places storage of surface water is difficult or impracticable.

BASAL GROUND WATER

AREAS WITHOUT CONFINING STRUCTURE

On each island, so far as known, there is a general or main water table below which all the permeable rocks are saturated. The great body of water that lies below the main water table may be called the basal ground water, to distinguish it from the perched bodies of ground water. For the most part, the rocks are so shattered and permeable that they do not notably regulate the occurrence and movement of the basal ground water except to offer a small amount of resistance to its percolation and hence to cause a slight building up of the water table with a resultant slight hydraulic gradient toward the sea. The artesian basin on Oahu forms a notable exception to this general rule.

In most parts of the Hawaiian Islands the main water table is very flat and lies very near sea level. In numerous wells examined by Lindgren[12] on the south side of Molokai, the water level was reported "at sea level" or only slightly above sea level. In only a few wells was it more than 2 feet above sea level. Lindgren states that the water table rises inland very slowly, so that a mile or more inland the water in wells may stand only a foot or two above sea level. In the well at Olaa Mill, in Hawaii, 4 miles from the coast, the water level is only a foot or two above sea level (p. 176). At the Kihei pumping plant No. 3, on the island of Maui, over 3 miles from the sea, the water table was originally only 6 or 8 inches above mean sea level, according to one report, and 2½ feet, according to another report. Although few specific data as to the slope of the water table are available, its characteristic flatness in many parts of the islands is a matter of common knowledge.

The land surface of all the larger islands has great relief. Even the relatively smooth areas generally have considerable slope. Thus most of the areas where water is needed for irrigation or other purposes lie as much as a few hundred feet above sea level, and, as the

[12] Lindgren, Waldemar, The water resources of Molokai, Hawaiian Islands: U. S. Geol. Survey Water-Supply Paper 77, pp. 27, 37–47, 1903.

main water table is generally very near sea level, the depth to ground water is great—in many places entirely too great for profitable pumping. This unfavorable condition severely handicaps the utilization of the large supply of water that occurs below the main water table. Fortunately, sugarcane raised on good soil is so valuable a crop that it may be profitable to lift the water as much as a few hundred feet for irrigation. In the highest areas, as on the upper parts of Mauna Loa, the depth to the main water table is doubtless thousands of feet.

In any locality the slope of the water table is essentially the resultant of two factors—the rate of recharge and the permeability of the water-bearing rock. The slope must be just great enough to give the necessary hydrostatic pressure to carry the water, against the friction offered by the rock, from the place where it is received by percolation from the surface to the sea or other place of discharge. The more permeable the rock the less is the pressure required and the gentler will be the slope of the water table. On the other hand, the greater the rate of intake or recharge by percolation from the surface, the greater is the pressure required to carry the water through the rock and hence the steeper will be the slope of the water table. The significant fact in regard to the Hawaiian Islands is that, as a rule, although the rate of recharge is great, the water table has only a slight slope because of the exceedingly great permeability of the rock.

There can be no question as to the large quantities of water that reach the main water table in most parts of the islands. In the Kau District the average annual rainfall ranges, according to the locality, from 30 inches or less to fully 200 inches (p. 169). Very little of this water reaches the sea as run-off. In the large tracts of lava rock with little soil or vegetation the ground-water recharge must be close to 100 per cent of the rainfall. In the forest belt and in the tracts where the volcanic ash forms soil at the surface there are large losses by evaporation from the soil and by transpiration of the luxuriant vegetation, but even in these areas the ground-water recharge is great. In other parts of Hawaii and in many parts of the other islands there is more run-off and more loss by evaporation and transpiration, but it is very evident that nearly everywhere great quantities of rain water seep into the rocks and sink to the water table. Lindgren [13] estimated a ground-water recharge on parts of the south side of Molokai equal to more than 50 per cent of the rainfall. Thus, for an area of 54 square miles having an average rainfall of about 48 inches a year, amounting to 126,000,000 gallons a day, he estimated

[13] Lindgren, Waldemar, The water resources of Molokai, Hawaiian Islands: U. S. Geol. Survey Water-Supply Paper 77, pp. 47–49, 1903.

the evaporation at 26,000,000 to 36,000,000 gallons, the run-off at 20,000,000 to 30,000,000 gallons, and the ground-water recharge at 60,000,000 to 80,000,000 gallons. The island of Lanai has an average annual rainfall of only about 16 inches. Wentworth[14] estimated the ground-water recharge on this island to be about 30 per cent of the rainfall, with a maximum in one area of perhaps 80 per cent. This estimate would give an average recharge of 42,000,000 gallons a day on the entire island.

The magnitude of the ground-water supply and the great rate of recharge have been demonstrated in several parts of the islands by heavy pumping from wells during successive years. Considerable water has been pumped for many years for irrigation on the west end of East Maui and on the isthmus connecting East and West Maui. In 1910 about 15 pumping stations had been established by the Hawaiian Commercial & Sugar Co. and the Maui Agricultural Co. The pumps were operated during the parts of the year when there was a shortage in surface water supplied by the ditches. In that year the Hawaiian Commercial & Sugar Co. pumped a little over 9,000,000,000 gallons, which is an average of about 25,000,000 gallons a day or 17,000 gallons a minute. The average pumping in September was about 70,000,000 gallons a day, or nearly 50,000 gallons a minute. In addition, the Maui Agricultural Co. pumped in that year about 1,500,000,000 gallons, with a daily average in September of about 20,000,000 gallons.[15] In 1919 the Hawaiian Commercial & Sugar Co. pumped about 18,000,000,000 gallons from wells, with a maximum pumpage of about 100,000,000 gallons a day.

On the leeward side of West Maui the Pioneer Mill Co. in 1911 pumped about 9,000,000,000 gallons of ground water. The maximum pumping during the year was about 45,000,000 gallons a day.[16]

The principal ground-water development on Kauai is that of the McBryde Sugar Co., which lifts a large part of its water more than 400 feet.[17] According to the published record this company pumped an average of about 20,000,000 gallons a day, or 14,000 gallons a minute, in 1911, and about 25,000,000 gallons a day, or 17,000 gallons a minute, in 1912.[18]

In 1920 I had the privilege of seeing several of the very interesting pumping plants of the Hawaiian Commercial & Sugar Co. on Maui. At the Kihei pumping plant No. 3 about 20,000,000 gallons a day, or about 14,000 gallons a minute, was pumped up through

[14] Wentworth, C. K., The geology of Lanai: Bernice P. Bishop Museum Bull. 24, pp. 19, 64–65, 1925.

[15] Leighton, M. O., Martin, W. F., and Pierce, C. H., Water resources of Hawaii, 1909–1911: U. S. Geol. Survey Water-Supply Paper 318, pp. 331–332, 1913.

[16] Idem, p. 258.

[17] Idem, p. 144.

[18] Pierce, C. H., and Larrison, G. K., Water resources of Hawaii, 1912: U. S. Geol. Survey Water-Supply Paper 336, p. 99, 1914.

one shaft about 300 feet deep and was lifted a total height of 400 to 450 feet. The shaft extends to the water table, about 300 feet below the surface. At the bottom of the shaft there is a sump, about 25 feet deep, which is supplied chiefly by a tunnel 260 feet long. The tunnel is 4 feet wide and 6 feet high, and its bottom is about 17 feet below the normal water table. The pumps and engines are in large chambers just above the water level, and the steam boilers are at the surface.

The permeable rocks extend to an indefinite depth below sea level. At no great depth below the water table they are saturated with salty water, which is essentially sea water. Fresh water derived from the rain percolates downward and, having less specific gravity than the salt water, floats on top of the body of salt water and percolates laterally to the sea. The presence of the salt water introduces a serious problem wherever the attempt is made to recover large quantities of this ground water.

The work of Badon Ghyben and later that of Herzberg on ground water along seacoasts produced an important theory or law in regard to the relation of the fresh water to the underlying salt water in permeable rocks along seacoasts and on islands in the sea.[19] The body of salt water on which the fresh water rests is, of course, not a rigid body but is in hydrostatic relation to the water in the sea. According to this theory the fresh water that originally accumulated on the body of salt water disturbed the hydrostatic equilibrium with the sea and caused the body of salt water to sag down until the equilibrium was restored. This sagging process was continued as additional supplies of fresh ground water were received. However, as the sea water has greater specific gravity than the fresh water, the column of fresh water at any given point on the island had to be higher than the column of sea water with which it was in equilibrium, just as if the two columns were in the opposite arms of a U-tube. Accordingly, as the fresh water extended below sea level the water table was necessarily raised above sea level. By this process the water table eventually attained a slope which was adequate to carry the fresh water laterally to the sea as fast as it reached the body of ground water by recharge from above. When this stage was attained there was no tendency for further depression of the salt water.

Under these conditions, the depth to salt water becomes a function of the specific gravity of the salt water and of the altitude of the water table above sea level. According to H. L. Lyon,[20] the specific gravity of sea water at the surface of the coast of Oahu is about

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[19] Brown, J. S., A study of coastal ground water, with special reference to Connecticut: U. S. Geol. Survey Water-Supply Paper 537, p. 16, 1925.

[20] McCombs, John, and Fiedler, A. G., Methods of exploring and repairing leaky artesian wells: U. S. Geol. Survey Water-Supply Paper 596, p. 8, 1927.

1.024 if ordinary fresh ground water is assumed to have a specific gravity of 1. Therefore, in the hypothetical U-tube 1.024 feet of fresh water is required to balance 1 foot of sea water and about 43 feet of fresh water is required to balance 42 feet of salt water. Conversely, if the water table stands 1 foot above sea level the salt water should be encountered 42 feet below sea level.

It can not be expected that exactly this ideal condition will be found in nature. Some mingling of salt and fresh water is to be expected by convection and diffusion. This will tend to give the fresh water a considerable content of salt but will further depress the true salt water. The principle should, however, be clearly recognized in all investigations relating to the basal ground water and should be put to the test whenever possible. This is essential if future ground-water developments are to be wisely made so that the maximum quantity of ground water may be recovered with the least trouble from salt and at minimum cost.

Lindgren's report shows that on Molokai wells that extended far below sea level invariably struck salt water and continued in salt water to the bottom. In the several deep wells for which information is given the salt-water surface was struck at levels ranging from about 75 to 160 feet below sea level. In general the salt-water surface sinks inland from the south coast as the water table rises, and it is believed to be relatively deep on the north side of the island, where the water table is relatively high. The depths given in specific wells seem to be somewhat greater than is required by the Ghyben-Herzberg law. The tests reported indicate that the water above the salt-water surface also contains salt in considerable amounts, although small in comparison with the salt content of the sea water found below the salt-water surface. Various results were obtained in pumping the wells that did not extend to the salt-water surface. If the rate of pumping was not too great the salt content generally did not increase notably, and in some wells it even decreased. However, if the rate of pumping exceeded a certain permissible limit the salt content tended to increase persistently.

In my visit to Maui I was told that on the central lowland or isthmus, where much of the pumping is done, the ground water has a wide range in salt content, some being too salty for use. In general it was found that the salt content was not greatly increased or decreased by pumping, although in one case cited it decreased from 115 to 90 grains per gallon (about 2,000 to 1,500 parts per 1,000,000). Moreover, it was said that some of the best water was found near the sea and some of the most salty far in the interior. It is, however, generally recognized on Maui, as on Molokai, that the usable water is relatively near the water table and that the deep water is salty. This principle was obviously recognized in the development at the Kihei pumping plant No. 3. Here the bottom of the tunnel is about 17 feet below the normal water level, and the drawdown is commonly 12 to 14 feet. In 1920 the water from this plant contained about 50 grains per gallon (about 850 parts per 1,000,000) of salt—that is, chloride computed as sodium chloride—whereas water containing as much as 90 grains per gallon (about 1,500 parts per 1,000,000) was considered fit to use for irrigating cane.

Whatever may be the precise relations of the fresh and salt water, it is obvious that the recovery of usable water from slight depths below the main water table is a skimming process. It may be on a huge scale where large developments are made for irrigation, but it is nevertheless like the recovery of cream from a pan of milk. Where these conditions prevail no wells should extend far below the water table, and it is inadvisable to attempt to pump a large quantity from one point, as from a single drilled well. The development at the Kihei pumping plant No. 3 seems to be essentially of the right type. The largest supplies of fresh water can doubtless be recovered by means of extensive infiltration tunnels run through the permeable rocks only slightly below the water table. It would seem that this method should be employed in so far as it is possible to do so within reasonable limits of cost.

AREAS WITH ARTESIAN STRUCTURE

On the island of Oahu artesian conditions exist, and consequently the occurrence and movement of the basal ground water on this island are different from those which have been described. The artesian conditions are due to deposition of a series of sedimentary beds along the coast and subsequent uplift of the land, forming a low, narrow coastal plain. The sedimentary beds consist largely of permeable materials, such as coral limestone and coral sand and mud, with interbedded lava flows and cinders, but also include, especially near the base of the series, some clayey strata which form a confining bed for the artesian water in the underlying permeable lava rock. The original head is reported to have been about 36 to 42 feet above sea level in different parts of Honolulu, 32 feet at Ewa, west of Honolulu, and 26 feet at Kahuku, near the north end of the island.[21]

A historical sketch of the artesian-water development on Oahu by McCombs [22] gives the following significant facts: The first flowing well on the island was drilled in 1879, and between that date and

[21] Leighton, M. O., Martin, W. F., and Pierce, C. H., Water resources of Hawaii, 1909–1911: U. S. Geol. Survey Water-Supply Paper 318, p. 147, 1913. McCombs, John, and Fiedler, A. G., op. cit., p. 6.

[22] McCombs, John, and Fiedler, A. G., op. cit., pp. 4, 5.

1925 about 600 wells were drilled. In 1925 the average withdrawal of artesian water, by natural flow and pumping, was more than 250,000,000 gallons a day, and the maximum daily draft was more than 350,000,000 gallons. This water is almost the only supply for 100,000 people, and in addition it is used to irrigate cane land that produces more than $11,000,000 worth of sugar a year. The first law providing for the conservation of the artesian water was enacted in 1884. Careful logs were kept for some of the early wells. The first systematic work in preserving well records and records of the static head was done under the supervision of Prof. W. D. Alexander, surveyor of the Hawaiian Government, and most of the records that are available for the period from 1879 to 1910 were preserved by him. In 1909 W. C. Mendenhall, then in charge of ground-water investigations in the United States Geological Survey, visited Hawaii and made arrangements for more extensive and systematic observations by T. F. Sedgwick, under the supervision of Marston Campbell, superintendent of public works. Mr. Sedgwick located most of the wells then in existence, made monthly readings of static head on many of the wells, and made numerous tests of salt content in samples of well water. His valuable work on this basis was continued until 1916, when it was superseded by that of a commission authorized by the Territorial Legislature of 1915 to investigate and report on the water resources of Hawaii. The commission consisted of G. K. Larrison, Arthur G. Smith, and Mr. Sedgwick—Mr. Larrison at that time being the chief hydrographer of the Territory and the resident district engineer of the United States Geological Survey. This commission conducted detailed investigations in the Honolulu District, and as a result of its recommendations [23] the Legislature of 1917 passed an act which defines waste of artesian water and gives the chief hydrographer authority to investigate and prevent it. This law was subsequently amended to make it more effective.

Since 1917 the artesian investigations have been conducted by the division of hydrography in the Territorial government. The successive chief hydrographers of this division have also been district engineers in the Geological Survey. Underground leakage of artesian wells had long been suspected, but in 1918 work was begun by R. D. Klise in definitely locating leaks and making rough measurements of the amounts of leakage by means of a current meter which was let down into the wells. This work was continued by John McCombs, who supervised the recasing or plugging of defective wells and who has described the methods and results of the work in the water-supply paper already cited.

[23] Report of the Water Commission of the Territory of Hawaii to the Governor of Hawaii, 1917.

More recently the artesian water work has been carried on by K. N. Vaksvik, under the direction of M. H. Carson, district engineer. In 1925 the Territorial Legislature created the Honolulu Sewer and Water Commission, which has worked in close cooperation with the Geological Survey. Under the direction of Frederick Ohrt, chief engineer, this commission has conducted further studies of the artesian conditions in the Honolulu District.[24] A study of the geology of the artesian basin by Palmer[25] has thrown much light on the structure of this basin and the relation of the structure to the artesian conditions. The outline given in the following paragraphs is based largely on the reports by McCombs and Palmer.

There is good evidence that the mechanics of the artesian basins in Oahu differ in essential respects from those of ordinary artesian basins. In an ordinary artesian basin the head in the area of artesian flow is maintained by the sealed condition of the artesian reservoir at low levels or by the frictional resistance that the water has to overcome in percolating to the points of natural discharge. In the Oahu basins, however, the head in the areas of artesian flow is apparently maintained almost entirely by the counterpoise of the relatively heavy sea water.

It was observed early in the history of well drilling in the vicinity of Honolulu that flowing wells could be obtained only in certain definite areas on the coastal plain, which are separated from one another by belts in which no artesian water was found. It was also observed that within any one of these areas the water has virtually the same static head in all wells that are in good condition, but that there is a different head in each of the different areas.

The existence of distinct isopiestic areas, or areas of equal artesian pressure, is due to the division of the artesian reservoir into compartments. It has been shown by Palmer that these areas are interstream areas and that the walls between the compartments consist chiefly of relatively impermeable alluvial deposits in deeply buried ancient channels of the principal streams that cross the Honolulu District.

The absence of any noticeable hydraulic gradient is doubtless due to the great permeability of the water-bearing rock and the consequent virtual absence of frictional resistance to the percolation of the artesian water. The great permeability of the water-bearing rock is indicated by the large yield and specific capacity of the wells of the Honolulu city waterworks, as shown by the following table based

[24] Report of the Honolulu Sewer and Water Commission to the Legislature of the Territory of Hawaii, 1927.

[25] Palmer, H. S., The geology of the Honolulu artesian system: Honolulu Sewer and Water Comm. Rept., supplement, 1927.

on data furnished in 1920 by W. H. Bromley, chief engineer of pumps:

Yield of Honolulu waterworks wells, based on data furnished in 1920

Pumping station	Number of wells	Pumpage		Drawdown (feet)	Specific capacity (gallons a minute for each foot of drawdown)
		Gallons a day	Gallons a minute		
Beretania	4	7,700,000	5,300	7	200
Kalihi	3	5,200,000	3,600	3	400
Kaimuki	4	5,500,000	3,800	1¼	760
One well at Kalihi	1	4,000,000	2,800		

The confining bed serves to prevent escape of the artesian water in the area of artesian flow, and it is also known to extend to a considerable depth below sea level. If there were no difference between the specific gravity of fresh and salt water it would be necessary to assume that the artesian reservoir is throughout its extent confined by an impermeable or difficultly permeable bed. Otherwise there would be nothing except the slight resistance of the water-bearing rock to hinder the escape of the artesian water to the sea, and the head would necessarily be only slightly above sea level. On account of the difference in specific gravity, however, an equally tenable explanation of the artesian head is that at considerable depth there is no confining bed between the artesian reservoir and the sea and that the fresh water is in hydrostatic equilibrium with the sea water. The available geologic evidence and the evidence as to encroachment of salt water point to the second alternative as the correct explanation of the artesian head. Thus the whole structure seems to form not an imaginary but a real U-tube in which the two arms are separated from each other by the confining bed.

Originally the artesian water in a certain isopiestic area described by McCombs rose 36 feet above sea level. Therefore, if the fresh artesian water was in hydrostatic equilibrium with the sea water, the artesian water must have extended to a depth equal to 36 feet divided by 0.024, or about 1,500 feet below sea level. This reasoning would indicate that in this area the effective limits of the confining bed are either about 36 feet above sea level or about 1,500 feet below sea level. If the confining bed was effective to more than 1,500 feet below sea level but to only 36 feet above sea level, the recharge of the artesian reservoir by percolation from the surface must have caused artesian water to escape over the upper edge of the confining bed; if, on the other hand, it was effective to more than 36 feet above sea level but to only 1,500 feet below sea level, the recharge must have caused escape of artesian water under the lower edge of the confining bed. In either case the salt-water surface should originally have stood about 1,500 feet below sea level. There is evidence that the water escaped under rather than over the confining bed.

Theoretically, when artesian wells were drilled the discharge of these wells by natural flow or pumping took the place of the flow into the sea either over or under the confining bed. As long as the discharge from the wells did not exceed the recharge by percolation of rain water from the surface, the salt-water surface should, according to this theory, have remained essentially stationary, and there should have been virtually no decrease in the quantity of fresh water stored in the artesian reservoir. However, when the withdrawal from wells became so great that it exceeded the recharge, fresh artesian water must have been withdrawn from storage. In an ordinary artesian basin the withdrawal of water from storage would be registered largely by the decline in the water table in the outcrop area of the artesian aquifer, and the consequent lowering of the artesian head. If, however, the artesian structure forms a huge U-tube in which the fresh artesian water is balanced against the salt water, every foot of lowering of the artesian head means a rise of the salt-water surface by 42 feet and a correspondingly great withdrawal of fresh water from storage. As the artesian wells that go to the greatest depths have become salty and as salty water has progressively appeared in wells of less depth, it has been concluded that some of the water withdrawn through the artesian wells has been taken from storage and that the salt-water surface is rising in proportion as the head is going down.

The average rate of recharge of the artesian reservoirs on Oahu is certainly great. This is indicated by the heavy rainfall and large percentage of absorption over much of the intake area, by the constant, heavy withdrawals that have been made through the artesian wells during nearly half a century, and by the large rise in artesian head in response to rainfall. The average annual rainfall at 73 stations on Oahu is about 70 inches, and in much of the intake area it is more than 100 inches. The average daily withdrawal of artesian water on Oahu, about 250,000,000 gallons, is equal to about one-eighth of the average daily rainfall on the entire island. The rise in artesian head in response to rainfall is especially impressive if it is assumed that the theory of balance between fresh and salt water is wholly operative, for according to this theory a storage of 1 foot at the top of the body of fresh artesian water should mean a storage of 42 feet at the bottom, by depressing the salt-water surface. Thus it seems evident, on the one hand, that a large supply of artesian water is perennially assured by the heavy recharge in the intake area, but, on the other hand, that there is danger of salt-water contamination if withdrawals are made in excess of recharge.

The recharge of the artesian reservoir in the vicinity of Honolulu, has been estimated by McCombs[26] by two independent methods. By the first method he computed the average rainfall on the catchment area of the artesian reservoir and deducted therefrom the losses by run-off and by transpiration and soil evaporation. The computations of rainfall and run-off were based on large amounts of accurate data, but the estimates of transpiration and evaporation are more uncertain and may have introduced a large error. The second method is based on measurements of the discharge of artesian wells and the coincident changes in artesian head. During dry periods the recharge is believed to be of negligible quantity. Hence if during any one of these periods the aggregate discharge in a given isopiestic area and the lowering of the static level in the wells in that area are known, the yield of the corresponding compartment of the artesian reservoir per unit of drawdown can be computed. This yield, or "specific draft," was computed for three of the isopiestic areas in terms of millions of gallons for each one-hundredth of a foot of lowering of the water level in the wells. After the specific draft has been computed for a given area, any rise or decline in the static water level in that area can be expressed as increase or decrease of storage in the corresponding compartment of the artesian reservoir, and the recharge during any period can be computed as the discharge through wells plus the increase or minus the decrease in storage. This second method is comparable with quantitative methods recently used with considerable success in other areas and is probably more reliable than the first method. By the use of both methods McCombs concluded that the safe yield of the artesian reservoir in the Honolulu District is about 42,000,000 gallons a day.

The work that has been done in the Honolulu District in locating and stopping underground leaks in artesian wells is a substantial achievement of obvious practical value. The total underground leakage discovered in Honolulu to 1925 was approximately 7,750,000 gallons a day, of which 5,900,000 gallons a day has been stopped by suitable repairs. The conservation effected in thus saving artesian water that would otherwise have been wasted by flowing into the sea through underground passages will be better appreciated by the statement that it amounts to about one-fourth of the total quantity of artesian water consumed from the Honolulu waterworks, which in 1925 averaged 22,000,000 gallons a day, or one-seventh

[26] McCombs, John, Methods of estimating safe yields of Honolulu artesian area: Honolulu Sewer and Water Comm. Rept., pp. 55–65, 1927.

of the total artesian supply, which has been estimated at 42,000,000 gallons a day. Moreover, if this program of conservation had not been put into operation the leakage would have become worse from year to year and would have vitiated any attempt to conserve the artesian supply by restricting its use.

The suggestion has been made by Mr. Stearns that the recharge might be increased by impounding or spreading storm water to make it seep into the permeable lava rocks and percolate into the artesian reservoir instead of permitting it to run to waste in the sea. This suggestion is worthy of careful consideration. If water that would otherwise run to the sea can be diverted into the artesian reservoir the supply that can be obtained from wells will be correspondingly increased.

PERCHED GROUND WATER

WATER PERCHED ON BEDS OF VOLCANIC ASH

The perched water that is recovered in the Kau District and is described in this report is found above beds of fine-grained volcanic ash or tuff. The work done by Messrs. Stearns and Clark shows that these ash beds were laid down as continuous and uniform mantles over extensive areas and that they follow the irregularities of the preexisting surface. They are generally covered by more recent lava flows, especially in the low places or preexisting valleys. The ash is not impermeable, but it is much less permeable than the overlying lava. Hence, the rain water that seeps into the crevices of the lava may descend to an ash bed and thence percolate over its upper surface, in many places forming underground streams in the preexisting valleys, much as it would form surface streams if the lava were absent. In some places the ash beds were cut through by stream erosion before the overlying lava was extruded, and in these places the underground stream is likely to cascade through the openings in the underlying lava to the main water table far below or to an intervening ash bed. The flow of these underground streams varies greatly with the rainfall, but the lava has considerable equalizing effect, so that the discharge of springs and tunnels fed by perched water from an ash bed is much less intermittent and variable than the discharge of a comparable surface stream. As is shown by this report, the discharge from deeply buried ash beds fluctuates much less than that from ash beds which have but little lava over them.

The method developed by Mr. Clark for recovering the perched water supplies of this type is to run a tunnel through an ash bed, nearly along a contour of its upper surface, to intercept the underground streams, much as a canal would be run over the land surface to intercept surface streams. The roof of the tunnel must be formed by the overlying lava, so that any water percolating over the ash bed may find its way into the tunnel. No large streams of perched water were discovered in the Kau District, but the aggregate of many small streams recovered by the tunneling resulted in notably enlarging the water supply for fluming on the two large plantations in the district. (See pls. 32, 33.)

Where an ash bed crops out it is likely to deliver its water at the surface through springs, but it may remain buried under lava rocks or what was once its outcrop may be concealed by talus, landslide débris, or congealed lava cascades. Where the ash bed is not exposed in a clean, fresh outcrop the water is likely to sink before it reaches the surface unless it is intercepted by a tunnel.

Tunneling for high-level water is not a new idea in the Hawaiian Islands. Tunnels have been run in many places with variable success. Some have proved to be profitable undertakings, but many of them yield little or no water. Not much is known as to the geology of most of these tunnels, and therefore it is not possible to say how much tunneling has been done in ash beds. However, it is probable that high-level water is extensively associated with ash beds and that small or moderate supplies can be obtained in many places by intelligent tunneling in these beds. Wherever ash beds are to be exploited for water supplies, use should be made of the knowledge gained in the Kau investigation as to the mode of occurrence of the volcanic ash and the best methods of recovering its water. A detailed geologic survey of the islands will show the location, stratigraphic position, and water prospects of the principal ash beds.

WATER PERCHED ON SOIL AND ALLUVIAL DEPOSITS

It has been explained that streams are somewhat more persistent and less ephemeral on old land surfaces than in the areas covered by very recent lava flows such as are found in the southern and western parts of the island of Hawaii. This difference is due chiefly to the residual soil and the alluvial material which largely mantle the older surfaces and retard the absorption of the surface water. The Nuuanu Valley, which lies directly back of Honolulu, is underlain by considerable deposits of alluvium that include water-bearing beds by which several springs and wells are supplied. Some of this alluvium lies as much as 1,000 feet above sea level, and its water is undoubtedly perched high above the main water table.

Old soil-covered surfaces buried beneath later lava flows should be favorable horizons for prospecting for high-level water. If a tunnel in permeable lava rock is exceptionally dry the explanation is generally to be found in an overlying bed of soil, alluvial clay, volcanic ash, or other relatively impermeable material that forms a roof over the tunnel and prevents ready downward percolation of the rain water. Small amounts of water are likely to be found above the impermeable material, and it is reasonable to suppose that underground streams of considerable size and permanence may be found in the ancient valleys of old land surfaces. Not much information is at present available as to the occurrence and extent of major erosional unconformities with basal residual and alluvial deposits nor as to existing tunnels that may obtain water from such unconformities. There are several unfavorable possibilities. The large valleys are likely to be cut deep into basalt and to head in amphitheaters. Buried valleys of this kind, even if they contain underground streams, are likely to be at too low an altitude for their water to be of economic value. The ancient stream channels above the amphitheaters are likely to be cut into the underlying lava and to be lacking in tight alluvium. Channels of this kind have little or no value in holding up ground water. Even the channels of relatively large streams are likely to have steep gradients and hence to have rock bottoms or only coarse, permeable alluvium.

As is shown by this report, the Kau District contains a pronounced erosional unconformity. When the investigation was begun it was hoped that valuable high-level supplies of water might be developed in buried valleys of the ancient land surface represented by this unconformity. However, no favorable conditions for development of this kind were found, and all the high-level developments in the district have been in the beds of volcanic ash, one group of which lies stratigraphically above and the other below the unconformity.

WATER PERCHED ON INTRUSIVE ROCKS

In parts of the Koolau Range, which is the principal mountain range of Oahu, large quantities of ground water occur at altitudes of several hundred feet above sea level and give rise to large perennial springs. In 1913 to 1915 the well-known Waiahole Tunnel was driven entirely through this range, a distance of 14,567 feet, at altitudes of 752 to 724 feet above sea level. The purpose of this project was to divert the large spring-fed streams on the precipitous windward side of the range and to carry the water through the tunnel to the leeward side to be used on the upper levels of the Oahu Sugar Plantation. In driving this tunnel very large quantities of water were found to be impounded by igneous dikes that extend through the permeable lava rock. The tunnel was driven from both ends. The windward part, driven from the north portal, broke through the first dike when it had penetrated about 200 feet and encountered a flow of about 2,000,000 gallons a day. As the work progressed the quantity of water increased, until at about 900 feet from the north portal the flow was 26,000,000 gallons a day, and at about 1,400 feet it was 35,000,000 gallons a day. The leeward part of the tunnel, driven from the south portal, was dry to a distance of 10,518 feet, where the first dike was struck. When the drill holes passed through this dike water spouted from them under pressure. The flow in the leeward part of the tunnel reached 17,000,000 gallons a day by the time the two parts met, at 11,679 feet from the south portal. Thus, along the line of the tunnel the dikes are restricted to a zone of less than 4,000 feet wide lying below the highest part of the range, and the high-level water is confined within this zone.

The record of this tunnel is valuable in giving definite evidence of the relation of the high-level water to the dikes. According to Kluegel,[28] the dikes consist of hard close-grained rock that is apparently waterproof, range in thickness from 4 to 14 feet, are nearly vertical, and trend at angles of about 45° to the tunnel. Between the dikes there is porous lava rock, which was saturated with water under considerable pressure, so that when a dike was penetrated the water spouted out from the drill holes. A gage on some of the plugged drill holes showed a pressure of 65 pounds to the square inch, indicating a head of about 150 feet.

The great flow of water at first produced by this tunnel was obviously due to the draining of the water stored in the natural reservoirs formed by the dikes. As the underground storage was depleted the percolation into the tunnel declined. In April, 1915, it was about 43,000,000 gallons a day; by January, 1916, it was reduced to about 14,000,000 gallons, and by June, 1916, to less than 9,000,000 gallons. Since that time there has been considerable fluctuation in the rate of percolation into the tunnel, doubtless owing to irregularities in recharge from rainfall, but there has apparently not been much general decline. From February 3 to February 8, 1920, the total percolation amounted to about 9,000,000 gallons a day. A large part of the water that percolates into the tunnel is really diverted from springs whose discharge was notably decreased by the tunnel. On the basis of available stream-flow records it has been estimated that the decrease in spring flow amounts to about 5,700,000 gallons a day. Thus it appears evident that a large part of the water which percolates into the tunnel is merely diverted from the springs but that nevertheless the tunnel is effective in salvaging considerable water that would otherwise escape to the sea without appearing in high-level springs.

The following table shows the average percolation into the tunnel on the south side of the drainage divide for each month from 1918

[28] Kluegel, C. H., Engineering features of the Waiahole water project of the Waiahole Water Co.: Hawaiian Eng. Assoc. Bull. 55, 1916. The information here given in regard to the Waiahole Tunnel is obtained chiefly from this paper.

to 1927, inclusive. These records were obtained by the Waiahole Water Co., and were furnished by the Bernice P. Bishop estate. They represent the difference in flow as recorded at two gaging stations, one at the inlet and the other at the outlet of this section of the tunnel, and they are subject to the errors that are common to this method.

Average monthly and annual percolation into Waiahole Tunnel on south side of drainage divide, 1918–1927, in millions of United States gallons a day

[Records of Waiahole Water Co. furnished by Bernice P. Bishop estate]

Month	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	Average
January	4.73	4.64	5.10	5.62	5.74	6.36	6.43	5.64	6.46	5.90	5.66
February	5.76	5.33	3.47	7.16	6.97	6.04	6.28	6.44	6.27	6.84	6.05
March	5.11	5.49	4.21	8.28	7.21	7.54	6.68	7.06	6.90	6.23	6.47
April	5.28	3.61	5.69	7.15	7.26	7.08	5.45	7.32	5.76	3.58	5.81
May	5.71	5.08	5.42	6.11	6.86	6.62	6.69	7.93	4.02	5.63	6.00
June	6.73	6.51	5.28	5.84	6.73	6.19	7.07	6.93	4.92	7.77	6.39
July	7.35	5.44	5.26	5.91	5.98	6.73	7.36	7.20	5.21	8.55	6.49
August	6.71	5.93	5.30	6.06	5.89	6.90	7.54	7.68	5.04	7.61	6.46
September	5.98	5.59	5.45	5.47	5.71	6.55	6.68	7.23	5.45	6.10	6.02
October	5.41	6.40	4.65	5.77	6.67	6.85	6.41	7.10	5.07	7.09	6.14
November	5.55	6.40	4.91	5.30	6.59	6.16	6.58	7.15	4.20	4.68	5.75
December	5.59	5.79	5.68	4.68	7.50	5.20	6.05	7.64	4.86	5.74	5.87
Annual average	5.81	5.53	5.04	6.11	6.59	6.52	6.61	7.05	5.27	6.30	6.08

During my visit to the Hawaiian Islands in 1920 I gave attention to the problem of high-level water available for the city of Honolulu, and subsequently an investigation of the region with respect to high-level water was made by H. S. Palmer, formerly a geologist in the United States Geological Survey and now professor of geology in the University of Hawaii. Palmer made a detailed report, which was submitted in manuscript form to the mayor of Honolulu, showing the structural features that are favorable or unfavorable to the occurrence of high-level water. He recommended tunneling in the Palolo and Manoa Valleys and also indorsed a project, previously recommended by Jorgensen,[29] to drive a tunnel through the head of the Kalihi Valley to the windward side and to tap a body of rock extending northwestward from that valley. He concluded that in all three of these regions there are dikes and sills which hold considerable bodies of water at high levels.

Many outstanding questions remain as to high-level water that is held up by intrusive rocks. Apparently such definite underground reservoirs as were tapped by the Waiahole Tunnel, with copious yields and with heads of as much as 150 feet, must be inclosed on all sides and at the bottom with tight rock. Merely a series of parallel

[29] Jorgensen, Jorgen, Development of water by tunneling in Oahu: Report on available water supply for the city of Honolulu by the Honolulu Water Commission, pp. 92–108, Honolulu, 1917.

dikes running through the permeable lava rock would hardly produce an adequate confining structural feature. Systems of intersecting dikes seem to be required. The water held at such high levels must, it seems, be perched on a sill or other impervious floor. Hence to tap this water the tunnel must be driven at the proper altitude. If it is too high, it will pass above the top of the saturated zone; if it is too low, it will penetrate the impervious rock without finding water or will pass through underlying dry lava rock.

There is abundant evidence that dikes do not occur promiscuously throughout the islands but are restricted to certain localities—probably the rift zones along which the lava rose that produced the innumerable flows. Thus the first requisite to prospect intelligently for high-level water of this type is to understand the volcanic history of the region and the nature of the volcanic processes and products. The relatively gentle leeward or southwest slope of the Koolau Range is essentially the dissected surface of the latest of the lava flows that formed the range. The dikes, with their high-level water, are found only near the crest of the range, where the lava vents apparently occurred. The geologic study of the high-level water in this range must consist largely in observing the structural features that crop out on the steep windward side and the occurrence and structural relations of the high-level springs on that side. To locate the high-level bodies of water, relatively short tunnels can be driven from the windward side in locations and at altitudes dictated by the geologic study. It may be most economical to prospect for the high-level water by drilling test wells near the heads of valleys on the leeward side of the range.

It seems likely that the largest supplies of high-level water are in general to be found in perched basins formed by dikes and sills and that only smaller supplies are commonly available from beds of ancient soil, alluvium, or volcanic ash. There is obviously a very marked difference between the occurrence of the high-level water in the Kau District, where the water merely seeps over the ash beds, and that of the high-level water in the Waiahole country, where the porous lava rock was originally saturated to a depth of at least 150 feet and the perched water gushed out in great volume when openings were artificially made in the containing rock walls.

Doubtless the heavy rainfall on the crest of the Koolau Range is a requisite for the large supply of high-level water, as well as the dike system. Large perennial high-level springs, comparable to those on the windward side of the Koolau Range, are also found on the humid windward sides of Molokai and of the Kohala Mountains in Hawaii. The heavy rainfall is certainly one of the requisites of these springs in both areas, but investigation will probably show that these areas also have definite rock structure which holds up the water. The general topographic and structural relations suggest that they may be ancient centers of extrusion, riddled with dikes and sills. Some causal relations may, moreover, exist between the humidity and the dike structure. Thus faulting on a grand scale apparently exposed the dike-ribbed heart of the old Koolau volcano and at the same time produced the high escarpment that concentrated the rainfall over this dike zone. The erosion of the escarpment resulting from the heavy rainfall has tended further to expose the dike zone and to bring the perched water to light in large springs.

These conjectures lead to the question to what extent the extinct or active rift zones or centers of extrusion may be zones of high-level water, even where they have not been exposed by pronounced faulting and erosion and are not marked by large high-level springs. The question arises whether the rift zones on Hawaii, outlined in this paper, are favorable localities for finding high-level water, and, if so, whether it would be practicable to prospect any of these localities by tunneling or drilling. These possibilities were considered by Messrs. Stearns and Clark, especially with regard to the southwest rift zone in the Kau District, but the aridity of the area where the test would have to be made seemed to make the prospects too poor to warrant recommendation of the expensive prospecting that would be required.

WATER PERCHED ON OTHER STRUCTURAL FEATURES

There are doubtless many small supplies of high-level water that are not perched on any of the definite structural features that have been described. Large quantities of water percolate from the surface to the main water table. In the humid areas, where rain falls frequently and is temporarily held by the soil and vegetation and where the largest streams are perennial or nearly so, water must be seeping into the rocks and starting on its downward journey almost continuously. This water, on its way to the main water table, percolates through an indefinite number of lava flows and doubtless commonly follows certain more or less definite routes. Obviously there must be much retardation even in so permeable a rock as the extrusive basalt, tending to equalize the downward flow and to make it perennial though fluctuating greatly in amount. Hence, some seepage is to be expected in tunnels even where there is no special structure to produce a perched water body, and the complete absence of water in a tunnel is an indication that there is a relatively impermeable bed of some sort in the rock above the tunnel.

FUTURE INVESTIGATIONS OF GROUND WATER

The foregoing outline shows that there are still numerous problems of various kinds in regard to the ground-water conditions and prospects in the Hawaiian Islands but that there are now many available methods of effectively attacking these problems. It seems to me that one of the chief results of the investigation in the Kau District has been to develop a better understanding of the volcanic and other geologic processes that have produced the structure of the Hawaiian Islands and of the causal relations between this structure and the occurrence of the ground water. With this better understanding of the basal principles of the geology and hydrology of the islands it becomes possible to plan future investigations with more effective methods than have been available in the past.

In future ground-water investigations in the Hawaiian Islands the best results will, I believe, be obtained by carrying out the original program of making a comprehensive and detailed geologic and hydrologic survey of one unit area after another until the entire area of the islands is covered. These surveys should be made by geologists who are thoroughly trained in volcanology and who understand the distinctive character of the geology of these islands. Hasty work by geologists from the mainland who are accustomed to different geologic conditions will lead only to superficial and erroneous interpretation of Hawaiian geology and to unsatisfactory recommendations as to ground-water developments.

In making future surveys consideration should continually be given to the problem of finding ways of testing the ground-water conditions by relatively inexpensive tunneling or drilling that will give a reliable basis for more expensive developments.

GEOLOGY AND WATER RESOURCES OF THE KAU DISTRICT, HAWAII

By Harold T. Stearns and William O. Clark

Part I.—GEOGRAPHY AND GEOLOGY

By Harold T. Stearns

INTRODUCTION

LOCATION AND AREA

The Kau District[1] lies in the southern part of the island of Hawaii. (See pl. 2.) It is the largest district of the island, having a maximum extent of about 38 miles north and south and 35 miles east and west, and includes an area of about 1,023 square miles, or more than one-fourth the area of the island.

GEOGRAPHIC RELATIONS

The Kau District includes the crater and entire west half of Kilauea Volcano, a large portion of the summit crater of Mauna Loa, and nearly one-half of the great Mauna Loa dome. (See pl. 2.) On the south the district is bordered by the Pacific Ocean, on the north it rises to an altitude of 13,675 feet at the summit of Mauna Loa, on the east it rises gradually to the top of Kilauea, and on the west it is hemmed in by numerous cinder cones.

Many of the boats now calling at Honolulu make a stop at Hilo, the main port of the island of Hawaii, from which there is an interisland service to the other islands. Interisland freighters call at Punaluu and Honuapo, the two ports of the Kau District.

HISTORICAL SKETCH

The history of the Kau District is intimately connected with the history of the entire island. The Hawaiian Islands were discovered by Captain Cook in 1778. He called them the Sandwich Islands in honor of the Earl of Sandwich, who was at that time first lord of the British Admiralty. This name has since been abandoned. The

[1] In Hawaii a district is a legal subdivision comparable to a township.

native Hawaiian is Polynesian and is closely related to the Samoans, Tahitians, and Maori. Fornander[2] says that the Hawaiian Islands were "undoubtedly occupied by the Hawaiian branch of the Polynesian race as early as 580 A. D."

Ellis[3] has given a detailed description of the Kau District as he found it in 1823. At that time it was densely populated by natives who lived by agriculture and fishing. The head chief (alii) resided at Kapapala. Ruins of several abandoned Hawaiian villages are still visible on the coast. At the time of Ellis's visit the famous tabu system[4] had broken down, although kahunas or priests still had considerable influence. Human sacrifice was made on important occasions, and infanticide was a common practice. Ellis states that he had reason to believe that two-thirds of all the children born perished in this way.[5] The ruins of several of the ancient Hawaiian temples (heiaus) can still be seen in the district and their location is shown on Plate 1.

The traditions of the natives of Kau contain many references to the goddess of volcanoes, Pele. This is not surprising, in view of the fact that this district contains two active volcanoes which many times have sent lava flows over various parts of the district. Formerly natives passing the volcano Kilauea were accustomed to offer a twig of ohelo berries to their fiery goddess. This practice has not entirely disappeared.[6]

Since the settlement of the area by the whites the old Hawaiian customs have been rapidly disappearing. The grass huts of ancient Kau have disappeared, and at the present time the towns have electric lights and paved roads. The picturesque thatched villages have been replaced by modern buildings, and the dark-skinned natives are gradually being absorbed by other peoples. The importation of Chinese, Japanese, and Filipinos for labor on the plantations has given rise to a cosmopolitan population. Racial intermixture is common, especially between the Hawaiians and Chinese and the Hawaiians and Caucasians. The islands have become a veritable melting pot of races.

POPULATION

The total population of the Kau District in 1920, according to the United States census, was 4,028, and although the area is about twice

[2] Fornander, Abraham, Fornander collection of Hawaiian antiquities and folklore: Bishop Mus. Mem., vol. 6, pt. 2, p. 222, 1919.

[3] Ellis, William, Journal of a tour around the largest of the Sandwich Islands, Boston, 1825.

[4] For further information regarding the tabu system see Alexander, W. D., A brief history of the Hawaiian people, p. 48, New York, 1891.

[5] Ellis, William, Polynesian researches, vol. 14, p. 328, London, 1859.

[6] Stearns, H. T., The 1924 eruption of the Hawaiian volcano: Sci. Am., vol. 132, p. 242, 1925.

as large as any of the other eight districts of Hawaii, it ranks only sixth in population. The population of the entire island of Hawaii is 64,895, hence less than one-sixteenth of the population resides in the Kau District. The four principal villages are Pahala, Waiohinu, Hilea, and Naalehu.

INDUSTRIES

The chief industry in the Kau District is the production of sugar from cane, and next in importance is cattle raising.

Sugar industry.—There are only two sugar plantations in the district. The headquarters and sugar mill of the Hawaiian Agricultural Co. are in the village of Pahala, on the Volcano Road. The headquarters of the Hutchinson Plantation is at the village of Naalehu, and its sugar mill at Honuapo. From 18 months to 3 years is required for a crop of sugar cane to mature, the length of time depending upon the altitude. The cane is grown on the island of Hawaii at a higher altitude than on any of the other islands and possibly than anywhere else in the world. The record altitude of about 2,900 feet above sea level is held by the Hawaiian Agricultural Co., and at this altitude three years is required to mature a crop. The general practice on the island is to burn over a cane field before cutting it in order to destroy the dead leaves. This decreases the labor of stripping off the leaves. The cane is then cut at the level of the ground and transported to the mills, either by railroads or by flumes that are supplied with water from springs or tunnels on the slopes above the cane fields. In some places it is transported part way by water and then loaded on freight cars and hauled to the mills. However, the steep grade of the land in the Kau district apparently makes it impracticable to use railroads except in a very small portion of the area. Moreover, the economical use of railroads is more or less dependent upon the lack of water for fluming. The railroad between Naalehu and Honuapo was replaced by a flume in 1924 because of the increased water supply as a result of new development.

At the mill the cane is crushed by rollers and the juice extracted, boiled, and evaporated to sugar. The pulp left after the extraction of the juice is called bagasse. It is burned in the furnaces of the mills as fuel, and at some plants the bagasse and low-grade molasses furnish all the fuel required—an especial advantage in a region far from oil and coal supplies.

Stock raising.—Most of the land in the Kau District that is not planted to cane is used for grazing livestock. The Kapapala, Kahuku, and Keauhou ranches practically control the whole range. The range is partly covered by hilo (*Paspalum conjunctivum*) and maneanea (*Cynodon dactylon*), grasses of very poor food value.

These grasses, however, are being replaced by better ones, and it may not be long before the number of head of stock can be increased. At present cattle, horses, mules, asses, sheep, goats, and swine are raised in the district. These are named in the order of their abundance, but the cattle outnumber all the rest combined.

Coffee.—A small amount of coffee is grown in the Kau District. The coffee from the neighboring district of Kona is famous for its excellent quality and flavor. Because of its quality and the ease with which it is grown, this industry seems well worth encouraging.

Sisal.—During the World War, when prices were high, two sisal plantations were operated in the district, but they have since been unable to compete in foreign markets and have been virtually abandoned.

Fruits.—The accidental introduction of the Mediterranean fruit fly has destroyed some of the fruits of Hawaii, and laws protecting the mainland from the fly have placed prohibitions on the shipping of all fruits except bananas and pineapple. Neither pineapples nor bananas are grown commercially in the Kau District, although many varieties of bananas are easily grown for local consumption. The Los Angeles Steamship Co. is encouraging the banana industry of this area by making Hilo a port of call. The mango (*Mangifera indica*), perhaps the most delicious fruit of the island, is not grown commercially. The large tree is prized also for its shade and beauty. The mango usually ripens in July or August, although a few ripen at other times. The breadfruit tree (*Artocarpus incisa*), the ulu of the Hawaiians, thrives well in the Kau District and is used locally. Its fruit is very palatable and often reaches a diameter of 6 inches.

The papaya (*Carica papaya*) ranks next to pineapples and bananas in commercial value in the Hawaiian Islands. It has the general appearance of a melon and takes the place of the American canteloupe. The tree produces abundantly and when laden with fruit is often, to a newcomer, the strangest sight of the many new things on the island.

FAUNA

All the large mammals in the district have been introduced, and many of them have since gone wild. According to Bryan,[7] the largest land animal inhabiting the islands at the time of their discovery by Captain Cook was the Hawaiian rat. A native mouse was also common before the advent of white men. However, both the Hawaiian rats and mice may have originally come to the island accidentally on wrecks. The native bat appears to be the only natural mammalian inhabitant of the islands. Goats and pigs were introduced by Cook in 1788, and cattle and sheep by Vancouver from

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[7] Bryan, W. A., Natural history of Hawaii, p. 291, Honolulu, 1915.

California in 1794. Horses were introduced in 1803.[8] Deer have been introduced on some of the other islands and have multiplied rapidly.

Goats, cattle, and swine have multiplied rapidly from animals which early went wild until now they are pests. The writer estimated that there were 8,000 to 12,000 wild goats in the Kau District in 1924. Wild cattle and swine are common in the jungle and afford fine shooting. Burros have also gone wild.

The mongoose, introduced on Hawaii to exterminate the rat, has become a serious pest and has done very little to lessen the number of rats. Their brown weasel-like forms are often seen by even transient tourists. There are no snakes or harmful lizards in Hawaii.

The forests of the Kau District abound in birds. It is often stated that the native bird life has become nearly extinct owing to the introduction of the mynah bird (*Acridotheres tristis*), and for other reasons, but during his exploration of the jungles the writer found them teeming with bird life. The beautiful scarlet iiwi, elepaio, apapane, and amakihi were abundant. The native Hawaiian raven (*alala*) is frequently seen in the Kau forest, and it is interesting to note that its habitat is restricted to the Kau and Kona Districts, for some reason that is not apparent. It is a large bird, and its hoarse call coming suddenly from a limb overhead often startles one in the quiet of the forest. It is not gregarious nor a pest like the American crow.

FLORA

The flora of the Kau District has a great variety. The jungle includes several species of tree ferns, some of which reach a height of 40 feet. The gathering of the soft glossy, yellowish wool, called pulu by the natives, which is found at the base of the young leaves of the tree fern, was formerly an important native industry. The material was shipped to the United States and was used for filling pillows, mattresses, etc. The industry is now abandoned, because the pulu pulverized in the pillow to a fine dust which proved to be dangerous when breathed. In the lower forest zone kukui and ohia trees are plentiful. The oily nut of the kukui was burned for light in stone lamps by the native. The koa, or Hawaiian mahogany, is the common large tree in the upper forest zone in Kau. In the semiarid portions of the district the ohia and algaroba flourish. The algaroba is related to the common mesquite of the southwestern United States, much improved by its new surroundings. The beautiful, ever-blooming lavender bougainvillea and red hibiscus lend a brilliant touch of color to the green villages. Occasionally in the forest one finds beautiful beds of nasturtiums, begonias, and fuchsias

[8] Bryan, W. A., op. city., p. 295.

that have run wild from some dwelling. The bright scarlet bells of the fuchsia add much to the beauty of the drive from Volcano House to Halemaumau. In the Kau District there are several hedges of the night-blooming cereus, with its huge creamy-white blossoms whose glory fades with the appearance of dawn.

HAWAII NATIONAL PARK

The Hawaii National Park, approved by Congress August 1, 1916, was formally accepted by the Federal Government in July, 1921. The Kilauea section, including the crater of Kilauea and a portion of the Kau Desert, comprises an area of 79,265 acres, most of which is in Kau. The geology of this section is shown on Plate 1. The volcano is accessible to tourists, and the Volcano House offers a comfortable abode for those who care to remain. Excursions can be made from the hotel to the features described in this report. The Mauna Loa section includes the caldera of Mokuaweoweo and a strip of land connecting it with Kilauea. It has an area of 17,740 acres, most of which is in the Kau District. Plate 3 shows the geology of this section.

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PREVIOUS INVESTIGATIONS AND LITERATURE

Many geologists have visited the active volcanoes Mauna Loa and Kilauea and described their activity in detail. In 1909 volcanologic investigations were begun at Kilauea by the Massachusetts Institute of Technology, and in 1912 an observatory was constructed at Volcano House, on the rim of the caldera. T. A. Jaggar, jr., who first conceived the idea of the observatory, was placed in charge, and his researches have received world-wide recognition. In 1919 the Hawaiian Volcano Observatory and its staff were made a part of the United States Weather Bureau, and in 1924 it was transferred to the United States Geological Survey.[9]

In 1920 O. E. Meinzer, L. F. Noble, and W. O. Clark, of the United States Geological Survey, made a reconnaissance of the Kau District with a view to determining the possibilities of developing ground water. They recognized that there were three important geologic formations in the district. In 1923 Washington [10] gave a description of the three formations based on an unpublished memorandum by Noble and Clark to the United States Geological Survey. In 1924 the writer spent about seven months in the Kau District and began the first detailed geologic mapping on the Island of Hawaii. In this period most of the district was mapped geologically on the scale of 1:31,680, with 10-foot contour intervals, and a reconnaissance was made of the high slopes of Mauna Loa. The results of this geologic

[9] For a more complete history of the observatory see Report of the Hawaiian Volcano Observatory, January–March, 1912.

[10] Washington, H. S., Petrology of the Hawaiian Islands, II, Hualalai and Mauna Loa: Am. Jour. Sci., 5th ser., vol. 6, p. 119, August, 1923.

mapping are shown on Plates 1 and 2.[10a] The topographic maps greatly facilitated the geologic work and are remarkable for their representation of many of the volcanic features of the district.

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PHYSIOGRAPHY

VOLCANIC FORMS OF ACCUMULATION

VOLCANIC CONES

MAUNA LOA

Mauna Loa (Hawaiian, "long mountain") rises 13,675 feet above sea level in the form of an oval dome about 60 miles long and 30 miles wide, with its long axis in a northeast-southwest direction. Together with the smaller cone of Kilauea, it forms the entire southern half of the island of Hawaii. (See pl. 2.) On the summit of Mauna Loa is the crater Mokuaweoweo. Most of the northern slope is covered with recent lava flows, and much of it is devoid of vegetation because of the semiarid conditions that prevail there and the general absence of soil. About 14 miles north of the summit the lava flows of Mauna Loa and Mauna Kea (Hawaiian, "white mountain") unite to form a plateau. To the northwest rises the cone of Hualalai. and the lava beds from that cone merge southward and eastward with those from Mauna Loa. The western slope of Mauna Loa has an average gradient of 680 feet to the mile. Near the sea the gradient is much steeper, and in some places an abrupt cliff (or "pali"), several hundred feet high, forms the shore. This escarpment is particularly well developed at Kealakekua Bay and is thought to be due to faulting. The western slope lies in the belt of the westerly winds and abundant rains and hence is covered with dense vegetation up to about 7,000 feet above sea level.

The southern and southwestern slopes of Mauna Loa have a far gentler gradient than the western, for the average is only 400 feet to the mile. Most of these slopes are covered with recent lava flows. The southwestern slope is a ridge studded with cinder cones and is barren except for a small strip of forest between altitudes of 2,000 and 4,000 feet. The continual outpouring of basalt in this region has extended the island southward and formed Kalae, or South Point.

The southeast side of Mauna Loa has an average slope seaward of about 680 feet to the mile, similar to the west side of the mountain. Likewise, near the coast the steep slope changes to nearly vertical cliffs and because it lies in the path of the moist trade winds is covered with vegetation. It differs from the west slope in that it is partly carved into stream valleys. In the belt of land that lies between altitudes of 1,500 and 6,000 feet the vegetation is so dense that it is a veritable jungle and is known as the Kau Forest. Both of the sugar plantations and most of the settlements in the Kau District are on this southeastern slope. This slope of Mauna Loa merges northeastward into the southwest slope of Kilauea Volcano. The cone of Kilauea rises only 4,040 feet above sea level, and because of its location and less height it is often inundated by lava flows from its higher neighbor, Mauna Loa. This process has continued so long that the northern slope of Kilauea, except for a radius of about 2 miles, is buried beneath Mauna Loa lavas, and it seems not at all unlikely that within the next century a lava flow from Mauna Loa will pass over the top of Kilauea and discharge into its crater.

There are three trails leading to the summit of Mauna Loa. The Ainapo trail, the most direct and the steepest trail, ascends the southeast slope starting from Ainapo, 12 miles southwest of Volcano House. On this trail at an altitude of about 7,950 feet is Keneki station, where there is a water tank and unoccupied shelter—a convenient stopping place. (See pl. 2.) At the present time this trail is little used, because a new trail has recently been constructed from Volcano House to the summit by way of Puu Ulaula (Hawaiian, "red hill"). It is customary, when ascending the mountain, to stop over night at the Halfway House, near this hill. The third trail, which is seldom used, leads up the western slope from Kona.

The profile of Mauna Loa differs from that of most other volcanic mountains in that it is convex near the summit and concave near the base. (See pl. 4, *A*.) In ascending the Ainapo trail the traveler obtains the last view of the ocean while he is still 2 miles from the crater rim, because of the relatively flat summit. In fact, there is no place on the rim of the crater, the highest part of Mauna Loa, where one can look down on the coast below. The summit is not actually flat, however, for it has a slope of about 300 feet to the mile for a radius of 2 miles.

Because Mauna Loa is built over a great fissure in the earth's crust, it has an oval shape, with the long axis of the mountain coinciding with the long axis of the original fissure. The dome is asymmetrical because the flows have welled out of fissures on its flanks, as well as from Mokuaweoweo, the summit crater. These outpourings of lava have taken place in well-defined narrow zones. In general the sources of the eruptions on the south half of the mountain have been limited to a zone about 3 miles wide which extends from Kalae in a northerly direction about 18 miles to the prominent cone called Puu Keokeo, at an altitude of 6,870 feet, and thence N. 30° E. to Mokuaweoweo. After crossing Mokuaweoweo this zone of eruptions extends down the north side of Mauna Loa. At the north rim of Mokuaweoweo, where the zone leaves the floor of the crater, it forks, and a branch to the northeast forms the northeast rift zone of Mauna Loa. This northeast zone is fissured with open cracks and has been the source of most of the historic eruptions on the north side of the mountain.

These rift zones are believed to coincide with deep-seated fissures, and the convexity of the upper portion of the profile of the dome of Mauna Loa is due to the fact that most of the eruptions come from these zones part way down the slope rather than from the summit crater. The concavity of the lower slopes is due to the fact that as the diameter of the cone increases a larger number of lava streams than at the summit is necessary to make a complete covering on its outer surface. The smaller number of flows per unit area causes a flattening of the outer slopes of the cone.

The Kau District comprises all of the region between the southwest and the northeast rift zones of Mauna Loa. (See pl. 2.)

KILAUEA

The volcano Kilauea forms a dome 4,040 feet high on the southeast slope of Mauna Loa. On the summit is a caldera (see p. 49) about 2 miles in diameter, within which lies the active crater of Halemaumau (Hawaiian, "house of everlasting fire"). Except for about 4 square miles the northern slope is buried beneath the lava beds of Mauna Loa. The eastern slope extends about 30 miles to East Point, where it passes beneath the sea. It has an average gradient of about 135 feet to the mile and hence is much less steep than any of the slopes of Mauna Loa. The distance from the summit crater to the ocean on the south side of the mountain, however, is only 10 miles, and the slope, although gentle near the top, is broken by vertical cliffs over 1,000 feet high near the coast. The western slope of Kilauea is partly buried by the lava flows from Mauna Loa. Southwestward from the crater the slope extends 20 miles to the sea. This slope is much steeper than the eastern slope, but is not broken by cliffs like the southern slope.

Kilauea, like Mauna Loa, is built over a definite fissure system, which is represented on the surface of the cone by rift zones fissured with cracks and studded with cones and craters. A prominent rift zone consisting in part of a shallow graben extends southwestward from Halemaumau to the sea. Numerous craters and fissures of this zone have poured out lava in recent time. Southeastward from Kilauea crater a rift zone, from 1 to 2 miles wide, extends for a distance of about 8 miles. It then makes an abrupt turn to the northeast and continues for 26 miles to East Point, forming the northeast rift zone of Kilauea. Because the amount of lava extruded from this rift zone has greatly exceeded that from the southwest rift, Kilauea has a long, gentle slope to the east and an elongation of the cone in that direction.

The entire western half of Kilauea lies in the Kau District.

SECONDARY CONES

Numerous cones, ranging in height from a few feet to several hundred feet, stud the rift zones of Mauna Loa and Kilauea. Most of these cones consist of lava spatter and cinders and are formed over vents. These are adnate cones, for they are intimately connected with the internal structure of the volcano and are alined in definite patterns along rifts. Their origin is discussed in detail on pages 120–125. There are also tuff cones, found only at the coast, which are formed by explosions resulting from lava flows entering the sea. These cones, sometimes called adventive cones, have no relation to the internal structure of the volcano.

The conspicuous secondary cones occurring on the southwest rift zone of Mauna Loa north of the Volcano Road, which encircles the island, are Puu Akiki, Ihuanu, Halepohaha, and Keokeo. South of the road, along the seashore, are numerous tuff cones, notable among which are Puu Hou, formed where the lava of 1868 entered the sea (see pl. 1), and the hills of Pele (Na Puu a Pele), 8 miles to the east (see pl. 2). The northeast rift of Mauna Loa is covered with secondary cones, which appear like pimples on the bulky dome. The more prominent of these are Puu Ulaula, Kulua, Laau, and Kulani.

Adnate cones on Kilauea are limited to the rift zones. On the coast are a few adventive cones that were formed by lava flowing into the ocean. Arranged in order of distance southwest from the crater the principal secondary cones are Cone Peak, Koae, Kamakaia Hills, Ulaula, and Kolekole. (See pl. 1.) The largest cones on the southeast rift are Puu Huluhulu and Kani Nui o Hamo. Heiheiahula, Illewa, Kaliu, Honuaula, and Kapoho are the most prominent of those on the northeast rift.

LAVA FLOWS

The lava flows of Mauna Loa and Kilauea consist entirely of basalt and are of two kinds, pahoehoe and aa. Pahoehoe is smooth and billowy; aa is bristling and jagged. (See pp. 108–112.) At the time of extravasation the lava had various grades of viscosity, depending upon its temperature, composition, and gas content. The temperature of the lava at the points of extrusion ranges from about 1,000° to 1,200° C. The gradient at which the lava will flow depends on the viscosity and the copiousness of the lava. Some of the lava is sufficiently fluid to move forward over practically level land. Very viscous lava, in falling over a precipice, will form an avalanche of more or less solid blocks, whereas a fluid basaltic lava will fall in the form of cascade, somewhat similar to water. (See pl. 4, *B*.)

During an eruption the lava running down the sides of a cone may leave island-like areas of the older land surface ranging in size from a few square feet to a square mile or more. Such a portion of older land exposed within a lava flow is known in Hawaii as a kipuka (Hawaiian, "the hole"). The land in a kipuka may be lower or higher than the surface of the lava bed surrounding it. Kipukas are caused by topographic irregularities or merely by the viscosity of the flow. Russell[11] has given the name "steptoe" to island-like areas that rise above the surface of the surrounding lava field. His definition of this term, however, does not include areas of old land which lie lower than the surrounding lava field, such as many of those in Hawaii. Because of the etymology of the term "kipuka," its general use on the United States Geological Survey topographic maps of Hawaii, and its adaptability to these areas, regardless of their altitude, that term is used in this report.

Lava flows that issued from the southwest rift zone of Mauna Loa in 1868, 1887, and 1907 crossed what is now the Volcano Road in the western part of the Kau District. Farther west, in the Kona District, is the lava flow of 1919, which issued from a fissure about 8,000 feet above sea level in the Kau District. The flows of 1832 (?) and 1916, which issued from fissures in this same rift, do not extend to the Volcano Road. (See pl. 1.)

Numerous flows have issued from the northeast rift of Mauna Loa in historic time, but those of 1852 and 1880–81 are the only ones in the Kau District. (See pl. 2.)

[11] Russell, I. C., Preliminary report on the geology and water resources of central Oregon: U. S. Geol. Survey Bull. 252, p. 78, 1905.

Several outpourings of lava have been extruded in historic time from the southwest rift zone of Kilauea. In this zone are the flows of 1823, 1868, and 1920. (See pl. 1.) The lava flows on the southeast rift zone have been small in volume, and all except those of 1832 and 1868 in the crater of Kilauea Iki, 1 mile east of Kilauea crater, have been outside of the Kau District. A detailed description of the historic flows will be found in the section entitled "Geology."

VOLCANIC FORMS OF SUBSIDENCE

CALDERAS

The term caldera is defined by Page[12] as "a Spanish term for the deep caldron-like cavities which occur on the summits of extinct volcanic mountains and islands and are evidently the extinguished craters of ancient volcanoes." This term has been used to include everything from a crater of large size to a circular depression essentially due to erosion by streams. Daly,[13] after discussing at length the use of the term, suggests limiting it to amphitheatral or circular basins of considerable size formed by a volcanic explosion. He then introduces the name "volcanic sinks" for basins of similar size and shape due to subsidence. One objection to the term "volcanic sink" is the diverse use of the word "sink." Moreover, on many volcanic mountains, especially on Kilauea and Mauna Loa, there exist numerous circular pits due to the collapse of the roofs of lava tubes or tunnels. There are also larger pits which are holes fluxed and stoped by magma in the land mass. Generally the former, and sometimes the latter, are referred to as sinks, or sink holes; hence the introduction of the term "volcanic sink" for a caldera of subsidence is confusing. Without detailed field work, it is usually difficult to determine the origin of a caldera, and therefore it is desirable to retain this word in its generic sense as meaning a circular or amphitheater-shaped depression on a volcanic mountain. Instead of including in the definition the process by which the depression was formed, an adjective can be placed before the term when it is wished to indicate the process. For instance, "explosion caldera" can be used for a caldera formed by explosion, and "collapse caldera" for one formed by subsidence.

MOKUAWEOWEO

Mokuaweoweo, the summit caldera of Mauna Loa, has a circumference of 9.5 miles. It is 19,500 feet long and 9,200 feet in greatest width, and has an area of 3.6 square miles.[14] Within this caldera is

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12 Page, David, Handbook of geological terms, geology, and physical geography, p. 125, 1865.

13 Daly, R. A., Igneous rocks and their origin, pp. 144–147, 1914.

14 Wood, H. O., Effects in Mokuaweoweo of the eruption of 1914: Am. Jour. Sci., 4th ser., vol. 41, p. 385, 1916.

a central crater having an area of 2.3 square miles and a depth of about 600 feet. (See pl. 3.)

A geologic and topographic reconnaissance of Mokuaweoweo was made in August, 1924. The Hawaiian government map of 1885 was used as a base, because the general outlines of the caldera have not materially changed since that time. The altitude of 13,440 feet at the stone monument, or "ahu," at the head of the Ainapo trail was used as the base. The mapping was done in one week on the scale of 2 inches to the mile on an enlargement of the Hawaiian government base map, with the assistance of Charles Stone, jr. All fissures, spatter cones, cinder cones, pit craters (see p. 50), faults, water and ice holes, trails, and fumaroles in the vicinity of the caldera were mapped. The areas of old and new lava were also sketched on the map. However, after the writer left the field an excellent topographic map was made by Edward G. Wingate, of the topographic branch of the United States Geological Survey, and the writer has since transferred the geologic boundaries to the new topographic base. (See pl. 3.) The geologic boundaries are probably not as exactly located as they would have been if this base map had been available at the time the work was done in the field. The map will serve as a useful base for recording changes in the features and altitude of the floor of the caldera. All the maps made before show the floor altitudes considerably lower, which doubtless indicates that the crater floor has been filling up. However, the figures for cliffs on the older maps are probably somewhat too large because of poor barometric determinations and perhaps poor estimates.

Clear and practically cloudless weather continued throughout the writer's sojourn at the summit, although mild winds blew during most of the days. On August 22 and 23 cirrus and cumulus clouds drifted in from the west. One-eighth to 1 inch of ice froze every night on the water holes on the rim. On August 22 there was 1 inch of ice. At 6.30 p. m. on August 24 a thermometer registered 37° F., and the temperature fell rapidly all night.

During the entire time at the summit avalanching of rocks from the walls was common, especially on the east side, and made climbing in and out of the great caldera dangerous. At 12.10 a. m. August 23 two smart earthquake shocks were felt in quick succession. The first shock had an intensity of IV on the Rossi-Forel scale, and the second one an intensity of VIII or IX. The camp was 40 feet from the rim, at the head of the Ainapo trail, and when the earthquakes occurred tons of rock avalanched from the wall in front of the camp, sending up a cloud of dust that was clearly visible in the starlight. Other avalanches were heard thundering to the bottom of the caldera at various places on the rim, especially a short distance northeast of the camp. In the morning the pass to the floor, a quarter of a mile northeast of the camp, was no longer recognizable. A thin section of the rim had fallen down and left a vertical cliff, and a new crack several hundred feet long and over a foot wide had opened a few yards from the brink of the rim. Avalanching was frequent all that day, especially at East Pit.

The principal scene of eruptions in Mokuaweoweo is a fissure zone about 1½ miles long which extends northeastward from the southwest side of the main crater. In this zone lie dozens of cinder cones that form cone chains and are known as Na Puu Waenakonu (Hawaiian, " the hills in the center of the crater "). (See pl. 12, *A*.) The highest cone in the zone rises nearly 100 feet above the adjacent lava fields on the floor of the caldera. This cone was formed during the eruption of 1914[15] and is still steaming. Southwest of this cone is a small crater in which a lava lake existed in 1903 (?). The south wall of this crater is covered with a thin veneer of vesicular lava, which is solidified spatter from the lava lake. (See pl. 12, *B*.) Northwest of the cone is a field of hot khaki-colored pumice from which dense blue sulphur fumes ascend. A few feet north of this pumice is a depression 15 to 20 feet deep which is covered with smooth pahoehoe. A few islands of aa project through the pahoehoe, and aa is visible in the cracks. (See pl. 13, *A*.) The cakes of pahoehoe on the sides of the island indicate that the crust of the former lava lake subsided after partly cooling. Heat radiates from the cracks in the floor and rim of the crater, although the latest recorded activity of the crater was in 1914. This little crater with its lake of solid lava was, when liquid, similar to the lava lake of Kilauea. The islands of aa are cooled epimagma (see p. 108) and formerly floated in the lava like the crags in the lake of Halemaumau. Northeast of this lake is a line of driblet and pumice cones 10 to 75 feet high. (See pl. 5.) Near the large cone formed in 1903 are the remains of another lava lake. On the west side of this lake is a hot solfatara which is depositing crystalline sulphur.

This fissure zone passes from the floor over the terrace on the south side of Mokuaweoweo, up to the rim of the caldera, and southwestward down the slope of Mauna Loa. The fissure that feeds the cone chain on this terrace is visible in the caldera wall. On the edge of the caldera rim about 200 feet above the terrace is a small driblet cone. When the eruption ceased the lava cooled in the fissure and now forms a dike in the caldera wall. This dike is unusual because it was formed with only three sides of it inclosed by country rock. Southwest from the caldera rim is a line of driblet cones which poured out lava that cascaded down the vertical wall of the

[15] Wood, H. O., Am. Jour. Sci., 4th ser., vol. 41, pp. 383–407, 1916.

caldera and spread out on the floor. This is a remarkable example of the way in which the heavy basaltic magma of Hawaii is buoyed up by gases to very uneven levels, for during this eruption lava was extruded at the same time and from the same fissure on the rim of the caldera, at 13,325 feet above sea level, and on the caldera floor, 300 feet below.

The floor of the caldera is covered with aa and pahoehoe, much of which has been laid down in historic time. The surface of the more ancient lava beds is brown, in contrast with the glistening black of the historic flows.

The peculiar outbursts of lava at different altitudes regardless of the floor of Mokuaweoweo, so well illustrated by the fissure eruptions described above, constitute positive proof that the lava exists in fissures. Furthermore, they indicate that the lava column is not proportionate to the size of the caldera. The molten magma, once it starts upward in a fissure, does not change its course until it reaches the surface, unless its advance is seriously interrupted by leakage into intersecting fissures. Moreover, the altitude of the place at which the fissure intersects the surface does not seem to matter. Whether the fissure opens into loose rock débris or intersects a vertical cliff, the effect is the same. If the magma rises through talus it is chilled sufficiently to bridge the gaps between the talus blocks and thus form confining walls of glassy basalt which are sufficiently impervious to prevent further magma leakage. This explanation accounts for the several fissure eruptions issuing in the talus high above the floor of Mokuaweoweo.

The caldera of Mokuaweoweo is due to subsidence, for its walls are bounded by active faults. Mokuaweoweo is a classical example of a mature caldera on the summit of a basaltic dome. In the youthful stage of such a dome a superfluent vent exists. Gradually, with the approach of maturity, superfluent discharges become less frequent, and one pit crater after another is fluxed and stoped in the summit of the dome along the rift zones. With maturity, the walls separating the pits slowly break down, forming one large depression on the summit. Mokuaweoweo is an excellent example of this stage, for it shows clearly its formation by the collapse of the walls between the summit pit craters. There still remain, however, the craters of Hohonu and Hou, which have not been united to the caldera. At old age, with its accompanying faulting and floor fills, the outlines of the several pits probably will be obliterated and one great elongated caldera will be formed.

KILAUEA

Kilauea, the summit caldera of Kilauea Volcano, is 7.85 miles in circumference, 2.93 miles (15,500 feet) long from north to south, and 1 95 miles (10,300 feet) wide from east to west, comprising an area of 4.14 square miles.[16] It is nearly 500 feet deep near the Volcano House, which is on the north rim. (See pls. 1 and 6, *B*.) In the southwestern part of the caldera is the active crater of Halemaumau, which is usually occupied by a lake of boiling lava. Since the explosive phase of Kilauea Volcano in May, 1924, Halemaumau has been a yawning, steaming pit about 3,400 feet in diameter and 1,300 feet deep. The floor of the caldera is covered with fresh flows of pahoehoe and aa and is encircled by nearly vertical fault cliffs.

Dutton [17] early recognized that the caldera was due to collapse, for it is bounded by well-defined faults. Moreover, the absence of any considerable ash surrounding the caldera or interstratified with the lava beds in Kilauea shows that this depression is not due to explosions. The caldera is not bounded by one single circular fault but by a series of curved faults, which in some places, because of differential movement of the fault blocks, form a terraced escarpment.

PIT CRATERS

Pit craters occur on both Mauna Loa and Kilauea. They are deep circular depressions bounded by vertical walls in a relatively smooth lava plain. The lava beds exposed in the walls do not dip away from the pit and hence were not extruded from the crater. In this respect a pit of this kind differs from the crater in the top of a cone, where the lava beds in the walls slope away from the crater. Pit craters are fluxed and stoped in the general land mass by the magma.

Pit craters range in diameter from a few feet to about 1 mile and in depth from 50 to several hundred feet. Keanakakoi, a typical pit crater, half a mile southeast of the Kilauea caldera, is shown on Plate 6, *B*. A chain of five pit craters lies south of the Volcano Road in the southwest rift zone of Mauna Loa, near the Kahuku ranch. Three pit craters of this group—Lua Palalauhala, Lua Poai, and Lua Puali—are shown on Plate 1. The pit craters on Kilauea and Mauna Loa are described in detail on pages 127–129.

FAULT SCARPS

Fault scarps are so numerous in the Kau District that only the more prominent ones will be described.

MAUNA LOA

Kahuku fault scarp.—Extending northward 10 miles from Kalae to the Kahuku ranch is a vertical fault escarpment which in places

[16] Bryan, W. A., Natural history of Hawaii, p. 165, 1915.

[17] Dutton, C. E., Hawaiian volcanoes: U. S. Geol. Survey Fourth Ann. Rept., p. 105, 1884.

is 600 feet high. On Plate 1 it is shown as Pali o Kulani and Pali o Mamalu. For convenience in this report it will be called Kahuku Cliff, the name commonly used by the white people of the region. The fault scarp faces west, the block of lava on that side having subsided with reference to the block on the east.

Half a mile north and 1 mile east from the Kahuku ranch there begins another fault escarpment, which extends northward for about 3 miles with a height of 250 feet. It is shown on Plate 1 as Pali o Ka Eo. This escarpment is the échelon extension northward of the Kahuku fault.

Waiohinu fault scarp.—The Waiohinu fault scarp is near the village of Waiohinu on the Volcano Road, about 5 miles east of the Kahuku ranch. From the Volcano Road half a mile west of Waiohinu it extends southeastward 4½ miles to Waikapuna Bay. The last movement on this fault plane occurred in 1868. Its long, complicated history is given at length on pages 92–94.

Kaoiki fault scarp.—The Kaoiki fault scarp begins 2 miles northeast of Volcano House near the Kau-Hilo boundary, extends southwest 18 miles, and disappears beneath recent lava beds. The Volcano Road from the Kilauea caldera to the village of Pahala skirts the base of the escarpment. It is shown on Plate 1 as Kaoiki Pali. The cliff rises in places 500 feet above the slopes of Kilauea, and although lava flows from Mauna Loa have cascaded over it and down the slopes of Kilauea, yet the cliff still forms essentially the boundary between the two domes. The escarpment has a terraced appearance due to movement along a series of parallel fault planes.

KILAUEA

Hilina fault scarp.—A seaward-facing cliff known as Hilina Pali, 7 miles due south of Halemaumau and about 2 miles from the ocean, was formed by faulting. (See pl. 1.) It has a vertical height of 1,500 feet in one place but in general is about 1,000 feet high. It originates 3½ miles east of the Kau-Puna boundary as a branch of another large fault escarpment. (See pl. 1.) Where it crosses the Kau boundary it is known as Poliokeawe Pali. It trends southwest from the boundary for 10 miles and finally dies out in a steep slope shown on Plate 1 as Kukalauula Pali. This steep slope is due to the branching of the main fault into numerous minor faults, fan-fashion, which die out westward. Lava flows originating in the southwest rift zone have buried these small faults. The scarp, however, shows the effects of recent movement.

Kapukapu fault scarp.—Two miles south of the Hilina fault scarp and parallel with it is a prominent fault scarp over 1,000 feet high and 4 miles long which faces seaward and forms the coast line for a distance of 2 miles. Puu Kapukapu is a horstlike hill on this scarp. (See pl. 1.) A block diagram showing the Kapukapu and Hilina escarpments forms Figure 1.

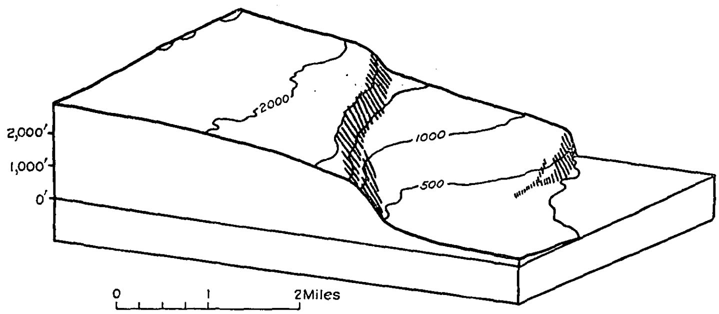


FIGURE 1.—Diagram showing the Kapukapu and Hilina fault escarpments on the south side of Kilauea. (After C. K. Wentworth)

VALLEYS

GENERAL FEATURES

The formation of soil by the weathering of basalt is a slow and quite insignificant process in the Kau District, because practically all the ancient lava beds are heavily mantled with a thick ash deposit and the more recent lava beds remain only a relatively short time at the surface before they are buried by fresh flows. Thus weathering rarely continues long enough in Kau to form an inch or two of soil on a bed of basalt before it is covered by a later flow. This lack of soil cover and the porous condition of the basalt, combined with the frequent displacement of the streams from their channels by lava flows, make stream erosion a slow process on the slopes of these active volcanoes. In fact, there is no stream in the Kau District that flows in a channel of its own making over 10 feet deep. However, in the past great valleys 2,000 feet deep were carved on the southeast side of Mauna Loa, indicating that there was a long period during which the volcano was in repose. These ancient valleys have since been partly filled by lava flows as a result of renewed activity on the summit of the dome. The flows have formed great fan-shaped areas of lava which have pushed out the shore line so that the ancient valleys lie entirely inland.

Wood Valley, one of these ancient valleys, is 15 miles southwest of Kilauea caldera, on the south slope of Mauna Loa. (See pl. 1.) It is the easternmost and shortest of the valleys on Mauna Loa in the Kau District. Three intermittent streams, Waiakaloa, Makakupu, and Peleliilii, occupy it at the present time. They flow only during heavy rains, and even then fail to reach the sea, 8 miles away, because of the porous basalt in their channels. Wood Valley is an amphitheater-headed valley about 1 mile wide and 1 mile long, bounded on three sides by precipitous walls in places over 1,000 feet high. In contrast to its steep walls is its smooth valley floor, which is farmed intensively. The axis of the valley trends N. 40° W., and the brink of the cliff at its head is 3,750 feet above sea level. This place is 4 miles from the Volcano Road and lies at the south side of the Kau Forest. (See pl. 1.) Formerly the valley was deeper, but numerous lava flows have cascaded over its walls and built up its floor. Moreover, a branch from the landslide of 1868 entered the valley and spread out on the floor. The western wall is called Ipuu Ridge. This ridge, or spur, has a precipitous cliff on its southwest side which formerly made the east wall of a valley parallel to Wood Valley. The numerous lava flows west of the spur, however, have entirely obliterated the other side of this ancient valley.

Five miles southwest of Wood Valley is another ancient valley called Moaula, in which is located Moaula Gulch. (See pl. 1.) The slope of Mauna Loa that lies between Wood Valley and Moaula Valley has been so often flooded by lava flows that any valleys that may have formerly existed there have been entirely obliterated. However, 1 mile northeast of Moaula Valley there is a small hill, called Alili, which is a small remnant of an ancient buried valley spur. Moaula Valley is an amphitheater-headed valley 1½ miles long and about half a mile wide. On the north and northwest is a precipitous wall which reaches a height of 2,000 feet at Kaumaikeohu Peak. Although the valley lies in the rain belt of the Kau Forest, 5½ miles from the sea, it is not due to erosion by the intermittent stream occupying Moaula Gulch but is an alcove on the northeast side of a much larger ancient valley now deeply buried and has been preserved because much less lava entered it. The outline of this larger valley is still preserved in the bordering hills, Kaumaikeohu, Puu Iki, Na Puu Kulua, and Enuhe Ridge. This ancient valley, now occupied by the intermittent stream called Punaluu, is 5 miles long and 2 miles wide. Although the numerous flows that have cascaded over its head wall have given the wall a much gentler slope, the former amphitheater at the head of the valley is still discernible. Puu Iki, the unburied portion of the head wall, lies 8½ miles from the sea. The axis of the valley trends approximately N. 40° W., parallel to Wood Valley.

Adjacent to Punaluu Valley and parallel to it is a similar ancient lava-filled valley now occupied by Ninole Gulch, in which an intermittent stream finds its way to the sea during heavy rains. (See pl. 1.) This valley, called Ninole, is about 5 miles long and 1½ miles wide. Its head wall has been so deeply buried by lava flows that only a steep slope remains. The sides of the valley still rise as cliffs above the lava fill and form parts of a series of ridges named Na Puu Kulua, Enuhe, Kaiholena, and Makaalia. Na Puu Kulua and Enuhe Ridges are unburied remnants of the former divide between Punaluu and Ninole Valleys.

To the southwest, parallel and adjacent to Ninole Valley, lies Hilea Valley, occupied by an intermittent stream. Fewer lava flows have entered this ancient valley than any of the others; hence its form is well preserved. Hilea Valley is 5 miles long, 1 mile wide, and, in places, 2,000 feet deep. The seaward end of the valley is now 2 miles from the coast because of the seaward extension of the land by lava flows since the valley was formed. Its axis trends N. 40° W. The valley is similar in shape to many of the box canyons in the arid portion of the United States. At its head is the steep wall Palimuku, which at the peak of Makaalia attains an elevation of 4,360 feet above sea level. The valley is bounded by Kaiholena Ridge, Makaalia, Puu One, and Kaalaiki.

In the Kau District west of Hilea Valley there are no valleys, ancient or modern, on the slopes of Mauna Loa, although the village of Waiohinu stands in a reentrant that probably marks the site of a short buried valley now filled with lava beds.

CAUSE OF AMPHITHEATER-HEADED VALLEYS

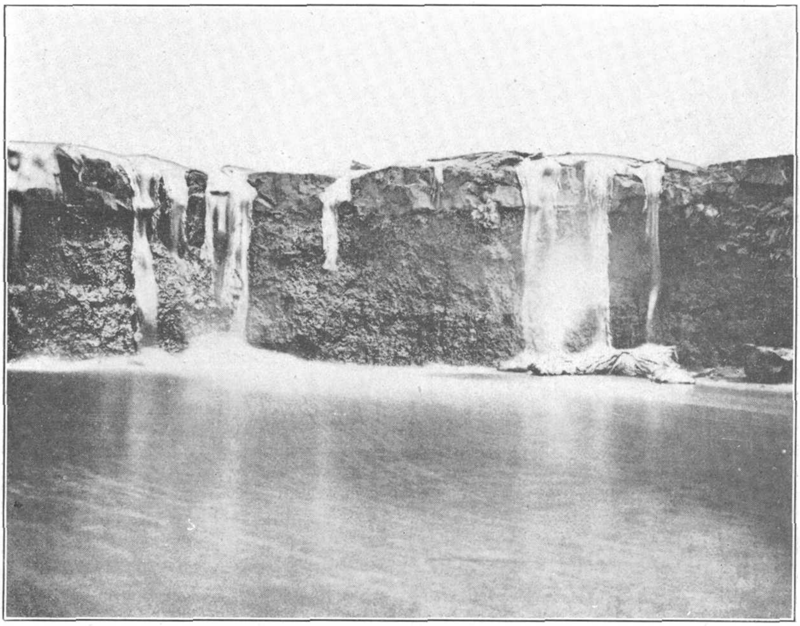
These ancient basalt-filled valleys on the south slope of Mauna Loa are unlike any of the usual valleys of the United States. The amphitheater-shaped heads and the steep side walls, which decrease in height seaward, are characteristic of the valleys of Hawaii. Moreover, the former divides, such as Kaiholena and Enuhe Ridges, have knifelike crests near the heads of the valleys, which change seaward to broad, smooth triangular spurs. This change in shape of the divide is due to the recession on the slope of a dome of two adjacent and enlarging amphitheater-headed valleys.

Amphitheater-headed valleys are common on other parts of the island of Hawaii and on several of the other Hawaiian Islands. They owe their origin primarily to the extremely permeable beds of the water table in a basaltic island, but the removal of the rock is effected chiefly by chemical weathering.

The extremely permeable condition of beds of basalt is due to the process by which they are formed. They contain innumerable open spaces of all sizes, including joint cracks due to shrinkage of the basalt at the time of cooling; vesicles and cavities due to the expansion of gases by release of pressure during the cooling process; tubes and caverns produced by liquid lava flowing out from under a hardened crust; interstitial spaces in cinders and aa lava formed in place;

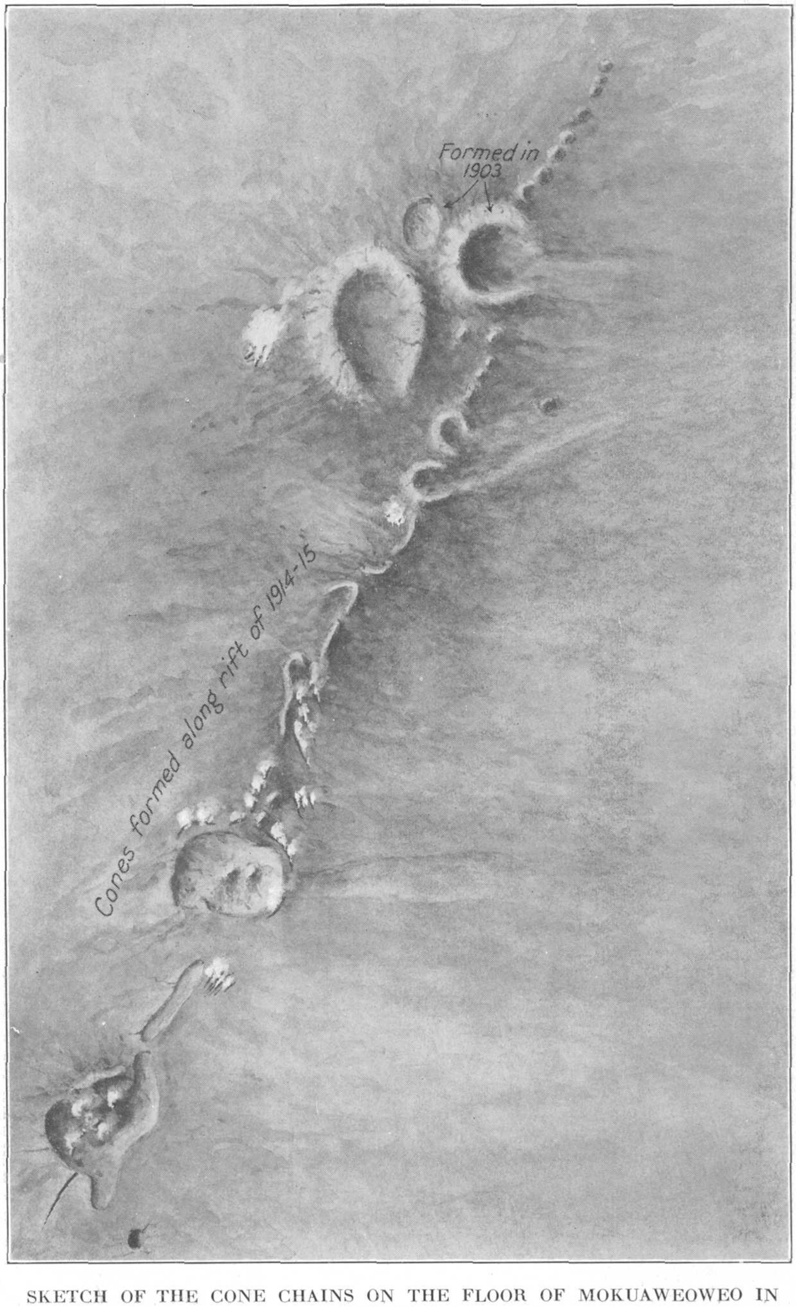
A. AIRPLANE VIEW OF MAUNA LOA FROM ALTITUDE OF 8,000 FEET

Photograph by Air Corps, War Department.



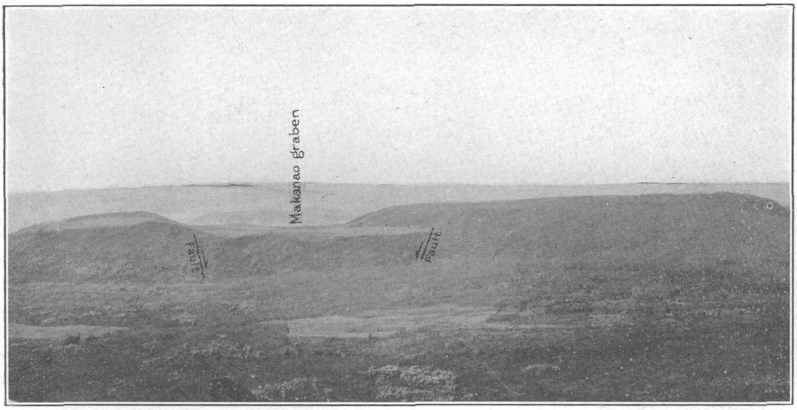
B. A WATERFALL NEAR HILO REPLACED BY A CASCADE OF FLUID LAVA DURING THE ERUPTION OF MAUNA LOA IN 1881

Photograph by I. Williams.



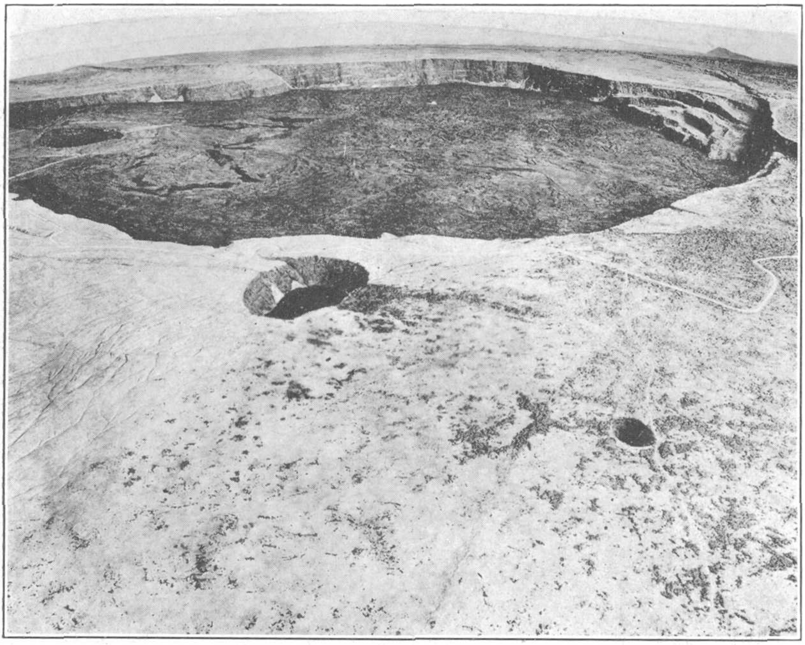
SKETCH OF THE CONE CHAINS ON THE FLOOR OF MOKUAWEOWEO IN AUGUST, 1924

Shows the position of steam vents Drawn by C. A. Weckerly from the notes of H. T. Stearns.



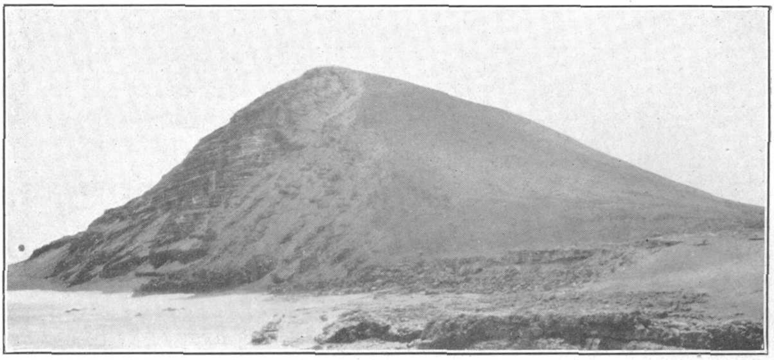
A. MAKANAO GRABEN, 1½ MILES NORTHEAST OF HILEA, FROM PUU ENUHE

Photograph by W. O. Clark.



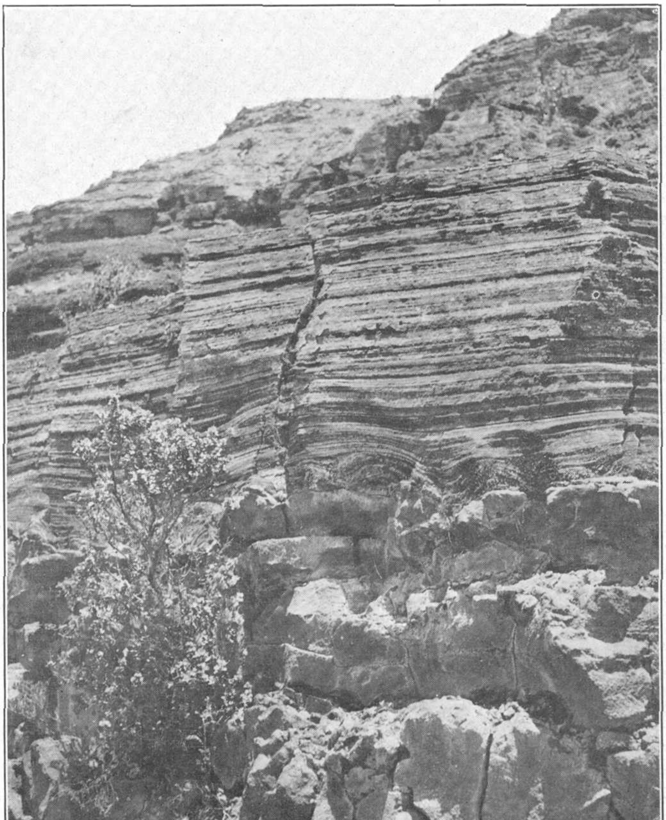
B. MODEL OF KILAUEA CALDERA WITH THE CONE OF MAUNA LOA IN THE BACKGROUND

The large pit crater in the foreground is Keanakakoi; the small one is Puhimau, on the Cockett trail. Photograph of model at Harvard University.



A. PUU HOU, THE TUFF CONE FORMED BY THE LAVA FLOW OF 1868 FROM MAUNA LOA ENTERING THE SEA

Cone is 273 feet high. Photograph taken June 14, 1924, by H. T. Stearns.



B. KAMEHAME ASH BED ON THE RIM OF KILAUEA CALDERA

Photograph by National Park Service.

large open spaces at the contact of one lava flow with another; and tree molds resulting from lava surrounding a tree and solidifying before the tree has burned away. Rain falling on the slope of a basalt cone like Mauna Loa or Kilauea disappears quickly into the openings. It is for this reason that there are no perennial streams in the Kau District. Although large floods often occur in the upper stretches of a stream, yet near the coast the channel is usually dry because of leakage into the basalt in its bed.

The increase of rainfall with altitude is less important than the permeable condition of the rock in the formation of amphitheater-headed valleys. However, the amount of water entering the upper course of a stream bed from springs is in direct proportion to the increase in precipitation, and the larger number of springs at the head of a valley, due to the increased precipitation, causes a larger amount of sapping there than in the lower stretches of the valley. This process of sapping is accelerated by the jointed, fractured character of the basalt.

Examples of amphitheater-shaped valleys are numerous along the Snake River between Twin Falls and the Malad River in Idaho. They are formed in this area by large springs emerging from porous basalt under conditions similar to those which exist in Hawaii, except that the source of the underground water is much farther away. The Blue Lakes alcove, an amphitheater-shaped depression with vertical walls over 200 feet high, near Twin Falls, Idaho, owes its origin to the sapping of jointed and porous basalt by a spring having a discharge of about 150 cubic feet a second.[18]

The form of the water table in a cone of permeable basalt is an important factor in the formation of amphitheater-headed valleys, because it is the outcrop of the water table that determines the location of the springs. In general the water table forms a low dome whose highest part lies under the area receiving the greatest amount of rainfall. Thus, in the Kau District, for the first 2 or 3 miles inland from the coast, the water table is nearly flat and lies close to sea level. It rises a little more rapidly in the next 5 miles, because the precipitation on the area above it increases greatly. Finally, because precipitation decreases on the upper side of the rain belt, the water table slopes northward, and under the summit of Mauna Loa it may be again near sea level.

The headward erosion of a stream progresses slowly at first because of the perviousness of the rocks, but gradually the stream becomes more permanent by tapping the underground water. If sufficient time elapses, and no interruptions occur as a result of lava

[18] Russell, I. C., Geology and water resources of the Snake River Plains of Idaho: U. S. Geol. Survey Bull. 199, p. 127, 1909.

flows or faulting, a short box canyon is formed. This accelerates the work of sapping, because as the canyon extends farther into the rain belt and is cut deeper it offers the easiest outlet for ground water. As this development progresses, more and more ground water finds its way into the upper end of the valley. This increases weathering and results in the draining of the saturated zone in the upper stretches of the valley, which causes the drying up of the springs in the lower course. This localization of the water supply and its accompanying weathering at the head of a box canyon forms the amphitheater-headed valleys so characteristic of Hawaii.[19]

EXPLANATION OF THE "MOHOKEA CALDERA"

In October, 1895, before the Social Science Association of Honolulu, J. S. Emerson, an engineer of the Hawaiian Trigonometrical Survey, described as a caldera a large depression on the southwest slope of Mauna Loa, and in 1902 his paper was published.[20] In 1902 Hitchcock read before the Geological Society of America a paper entitled "Mohokea caldera on Hawaii,"[21] and again in 1905 he presented a paper before the same society giving additional evidence that this depression was a collapse caldera.[22] He described it again in 1909.[23] In 1917 Powers[24] enlarged further upon the theory of the Mohokea caldera and stated that the peaks called Kaumaikeohu and Iki were probably cones. In another publication[25] he favored the idea that the ash deposits in the vicinity of the caldera and on the southern flanks of Mauna Loa resulted from explosions in this caldera. The caldera is described by Hitchcock as an elliptical depression 6 miles long from northwest to southeast and 5 miles wide, truncated on its seaward side by a fault. It is shown on his map[26] (taken from the Government map of Hawaii, 1901) as a horseshoe-shaped depression with a rim 300 to 1,500 feet high, in which rise the hills Na Puu Kalua and Puu Enuhe. Hitchcock stated that the extensive aa flows near Punaluu, a small village on the coast 3 miles from Puu Enuhe, originated in the Mohokea caldera and cited this fact as evidence of the existence of the caldera.

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[19] See also Wentworth, C. K., Estimates of marine and fluvial erosion in Hawaii: Jour. Geology, vol. 35, pp. 117–133, 1927.

[20] Emerson, J. S., Some characteristics of Kau: Am. Jour. Sci., 4th ser., vol. 14, pp. 431–439, 1902.

[21] Hitchcock, C. H., Geol. Soc. America Bull., vol. 14, pp. 6–8, 1903.

[22] Hitchcock, C. H., Mohokea caldera: Geol. Soc. America Bull., vol. 17, pp. 485–496, 1906.

[23] Hitchcock, C. H., Hawaii and its volcanoes, p. 149, 1909.

[24] Powers, Sidney, Tectonic lines in the Hawaiian Islands: Geol. Soc. America Bull., vol. 28, p. 610, 1916.

[25] Powers, Sidney, Explosive ejectamenta of Kilauea: Am. Jour. Sci., 4th ser., vol. 41, p. 242, 1916.

[26] Hitchcock, C. H., Mohokea caldera: Geol. Soc. America Bull., vol. 17, pl. 64, p. 486, 1906.

All these flows were carefully examined by the writer and found to have originated near the summit of Mauna Loa. They spilled into the upper portions of the ancient valleys and spread out as great fan-shaped areas of lava at their mouths. The fact that these flows are barren and fresh-looking near the coast and are covered with vegetation higher up in the rain belt probably led Hitchcock to think they had issued at the edge of the forest.

All the lava beds that exist in the walls of the so-called Mohokea caldera have a gentle dip to the southeast, a fact not at all in accord with the structure in other collapse calderas. Moreover, the circular or semicircular faults that bound a collapse caldera are absent. The peaks of Kaumaikeohu and Iki do not contain cinders, summit craters, lava beds with quaquaversal dips, or any other features characteristic of cones. Moreover, the ash beds do not thicken near the supposed caldera. They have a uniformly fine texture wherever exposed in the Kau District and do not contain coarse materials, such as bombs or blocks characteristic of an ash deposit near its source. It is concluded, therefore, that there are no valid reasons for a belief in the existence of the Mohokea caldera. When this region was carefully surveyed by the United States Geological Survey in 1921, no caldera was found. (See pl. 1.) It is probable that the partly filled ancient amphitheater-headed valleys of Moaula, Punaluu, and Ninole were mistaken by Hitchcock for a caldera.

PLAINS

A lava plain lies 2 miles south of the village of Pahala, at the mouth of Moaula Gulch. It has been made smooth by the deposition of alluvium from Moaula and Punaluu Gulches. This plain, shown on Plate 1 as Keoneeleele and Kanenelu Flats, covers about 4 square miles and has a seaward gradient of about 50 feet to the mile.

A relatively smooth plain covering about 25 square miles occurs on Mauna Loa at Kalae, the south point of Hawaii. This plain, shown on Plate 1 as the Kamaoa Homesteads, is a lava plain made smooth in part by thick ash deposits. It slopes southward to the sea at about 200 feet to the mile.

Much of the surface of the cone of Kilauea and part of the cone of Mauna Loa are relatively smooth and may be regarded as lava plains dipping gently seaward.

SHORE FEATURES

The coast of the Kau District lies largely on the leeward side of Kilauea and Mauna Loa and hence is rarely visited by storms. The results of wave work are insignificant in this area, because much of the shore line has been constantly lowered by faulting or built out by lava flows from the two volcanoes.

The activity of volcanism and faulting accounts for the absence in Kau of any pronounced eustatic bench, such as is described by Wentworth and Palmer [27] as occurring on the Hawaiian Islands. A bench 5 to 10 feet above sea level, covered with waterworn cobbles and blocks, occurs between Waikapuna Bay, 4 miles southeast of Waiohinu, and Kaalualu, 6 miles south of Waiohinu. (See pl. 1.) Although it corresponds in height above sea level to the eustatic bench described by these authors, it is not of eustatic origin but is due to uplift resulting from movement on the Waiohinu fault in 1868.

Along some parts of the shore of the Kau District there are large waterworn boulders, several hundred feet from the coast, which have been carried inland by the earthquake sea waves which so frequently inundate this coast.

No wave-cut cliffs occur on the coast of Kilauea in the Kau District. On Mauna Loa, however, from Honuapo village, 5 miles east of Waiohinu, to Waikapuna Bay, there is a sea cliff 25 to 150 feet high. Westward from Waikapuna Bay to the Kau boundary the shore of Mauna Loa is devoid of cliffs except for the Kahuku fault escarpment.

This portion of the coast, except for several miles where a thick ash bed meets the sea, consists of lava built out by recent flows. The absence of fossils in the ash bed at sea level suggests the subaerial deposition of the ash and the lowering of the land since the ash was deposited.

Sea mills, natural bridges, and many other interesting features are found on the coast. All these features owe their formation to original structures in the lava beds. For instance, lava tubes or caverns often give rise to natural bridges and spouting horns.

Sandy beaches occur only here and there on the coast of the Kau District and most if not all of them are due to the destruction of tuff cones formed where lava has entered the sea. Thus, near Puu Hou (Hawaiian, "new hill"), 4 miles northwest of Kalae, there is a large beach of black sand. When the lava flow of 1868 from Mauna Loa reached the sea at this place the contact of the hot lava with the water caused huge explosions, which formed the tuff cone Puu Hou, 273 feet high. (See pl. 7, *A*.) The cone consists largely of volcanic sand and because of its loose and unstable condition was rapidly cut back by the waves during the first few years of its existence. Wave work on this cone is much slower at the present time because the beds of volcanic sand in it are now partly consolidated. The waves have cut the cone in half and have redeposited the volcanic sand for several hundred yards along the shore.

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[27] Wentworth, C. K., and Palmer, H. S., Eustatic bench of islands of the north Pacific: Geol. Soc. America Bull., vol. 36, pp. 521–544, 1925.

A remarkable green beach, occurring 3 miles northeast of Kalae, is the result of the partial destruction by the waves of Puu Mahana, a tuff cone that consists largely of green olivine crystals.

EFFECTS OF WIND WORK

The Kau Desert comprises the western half of the cone of Kilauea. The island of Hawaii lies in the belt of the trade winds, which ascend the east slope of Kilauea, become chilled, and drop their moisture. After they pass over the top of the cone the cooling ceases, and in the descent they become drying winds. Thus, the windward side of the rim of the Kilauea caldera receives about 100 inches of rain annually, while the Kau Desert, on the southwest side, receives less than 15 inches. There are places on the coast of Kilauea where a whole year may elapse without rain.

In 1790 and 1924 Kilauea had explosions which spread ash over much of the Kau Desert. This ash, together with the ash from earlier explosions, has been piled by winds into dunes 10 to 30 feet high which migrate southwestward before the prevailing winds. The area of these dunes is shown on Plate 1 by the usual sand symbol.

About 1 mile south of the Kamakaia Hills, which lie 7 miles southwest of the Kilauea caldera, there is an area where dunes have migrated over a few ohia trees, leaving in their wake dead trees and fragments of wood.

South of Hilina Pali, on the coast of Kilauea, there is a narrow area of sand dunes which are being driven westward by the wind. The sand is derived mainly from alluvium deposited by intermittent streams that cascade over Hilina Pali. Sand storms frequently occur in this area. The general absence of sand dunes in the Kau District is due to the presence of fresh rock surfaces. However, wherever sandy beaches occur dunes migrating inland are found. A narrow area of low dunes extends inland for 2 miles from Waikapuna Bay. (See pl. 1.) A much wider area of dunes, many of which are grass covered, occurs 4 miles north of Kalae. In these dunes calcareous sand molds of roots and plant stems are found. Although no coral reefs exist along the coast of the Kau District, considerable coral sand and fragments of shells are washed ashore. It is this sand, migrating inland and forming an appreciable part of some of the dunes, that makes the calcareous molds.

Since the explosions of Kilauea in May, 1924, when a coating of fine ash was deposited over much of the Kau District, dust storms on the desert have been common. Some of these storms carry dust to an altitude of 6,000 feet and transport it many miles. Many of the rock surfaces are polished by the wind-blown sand, but the lava is relatively so recent in age that no other effects of wind erosion are observed.

STRATIGRAPHY

GENERAL CHARACTER AND AGE OF THE ROCKS

The difficulties of stratigraphic work in a volcanic country, where there are no water-deposited horizon markers, are numerous. The uneven thickness and peculiar distribution of the geologic formations in the Kau District, as shown on Plate 1, are due to the unavoidable use of a subaerially deposited ash bed as a horizon marker instead of the usual subaqueous deposit. Ash forms a layer over the entire surface regardless of its height or irregularities, and the dip of the ash bed is controlled by the slope of the rocks on which it was deposited. Thus, there may lie unconformably on the top of a ridge an ash bed 50 feet thick which was deposited during a period when several hundred feet of lava, as well as the same amount of ash, was accumulating in a near-by valley. Moreover, the extrusion of lava flows from Kilauea and Mauna Loa at different times and in varying amounts and the occurrence of lava beds from Mauna Loa on the southwest slope of Kilauea give additional complexity to the geologic development of the region.

The rocks in the district are all igneous and consist of beds of basalt, fragmental deposits, sills, and dikes. The beds of basalt range in thickness from a few inches to 75 feet, averaging about 10 feet, and have been extruded from either Kilauea or Mauna Loa. In general, the beds dip away from their respective sources. The fragmental deposits are all basic and small in volume as compared to the beds of basalt. They are very important, however, in the interpretation of the geology of the Kau District. The intrusive bodies are likewise basaltic or gabbroid, and only a few are exposed.

The general absence of fossils in the district has greatly handicapped the geologic work. Fossil plants have been found in ash beds at a few localities, but no one has yet been able to correlate them with any on the continent or to place the formations in which they occur in the geologic time scale.

Bird bones were found in 1926, 100 feet below the surface, by the foreman of a gang driving a tunnel 1,000 feet east of the shoulder of Kaumaikeohu. They were identified by Dr. A. Wetmore, of the United States National Museum, as those of a peculiar form of goose, representing an undescribed species, distinctly larger than that of the nene, the modern Hawaiian goose. The bones lay on top of an ash bed interstratified with basalt and according to W. O. Clark, who forwarded the bones to Doctor Wetmore and who examined the place where the bones were found, the skeleton of the goose was lying on the ash when the lava buried it. The geologic position of the ash bed can not be definitely determined until the tunnel has been driven farther into the hill.

The writer has nothing to contribute to the discussion of the geologic age of the Hawaiian Islands. It is a very speculative subject and involves the whole question of land connections in the Pacific. Such a discussion is wholly outside of the purpose of this report, but the subject has been treated by Pilsbry [28] and Dall.[29] From the amount of erosion and volcanic building on the island of Hawaii, it is reasonable to suppose that the oldest formations on this island are Tertiary or older.

A tabular summary of the general stratigraphy of the Kau District is given below. A more detailed description of the rock units is given in the succeeding pages. It is upon the recognition of the characteristics set forth in these descriptions that interpretations regarding the stratigraphy and geologic history of the volcanoes must rest.

Geologic formations in the Kau District

Age	Formation	Description
Recent and late Pleistocene (?).	Kamehame basalt.	Upper member, lava flows laid down in historic time.
		Lower member, lava flows with a few interstratified beds of volcanic ash and one heavy bed of ash near the top of the member in the rim of the Kilauea caldera.
Pleistocene (?).	Pahala basalt.	Ash member about 55 feet thick; in places separated into two or more beds by intercalated lava flows.
		Basalt member.
Great unconformity.		
Tertiary or older.	Ninole basalt.	Lava flows with a bed of compact volcanic ash about 15 feet thick near top.

TERTIARY OR OLDER LAVA FLOWS

NINOLE BASALT

The type section of the Ninole basalt is exposed on the walls of Ninole Valley at Puu Enuhe, where the formation consists of 1,000 feet of basalt with a 12-foot bed of volcanic ash 500 feet below the top. The lava beds are predominantly massive, gray, and in places 75 feet thick. Interstratified with the massive beds of pahoehoe are a few beds of aa. Some of the beds are partly altered by weathering. Megascopically the rocks collected from this section appear

[28] Hyatt, Alpheus, and Pilsbry, H. A., Manual of conchology, vol. 21, pp. xi–xix, Philadelphia, 1911.

[29] Dall, W. H., Notes on the Tertiary geology of Oahu: Geol. Soc. America Bull., vol. 11, pp. 57–60, 1900.

to be considerably different from the later flows, but a microscopic examination showed that the differences are megascopic only. The general appearance of the beds in the field and their megascopic texture are characteristic throughout Kau and hence are valuable criteria in distinguishing the formation.

The interstratified ash bed is 2 to 15 feet thick, more or less, and occurs at nearly the same horizon wherever exposed in the district. It is a compact, fine-grained dark-red to brown palagonitic tuff, consisting of pyroclastic basaltic fragments, that will stand for years in tunnels without support. The pick marks made over 20 years ago in this ash bed at Noguchi Tunnel, in Wood Valley, are still fresh. The variation in thickness in any tunnel is rarely over 2 feet, although in a few tunnels the bed shows local unconformities at its upper contact, due to small gullies that had been cut into the ash before it was buried. At Noguchi Tunnel a lava flow is interbedded with it, but in practically all other exposures it occurs as a single layer. No other ash beds are known in the Ninole basalt.

The Ninole basalt occurs for a distance of 15 miles between Wood Valley and Waiohinu, on the slope of Mauna Loa. (See pl. 1.) In much of this area it is covered with a veneer of later ash and lava. It has an exposed thickness of 2,100 feet at Makaalia Peak, at the head of Hilea Valley. The total thickness of the formation is unknown, but from its stratigraphic position it is regarded as an old land mass under the Mauna Loa Volcano. So far as known, it is not exposed anywhere on Kilauea.

The Ninole lava beds have a uniformly gentle dip, which ranges from about S. 15° E. to S. 70° E. Thus the beds do not dip away from Mokuaweoweo, the summit caldera of Mauna Loa, which lies due north of the area of the formation but more nearly away from a point about 8 miles down on the axis of the southwest slope of the mountain, a fact recognized by Noble in 1920. This point has an altitude of about 10,000 feet and now lies buried beneath later lava in the southwest rift zone of Mauna Loa. Hence, the Ninole basalt is evidently a part of an ancient volcano now nearly buried by the lava flows of the present Mauna Loa.

UNCONFORMITY

After the Ninole basalt was laid down, sufficient time elapsed for amphitheater-headed valleys over 2,000 feet deep and 5 miles long to be carved in it before the next flows were poured out. These ancient valleys, with their lava fills, are described in the section on physiography.

This unconformity has not been observed in the exposures on Kilauea, but this fact in itself does not prove that beds of lava equivalent in age to the Ninole basalt do not occur on Kilauea. It is an observed fact that two volcanoes may exist side by side, one dormant and being dissected by streams, the other active and pouring out lava flows so frequently that erosion can not occur on its slopes. For this reason even a great unconformity recorded on Mauna Loa need not necessarily extend to Kilauea. Therefore, new criteria have to be established for determining whether the Ninole basalt crops out on Kilauea.

The bed of palagonitic tuff in the Ninole basalt is significant in this connection. This bed of tuff has a nearly uniform thickness and a fine-grained texture wherever exposed in an area of 50 square miles in the heart of the Kau District. A lava flow is intercalated with it, hence it obviously did not originate from a single explosive eruption. Moreover, the fine texture and the great areal extent of the bed exclude any local source for the ash. If it had originated from Kilauea, 15 miles away, it should thicken northeastward. Its source is undetermined, but in all probability the ash was ejected from some vent nearer the center of the island than Kilauea. A more probable source is the vent that extruded the lava flows of the Ninole formation.

Vertical cliffs exposing 1,000 feet of Kilauea lava occur only 12 miles east of Noguchi Tunnel, the nearest exposure of the ash bed of the Ninole basalt to Kilauea, and altogether nearly 2,000 feet of lava beds are exposed in the dome of Kilauea. Regardless of the location of the source of the ash, the fact that it has a nearly uniform thickness wherever exposed in an area of 50 square miles indicates that it must have been deposited over a much greater area. Its compactness, dark-red to brown color, and fine texture make it easily identifiable, and as no such bed is found in the exposures on Kilauea, it is concluded that the Ninole basalt does not crop out on Kilauea. Moreover, the fact that there is no erosional unconformity of any magnitude on Kilauea gives further support to the belief in the absence of any Ninole basalt at the surface on Kilauea and makes it improbable that the ash bed of the Ninole basalt occurred in the upper part of the volcano and was removed by erosion.

The ash bed crops out high above the cane fields in the Kau District, and hence any water recovered by tunneling into it is particularly valuable for fluming cane down to the mills. Because of its compactness and slight permeability, tunnels driven in this bed have been highly successful in obtaining water. The water occurs in the crevices and openings of the overlying basalt and is held there in a perched position by the ash bed. An exception to this general rule occurs on the east side of Hilea Gulch in the fault block called the Makaalia graben. At this place a tunnel was driven in the ash bed and only a small flow of water was obtained, though enough to warrant the building of a flume to it. Slickensided basalt is exposed in the tunnel, and the ash bed is displaced by faulting. More water can not be developed at this place, and the flow from the tunnel is variable because of the small size of the intake area and the presence of faults. The intake area is the part of the Ninole basalt that overlies the ash bed and forms Kaiholena Ridge, an ancient divide between Hilea and Ninole Valleys. This divide is narrow, and although the rainfall on it is heavy, yet the total surface area of the ridge is too small to supply a large amount of water for the tunnel. Several large faults break the ridge into narrow blocks, and this makes the size of the drainage area tributary to the tunnel still smaller.

The Noguchi Tunnel, in the wall of Wood Valley near Ipuu Ridge (see pl. 1), is a short tunnel driven in this ash bed. A large amount of water flows from it, even after a prolonged drought. The tunnel was driven about 25 years ago, and no one remembers much about it except that water was supposed to have been located by a Japanese as the result of a dream after he had driven the tunnel about 100 feet straight into the mountain without success. The reason for the lack of success is apparent, for in the first 100 feet the tunnel constitutes a hole driven in the middle of the ash bed, so that ash forms the roof, sides, and floor. The impervious bed of ash completely shuts out any water perched above it. The last few feet of the tunnel rises steeply, and the tunnel stops at the end of a lava flow interbedded in the ash. All the water comes from this tongue of interbedded pahoehoe. Although this tunnel yields a large part of the water supply of the Pahala plantation, yet it evidently recovers only a portion of the ground water available. It is not unlikely that the interbedded lava flow has other projecting tongues which also might yield water if tapped. The margin of the lava flow could be explored farther by tunneling along the edge of it. There is still another possibility of developing water at this tunnel. The rock overlying the ash is nowhere exposed in the tunnel, and water may occur in the rocks immediately above the impervious ash roof. Moreover, ground water is in all likelihood perched on the surface of the part of the ash bed which passes up and over the interbedded tongue of lava that at present supplies the water in the tunnel.

The structure of this particular area is favorable for developing high-level ground water. The Ninole basalt with its ash bed completely encircles the head of Wood Valley, and once formed its walls. After this valley was formed lava flows from Mauna Loa spilled over its walls and everywhere buried the Ninole basalt except near the Noguchi Tunnel. Unless some geologic event occurred that can not be inferred from the visible structure, the ash bed of the Ninole basalt formerly cropped out in the ancient cliff around the head of Wood Valley and has since been buried by later lava flows. Ground water perched on the ash bed east of the Noguchi Tunnel doubtless escapes into the later lavas from the end of the ash bed and sinks through crevices in them to the bottom of Wood Valley. This water could probably be intercepted and recovered by contouring the head of Wood Valley with a tunnel in the ash bed. The tunnel should be driven along the contact of the ash bed and the overlying basalt and as nearly parallel with the valley wall as possible. It is impracticable, because of vegetation and later lavas, to find the ash bed of the Ninole basalt east of the Noguchi Tunnel. Hence, the most feasible method of development is to start a lateral eastward from the Noguchi Tunnel. As the tunnel progresses, new outlets to shorten the haul could be driven to the face of the cliff surrounding Wood Valley. The tunnel should be kept as close to this cliff as practicable. Such a tunnel might recover large quantities of water, because a wide rain belt lies above it and tributary to it.

PLEISTOCENE (?) LAVA FLOWS

PAHALA BASALT

GENERAL CHARACTER

The Pahala formation consists of lava flows with some layers of ash interbedded. It receives its name from the village of Pahala, which is on the Volcano Road about 21 miles southwest of Volcano House and is built at the edge of extensive fields of yellow ash that form the top member of the Pahala formation. The Pahala formation comprises all the lava beds that are unconformable on the Ninole basalt and were laid down before the end of the deposition of the ash bed member at its top. It is found on both Kilauea and Mauna Loa.

The finest exposure of the Pahala basalt on Mauna Loa occurs at the Kahuku escarpment. (See pl. 1.) About 600 feet of interbedded aa and pahoehoe lava flows overlain by 40 feet of yellow ash are exposed in this cliff. One massive flow 100 feet above the base of the section is about 100 feet thick and very conspicuous. The rest of the beds average about 15 feet in thickness. The rocks in the cliff have a bluish-gray color and are in general darker than the Ninole rocks. As the Ninole basalt is not exposed in the cliff the total thickness of the Pahala basalt at this place is unknown. The ash capping the section is yellow and has a fine texture throughout. In some places along the cliff it is fairly compact.

In the Kapukapu fault escarpment, on the southern coast of Kilauea, a section of over 1,000 feet of Pahala basalt is exposed. Halfway up in the cliff there is a thin bed of ash, and the cliff is capped with 40 feet of light-yellow ash. Four miles west of Puu Kapukapu, in Hilina Pali, there is a 1,000-foot section of Pahala basalt. In this exposure the lowest ash bed is 200 feet above the base of the cliff, and there are numerous thin ash beds between it and the top. Capping the cliff is a light-yellow ash bed nearly 30 feet thick. These two sections show the variation that can occur in the thickness and distribution of the ash in the Pahala formation. As no Ninole rocks are exposed on Kilauea the total thickness of the Pahala basalt on that mountain is unknown. However, it exceeds 1,000 feet.

The lava beds in the Pahala formation have originated from both Kilauea and Mauna Loa. This fact and the process of laying down basalt flows explain the variations in the thickness and distribution of the beds. Thus, near the summits of both volcanoes the total thickness of the Pahala is greater because of the convergence of the lava flows. The areal distribution of the Pahala formation is shown on Plate 1.

ASH MEMBER AT TOP

The top of the Pahala formation is marked by an ash bed which has a total thickness on both Mauna Loa and Kilauea of about 55 feet where not intercalated with lava flows. An excellent exposure of 55 feet of this ash occurs in a gulch on the top of Puu Enuhe. The ash at this place rests directly upon the Ninole basalt and is not overlain by later lavas; hence the exposure may be considered a complete section of the top member of the Pahala formation.

The ash was deposited subaerially. It has a 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 ash is limited to the semiarid regions, and the red ash 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.

Specimen A–18, from a bed of consolidated ash in a gulch southeast of Kaalualu ranch, was examined in thin section by C. K. Wentworth, who describes it as follows:

> It contains four principal materials—(1) olivine phenocrysts; (2) a few small grains of magnetite, some of which are included in the olivine and in general much less in amount than in the typical tuffs of Oahu; (3) light-green basaltic glass; (4) palagonite. The material is very similar in its freshness to the tuffs of Koko Head and Oahu.

The glass is present in large masses bounded by the curved reentrants of vesicles and having in places sharp, splintery outlines. It is also present in small irregular shards and other typical glass forms. The relationship of the zonally altered palagonite to the glass is interesting. In the tuffs of Oahu the palagonite has generally been formed by alteration of the glass around the margins of pellets and shards and peripheral to the vesicles, which in the Oahu examples are not uncommonly filled with secondary calcite. In the present slide the portions of glass that have been changed to palagonite show seemingly rather pronounced zonal structure, as if the alteration had taken place either from the outside toward the center, starting with a shard-shaped form, or had proceeded from the center outward. Some of these zonally altered masses are inclosed in clear glass, and a few of them seem to be inclosed in glass which is itself contained in filled vesicles.

The material examined by Wentworth is not typical of the Pahala ash, for it contains considerable débris from explosions caused by lava entering the sea near this place.

As the ash member is in many places interstratified with lava flows, it was obviously not all deposited at one time. The number of lava flows intercalated with the ash in any particular area is determined mainly by the accessibility of the area to lava flows. Because the ash fell like snow, hills of Ninole basalt, such as Enuhe, which were topographically inaccessible to lava flows and remained as kipukas during the laying down of the Pahala basalt, were covered with Pahala ash only. In areas such as the southwest slope of Kilauea, where lava flows were frequent, numerous lava flows are interstratified with the ash.

The intricacies of the deposition of the ash and the lava beds can not be shown conveniently on the geologic map of the district; hence, on Plate 1 areas covered with the ash member of the Pahala are not differentiated from those covered with Pahala basalt. As a rule, the ash conforms to the slope of the basalt on which it was deposited, and all the areas of Pahala basalt shown on the geologic map except nearly vertical cliffs are covered with ash.

From the village of Pahala northeast to Kilauea the top layer of ash is dark in color. It is unquestionably much younger than the Pahala ash, because it is interstratified with and in places rests upon lava beds that lie above the Pahala ash. This later ash wherever it rests on Pahala ash is not shown on the geologic map by the symbol of the later lava series, to which it belongs, because to do so would obscure small areas of Pahala ash that it is important to show on the map because of their bearing on the geologic history of Mauna Loa.

The presence of 600 feet of basalt belonging to the Pahala formation in Kahuku cliff, on Mauna Loa, and 500 feet of basalt at the base of Puu Kapukapu, on Kilauea, containing no interstratified ash beds, is evidence that a long period of volcanic activity occurred during which no ash was deposited. Moreover, in any exposure of Pahala basalt most of the ash occurs near or at the top of the formation—a fact which leads to the conclusion that there must have been one or more volcanoes on the island that ceased quiet lava effusions and entered upon explosive activity.

The upper 15 feet of the Pahala ash becomes appreciably coarser near Kilauea and in the upper part contains lenses of coarse lapilli. This change in texture is doubtless due largely to the fact that this region is more accessible to the ash eruptions from Kilauea. The lapilli and ash at this place are in part, at least, correlative with some of the ash deposits in the Kilauea caldera. The Pahala ash crops out in an area of over 300 square miles in the Kau District and has a fairly uniform thickness and a fine texture except for this slight change near Kilauea. Hence it is improbable that the major part of the Pahala ash originated in Kilauea.

The chief sources of the Pahala ash are at present unknown. Ash of similar character and thickness occurs in every district on the island. The plains of Waimea, which cover over 200 square miles on the north and west slope of Mauna Kea, are mantled with a similar ash deposit. Moreover, the slopes of Mauna Kea and Kohala are studded with cones, some of which, as shown by a rapid reconnaissance of these two volcanoes, are true ash cones, differing from cinder cones in that they are the product of great explosions rather than of lava or fire fountains. It is believed that these cones were the source of a large part of the great ash deposits on the Island of Hawaii, although the character and areal distribution of these deposits are such that they could have been derived from any one of the five volcanoes on the island.

The slopes of Mauna Loa are covered with cinder cones but have no true ash cones. The absence of ash beds in the walls of Mokuaweoweo indicates that Mauna Loa has not been an ash maker. Furthermore, no ash cones occur on Kilauea; hence no other explosions than those which have taken place in the central vent of the caldera have contributed ash to the Pahala beds. A reconnaissance of Hualalai showed that the cones on it are chiefly cinder cones; hence this volcano was probably the source of very little of the great ash deposit. It thus seems highly improbable that the ash originated in Hualalai or Mauna Loa, or any but a small portion in Kilauea. There remain only Mauna Kea and Kohala volcanoes as possible sources of the major part of the ash. Further geologic work on the island will doubtless disclose more data relative to this problem.

LATE PLEISTOCENE (?) AND RECENT LAVA FLOWS

KAMEHAME BASALT

CHARACTER

The Kamehame basalt receives its name from Kamehame Hill, 3½ miles south of the village of Pahala, where a prehistoric lava flow entered the sea. Northward from this hill is a wide strip of massive pahoehoe that originated largely on Mauna Loa. The Kamehame basalt covers hundreds of square miles of the surface of both Mauna Loa and Kilauea, and its areal distribution is shown on Plate 1. It comprises all the lava flows and ash deposits from Mauna Loa and Kilauea which lie above the ash member at the top of the Pahala basalt. Its total thickness nowhere exceeds 200 feet on the lower slopes of Kilauea and Mauna Loa and is usually 5 to 50 feet. The older rock series forms kipukas in the Kamehame basalt.

In this formation, especially near the Kilauea caldera, are beds of dark ash that range in thickness from a few inches to several feet. The lavas of this formation originated all along the Mauna Loa and Kilauea rifts and consist of approximately equal amounts of aa and pahoehoe. Two beds of lapilli and ash are associated with the lava on Mauna Loa, but these beds are limited to the vicinity of Mokuaweoweo and nowhere exceed 6 inches in thickness. The maximum thickness of the Kamehame basalt is exposed in the walls of the Kilauea caldera and Mokuaweoweo, where it exceeds 800 feet. A comparison of its thickness in the walls of these calderas with the thin veneer on their distant slopes shows strikingly the effect of the nearness of a lava formation to its source. Because a volcano increases in circumference outward from its summit crater, a much larger number of lava flows are necessary to veneer its outer slopes than to veneer the rim of the crater, even though each individual flow may be thinner near its source than at its margin.

The fragmental deposit in the Kamehame formation has a maximum thickness of about 35 feet in the floor of the Kilauea caldera, although it is much thinner on the rim. (See pl. 7, *B*.) The deposit consists mainly of lapilli, volcanic sand, and bombs. It is well stratified, and there are a few lava flows intercalated with it near the rim of the caldera. The deposit thins rapidly away from the caldera, so that 7 miles southwest of the rim it forms a layer only a few inches thick. The ash is gray to black and is easily identified in the field.

The Kamehame basalt includes many lava flows that have been extruded from Mauna Loa and Kilauea since the advent of white men. These flows were mapped as a separate lithologic unit and have been shown on Plate 1 by a separate symbol. There is, however, no great difference in appearance between the historic lava flows and many of the older ones in the Kamehame basalt. In fact, were it not for written records describing the historic flows, it would have been impossible to separate many of them from older ones. Both of the volcanoes have apparently poured forth numerous lava flows separated by only relatively short intervals during all of recent geologic time.

PREHISTORIC FLOWS

The extent and total thickness of the prehistoric lava flows of the Kamehame basalt from both volcanoes greatly exceed those of the historic flows. This leads to the conclusion that the interval of time from the end of the deposition of the Pahala ash up to the year 1823, when the first lava flow in the Kau district was recorded, was very much longer than the interval since 1823. It is impossible from the data at hand to give a close estimate of the length of time it took for the prehistoric flows in the Kamehame basalt to be formed. The present rate of extrusion suggests that it required perhaps three hundred times as long for the accumulation of the prehistoric flows as it did for that of the historic flows. If this is true, perhaps 30,000 years has elapsed since the Pahala ash was deposited.

The areal distribution of the prehistoric flows and their sources, so far as they remain unburied, are shown on Plate 1. The individual flows do not differ in size, thickness, or chemical composition from the historic flows.

HISTORIC FLOWS

The historic lava flows from Mauna Loa and Kilauea that form the upper part of the Kamehame basalt are usually black and have a fresh appearance. Where they have entered forested areas they have cut a swath through the trees. In the desert they are differentiated from the older flows only with difficulty. When viewed in bright sunlight their glassy surfaces almost invariably show an iridescence, which is absent from practically all the older flows, indicating that it lasts only about a century. The oldest historic lava flow in the district is the lava flow of 1823, which is about 12 miles southwest of Kilauea.

The areal distribution and sources of the historic flows are shown on Plate 1. Because of the general interest in these flows some of them are described individually in the following pages. Not all the historic lava flows from Mauna Loa and Kilauea are in the Kau District, and only those which issued in or crossed the district are described.

MAUNA LOA FLOWS

Lava flow of 1832 (?).—A lava flow dated 1832 (?) has been shown on the Coast and Geodetic Survey map of Hawaii (chart 4115) and other maps as a short flow near the summit of Mauna Loa, but a question mark has always followed the date. A field examination shows that the lava beds at the site indicated appear greatly weathered as compared with any dated lava flow on Mauna Loa. Moreover, there is no isolated flow, and no flow has its source at the place shown on the map, which is therefore concluded to be in error.

While the writer was traversing the high slopes of Mauna Loa, above the Kahuku ranch, in September, 1924, he found a fairly fresh looking aa flow that has entered the rain belt of the Kau Forest. On both sides of it and in the kipukas of the flow there is dense vegetation, but little or none is growing on the flow. The swath cut through the forest is very conspicuous. Realizing that plants take root rapidly on aa flows in the rain belt, the writer surmised that this was the flow of 1832. Careful examination showed remnants of partly charred wood lying on the surface of the flow near the tree molds. It is probable that wood does not last on the surface in this region much over 100 years; hence the flow was probably poured forth during the last century. The quotation below is taken from a letter written November 18, 1832, to Prof. Benjamin Silliman by Rev. Joseph Goodrich,[30] who was on the island of Oahu at that time. It is the only available record of the outbreak.

> On the 20th of June volcanic eruptions broke out upon the top of Mauna Loa, * * * and the mountain continued burning for two or three weeks; the lava was also seen running out of the sides of the mountain in different places; it discharged the red-hot lava from so many vents that it was seen on every side of the mountain; it was visible as far as Lahaina, upward of 100 miles.

Several old natives were questioned by the writer about the flow, but they knew nothing about it—though that is not surprising, as it is nearly 100 years since the flow took place.

The part of this flow that occurs in the area topographically mapped is shown on Plate 1. It is locally known as the Pele Iki flow. The source was not investigated, but the flow apparently issued from a fissure 9,000 to 10,000 feet above sea level on the southwest rift zone of Mauna Loa.

Lava flow of 1851.—On August 8–10, 1851, lava was extruded from the southwest rift of Mauna Loa near Mokuaweoweo, but most of it flowed into the Kona District. (See pl. 2.) No one visited the flow at the time, but the outbreak is described by Brigham.[30a]

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[30] Am. Jour. Sci., vol. 25, p. 201, 1834.

[30a] See note 31, p. 72.

Lava flow of 1852.—On February 17, 1852, at 3.30 a. m., fire was seen on the northeast rift of Mauna Loa near the summit, and lava poured out for about 40 hours. The flow from this source went to the north away from the Kau District, and it is therefore outside of the area covered by this report. However, at daybreak on the 20th lava broke out and formed a cone at about 9,500 feet on the northeast rift zone, in this district, and sent a flow toward Hilo. (See pl. 1.) Coan, who visited the source of the flow at the time, says that it issued from a fissure which connected with the source of the flow that had issued a few days before. The later eruption built up a large scoria cone, half a mile in circumference and about 200 feet high, which was the scene of violent fountaining. The jets are reported to have played 300 feet or more in the air.[31] The flow lasted 20 days and stopped within 10 miles of Hilo.[32] The flow, up to a point within 2 miles of the source, was studied and found to be aa lava, but the source cone was not visited. The lower portions of the flow are now covered with vegetation.

Lava flow of 1868.—The next flow of historic record that occurred on Mauna Loa in this district was that of 1868, near the Kahuku ranch, on the southwest rift zone. Fire was first seen on the summit on March 27, 1868, at 5.30 a. m. "In a few hours the smoke dispersed, and at night no light was visible."[33] On April 7 the lava broke out 3½ miles above the Kahuku ranch from several fissures, probably some time before daybreak, because the deck of a vessel at Kaalualu was covered with very fine ashes that morning.[34] However, it is reported that not until 6 p. m. was fire sighted above the Kahuku ranch. This may have been due to the position of the observer, or to the fact that the fire was visible only at dusk, or to the obscuring of the region of the fissures by clouds. Another observer describes new craters breaking out at 5 p. m., so that the eruption probably began early in the morning. At 9.30 p. m. the lava reached the sea. It is reported that the flow lasted four days. The lava is a picrite basalt, filled with large olivine crystals, and consists of both pahoehoe and aa. The area of the flow is shown on Plate 1. Measurements of the volume, allowing for rate of flow, thickness, and duration, indicate an average production of about 1,000,000 cubic yards of lava an hour. Where it flowed into the sea it formed several tuff cones consisting largely of the finer kinds of volcanic detritus, more or less stratified, of which Puu Hou is the most conspicuous. (See pl. 7, *A*.) Details of this flow and the basis of the measurements are described elsewhere by the writer.[35]

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[31] Brigham, W. T., The volcanoes of Kilauea and Mauna Loa: Bishop Mus. Mem., vol. 2, p. 65, 1909.
[32] Idem, p. 67. [33] Idem, p. 101. [34] Idem, p. 104.
[35] Stearns, H. T., Geologic effects of the catastrophic year of 1868 in Hawaii (in preparation).

After the earthquake of April 2, 1868, there was a destructive landslide near Wood Valley Camp, 5 miles north of Pahala. It was caused by the sliding of an old lava flow on a wet ash bed from an altitude of 3,500 feet to an altitude of 1,620 feet, a distance of 2½ miles. The water and mud acted as a lubricant, and the whole mass moved rapidly down the valley, destroying all the people, ranches, and stock in its path. The area of the "mud flow," as it is known locally, is shown on Plate 1. It is described in detail in the paper just cited.

Lava flow of 1880–81.—On May 1, 1880, lava broke out in the crater of Pohaku Hanalei (Hawaiian, "wreath (lei) made of rocks") and overflowed its floor.[36] This activity ceased, and about 9 p. m. November 5, 1880, lava broke out on the northeast rift above Puu Ulaula, at an altitude of about 11,000 feet. At the end of a large fissure is a pit crater called Pukauahi, and from it much of the lava was extruded. The lava continued flowing until August 10, 1881, and stopped within three-quarters of a mile of Hilo.[37] The last lava stream that flowed toward Hilo is massive pahoehoe and forms the largest historic flow from Mauna Loa. The earlier flows of the eruption were all aa in their lower stretches.[38] Several small branches flowed across the slope of Mauna Loa. The ends of these are typical aa and on a clear day are plainly visible from the top of Kilauea. One lobe of the flow reached Ohaikea, within 1½ miles of the Volcano Road. The Kau branch of this flow started toward Ohaikea on November 9 at 8 p. m., but no damage was done, as it was limited to the waste lands above Kapapala. The lava of 1880–81 has been described by Washington[39] as an aphyric andesine basalt. Its area in the Kau District is shown on Plate 1.

Lava flow of 1887.—The lava flow of 1887 near the Kahuku ranch, on the southwest rift zone, was ushered in with seismic disturbances at Hilea, 10 miles northeast of the ranch. A total of 618 shocks were counted between 2 a. m. January 16 and 7 a. m. January 18. Lava broke out on the northeast rift zone 3 or 4 miles northeast of Mokuaweoweo on the night of January 16. This discharge ceased after a few hours. About 7 a. m. on the morning of the 18th it broke out again from a fissure 4½ miles long near Puu o Keokeo (see pl. 1), and at noon on the 19th[40] it reached the sea. By noon of the 24th the flow had practically stopped. The lava is aa except at the source, where it is a pahoehoe grading into aa. It is described by Washington[41] as an andesine basalt.

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[36] Brigham, W. T., op. cit., p. 143.
[37] Idem, pp. 147–148.
[38] Cumming, C. F. G., Fire fountains, vol. 2, pp. 235–280, London, 1883.
[39] Washington, H. S., Hualalai and Mauna Loa: Am. Jour. Sci., 5th ser., vol. 6, p. 112, 1923.
[40] Dana, J. D., Characteristics of volcanoes, p. 212, 1890.
[41] Washington, H. S., op. cit., p. 112.

The area of this lava flow was carefully measured with a planimeter and divided into four units, each with different average thicknesses, according to miscellaneous measurements over the flow, which thickens toward the sea. The results are shown in the following table:

Area, thickness, and volume of different parts of the lava flow of 1887

Area	Average thickness	Volume
Sq. miles	*Feet*	*Cubic yards*
3.5	4	14,000,000
4.1	6	25,000,000
4.5	8	36,000,000
3.5	12	43,000,000
15.6	----------	118,000,000

The flow reached the sea in 17 hours. If all the lava on land was formed within that time, the rate of production was about 7,000,000 cubic yards an hour. However, some of the land margins of the flow were probably slowly moving during the remaining five days of the flow. As the flow is relatively narrow, this movement could not have been very rapid and probably would reduce the average production to not less than 5,000,000 cubic yards an hour during the first 17 hours. If 900 pounds is taken as the average weight of each cubic yard, then 2,250,000 tons of lava an hour was extruded. It is impossible to state the amount that went into the sea. The lava flowed for 150 hours, but there was probably a steady slowing down of the flow after the first 24 hours. It clearly demonstrates the tremendous power of volcanism.

The lava flowed a distance of 11 miles over rough aa before it reached the sea. As it reached the sea in 17 hours, it must have had an average velocity of about 0.7 mile an hour. However, it must have moved considerably faster in the feeding channel. The difference in altitude between the lower end of the fissure and the sea is 3,900 feet, giving an average gradient of 354 feet to the mile to the flow. The actual gradient was not uniform, however, because the slope decreases toward the ocean.

The fissure from which the flow of 1887 issued is thickly studded with dozens of large and small coalescing driblet cones, 10 to 100 feet high. They stand in line with their black exteriors and their brilliant-red throats like a row of blast furnaces in action.

Lava flow of 1907.—The lava flows of 1907 was introduced by an earthquake like all the other flows on the southwest rift. Fire was seen in Mokuaweoweo a few minutes after midnight on January 10. At 4 a. m. the glow abated and an outburst of lava occurred above the Kahuku ranch, near Puu o Keokeo.[42] The flow ceased on January 24.

Descriptions of the source of this flow are very inaccurate, as Wood[43] has pointed out. The sources and areas as determined during the writer's investigation are shown on Plate 1. The flow issued from three nearly parallel fissures at altitudes ranging from 2,400 to 6,700 feet above sea level. The arrangement of the three fissures suggests that a cracking en échelon preceded the flow. Altogether, there were nine separate places of extravasation, but none of these have been described by the many scientists who have visited the flow. All the sources were either reopened old fissures or new fissures adjacent to the old ones.

The lowest vents are in Kipuka Kepunoi, 1½ miles north of the Volcano Road, near the Kahuku ranch. There are small patches of massive pahoehoe in this kipuka that have welled out quietly from a zone 10 to 15 feet wide and half a mile long, fissured with cracks a few inches to a foot in width. The pahoehoe, although massive, exhibits a spiny surface and was grading into aa. Little or no spatter occurs at these openings, indicating that the frothy magma escaped from the higher vents. At an altitude of 3,750 feet the fissure from which the lower flows issued joins a prehistoric fissure and disappears. (See pl. 1.)

A higher fissure from which lava issued occurs at an altitude of 6,000 feet, due north and a little west of the lower fissure. It opened along an existing fissure and broke the pumice cone of Kapoalaala in two. This crack is 1½ miles long and extends up the slope in a northerly direction to an altitude of 6,550 feet. Pahoehoe poured out of it both above and below Kapoalaala, but the lava must have changed rapidly into aa, for lower down it is a bristling stream of slag. Spatter cones of various heights occur at the places where lava was extruded during this eruption.

A quarter of a mile above the source of the main flow there is a small patch of lava isolated from the main stream. A quarter of a mile west of this patch is a fissure that poured out a stream of lava in 1907 from the south side of Puu o Keokeo. Puu o Keokeo is an old compound pumiceous cone divided almost symmetrically from north to south by a fissure that seems to be one of the most active cracks in the southwest zone. The flow of 1916, nine years later, issued from this same fissure only one-eighth mile above the northern base of Puu o Keokeo.

The eruption of 1907 sent two branches, the Manuka and the Kahuku, across the Volcano Road, both of which stopped about 2

[42] Hitchcock, C. H., Hawaii and its volcanoes, p. 142, 1911.

[43] Wood, H. O., Notes on the 1916 eruption of Mauna Loa: Jour. Geology, vol. 25, p. 486, 1917.

miles from the sea. There is no detailed map including the Manuka branch from which to determine its volume, which was probably considerably less than that of the flow of 1887. The lava of the flow of 1907 has been identified by Washington as an aphyric andesine basalt. The flows of 1868, 1887, and 1907 are all crossed by the Volcano Road and therefore are easily visited. Their sources, however, are much more difficult to reach and hence have been neglected by geologists.

Lava flow of 1914.—Huge lava fountains appeared in Mokuaweoweo about 3.45 p. m. November 25, 1914. At the Hawaiian Volcano Observatory, on the rim of Kilauea, numerous local earthquakes were recorded before the eruption.[44] Activity continued in the caldera until January 11, 1915.[45] The several cones and the lava flow resulting from the eruption are in the central crater of the caldera. They have been described in detail by Wood.

Lava flow of 1916.—The lava flow of 1916 came with only an increase of local earthquakes as warning. At 3.45 a. m. May 19, the ship *Hamakua*, steaming around Kalae in a calm sea, experienced a strong shock that agitated the waters and shook the ship. At 4.15 a. m. lava broke out of a fissure above Puu o Keokeo. The fissure sent forth a high jet of fumes at 8 a. m., at an altitude of about 10,500 feet, and two days later gave issue to a flow at an altitude of about 8,000 feet. (See pl. 1.) On May 31 the flow ceased. This flow has been well described by Jaggar[46] and Wood.[47]

A remarkable line of driblet cones occurs along the fissures above Puu o Keokeo. Extending up the slope from this cone is the long line of black cones with their red glazed throats, and to the northwest is the cone at the source of the flow of 1919. Between Puu o Keokeo and the summit of Mauna Loa there are 30 to 35 large cones and many smaller ones. In 1924 a long low cloud of white steam, near the summit, stood out in direct contrast to the great black sea of stiffened lava.

Lava flow of 1919.—The flow of 1919, or Alika flow, broke out on the southwest rift zone about midnight September 26, 1919, and practically ceased moving October 29. Fire was last seen November 5, in the region of the source. The main outbreak came September 29, about 11 miles southwest of the first outbreak of the 26th. It was from this lower fissure vent that most of the lava was poured out. A large cinder cone was built at an altitude of

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[44] Jaggar, T. A., jr., The outbreak of Mauna Loa, Hawaii, 1914: Am. Jour. Sci., 4th ser., vol. 39, pp. 167–172, 1915.

[45] Wood, H. O., Effects in Mokuaweoweo of the eruption of 1914: Am. Jour. Sci., 4th ser., vol. 41, p. 383, 1916.

[46] Jaggar, T. A., jr., Lava flow from Mauna Loa, 1916: Am. Jour. Sci., 4th ser., vol. 43, pp. 255–288, 1917.

[47] Wood, H. O., Notes on the 1916 eruption of Mauna Loa: Jour. Geology, vol. 25, pp. 322–336, 467–488, 1917.

7,700 feet. The lava stream crossed the Volcano road 12 miles from the source at 9.30 a. m., on the day of the main outbreak, September 29, and reached the sea in the early morning hours of September 30, where the lava exploded from contact with the sea water and formed a tuff cone. The upper portion of the flow and the rift are in the Kau District.[48] A rough sketch of the area of the flow is shown on Plate 2. The lava is the normal aa and has been described by H. S. Washington as an aphyric andesine basalt.

KILAUEA FLOWS

Lava flow of 1823.—The lava flow of 1823 is the first one recorded from Kilauea. It covers an area of about 5 square miles in the Kaalaala and Kapapala lands, on the southwest slope of Kilauea. (See pl. 1.) The flow issued from the Great Crack, a fissure 6 miles long and 2 to 30 feet wide, one of the series of cracks that mark the southwest rift zone of Kilauea. The flow is known locally as the Keaiwa flow and near its source is black frothy pahoehoe, 1 to 12 inches thick. A short distance away from the fissure the pahoehoe crust is broken into fragments, which are turned up on end like cakes of ice in an ice jam. Near the sea the lava is the crinkly aa. It is so thin that there are many kipukas in it on level ground, and in no place does the thickness exceed 5 feet. In some places the undersurface of the lava cooled rapidly enough to form a mold of the vegetation. In Plate 8, *A*, are illustrated grass impressions on the under surface of a cake of this lava.

It is similar, microscopically, to the other historic lavas of Kilauea, but its physical characteristics, its source, and its manner of flow are somewhat unusual. Its source is described in the section entitled "Fissure eruptions." In Plate 8, *B*, is shown a view of the Great Crack. The spatter from this eruption is sparsely scattered along the entire crack and is remarkable for its thinness. Most of the clots resemble large cow dungs, and a skin on them chilled so rapidly that the details of the surface on which they fell have been preserved. The walls of the fissure are lined in many places by ball lava (pl. 9, *A* and *B*), the origin of which is described in the section on products of volcanism. The fissure, although in most places 10 to 30 feet wide, was undoubtedly much narrower at the time of the eruption, and the width at present is clearly due to collapse after the subsidence of the magma. Small phreatic explosions occurred at two places in the Great Crack immediately after the extravasation of the lava. The location of these places is shown on Plate 1.

The extreme thinness of the flow is evidence of the fluidity of the lava at the time it was poured out. It is unusually frothy for a

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[48] The above description is taken from Jaggar's detailed account (Hawaiian Volcano Obs. Bull., vol. 7, No. 11, October, 1919).

Kilauea lava and is much more like the frothy flows that have issued from fissures on the top of Mauna Loa. The lava seems to have flowed from the entire fissure simultaneously like a sheet, and as it burned native canoes in the sea near the shore at Mahuka it must have flowed fairly rapidly.[49] The end of the fissure is only half a mile from the sea, and the lava probably reached the sea in a very short time.

In several places the flow was confined to channels, and a row of old driblet cones, called Lava Plastered Cones (see pl. 1), stood at right angles to one of the main channels. As a result, the cones formed a dam to the flowing lava and caused it to pond. The dam held long enough for a thin crust to form before the lava found an outlet. The shore lines of the pond are now preserved on the slopes of the cones 5 to 34 feet above the present surface of the flow. In a few places the lava spilled over the rim into the old driblet craters, and one stream flowed seaward through a breach in a cone where lava had formerly found an exit at the time the Lava Plastered Cones were active.

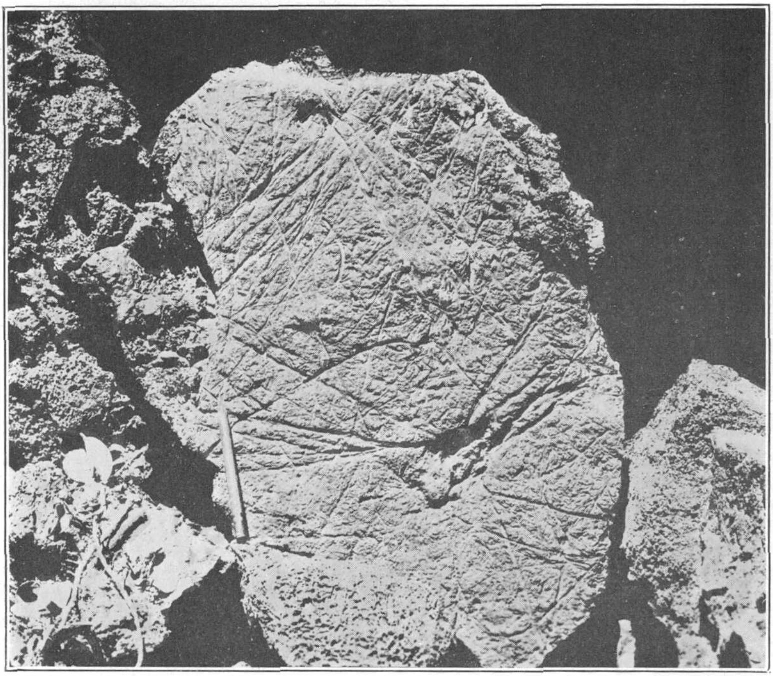
On the upper part of the flow tree molds 5 to 6 feet high are common. Some of them were probably considerably higher when first formed. Fragments of the charred wood from the tops of the trees still occur on the surface of the flow near the molds. (See pl. 10, *A*.) Details of this flow have been described elsewhere by the writer.[50]

Lava flow of 1832.—There is no account by an eyewitness of the lava flow of 1832. Goodrich[51] describes it as follows: "In January an earthquake had rent in twain the wall between Kilauea and Kilauea Iki, the large crater on the east, producing seams from a few inches to several yards in width, from which the region between the two craters was deluged with lava." The area and source of this flow are shown on Plate 1. The cascade into the caldera of Kilauea is still plainly visible, especially when viewed under the strong side lights of early morning from the trail to the Volcano House from Halemaumau.

Lava flow of 1868.—On April 2, 1868, a lava flow burst forth from a fissure on the southwest wall of Kilauea Iki and overflowed the tree-covered floor of this old pit crater. (See pl. 1.) The eruption built a few small driblet cones. There seems to be no record of the date when this flow ceased, but it was probably short lived.

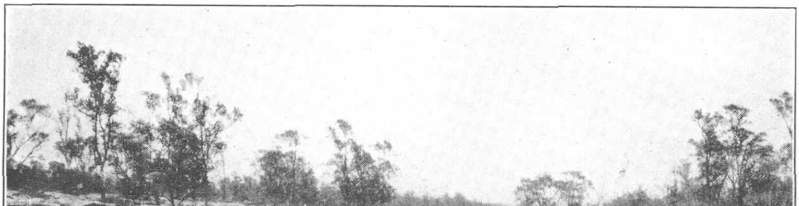
In the meantime lava broke out from fissures 9 miles southwest of the Kilauea caldera, on the southwest rift zone, and formed several small patches. (See pl. 1.) Fire was seen for several nights, but no one visited the flow at the time. A few months later Coan visited it

[49] Ellis, William, Journal (reprint of 1827 edition), p. 200, 1917.
[50] Stearns, H. T., The Keaiwa or 1823 lava flow from Kilauea Volcano, Hawaii: Jour. Geology, vol. 34, pp. 336–351, 1926.
[51] Goodrich, J., Am. Jour. Sci., vol. 25, p. 199, 1833.



A. GRASS IMPRESSIONS ON THE UNDER SURFACE OF A CAKE OF THE LAVA OF 1823 NEAR THE GREAT CRACK

Photograph by O. H. Emerson.

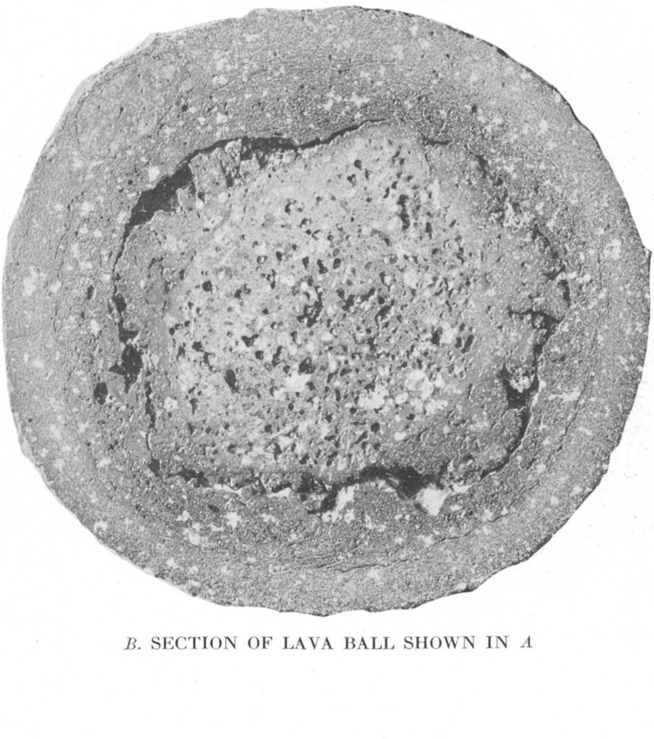


B. THE GREAT CRACK, THE SOURCE OF THE KEAIWA FLOW OF 1823 ON KILAUEA

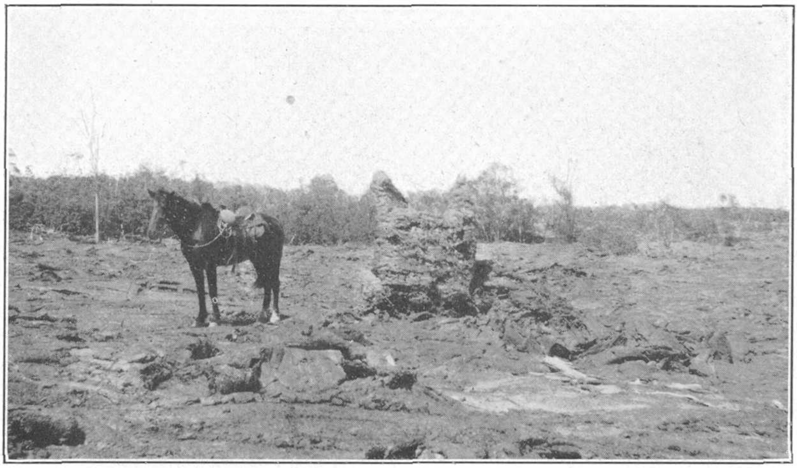
Only the upper 3 to 6 inches of lava on the edges of the crack was extruded in 1823. The trees grow on kipukas. Photograph taken July 25, 1924, by H. T. Stearns.

A. LAVA BALL FROM THE LAVA FLOW OF 1823 ON THE WALL OF THE GREAT CRACK, ON KILAUEA

Natural size.

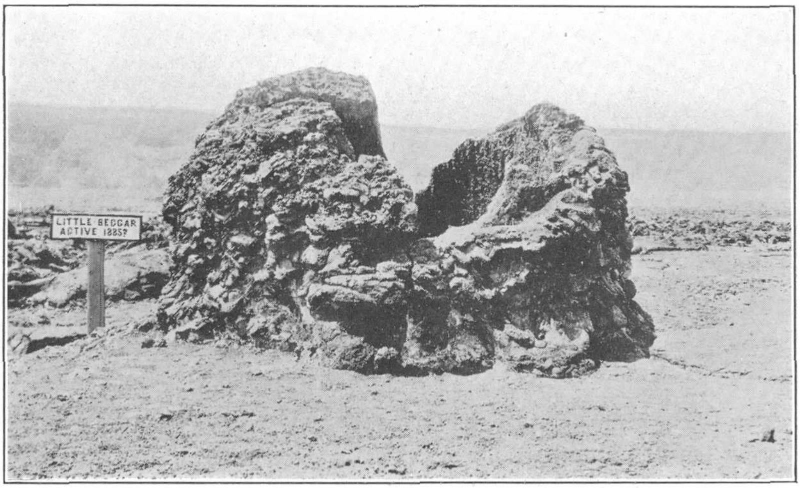


B. SECTION OF LAVA BALL SHOWN IN *A*



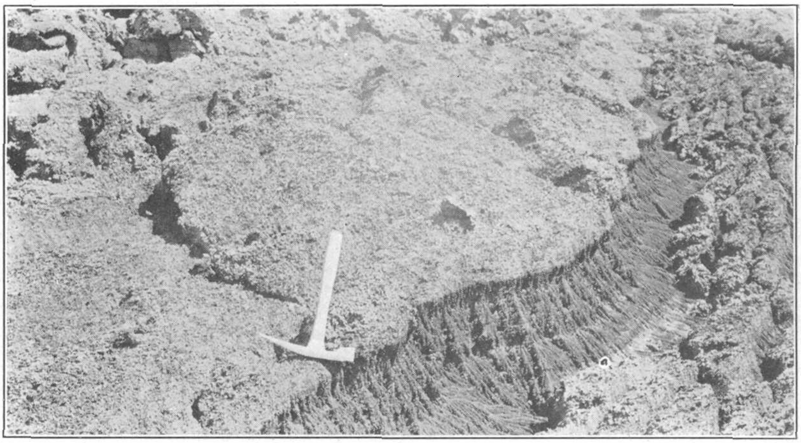
A. LAVA TREE MOLD WITH PIECES OF PARTLY CHARRED WOOD, WHICH ARE REMNANTS OF THE TOP OF THE TREE, ON THE LAVA FLOW OF 1823

Photograph taken July 11, 1924, by H. T. Stearns.



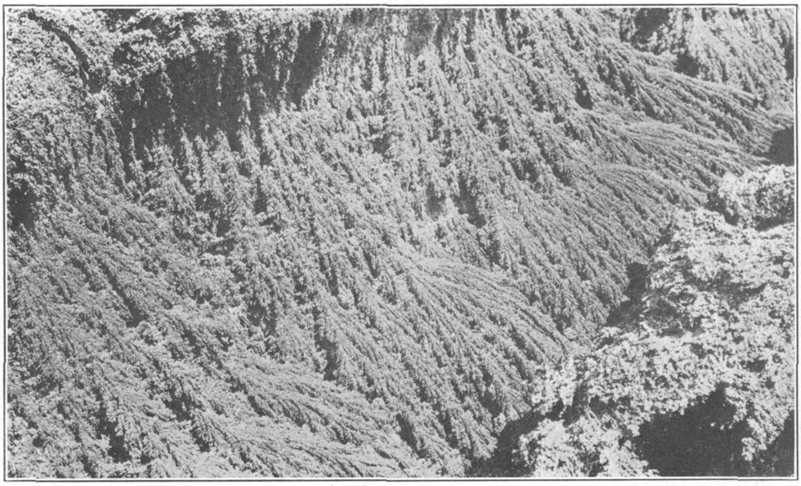
B. LITTLE BEGGAR DRIBLET CONE, ON THE FLOOR OF KILAUEA CALDERA NEAR HALEMAUMAU

Probably formed in 1894.



A. ARBORESCENT AA LAVA ON THE MAUNAIKI LAVA FLOW OF 1920 ON KILAUEA

Photograph by W. O. Clark.



B. DETAILED VIEW OF THE ARBORESCENT LAVA SHOWN IN *A*

Photograph by W. O. Clark.

while the lava was still hot. The main crack is not continuous but extends échelon fashion from northeast to southwest. It has an average width of about 3 feet and a length of 1½ miles. The lava rose in it to the surface but was poured out only in nine small separate spots, three of which are tiny driblet spires, a foot or so in diameter. The largest patch is 1,000 feet long and 600 feet wide and has an average thickness of 10 feet. All the lava extruded was pahoehoe of the sluggish, massive type.

In some places the solidified lava of 1868 can be seen in the fissure 15 feet below the surface. Four tiny driblet cones occur along the fissure, and three of them are isolated from the flows. The southernmost driblet is a beautiful spire standing 8 feet high. Details of this flow are described elsewhere by the writer.[52]

Lava flow of 1877 (?).—A lava flow is reported to have taken place in Keanakakoi in 1877. The floor of the crater is covered by black pahoehoe, on which there is no vegetation; hence the flow is undoubtedly of historic age. However, the records regarding it are confusing. Brigham[53] quotes the following from the Volcano House register:

> December 24, 1877, Rufus A. Lyman. Grand flow from north base of hill on the north side of Halemaumau. Two fountains at the source of stream. Some time during the year Wilkes Pea and his father, the latter guide of the Wilkes Expedition, found Keanakakoi occupied by boiling lava.

Hitchcock [54] dates it as May 21 on the statement by R. A. Lyman, in the Volcano House register. The copy of Hitchcock's volume in use by the writer is annotated in pencil by H. E. Wilson, Hilea, Hawaii, as follows:

> Statement about Wilkes Pea is an error. Pea, his father (Wilkes Pea), and his grandfather all deny having ever seen any activity in Keanakakoi.

The source of the lava in Keanakakoi is no longer visible. The flow doubtless welled out of a fissure in the bottom of the crater.

Lava flow of 1885.—Lava was extruded in March, 1885, from a fissure on the floor of the Kilauea caldera. A small driblet cone, called Little Beggar, was formed at the time. Another cone, now called Little Beggar, shown in Plate 10, *B*, is located near Halemaumau. It has a sign near by with the caption "Little Beggar, 1885." Jaggar, in a personal communication, writes that L. A. Thurston says that the present Little Beggar was formed in 1894 and that the original Little Beggar of 1885 was different and buried.

Northeast of the present Little Beggar, in a kipuka in the later flows, there is a fissure from which lava has poured out. Its alinement with the Little Beggar suggests that it was formed at the same

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[52] Stearns, H. T., Geologic effects of the catastrophic year of 1868 in Hawaii (in preparation).
[53] Brigham, W. T., op. cit., p. 132.
[54] Hitchcock, C. H., Hawaii and its volcanoes, p. 217, 1911.

time. If the Little Beggar now in existence was formed in 1894 this lava was probably extruded in that year, and if this Little Beggar originated in 1885 this lava probably did also. Outbreaks occurred in the region of the kipuka in 1877, and hence the date of the eruption is uncertain. Many outbreaks have occurred on the floor of the caldera, but only those which are preserved to-day are described.

Lava flow of 1894.—During 1893 the lava lake of Halemaumau gradually rose, and in 1894 lava poured over much of the floor of the caldera. L. A. Thurston [55] has graphically described the overflow as he saw it in July, 1894. It was probably at this time that the Little Beggar shown in Plate 10, *B*, was formed. Large areas of the Kilauea caldera are still covered with lava of 1894, but so many changes have taken place since the outpouring that it is difficult to reconstruct the details of the floor.

Lava flow of 1918.—The first overflow of the lava lake of Halemaumau of recent date began February 23, 1918. The lava overflowed the road terminus and spread over part of the floor of the caldera. It ceased overflowing on March 8, 1918.[56]

Lava flow of 1919.—The lava of 1919 resulted from the overflow of Halemaumau that began on February 7 and continued for several months. The area of this flow that is not covered by the flow of 1921 is shown on Plate 1. It is a massive pahoehoe and has been described elsewhere in detail.[57]

Lava flow of 1920.—The lava flow of 1920 began December 21, 1919, and ceased July 28, 1920. This flow is the third that has occurred on the southwest rift within the last 100 years. Its daily activity is admirably recorded in the Bulletin of the Hawaiian Volcano Observatory, and a detailed description is unnecessary in this paper. Lava issued from five different fissure vents in 1920. These vents are 5 to 8 miles southwest of the Kilauea caldera. (See pl. 1.) One of these vents extruded considerable lava, built up the cone of Maunaiki, and formed a flow 6 miles long, whereas lava from the others forms only small patches covering a few acres. The Maunaiki vent poured out prolonged floods of pahoehoe, which changed seaward into aa. Short aa flows burst from the vent on several occasions, but the cone is veneered mostly with pahoehoe. The growth of Maunaiki was complex. Both the aa and pahoehoe have been examined by Washington [58] and found to be labradorite basalt.

About 200 feet east of the west margin in the Maunaiki flow of 1920 and 50 feet southwest of the Kamakaia trail there is a remark-

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[55] Thrum's Annual, 1895, p. 78.

[56] See Hawaiian Volcano Obs. Bull., vol. 6, February and March. 1918.

[57] See Hawaiian Volcano Obs. Bull., vols. 6 and 7, 1918 and 1919, especially February to July, 1919.

[58] Washington, H. S., Petrology of the Hawaiian Islands: Am. Jour. Sci., 5th ser., vol. 6, p. 351, 1923.

able formation in the aa lava. The spiny crust of the aa stream parted, and the portion southwest of the break moved seaward. An extremely beautiful arborescent form of aa developed at the separation, a form of aa hitherto unknown. The arborescent portion is dark red, in contrast with the brownish-black crust. It is illustrated on Plate 11, *A* and *B*. Jaggar [59] has suggested that the arborescence may be due to the dendritic tendency of the process of iron oxidation. It is exposed the entire length of the crack, a total of about 50 feet.

Charles Stone, jr., rodman for the United States Geological Survey party which made the topographic map of this region, has seen this exposure of aa several times. He reports that he saw aa of the same type while rodding for a Geological Survey party in a historic flow above Kahuku.

A peculiar cirquelike depression occurs on the southwest side of the dome of Maunaiki and is due to a mass of cold aa sliding down the slope of the cone on a hot, viscous layer. On the summit of the dome of Maunaiki is a small, insignificant crater, which is far less conspicuous than a depression on the east side of the dome that resulted from the collapse of a tube. The original fissure from which the flow issued is buried but may be traced up the mountain toward the Kilauea caldera. The profile of the Maunaiki Dome is shown in cross section E–F, Plate 1.

Tree molds are associated with most of the flows of 1920. Some of the tops of the trees that fell on the lava crust are not even scorched. A small tongue of aa entered an ohia grove and not only burned trees down at their base but also pushed some of them over. In some places, however, it failed to kill small shrubs less than 6 inches from the edge of the flow.

Lava flow of 1921.—The flow of 1921, inside of the Kilauea crater, is unique in that it is the only flow to spill over the rim of the great caldera in historic time. This event made Kilauea a superfluent volcano. The overflow resulted from the building up of the floor of the caldera by successive lava flows until the lava overflowed the rim. In view of the fact that the caldera was 1,500 feet deep when visited by Byron, in 1825, this overflow in 1921 represents the climax of a whole century of filling. The lava flow of 1921 and its rift are shown on Plate 1. The flow began March 15 and culminated March 18–24. A line of driblet cones developed on the source rift. The flow is described elsewhere in detail.[60]

INTRUSIVE ROCKS

Very few intrusive bodies are exposed in the Kau District. This was foreseen because of the small amount of dissection that has

[59] Hawaiian Volcano Obs. Bull., vol. 9, p. 47, 1921.
[60] Idem, pp. 41–42.

occurred on these active volcanoes. Moreover, the rift zones, where most of the intrusions occur, are not crossed diagonally by any fault scarps.

A 10-inch dike is visible on the seaward side of Puu Kapukapu. An exposure of it shows 5 inches of dense rock on each wall inclosing 10 inches of vesicular rock. The strike of the dike is N. 50° W. At an altitude of 350 feet above the base of the east shoulder of Puu Kapukapu it disappears under talus. It stops at the lowest ash bed of the Pahala formation at an altitude of 500 feet, which indicates that it is of Pleistocene (?) age.

At an altitude of 600 feet on Hilina Pali there is a 6-inch dike exposed for 100 feet. It crosses an ash bed in the Pahala formation and hence is later in age than the one exposed in Puu Kapukapu. Its strike is about N. 45° W.

The feeder dike of the flow of 1921 in Kilauea is visible for about 1,000 feet in Halemaumau as a result of the explosions of May, 1924. Several lava tubes filled with lava are also visible in Halemaumau. At about 800 feet below the northeast rim a thin intrusive body was exposed in May, 1924. By June the pit had enlarged and more of the intrusive body was exposed. At that time it was hot and about 100 feet thick. Beautiful columnar jointing shows in it, and during the summer of 1924 it was continually a source of red-hot avalanches. It seems to be a sill intruded from Halemaumau between lava beds. The stratification of the lava beds seems to pass into the body of the sill and die out, giving the impression that the intrusive body had absorbed large portions of the beds near by. Intrusions of such bodies may account for some of the doming that has occurred in the floor of Kilauea. The much-discussed laccolith of Uwekahuna Bluff [61] may have a similar origin. According to Powers [62] there are about 20 dikes in the walls of the Kilauea caldera. They are mainly in the northeast side of the caldera, range in width from 0.3 to 1.0 meter, and are composed of aphanitic basalt.

No dikes other than those at Kilauea and the two in the fault scarps to the south of it were found, a fact which affords further evidence in favor of the permanency of rift zones and their control of the location of extravasation. When Kilauea and Mauna Loa are dissected their rift zones will undoubtedly show the same countless number of dikes that exist in the old rift system of Oahu.

SOILS

Volcanic ash covers most of the surface in the Kau District. The only soil formed by the decomposition of lava mantles the surface

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[61] Daly, R. A., The nature of volcanic action: Am. Acad. Arts and Sci. Proc., vol. 47, p. 116, 1911. Powers, Sidney, Intrusive bodies at Kilauea: Zeitschr. Vulkanologie, Band 3, p. 28, 1916.

[62] Powers, Sidney, op. cit., p. 32.

of the prehistoric flows. This cover is usually thin and supports only scanty vegetation except in the region of heavy rainfall. A very instructive experience is to follow from sea level to the source a recent lava flow that issued at an altitude of about 10,000 feet on Mauna Loa. At sea level the surface of the flow is devoid of vegetation because of the semiarid conditions that prevail at the lower altitudes. Toward the mountain the barrenness of the lava surface gives way to small plants and finally to shrubs. Then, in less than a mile, where the flow traversed the rain belt, the rough surface of the lava disappears entirely under a thick growth of vegetation that is impassable without a trail. This quick transition has led several geologists to describe lava flows as originating seaward from the jungle, whereas they really started above the rain belt. Upon pulling up a plant in this forested portion, one is surprised to see the fresh glassy surface of the lava flow instead of soil at the roots. Above the forest the vegetation again decreases, and at 7,000 to 8,000 feet above sea level the jungle changes to ohia and ohelo bushes, and finally at 9,000 to 10,000 feet the flow is absolutely devoid of vegetation and almost perfectly fresh.

Four kinds of soil exist in the Kau District—dark-red soil, yellow and light-red soil, alluvial soil and landslide soil.

Dark-red soil.—The surfaces covered with ash are practically the only areas with sufficient soil for agriculture. The dark-red soil formed by the decomposition of the ash in a warm, moist climate produces fine crops and gives the largest yield of sugar per acre.[63]

Yellow and light-red soils.—The same ash that forms the dark-red soils in the moist portions of the district forms a yellow or light-red soil in the hot, dry areas. Thus the thick ash member at the top of the Pahala basalt is light yellow in the Kau Desert, but on the slopes above the village of Pahala it is dark red. The manner of deposition of the ash leaves no doubt that the color is due to differences in the climatic conditions and in the resulting vegetation. With suitable irrigation the light-yellow soil in the dry portions of the district yields excellent crops and is nearly comparable in productivity to the dark-red soil.

Alluvial soil.—The ash when washed from the hillsides and redeposited forms an alluvial soil, such as occurs on Keoneeleele Flat, south of Pahala. There is very little alluvial soil of this kind in the Kau District, and as none of it has been cultivated its productivity can not be predicted.

Landslide soil.—A large part of Wood Valley is covered with soil deposited by the landslide of 1868. The area of the slide is shown

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[63] Maxwell, Walter, Lavas and soils of the Hawaiian Islands: Hawaiian Sugar Planters Assoc., Div. Agriculture and Chemistry, Spec. Bull. A, Honolulu, 1905.

on Plate 1. Good crops are raised on the soil, especially after the rocks are removed.

STRUCTURE

The geologic structure of the district has been made complex by several epochs of faulting and the imbrication of the lava flows of Mauna Loa and Kilauea. Four structure sections are shown on Plate 1, and a detailed description of them is given on pages 97–101.

FAULTS

Faulting has played a conspicuous part in producing the geologic structure of the region. Some of the faults are still active, and during the present investigation the writer had the good fortune to be able to watch the process. Earthquakes, most of them mild, are common in the district. Several faults will be described because of their relation to seismic centers and their part in the geologic development of the region.

All the formations in the Kau District, irrespective of age, show faulting, and even a casual inspection of the geologic map (pl. 1) shows immediately the huge mosaic fault pattern developed. Most of those shown are normal faults.

CAUSE OF FAULTING

A large number of the faults are of volcanic origin, which would be expected in view of the fact that the Kau District includes large portions of two great active volcanoes. Faults originating from volcanism may be due either to rupturing of the crust by the rising magma or to collapse following an outflow of lava or its subsidence. Some may be due to the gas pressure or heating effects of the hypomagma (see p. 108) or to its stoping and sapping effects. Indirectly, the hypomagma may aid faulting along planes of weakness in the crust because of its mobility and ease of displacement.

Stress and strain also may be exerted on the rock because of solar and lunar attraction, isostatic adjustment, the Chandler or free nutation, " forced " nutation,[64] rock tides, uneven heating effects of the crust,[65] and effects of ocean tides on an island situated in the middle of the Pacific. Any one of these or a combination of several of them is capable of setting up stresses which by accumulation might cause faulting. It is also possible that some of the faulting arises simply from settling as a result of loading a huge heap of scoriaceous

[64] Perret, F. A., Some conditions affecting volcanic eruptions: Science, new ser., vol. 28, pp. 277–287, 1908. Wood, H. O., On cyclical variations in eruption at Kilauea: Hawaiian Volcano Obs. Second Rept., 1917. Jaggar, T. A., jr., and others, The lava tide, seasonal tilt, and the volcanic cycle: Monthly Weather Review, vol. 52, pp. 142–147, 1924.

[65] Jaggar, T. A. jr., Seismometric investigation of the Hawaiian lava column: Seismol. Soc. America Bull., vol. 10, pp. 155–175, 1920.

and cavernous slag with lava flows. Such a pile of loose, cavernous slag would, in fact, slowly settle under its own weight by gravity.

Soundings in the ocean surrounding the Hawaiian Islands indicate that the cones that rise above sea level are peaks on a great volcanic ridge, which is about 35,000 feet high measured from the ocean bottom. As the zone of flowage is assumed to extend about 11 miles below the surface of the earth, the cavernous slaggy lavas of this huge ridge, if buried or depressed to this depth, must become greatly compressed—perhaps to one-third or less of their surface volume.

This great change in volume of the basalt in the zone of flowage would require some compensation in the rocks lying above it. Moreover, the fissures that supply the volcanoes with magma doubtless extend downward to a reservoir which lies in or near the zone of flowage. Hence, stoping and digestion of the confining walls of the reservoir and shafts by the magma and subsequent extrusion of this material at or near the surface would also form space in or near the zone of flowage. Replacement of this space by rocks pressed into it from the surrounding areas would set up a slow circulation that would reduce the volume of the rock in the basement of the ridge. Thus the compressibility of the basalt aided by a partial digestion of rock near the magma chambers could easily cause the subsidence and downfaulting of large blocks at the surface. It is probably this process or some variation of it that explains many of the high fault escarpments in the Hawaiian Islands.

The smooth southern slopes of the domes of Mauna Loa and Kilauea are broken by huge fault scarps that probably have originated from this type of faulting. Because these fault escarpments face the ocean they are called "seaward slip faults," to differentiate them from the faults that are more intimately connected with the rift-zone grabens or faults radial to Mauna Loa or Kilauea. The seaward slip faults on both of these domes lie between the respective rift zones of the domes. This process of faulting is going on to-day in the Kau and Puna districts, where portions of the shore are slowly settling below the water level.

NORMAL FAULTS

Normal faults are the most common type in the Kau District. There are many varieties of these faults, but the most numerous are the en échelon or step faults.

STEP FAULTS

Step faults in which the vertical displacement of the crust is along roughly parallel lines in such a way that a line connecting the points of maximum displacement of the several faults is oblique to the line of the fault traces are everywhere visible in the Kau District. The

Waiohinu and Koae faults are excellent examples of this type. The Koae system forms the southern boundary of the southwest rift zone graben of Kilauea. Step faults in which the vertical displacement of the crust is along roughly parallel lines in such a way that a line connecting the points of maximum displacement of the several faults is at right angles to the line of the fault traces develop a topography characterized by terraces arranged stairway fashion. This type is best exemplified by the Kaoiki Pali faults, west of Kilauea. Step faults of these two types are almost invariably combined, and together they form the most common type of faults in the Kau District. This combination seems to be characteristic of faults in a basalt region, for the writer has seen it clearly developed in the basalt-filled valley of Soda Springs, Idaho, in the basalts of the Connecticut River Valley, Conn., and elsewhere in traps ranging in age from Triassic to Recent. This combination of two varieties of step faults, which for convenience will be called the Kau type of fault in this report, is better developed in the Kau District than in any other part of Hawaii. It occurs mainly along the coast and is particularly well developed between the rift zones of Mauna Loa and of Kilauea.

FAN FAULTS

A fan fault occurs where a large fault breaks up into a number of smaller ones which radiate from the main fault like the ribs of a fan. Hilina Pali, south of Kilauea, is a vertical fault scarp over 1,500 feet high, which, within a mile, dies out in a number of smaller faults that radiate from it toward the southwest. These smaller faults were veneered with lava, so that an abnormally steep slope is the only surface indication of the original faults.

TRANSVERSE FAULTS

Transverse faults cut obliquely across step faults. Several recent ones occur near Keauhou, on the south coast of Kilauea. (See pl. 1.) On some of these there appears to have been movement in 1868. Examples of transverse faults are given on pages 90–94.

RADIAL FAULTS

Faults radiating from Mokuaweoweo and Kilauea are more or less insignificant. The Kahuku fault, on Mauna Loa, is the only large one in the Kau District. A few small ones occur on Kilauea.

CIRCULAR FAULTS

Circular faults are common in the southeast rift zone of Kilauea and on the summits of both Mauna Loa and Kilauea. Circular faulting is caused by the stoping and sapping of portions of the wall rock of a fissure by the hypomagma, which may or may not rise to the surface. Many of the circular faults are associated with pit craters. In some places, as the east lobe of Pauahi crater, 5 miles southeast of the Kilauea caldera, a circular block of crust has subsided and formed a fault basin. (See pl. 1.) Here the cavity underneath was not large enough to cause a catastrophic subsidence, or else the cavity was deep seated and only slightly affected the surface. A large depression west of Heake Crater, near by, has had the same origin. It may be that as time goes on these basins will settle more and more, and when the walls become nearly vertical and the floor shattered or covered with avalanche débris they will be called pit craters. Thus circular fault basins are an intermediate stage in the formation of pit craters.

Circular faults bound Mokuaweoweo and Kilauea calderas. Both of these calderas have resulted from stoping and faulting. Although circular faulting has played a large part in their formation, they are also due in part to faulting in their respective rift zones. This is especially well shown at the Kilauea caldera, where the regular circular fault pattern is elongated in a southwesterly direction by the graben of the southwest rift zone. An even better example is the depression formed by the intersection of two grabens at Haleakala crater on Maui. The topography of both Kilauea and Haleakala suggests that one side, the south half of the mountain in Kilauea, is slowly subsiding.

GRABENS

The Kilauea caldera has been described as partly due to the graben of the southwest rift zone. This graben, which will be called the Koae graben, extends from the Kilauea caldera to the sea in a southwesterly direction. (See pl. 1.) It is deepest and most conspicuous near the top of the cone, where the fluxing action is at its maximum. Here it intersects with the southeast rift zone, which passes out to sea beyond the area mapped. The rift-zone grabens are shallow, broad, and bounded on both sides by low fault terraces, which together with their scarps facing the rifts are undoubtedly due to the settling of this zone to fill up the elongated voids below. The settling of strips of land parallel to a fissure vent is of frequent occurrence in basaltic regions. Such strips have been seen in Idaho by the writer,[66] and those in Iceland have been described at length by Thoroddsen.[67]

The Val de Bove, on Mount Etna, has been described by Friedlaender [68] as a rift-zone graben.

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[66] Stearns, H. T., Geologic examination of the proposed dam and reservoir sites near Soda Springs, Idaho (unpublished report to U. S. Bur. Reclamation, 1923).

[67] Thoroddsen, T., Island: Min. pet. Mitt., Erg. Heft 152, 1905.

[68] Friedlaender, I., Über vulkanische Verwerfungstäler: Zeitschr. Vulkanologie, Band 2, Heft 4, p. 205, 1916.

The grabens on the rift zones of Kilauea are shallow, doubtless because of continual filling by lava from fissures within them. The fault blocks bounding the grabens of the rift zones of Kilauea are continually moving and are the sites of many earthquakes. Movement occurred on the planes of a large number of the faults on the northeast rift in May, 1924.

An unusual type of dike is formed in connection with these faults. As there are numerous open fissures parallel to faults, lava sometimes spills into a fissure, forming a dike from the surface downward.

The elongation of Mokuaweoweo in the direction of the southwest rift zone causes the caldera to approach a graben in appearance. Elsewhere in the Mauna Loa rifts either grabens have not developed characteristic topographic features or else they have been filled as rapidly as formed. The settling of the crust of the southwest rift zone along the Kahuku fault doubtless compensated for the withdrawals of lava along this rift.

The finest example of a graben in the Kau District is the Makanau graben, in the top of Makanau Hill, above Hilea. (See pl. 1.) It is not as conspicuous on the map as in the field. (See pl. 6, *A*.) Slickensided basalt was found in a tunnel along the southern fault.

The inward-facing slopes at Clover Hill, Kaalaiki, and Ohaikea and 1 mile west of Honuapo suggest the presence of dropped blocks or grabens. Some can be correlated with the Ninole basalt, for they are buried beneath a thick deposit of Pahala ash, but others are prehistoric, with both scarps clearly visible. The one a mile west of Honuapo is an example of the latter type. (See pl. 1.)

A horst and graben topography is found in the group of fault blocks near Keauhou Beach, at Puu Kapukapu. It is particularly conspicuous when viewed from the high slopes above Hilea. Faulting at this place has broken the Pahala and Kamehame basalts. Pakanaka Hill, in Ninole Valley, consists of Ninole rocks and may be a horst. It is capped with a thick deposit of Pahala ash and completely surrounded by Kamehame basalt.

The simple graben seems to result from subsidence over stoped-out fissures, whereas the graben and horst topography, which is confined to areas of the Kau type of faults, appears to result from normal tension faulting. In some places a seaward block has been torn by tension stress from the adjacent slope and has allowed a wedge to drop behind it. Other grabens, however, seem to have resulted from a special kind of step faulting, in which two blocks settled down but the inland block dropped lower. It is in this manner that Puu Kapukapu, the Makanau graben, and the Ohaikea graben developed. The graben near Honuapo seems to have been developed by the wedge method. The origin of the others is not clear.

ROTATIONAL FAULTS

The Waiohinu fault, which is both rotational and transverse, is described below under "Examples of faults." Another example of

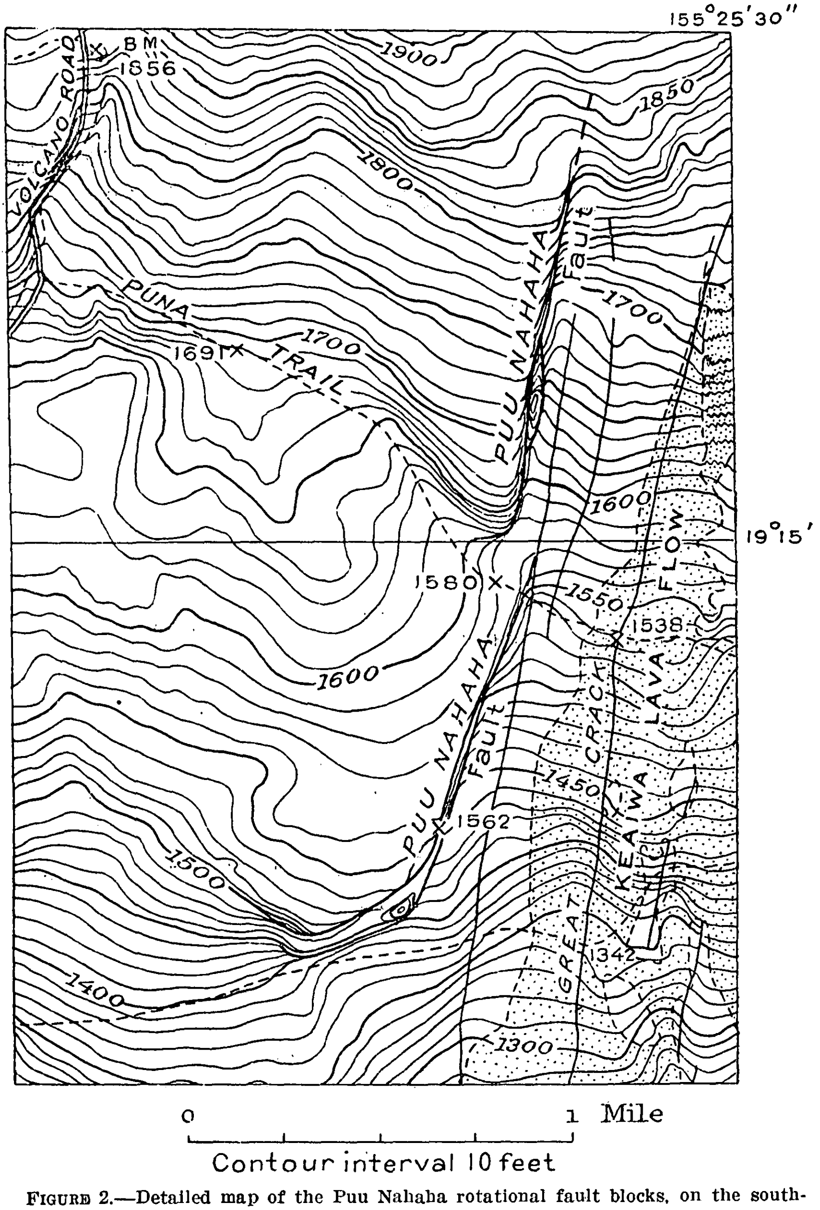

FIGURE 2.—Detailed map of the Puu Nahaha rotational fault blocks, on the southwest slope of Kilauea

the result of rotational faulting, called Puu Nahaha, which is 4 miles northeast of Pahala, is shown in Figure 2. The 10-foot contour map illustrates the two rotated blocks so well that description is unnecessary. The faults break the prehistoric lavas of the Kamehame basalt.

The last movement has taken place recently, for there are fresh cracks near by. A pahoehoe flow from Mauna Loa has spilled over the scarp of one of the blocks and is preserved as a beautiful frozen cascade of lava. In many places the cascade has been shattered by a later movement.

Rotational faults are not common in the Kau District, and those observed seem to have resulted from two epochs of faulting with opposite displacements, such as are described in the history of the Waiohinu fault.

REVERSE FAULTS

Only a few small reverse faults with displacements of a few inches have been observed in the Kau District. Some occur in Halemaumau and on the floor of the Kilauea caldera, where molten lava has pushed up a crag or block. During periods of tumescence, or swelling of the lava column, reverse faults may be formed, but they would be difficult to distinguish from remnants of relief formed during normal faulting.

EXAMPLES OF FAULTS

MAKUKOA FAULTS

Two easily accessible transverse faults occur north of the Volcano Road between Pahala and the Volcano House. These are shown in detail in Figure 3. They are prehistoric because they displace both Pahala and Kamehame rocks. They are called the Makukoa faults for convenience.

The southwestern one (No. 1, fig. 3) consists of two parallel faults with a narrow strip dropped between, forming a small graben. The downthrow is on the northeast side. Within a mile to the north the two parallel faults die out into cracks. They are older than the lava flow south of them, and doubtless they once extended farther seaward but have been buried by later flows.

The one nearer Kilauea (No. 2, fig. 3) has a more interesting history. It has a downthrow of about 15 feet on the southwest side, and the fault is now marked by an open valley. At first it was thought to be a narrow graben like No. 1, but careful examination showed that it is a single transverse fault breaking thick Pahala ash beds which have been buried by a prehistoric Kamehame lava flow. The downthrow exposed about 15 feet of basalt on the northeast side. On the southwest wall about 50 feet of Pahala ash is exposed, consisting of yellow ash overlain by 20 feet of thin-bedded black ash and that in turn by brown ash. The exposure on the northeast side of the fault has been considerably reduced by erosion. This fault fissure became the site of a stream because of the imperviousness of the ash, but at No. 1 the water sank into the broken lava. In time the stream eroded a wide gully in the soft ash, which gives the grabenlike appearance to the fault. The head of the valley, however, now ends abruptly in a 20-foot cliff caused by a later lava flow spilling into the gulch and partly filling

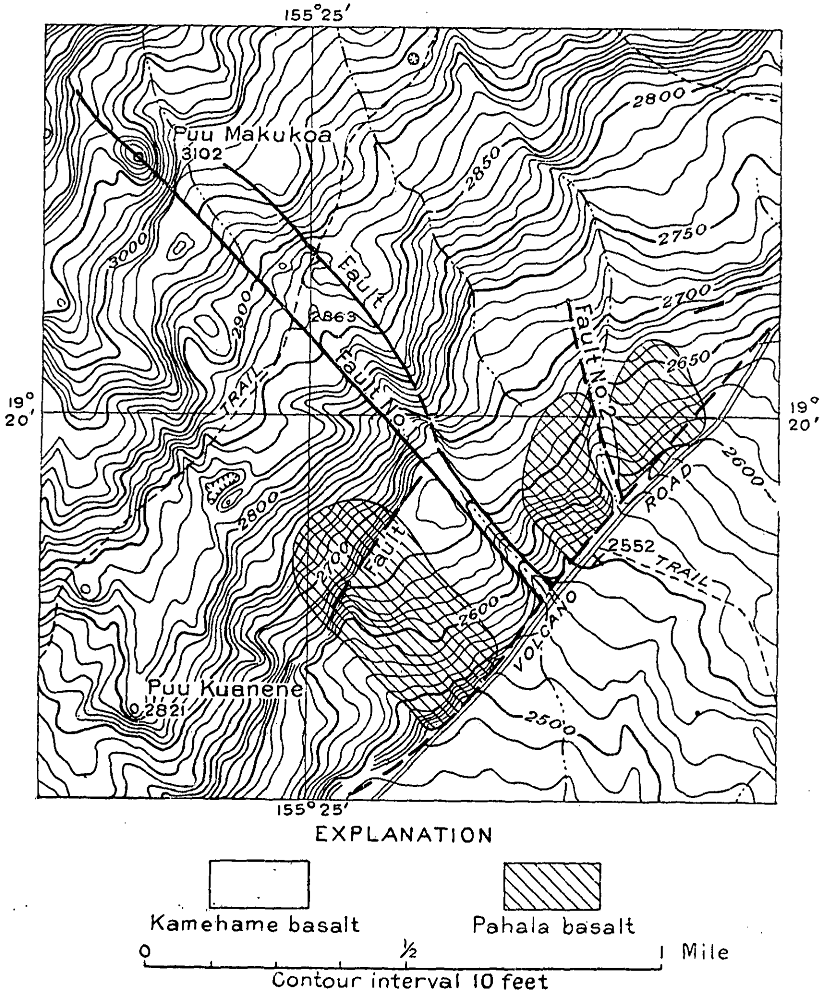

FIGURE 3.—Makukoa faults, on Mauna Loa

it. An exposure at the head of the gulch shows a 2½-foot lens of large, well-rounded cobbles overlain by 2 to 3 feet of Pahala ash, indicating that the fault originated near the end of the formation of the Pahala basalt. No. 2 is therefore older than No. 1 unless No. 1 originated at the same time and moved again in prehistoric time.

On the ash overlying the cobbles there once grew considerable vegetation, for molds of trees 1 foot in diameter are still preserved in it. A prehistoric Kamehame lava flow came down the valley and partly filled it, except the south end, inundating the forest growing there and forming the tree molds and tree casts. These molds and casts are excellently exposed. Some of the roots still exist in the ash, radiating from the old stump molds in the lava. About 6 inches of the brown ash just below the lava has been baked black. The lava flow evidently created a barren country, for a 3-foot wind deposit occurs on the west side of the flow. After another lapse of time another prehistoric lava flow came down the slopes of Kilauea, buried the seaward end of the fault, and flooded back into the old valley, entirely covering the floor. Only a small portion of the fault is now visible. The history of this fault shows that in a region of active volcanism faults and valleys may be completely obliterated in a relatively short time.

WAIOHINU FAULT

The Waiohinu fault, known to the natives as Kaulu and Waipio Palis, passes within half a mile of the village of Waiohinu and extends 4½ miles in a southeasterly direction to the sea at Waikapuna Bay. (See pl. 1.) The fault scarp is very conspicuous from the Volcano Road, but is considerably overgrown by trees and brush in the upper part. It is a typical step fault and is transverse to the southwesterly trend of the faults on Mauna Loa. It is not radial either from Mauna Loa or from Kilauea. If projected up the slope of Mauna Loa it would intersect the southwest rift zone of Mauna Loa in the vicinity of Puu o Keokeo. All the lava beds involved in this fault originated on Mauna Loa.

The first movement along the fault may have been coincident with the deposition of the ash member at the top of the Pahala basalt. The downthrow was on the west side, creating a fault scarp which was several hundred feet high at the coast and which died out rapidly inland. At the present time the visible extension of this old fault scarp called Waikapuna Pali is only 1 mile long. Beyond this distance the scarp is covered by later lavas. Two benches, now covered with a veneer of lava, are discernible on the west side of the pali and show that this fault was a step fault. Waikapuna Bay now occupies the reentrant formed by the downthrown block.

After a period of quiescence a thick flow of olivine basalt (picrite basalt) that belongs to the Kamehame basalt came down Waiohinu Valley, buried the upper end of the fault, and cascaded over Waikapuna Pali. After this lava flow there was renewed movement along the fault. This time, however, the downthrow was on the east side, the maximum movement occurring at the upper end of the fault. Waipio and Kaulu Palis were formed. This movement made the Waiohinu fault a rotational fault.

After this period of faulting a late prehistoric pahoehoe flow with no olivine phenocrysts came down Waiohinu Valley. After flowing seaward about 3 miles on the east side of the fault it crossed the fault scarp at its lowest place, in the region of the pivot of rotation, and then flowed into the sea along the west side. Upon reaching the sea the flow built out a lava fan partly filling Waikapuna Bay. A small part of it crossed the fault again at the shore and flowed eastward, building a platform at the foot of Waikapuna Pali. Where the lava crossed the fault line for the first time it passed up over a low scarp that had resulted from the faulting of the olivine basalt. In doing this, the lava formed a pool and thickened until it overtopped this 10-foot scarp. Pressure developed on the crust of the pool and caused a line of large pressure domes 10 to 20 feet high along the obstructing scarp. In one place a trickle of lava broke out of a confining lava tube and flowed down into the depression at the foot of Waipio Pali.

A period of quiescence then ensued until late in March, 1868, when activity was renewed along this fault. On April 2 occurred the severe earthquake shock which destroyed every building in Waiohinu and caused widespread destruction in Kau. This marked the climax of the seismic crisis of 1868 in Hawaii. The old road crossing the fault was broken, and the land on one side of the fault is reported to have moved horizontally the entire width of the road.[69] Accounts written at the time also describe a ledge impassable for horses which was formed in the trails crossing the fault.

The region of the fault has changed considerably in aspect since 1868. At the present time only the old stone walls marking sites of former native huts and a few coconut trees are left. Lantana, an almost impassable thorny bush, covers the old roads so that they are no longer distinguishable. Reopened cracks along Waipio Pali are evidence of recent movement. Farther seaward the shattered and upset pressure domes at the place where the last lava flow crossed the fault indicate increased movement. At this place the vertical component of the movement is negligible, but seaward from the domes it is evident that the movement was upon the west side. Although only a few inches at the upper end, the amount increases seaward until at the coast there is an upthrow of 10 to 12 feet. It is this upthrow that accounts for the raised beach extending from Waikapuna Bay to Kaalualu. The faulting was en échelon with the old fault line but closely followed it. Where the last flow crosses

[69] Wood, H. O., On the earthquakes of 1868 in Hawaii: Seismol. Soc. America Bull., vol. 4, p. 199, 1914. Quotes a newspaper statement.

the fault at Waikapuna Bay there is a small graben 25 feet wide caused by the dropping of a narrow wedge. The roofs of many of the lava tubes within several hundred feet of the fault have collapsed. The fractures of the rocks involved in the movement now look as fresh as if the faulting had taken place only a few weeks ago, a condition due to the semiarid climate of the coast in this region.

Because the displacement increased toward the shore, it is possible that the vertical movement of the fault out to sea may have been considerably more than 12 feet. There was undoubtedly some horizontal movement, but the matching up of features in the lava (tubes, ropy surfaces, etc.) indicates that the horizontal component probably did not exceed 2 feet at any place.

A summary of the history of this fault gives the following sequence of events: (1) Downthrow on the west; (2) lava flow; (3) downthrow on the east; (4) lava flow; (5) upthrow on the west with a scissor motion. The last movement seems to be a rejuvenation of the previous faulting but with the place of maximum displacement shifted seaward.

KAHUKU FAULT

The Kahuku fault, near the Kahuku ranch, on Mauna Loa, is 13 miles long. It is oriented due north and south and hence is not exactly radial from Mokuaweoweo. It consists of Pali o Ka Eo, Pali o Mamalu, and Pali o Kulani. The last two palis mentioned are continuous and form a fault scarp 10 miles long which reaches a maximum height of 600 feet. (See pl. 1.) Pali o Ka Eo is an en échelon branch of the fault but less well defined than the others because it is veneered by lava flows. The downthrow on the Kahuku fault was on the west side; the maximum displacement can not be determined because the downthrown block has been built up by recent and prehistoric lava flows of the Kamehame basalt. The absence of any considerable ash on the face of the cliff may indicate that the last movement occurred after the Pahala formation was laid down. As can be seen from the map, this fault is made up of several minor step faults and one transverse fault. The movement seems to have died out seaward. The fault dies out inland among a number of large cinder cones and massive flows. It was caused by the collapse of a portion of the rift zone, probably owing to the large cavities left below by the extrusion of the lava. It is believed that this fault is evidence in support of the view that the lava issuing from the surface fissures leaves fissure-shaped voids beneath.

EFFECTS OF FAULTING

Much of the topographic relief in the Kau District is due to faulting. Faults form the cliffs and the steep slopes of the calderas and usually control the form of the coast line and the location of stream valleys. In the youthful stage of a basaltic dome faults play a minor part, but as the dome reaches maturity they become more and more dominant, until in old age they control the topography.

There is evidence everywhere along the coast of the Kau District that the shore has subsided as a result of faulting, the amount of subsidence ranging from a few inches to several thousand feet. The variation is due to faulting at many different times on a volcanic cone which was in the process of building, hence the part of the coast that has been continually built up by lava flows shows less subsidence than the parts which have not been overflowed by lava in many centuries. The total amount of subsidence for any one portion of the coast can be computed only from the time of the last lava flow that occurred there, because any antecedent movement is usually obscured. In 1868 about half of the coast of the Puna and Kau Districts subsided several feet. Even the shore east of Kalae, on Mauna Loa, has gone down, although from the presence of the Kahuku radial fault it might be inferred that the coast on the east side of the fault has been stable or uplifted. The Pahala ash along the shore occurs at tide level, and as no marine fossils have been found in any part of its section the ash is doubtless a subaerial deposit that has been lowered by faulting. The Hilina-Kapukapu fault system shows that the southern coast of Kilauea has subsided 1,000 to 2,000 feet. Subsidence has also occurred along the shore of Mauna Loa west of the Kahuku fault.

Except between Kaalualu and Waikapuna Bay on Mauna Loa there is no positive evidence of uplift along the Kau coast, although in several places the accumulation of lava flows at the shore has made flats that look like benches. In this manner Keoneleele Flat, 3 miles south of Pahala, has been built up out of the sea by Kamehame flows.

EPOCHS OF FAULTING

Faulting is and has been a more or less continual process in the Kau District. The significant faulting, however, falls within fairly well-defined epochs, though this apparent grouping into epochs may be due entirely to perspective. There are at least three epochs of faulting in the region.

The first epoch occurred at or near the end of the time when the Ninole basalt was laid down. Strips of land along the southeast side of the ancient Ninole dome were lowered by great seaward slip faults. Remnants of the escarpments formed by these faults and perhaps somewhat modified by marine erosion are still preserved in the seaward-facing cliffs of Ninole basalt. (See pl. 1.) Because of the events that have occurred since this epoch of faulting it is difficult to reconstruct the details. It is clear, however, that there is a series of faults that are roughly parallel to one another and have a general northeast trend. One of the series of faults trends northward from Honuapo toward Kaumaikeohu Peak. (See pl. 1.) A single fault transverse to the series was found displacing Ninole basalt in the southwest side of Puu Enuhe. The Pahala and Kamehame basalts lie unconformably on the fault blocks formed during this epoch of movement.

In the second epoch a series of parallel faults was formed which extends northeastward for about 28 miles from Punaluu, a small village on the coast near Ninole Valley, to the Kau-Hilo boundary line 2 miles north of Volcano House. (See pl. 1.) The escarpment formed during this epoch has been described under "Physiography" as the Kaoiki fault scarp. At the surface the movement has broken mainly Pahala rocks, although in a few places the Kamehame basalt is slightly displaced. The Ninole basalt is everywhere buried along the line of faulting, but it is probable that the Kaoiki fault series, which has nearly the same strike as that of the older faults a few miles away, began in the first epoch of faulting and culminated in the second. During early Pleistocene (?) time a considerable number of Pahala lava flows from Mauna Loa and apparently also some from Kilauea crossed this series of faults. However, the accumulation of lava progressed less slowly than the deformation, with the result that the scarps are still preserved. A careful study of the faults indicates that the movement on them has decreased in time from northeast to southwest. This time progression in the cessation of movement in a direction away from the summit of Kilauea suggests that as Kilauea was built up there was a decrease in the amount of movement on the faults.

Parallel with and not more than 2 miles south of the Kaoiki fault system is a series of parallel cracks and minor faults which make up the southwest rift zone of Kilauea. Although no Pahala rocks are exposed in this zone, where recent extrusion has buried all the older rocks, yet the parallelism of the rift to the Kaoiki fault system seems more than a coincidence. It is believed that the rift zone is located on an ancient fault, which probably originated at the same time as the Kaoiki fault system.

The third epoch of faulting developed the high escarpments on the south side of Kilauea, of which Hilina Pali and Kapukapu are most conspicuous. (See pl. 1.) The fact that Puu Kapukapu is a horstlike block of Pahala basalt covered with Pahala ash and completely surrounded by Kamehame lava flows indicates that this block was elevated above the surrounding area before any Kamehame flows entered this region and therefore that faulting began at or near the end of the time when the Pahala formation was laid down. The amount of displacement by this group of faults is tremendous, for scarps over 1,000 feet high were developed. The faulting that began in the area probably near the end of the Pahala epoch has continued until the present time, for the Kamehame lava flows from Kilauea that have crossed the faults have been displaced. During the numerous earthquakes of 1868 movement on many of these faults occurred, and the movement is still going on, for slight earthquakes are common in the area.

The Hilina-Kapukapu fault system occupies the same geographic position on Kilauea as the Kaoiki fault system does about 8 miles to the north, on Mauna Loa. The formation of the Kaoiki fault system is believed to be concurrent with that of the Ninole faults of the first epoch of deformation, which probably died out near the end of early Pleistocene (?) time (Pahala epoch). The formation of the Hilina-Kapukapu system probably began near the end of the Pleistocene, and movement has continued into recent time. Although there was a gradual cessation of movement in the Kaoiki fault system coincident with the building of Kilauea, there was an increase of movement in the Hilina-Kapukapu system. This doubtless indicates that as Kilauea increased in size it strengthened the southeast side of Mauna Loa, which was subsiding along the Kaoiki fault system. Also, the seismic activity shifted 8 miles southeastward to the coast of Kilauea.

CROSS SECTIONS

Section A–B is a cross section from the coast along the crest of Kaiholena Ridge to Makaalia, and thence northwestward to an altitude of 7,000 feet above sea level on Mauna Loa. (See pl. 1.) The section is nearly longitudinal to the structure of the Ninole basalt. The major part of the rocks in the section consist of Ninole basalt, which has originated from a vent on Mauna Loa about 8 miles southwest of Mokuaweoweo. The effect on the topography of the first epoch of faulting is shown in the section. The gaps or notches in Kaiholena Ridge are filled with small lenses of Kamehame basalt. These lenses are portions of lava streams that have spilled over from Ninole Valley into Hilea Valley. The crest of the ridge is still covered with Pahala ash, but only because it was too high to be inundated by lava flows. For 3½ miles northwest of Makaalia peak the Pahala basalt is exposed in a kipuka that has not been covered with Kamehame basalt. The shore has been built out 1¾ miles by the Kamehame basalt, which has come down the valleys adjacent to the ridge.

Section C–D, Plate 1, is drawn at right angles to the slope of Mauna Loa through Wood Valley and across the southwestern slope and the southwest rift zone of Kilauea. The ancient core of Ninole basalt in Mauna Loa is exposed in tunnels penetrating the veneer of Pahala rocks. The steep slope on the left side of the section is due to both faulting and erosion. Wood Valley is the northeasternmost valley eroded in the Ninole basalt that is not completely obscured by later lava flows. However, it is unlikely that any other valleys were eroded northeast of Wood Valley, because this is probably the place where the trade winds first began to lose their moisture. In this area, as in the region crossed by section A–B, some of the faults belong to the first epoch of faulting. In this area, however, the faulting continued and broke Pahala rocks, for displaced beds of this formation have been artificially exposed in a tunnel at the head of Wood Valley. The faulting is of the usual Kau type, hence it is impossible to represent all the details of the faults in the section, and only the most important ones are shown. Seaward of the Kaoiki fault system the Pahala formation is faulted down and buried by later flows from Kilauea and Mauna Loa. About 2½ miles southwest of this section a lava flow issued in prehistoric time from the Kaoiki fault. The recent rotational fault of Puu Nahaha may be due to the revival and extension upward through the Kamehame formation of one of the old buried faults of the Loa Ridge. The term Loa Ridge as used in this report comprises all of the present Mauna Loa and the parts of Mauna Loa buried beneath adjacent volcanoes. It includes all the lava flows extruded from the Mauna Loa rifts.

The region for half a mile east of Puu Nahaha is rent with cracks and is the source of many fissure eruptions. It comprises the southwest rift zone of Kilauea. A graben too shallow to show in the section exists there also. The fissure mouth of the lava flow of 1823 is shown in the section but should be considered only one of the many small and obscured fissures that exist in the graben. The fact that Kilauea lavas find their exit along fissures parallel and adjacent to the ancient faults of the Loa Ridge is evidence that these faults have extended downward and tapped the magma reservoir. At the present time fumaroles occur at several places in this fissured zone and prove the existence of hot rock not far below. The cross section shows graphically the age and origin of Kilauea and indicates that the magma wells up along the old faults of the Loa Ridge. This region is still being extended seaward by lava flows from the rift zone.

Section E–F, Plate 1, cuts Kilauea midway between the Kilauea caldera and the end of its southwest zone, near Pahala. It also intersects Mauna Loa at nearly right angles to the slope. Although the lavas exposed along the entire line of the section belong to the Kamehame basalt, yet Pahala rocks are exposed a quarter of a mile to the southwest, along Kaoiki Pali. These rocks certainly underlie the Kamehame basalt at shallow depths in the area crossed by this section. Like the two preceding sections, this one shows two major faults that belong to the Kaoiki system of Mauna Loa. Although these faults break Pahala rocks, the faults do not seem to have been active as recently as those in the vicinity of section C–D. The eastern fault forms Kaoiki Pali and has been named the Kaoiki fault. The inland one forms Ohaikea Pali and is called the Ohaikea fault. These two faults are not as simple as shown in the section, for there are many minor parallel ones. They should be considered as representing the major lines of movement of the fault system. The section crosses the low dome of Maunaiki, which was formed by a fissure eruption in 1920. In this general region the lava issued from five different cracks that form part of the en échelon system of fissures belonging to the southwest rift zone of Kilauea. This rift, like the Great Crack, shown in section C–D, runs parallel to the Kaoiki fault, a fact which suggests that the lava is rising along an ancient buried fault of the Loa Ridge. The first fault east of Maunaiki is the southwestern extension of the Koae fault system that bounds the seaward side of the southwest rift zone graben of Kilauea. This graben is too shallow to show in section C–D but is deep enough to be represented in this section. It owes its origin to the collapse of the rift zone to replace the stoped out voids along the fissures. Because of the constant filling of the graben by lava flows from fissures within its walls, the total displacements of its bounding faults are not represented by the topography, and as no deep cuts have been made it is impossible to represent the exact displacement in the section. The graben corresponds in origin to the Kilauea caldera and would be much deeper were it not for the continual filling of it by lava flows. The faulting that formed it appears to have been associated with the extrusion of the Kamehame flows and probably originated when Kilauea ceased its superfluent discharges. The east end of the cross section shows the Hilina-Kapukapu fault system with its fault scarps. All the rocks exposed in these cliffs, except for a thin veneer of Kamehame flows, belong to the Pahala formation and include eight interstratified ash beds. In Hilina Pali a narrow dike 4 inches thick is exposed for about 100 feet. Its upper extremity is at the base of one of the intercalated ash beds. The same cliff is crossed by a transverse fault which displaces five ash beds. There is abundant evidence that the epoch of faulting began near the end of the deposition of the ash member at the top of the Pahala basalt and after most of the dome of Kilauea had been formed. Numerous Kamehame lava flows have cascaded over these fault scarps, and because many of them have been broken in historic time the faulting must be still in progress. The Hilina-Kapukapu fault system marks the decadence and destruction of the Kilauea dome.

Section G–H, Plate 1, extends from the south coast to Kilauea through Halemaumau and up the slope of Mauna Loa. Like the two preceding sections, it shows the Kaoiki fault system, approximately the same distance from Halemaumau as from the rift system. Along this section, however, the faults have long been dormant and are veneered by lavas from Mauna Loa. No trace of them exists 3 miles northeast of the line of the section. The ancient dome of Ninole basalt died out in this direction, hence its coastal fault system may have died out also. Kilauea is situated at the intersection of this fault system with the Kea rift, a pronounced geovolcanic line extending from the north point of Hawaii through Kohala and Mauna Kea to Kilauea. This position is strong evidence that the coastal faults of the ancient dome of Ninole basalt formed a place of weakness on the great Kea rift and became a seat of active volcanism. The lava flows from this place built up the dome of Kilauea on the dropped blocks on the southeast side of Mauna Loa. Underlying and perhaps interstratified with the Pahala lavas from Mauna Loa in this place there are probably lava beds from Kilauea that flowed northwestward before the renewal of activity on Mauna Loa. The visible fault scarps are therefore the result of movement continued along preexisting ancient faults which broke the lavas of both Mauna Loa and Kilauea. The Ninole formation is doubtless buried several thousand feet. With the approach of old age of the Kilauea dome the faults of the Hilina-Kapukapu system began to destroy the seaward slope. At the same time effluent discharges increased from the two rift zones of Kilauea. The voids created by these discharges, together with the sapping at the intersection of the two rifts, caused the collapse of the dome. This is shown by the numerous faults in the cross section. With little or no superfluent discharge from Kilauea for a long time, sufficient lava has not been extravasated on the summit to prevent these faults from forming the caldera of Kilauea and its adjacent grabens. At the same time new faults are developing parallel to and on the inland side of the coastal faults of the dome, which are now no longer inundated by lava flows. Thus the destruction of the dome of Kilauea is progressing to-day in the same way that the ancient dome of Ninole rocks underlying Mauna Loa was partly destroyed in Tertiary (?) time. As the Hilina-Kapukapu fault system is becoming more profound, it is not unlikely, if history repeats itself, that the fires of Kilauea will migrate to the intersection of these faults with the southeast rift of Kilauea. In the meantime, Mauna Loa is in its prime of activity and is pouring out vast floods of lava. It is situated in so strategic a position that its flow may bury the great caldera of Kilauea within the next few centuries in much the same manner as it buried the ancient dome of Ninole basalt.

GEOLOGIC HISTORY

ISLAND OF HAWAII

The geologic history of the Kau District is intimately connected with the volcanic development of the entire island; hence it will be necessary to outline briefly the geologic history of Hawaii so far as it is known. It is generally agreed that Kohala Mountain, in the north end of the island, is the oldest seat of volcanism, because of the large amount of erosion that has taken place there since the volcanic activity ceased. A few well-preserved cinder cones on its slopes, however, indicate that there may have been short spasms of renewed activity even into Recent time. There is likewise no doubt that Mauna Kea was the next of the five seats of volcanism on Hawaii to become extinct or dormant, because the remaining three have been active in historic time.

Most of the Pahala ash was probably derived from the ash cones on Mauna Kea. As many of the summit cones which have been the source of part of the Pahala ash show signs of glaciation, it is concluded that at least part of the Pahala ash was deposited in Pleistocene time. This volcano probably completed its major activity before the end of the Pleistocene epoch.

The ages of the other three volcanoes on the island, Mauna Loa, Kilauea, and Hualalai, are matters of conjecture, for these volcanoes are still active. Hualalai is the least active of the three. If long periods of dormancy can be taken as evidence of the dying out of the volcanic fires of basaltic cones, it is probable that Hualalai is older than either Kilauea or the active portion of Mauna Loa.

Jaggar,[70] in his discussion of the age of the different vents in Hawaii, makes the following statement:

> And even height must be examined in the light of relative age; Mauna Kea is built upon the piedmont plain of Kohala—or is it built upon a high ridge over the southeastern extension of the Kohala fissure? In such case the relative greatness of the individual volcano Kea is 4,216 meters less the height of its Kohala foundation. If Hualalai overlaps the high piedmont plateau of Kea's lavas, its real height is 2,521 meters less Kea, less Kohala. So small are all these clustered vents in proportion to the great Hawaiian ridge, made by imbrication of dome on dome and cone on cone through millennia, that great caution must be exercised in all arguments dealing with size, permanency, and precise location.

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[70] Jaggar, T. A., jr., Seismometric investigation of Hawaiian lava column: Seismol. Soc. America Bull., vol. 10, p. 190, 1920.

In order to give a clear history of the region it will be necessary to recapitulate part of what has been written before and also to disregard the vents as they now exist, dealing as far as possible with their ancestors.

Hawaii is a portion of the great Hawaiian ridge that stands above sea level. Imbrication of dome upon dome was necessary before the ridge rose above the Pacific Ocean. After the ridge reached sea level the building was controlled primarily by fissure eruptions, the particular vents at the time being due to special conditions. The vents shifted occasionally, hence they may or may not have been in their present location for any great length of time. For this reason the vents of Mauna Loa, Kilauea, Mauna Kea, and Hualalai will be omitted from the geologic history as much as possible, and the development will be described as taking place along the Kea Ridge, extending from the north point of Hawaii through Kohala Peak, Mauna Kea, and Kilauea, and along the Loa Ridge, extending from the south point of Hawaii through Puu o Keokeo and Mokuaweoweo to Mauna Kea.[71] Two secondary ridges also occur. The one extending through Hualalai to Mauna Kea will be called the Kona Ridge, and the one extending from Cape Kumukahi toward Kilauea the Puna Ridge. (See pl. 2.) A study of the topography and geology shows that the Loa and Kea Ridges have controlled the development of the island of Hawaii. Also, there is evidence that these two ridges were built up by lava flows from two major volcanic rifts.

The oldest land mass on the island of Hawaii appears to be the buried dome consisting of Ninole basalt on the Loa rift. The strike and dip of the lava beds in the Ninole basalt in the Kau District indicate that the lava was poured out of a vent on the axis of the Loa Ridge about 8 miles southwest of Mokuaweoweo. The height of the land mass built around this ancient vent, according to an estimate based on the dip of Ninole beds, must have been about 10,000 feet. When the cone reached this height volcanic activity ceased for a period of time long enough for valleys more than 2 000 feet deep to be carved on its southeastern slope.

The dome of Kohala, rising over 5,000 feet above sea level and located on the Kea rift in the northern part of the island of Hawaii, appears to have been the second land mass to be built above the ocean. On the east side of this volcanic dome are a number of box canyons more than 2,000 feet deep which are comparable in size to the ancient valleys in the Ninole basalt in the Kau District. If the conditions of present erosion are similar to those that existed on the old Ninole land mass, then the lava flows in Kohala Mountain should be approximately contemporaneous with the lava beds of the Ninole formation.

[71] This differs from Dana's Loa Range (Characteristics of volcanoes, p. 27, 1890).

However, the east coast of Kohala is the windward side of the island and hence receives a heavy rainfall. The region occupied by the ancient Ninole valleys in the Kau District is also a region of heavy rainfall, although at the present time it receives less than the east coast of Kohala. If the cone of Kilauea did not exist or at least was not high enough to obstruct the trade winds at the time the Ninole valleys were formed, more rain would have fallen in the Kau District than at present, and the rate of erosion on the Ninole land mass may have been even more comparable to the rate of erosion on Kohala Mountain. Even though the rate of erosion was comparable, however, the amount of filling by lava flows that has occurred in the Ninole valleys since they were formed indicates that they are probably older than those on Kohala Mountain. Hence, the present stage of valley cutting on Kohala Mountain is similar to that on the ancient Ninole Dome before its valleys were filled by later flows.

If the rate of cone building was the same, it is believed, in view of the facts that the Ninole land mass was higher than Kohala Mountain and that its valleys have been deeply filled with lava flows since they were formed, that the Ninole land mass, on the Loa rift, is older, at least in part, than Kohala Mountain, on the Kea rift. If this conclusion is sound, then the Loa rift reached its maximum growth in a dome about 10,000 feet high in the form of the Ninole land mass at or before the time volcanic activity culminated in the growth of Kohala Mountain. The sites of greatest activity presumably then shifted from the Loa rift and the Kohala region of the Kea rift to the point of the intersection of the two rifts and resulted in Mauna Kea.

While Mauna Kea was in its prime, activity in the Kohala and Loa regions of the great rifts declined, and faulting became dominant along the two ridges. Large step faults were developed in the Kau District on the southeast side of the Loa eminence, causing the subsidence of a large portion of the southeastern slope of the mountain.

Presumably owing to the increase in height of Mauna Kea and the profound faulting of the Ninole basalt on the southeast side of the Loa Ridge, lava broke out at the intersection of these faults with the Kea rift system, and Kilauea was born. According to Jaggar,[72] Hualalai also was born about the same time as Kilauea.

Finally a new vent on the northeast slope of the old eminence of the Loa Ridge became vigorously active and built up the cap on the Loa Ridge, with the great fire pit of Mokuaweoweo at its summit. This cap, or dome, on the Loa Ridge is very distinct when viewed from Puu o Keokeo or any high place on the slopes of the Loa Ridge.

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[72] Jaggar, T. A., jr., op. cit., p. 195.

At the present time Mauna Loa is the name by which the whole Loa Ridge is known.

The great fan-shaped area of Pahala lava beds that extends from the Volcano Road to Kalae, locally known as the South Point country, suggests that the southwest rift of the Loa Ridge up to 7,000 feet above sea level was active earlier than Mokuaweoweo, or at least before Mokuaweoweo was able to pour lava into the Ninole valleys.

While Hualalai and Kilauea have passed into late maturity or old age, Mokuaweoweo has passed from an extremely active youth to a present vigorous maturity. In the nineteenth century it produced huge quantities of lava and was one of the most active volcanoes in the world.

The sequence of events in the geologic history of the island, as conjectured from the available data, can be summarized as follows: (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; (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 7,000 feet; (10) birth of Mokuaweoweo vent; (11) decadence of Hualalai; (12) maturity of Mokuaweoweo and Kilauea.

Many facts regarding the controlling fissures, geologic development, etc., of a large portion of the island are practically unknown. This is especially true of Hualalai and the interior plateau. For this reason the sequence of events given above should be considered tentative only.

KAU DISTRICT

The lava beds that were poured out from one or more vents on the Loa Ridge before the seat of activity had moved to Mokuaweoweo have been mapped as the Ninole basalt, which is tentatively classified as Tertiary or older. The dome that was built up around the most active place on the rift and the source of many if not all of the Ninole rocks exposed in the Kau District will be called the Ninole Dome. The ash bed in the upper part of the Ninole basalt indicates that near the end of the Ninole epoch the Loa rift was probably the scene of explosive eruptions. The fact that erosion proceeded in the Ninole formation unimpeded by lava flows from the Loa Ridge signifies that for a long period central Kau was not inundated by lava flows. This period of quiescence on the Loa Ridge during which the wide box canyons were cut in the Ninole formation is tentatively assigned to late Tertiary time.

The decadence of volcanism on the Loa Ridge was accompanied by faulting that broke down the entire southeast side of the ridge. The faulting was of the usual Kau type and similar in all respects to the faulting that is destroying the coast of Kilauea at the present time. This first epoch of faulting created a fault scarp, in places over 1,000 feet high, which is still distinguishable on the faces of the ancient ridges composed of Ninole rocks. At about 4,500 feet above sea level, inland from Kapapala, a deeply buried fault scarp, presumably formed during the first epoch, is still visible. No attempt was made to show this fault on the map, because it is almost obscured by later lava flows.

The faulting of the Ninole basalt probably accelerated erosion on the slopes of the Loa Ridge. It is thought that at that time Kilauea did not exist and intercept the moist trade winds; hence heavier precipitation than at present probably played a large part in the erosion of the valleys. Erosion of the Ninole rocks probably had not proceeded far when the southern extension of the Kea Ridge became active, and lava was extruded from the intersection of the ancient faults and the Kea rift in the present vicinity of Kilauea.

The exact relation of the Puna Ridge to Kilauea is unknown, but a casual examination indicated that it may have been developed on the fault system that is at present destroying the south side of Kilauea.

Jaggar [73] has suggested that Hualalai began its eruptions before or at the same time as Kilauea and that both resulted from the migration of activity from Mauna Kea. If this suggestion is correct, then Hualalai and Kilauea must have originated a long time before the last explosive gasps of Mauna Kea, for Pahala ash, presumably largely derived from these explosions, occurs at least 1,000 feet above the basal lavas of Kilauea in Hilina Pali. This time interval may not have been as long as the occurrence of the ash would indicate, for during its youth Kilauea probably produced lava much faster than at the present time. However, there is ample field evidence to show that Kilauea originated after or during the long period of Loa's quiescence. Because of the occurrence of at least 1,000 feet of lava overlain by Pahala ash, the absence of the ash bed in the Ninole basalt, and the absence of the Ninole-Pahala unconformity in the exposures of Kilauea, the birth of Kilauea is assigned to the early part of the Pahala epoch.

The thick exposures of Pahala rocks in Kahuku Cliff may be interpreted as indicating activity in the vicinity of Puu o Keokeo

[73] Jaggar, T. A., jr., op. cit., p. 195.

on the southwest rift of the Loa Ridge at the same time as at Kilauea. This suggestion seems highly probable in view of the great fan-shaped area of Pahala lavas that now forms the whole South Point region of Hawaii. It is still a very active region on the Loa Ridge, and Jaggar [74] has expressed the opinion that it is the most likely site of the next large vent on the ridge.

The next scene in the development of Kau was the formation of the Mokuaweoweo vent, which has been considered by all other writers the source or major vent of the lavas of "Mauna Loa," the term being used by them to designate the entire Loa Ridge. To prevent confusion the writer will avoid, as far as possible, the use of the name Mauna Loa and will use the term Mokuaweoweo vent to designate the source of the lava beds in the new dome on the Loa Ridge. As the lavas from this vent have come down into Ninole valleys and are in places covered with thick deposits of Pahala ash, the Mokuaweoweo vent doubtless originated during the Pahala epoch, before the extinction of Mauna Kea. The lavas extruded from it before the end of the deposition of Pahala ash are in no place comparable in thickness to those of Kilauea, unless the South Point lava flows are included. The writer has already suggested that these belong to earlier activity along the southwest rift, below 7,000 feet. Thus, Mokuaweoweo is believed to have been in its youth when Hualalai and Kilauea were in their prime.

Throughout the Pahala epoch faulting continued on the southeast side of the Loa Ridge, but with the increase of height of Kilauea it became negligible or ceased entirely. In the meantime, with the increasing age of Kilauea, faulting commenced on its south side. It may be that as this faulting progressively deepened it tapped the magma reservoir, caused a migration of some of the activity from Kilauea to these faults, and built up the Puna Ridge and its cones. If this is so, the process is similar to that by which Kilauea is supposed to have originated on the faults on the decadent Loa Ridge, probably after Tertiary time.

The faults along the shore of Kilauea are the active faults of Hawaii to-day. Beginning their history, probably in late Pleistocene time, with the coming on of the old-age stage of Kilauea they have become increasingly active, until to-day they are frequently the seat of earthquakes and are destroying the dome of Kilauea. In origin and position these seaward slip faults on Kilauea correspond to the faults along the Volcano Road on the southeast slope of the Loa Ridge. Hence, if history repeats itself, the activity of Kilauea will eventually migrate to the Puna Ridge.

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[74] Jaggar, T. A., jr., op. cit., p. 195.

In Quaternary time Mokuaweoweo built up the domelike cap on the Loa Ridge. During the nineteenth century there were 22 recorded risings of basalt in Mauna Loa, 12 of which produced outflows of lava that continued for periods of weeks or months.[75]

The sequence of events in the geologic history of the Kau District can be summarized as follows:

Tertiary (?) time

1. Building up of the Loa Ridge above sea level, and extrusion from a vent on this ridge of the lava beds composing the Ninole basalt.
2. Cessation of volcanic activity on the Loa Ridge and the erosion of deep box canyons in the Ninole basalt.
3. Beginning of faulting on the southeast side of Loa Ridge.

Pleistocene (?) time

4. Birth of Kilauea Volcano at the intersection of the faults on the southeast side of the Loa Ridge with the Kea rift.
5. Renewed activity from vents below an altitude of 7,000 feet on the southwest slope of Loa Ridge.
6. Decline of faulting on southeast side of the Loa Ridge as a result of the growth of Kilauea.
7. Birth of Mokuaweoweo vent on Loa Ridge.
8. Immense deposits of fine ash; maturity of Kilauea; almost complete cessation of faulting on southeast side of Loa Ridge.
9. Active faulting on southern slope of Kilauea.

Recent and late Pleistocene (?) time

Prehistoric time

10. Passing from youth to maturity of Mokuaweoweo.
11. Increased activity on northeast rift (Puna Ridge) of Kilauea.

Historic time

12. Dormancy of Mauna Kea, old age of Kilauea, and approaching old age of Mokuaweoweo, with the beginning of a caldera at its summit. Rapid destruction of the Kilauea cone by faulting.
13. Lava flows and explosions at Kilauea and Mauna Loa.

VOLCANIC PRODUCTS

MAGMA

Magma, as the term is used by the writer, is the proximate or immediate source of all products of volcanism. It is the molten lava with its included gases. Jaggar[76] has found, after a careful study of the Kilauea lava column, that there are several types of magma, which he names and defines as follows:

Pyromagma (fire magma) is the foaming, gas-charged, so-called "liquid" magma of the lava lakes, lava flows, and lava blowing cones and wells. Its bubbles are alive, spherical, and expanding. It is the "lake magma" of Hawaii, believed dependent on the heat of gas reaction for its mobility, and

[75] Jaggar, T. A., jr., op. cit., p. 191. [76] Idem. p. 163.

is not a simple hydrostatic fluid but a silicate glass bubbling with rising gases which burn in the air with visible flames.

Epimagma (upper magma) is the bench magma of Halemaumau, the slowly mobile but stiff upper portion of the live lava column honeycombed with pyromagmatic passages; it is the pasty substance behind the walls of the wells, cupolas, and tunnels. Its bubbles are dead vesicles, deformed, and subject to aeration. [See pl. 13, *B*.]

Hypomagma (under magma) is the lava column underground, where pyromagma and epimagma are one—namely, where gas is still in solution. Pyromagma, hence, grades down into hypomagma; it is more sharply differentiated from the moment bubbles form and their rising mixes gases, the mixture generates heat, and vesiculate convection stirs the foam along definite passages kept open in the epimagma.

LAVA FLOWS

Basaltic lava, the chief product of the volcanoes Mauna Loa and Kilauea, ranges in composition from a labradorite to a picrite basalt. The petrology of the basalt of Kilauea and Mauna Loa has been described by Washington, Cross, Daly, Powers, Noble, Coan, and others. The petrography, chemistry, and petrology are discussed elsewhere in this report. The basalt is extruded as flows ranging in thickness from a few inches to 40 feet, with an average of 5 to 10 feet. There are two types of lava formed at these volcanoes—pahoehoe and aa.

The type of lava flow with a relatively smooth, often satiny or shiny surface, that moves forward by projecting one toe after another is called pahoehoe. The general aspect of a pahoehoe flow is shown in Plate 14, *A*. The lava is supplied to the advancing margin of the flow through a great number of ramifying tubes, which range in diameter from a few inches to several feet and connect to form one or more main supply tubes that extend back to the source of the flow. Some of these main tubes are 50 feet in diameter, but tubes 10 to 20 feet in diameter are much more common. The pahoehoe lava of the Hawaiian Islands corresponds to the "Fladen Laven" of the Germans[77] and the "lave a corde" of the Italians. Jaggar[78] suggests the term "dermolith" for pahoehoe. The vesicles in the pahoehoe flows are usually spherical and uniformly distributed, especially in the upper part of the flow. (See pl. 14, *B*.)

The other type of lava flow common on both Kilauea and Mauna Loa is the aa flow, which consists of a field of bristling, jagged, and jumbled blocks produced "by the granulation by motion of a stiff, overcooled fluid on the point of solidifying."[79] It corresponds to the

[77] Wolff, F. v., Der Vulkanismus, vol. 1, p. 371, 1914.

[78] Jaggar, T. A., jr., On the terms aphrolith and dermolith: Washington Acad. Sci. Jour., vol. 7, p. 277, 1917.

[79] Wood, H. O., Notes on the 1916 eruption of Mauna Loa: Jour. Geology, vol. 25, p. 335, 1917. This article has a fine description of the motion of an aa flow.

German "Block Lava" or "Schollen Lava" and the Italian "lava a blocchi." Jaggar has suggested "aphrolith" for it. The characteristic feature of aa lava is the spinosity of the surface of the blocks. (See pl. 15, *A*.) The writer has been unable to find any other persistent characteristic of aa lava. In general, it is more crystalline and has a more stony texture than pahoehoe, and usually the vesicles are more irregular in shape and often larger than those in pahoehoe.

Just as tubes are a characteristic feature of pahoehoe, so are channels, as much as 30 feet deep and 50 feet across, characteristic of aa. These channels were occupied by the river of lava that supplied the front of the advancing aa flow. (See pl. 15, *B*.) Their banks were in places built up by splash to form levees, which enabled the lava river to flow at a higher level than the general surface of the flow and to advance without spreading laterally. Some of these channels are distinct topographic features. A large one in the lava flow of 1887, 3 miles southwest of the Kahuku ranch, is shown on Plate 1.

In places a complete gradation from pahoehoe to aa will be found in a single lava flow. Moreover, it is possible to find a series of lava flows that represent all types between typical pahoehoe and typical aa. These intermediate phases within the same flow and in a series of flows have been ignored by most writers.

The Keaiwa lava flow of 1823, from Kilauea, is an example of an intermediate type. The surface is relatively smooth for about 100 yards from the crack from which it issued. It has a glassy texture, lacks the spinosity of aa, and exhibits ropy structure and many other characteristics of a pahoehoe flow. However, it has the irregular vesicles of aa, and farther from the crack it is a broken mass of bristling jagged blocks. Many unnamed flows near the summit crater of Mauna Loa show both aa and pahoehoe characteristics.

The Maunaiki flow of 1920, the Kau branch of the flow of 1880–81 from Mauna Loa, the Kamooalii flow from Kilauea, and many unnamed flows started as pahoehoe and ended as aa. The problem of what causes aa and pahoehoe lava is still unsolved, although much work has been done on it.[80]

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[80] Dana, J. D., Characteristics of volcanoes, pp. 9, 241, 1890. Hitchcock, C. H., Hawaii and its volcanoes, p. 280, 1911. Day, A. L., and Shepherd, E. S., Water and volcanic activity: Geol. Soc. America Bull., vol. 24, p. 598, 1913. Mercalli, G., Vulcani attivi della terra, p. 179, 1907. Waltershausen, S. von, Der Etna, vol. 2, pp. 393 et seq., 1880. Washington, H. S., The formation of aa and pahoehoe: Am. Jour. Sci., 5th ser., vol. 6, pp. 409–423, 1923. Wood, H. O., Notes on the 1916 eruption of Mauna Loa: Jour. Geology, vol. 25, pp. 322–336, 467–488, 1917. Jaggar, T. A., jr., numerous papers. Daly, R. A., Igneous rocks and their origin, pp. 290–291, New York, 1914. Emerson, O. H., The formation of aa and pahoehoe: Am. Jour. Sci., 5th ser., vol. 12, pp. 109–114, 1926.

Washington,[81] after making several analyses of aa and pahoehoe from these volcanoes, states: "The differential amounts of the iron oxides in the two forms appear to be too small to be the immediate cause of or even to be directly connected with the great outer differences of the two types of flows."

An examination of Mokuaweoweo in August, 1924, showed that nearly half the floor of its crater and all of the floor of the adjacent crater of Pohaku Hanalei was covered with aa. The writer has collected hand specimens of lava from a flow in Mokuaweoweo that is pahoehoe on the surface and typical aa on the underside. Near Maunaiki, on Kilauea, it is possible to see where pahoehoe grades into aa. In most places this change seems to take place within a few feet, yet upon careful examination aa lava can be seen in the cracks of the pahoehoe, showing that the transition is gradual underneath the surface. In some places a typical pahoehoe with a frothy glass crust half an inch to 1 inch thick grades into one with a dense glass crust, and this in turn into a pahoehoe with a lacy crust that is in part rough and bristling. The typical spinose aa can usually be seen in the cracks of pahoehoe of this type. Farther on this pahoehoe grades into aa. A fine example of a flow of this type occurs on the floor of Mokuaweoweo. On the end of this aa flow there are many blocks of basalt weighing 5 to 20 tons that look like normal cakes of pahoehoe on the upper sides yet have typical aa on their under surfaces.

Many writers are in accord with the view that aa lava is more highly charged with volatile matter than pahoehoe when it issues. This conclusion is based chiefly on the loud roaring and hissing noises of a moving aa flow and on the abundance of gases. However, Wood [82] states in his description of the aa flow of 1916 from Mauna Loa that there was no excessive evolution of the volcanic gases from this flow.

Jaggar,[83] in describing pahoehoe, states:

It is a "live" lava, its gases trapped in solution; and when flowing or contained in a pit its vesicles are distended and spherical, with juvenile gases at a maximum where it first departs from the hypomagma below. The extreme type of aa, on the other hand, is made by this same slag preserved effervescent as long as possible within a hot container, extraneous to the source wells; such is the pool in a lava heap fed by a small vent, or the fluent river in lava banks of its own incrustation. An essential condition for aa consolidation is that the fluid, without renewal, be free to effervesce to the limit, with stirring, in order to develop granular solidification or efflorescence of the aa type. Perfect aa

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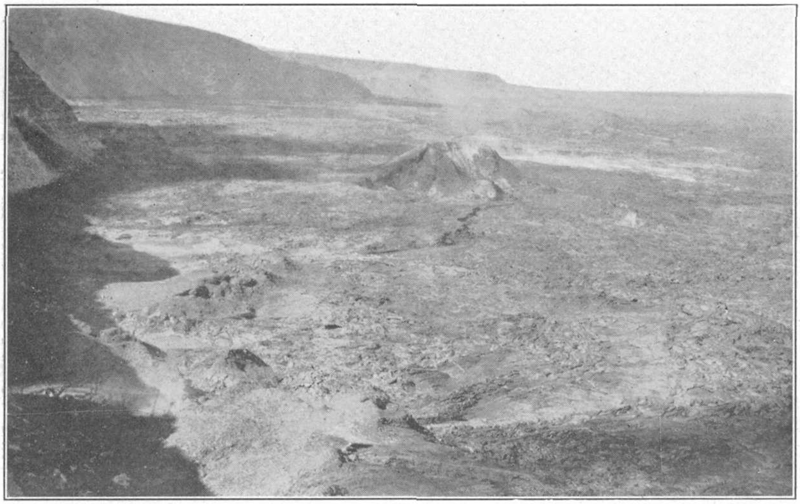
[81] Washington, H. S., The formation of aa and pahoehoe: Am. Jour. Sci., 5th ser., vol. 6, p. 416, 1923.

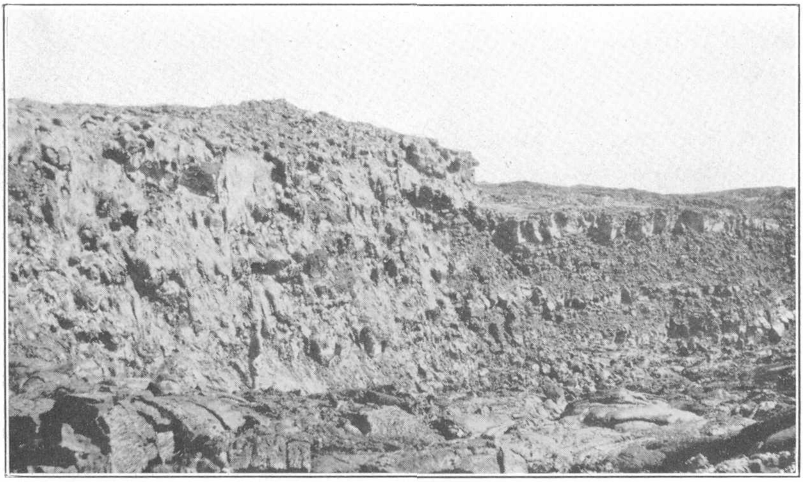
[82] Wood, H. O., op. cit., p. 335.

[83] Jaggar, T. A., Jr., Seismometric investigation of the Hawaiian lava column: Seismol. Soc. America Bull., vol. 10, pp. 167–168, 1920.



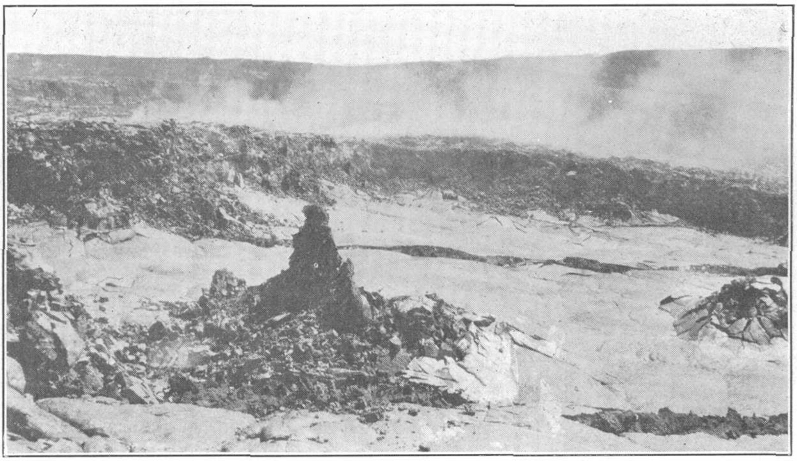
A. VIEW LOOKING NORTHEAST ALONG THE FISSURE ZONE IN MOKUAWEOWEO

Showing the cone chains, the cone of 1914, and the fuming solfatara. Photograph by H. T. Stearns.



B. VIEW LOOKING SOUTH TO THE RIM OF THE LAVA LAKE OF 1903 (?) THAT FORMS THE RIM OF THE SOUTH LUNATE PLATFORM IN MOKUAWEOWEO

Showing the veneer of spatter. Photograph by H. T. Stearns.

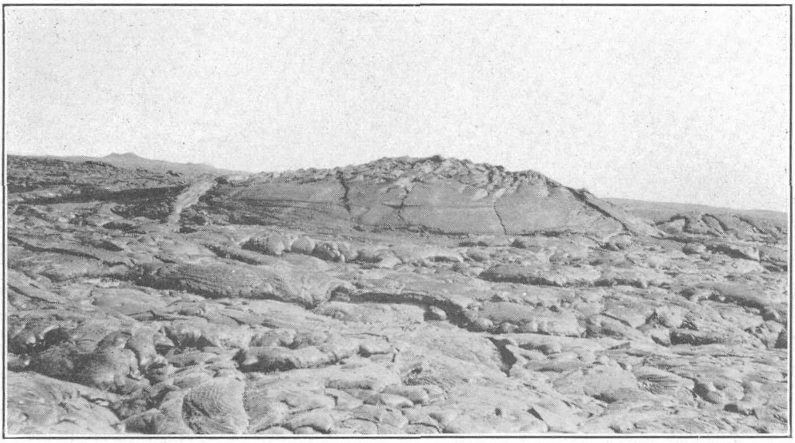


A. VIEW LOOKING SOUTHWEST TO THE FROZEN LAVA LAKE OF 1914 ON THE FLOOR OF MOKUAWEOWEO, IN WHICH RISE ISLANDS OF AA

In the background are sulphur fumes rising from a patch of khaki-colored pumice. Photograph by H. T. Stearns.

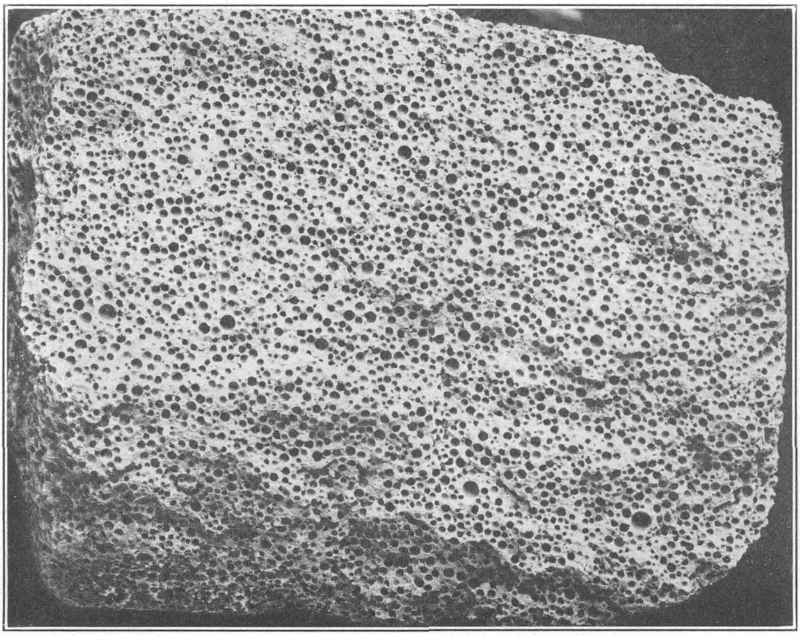
B. THE LAVA LAKE OF HALEMAUMAU

The islands or crags are epimagma rising in the lake of pyromagma. Photograph by T. A. Jaggar, jr., September 9, 1920.



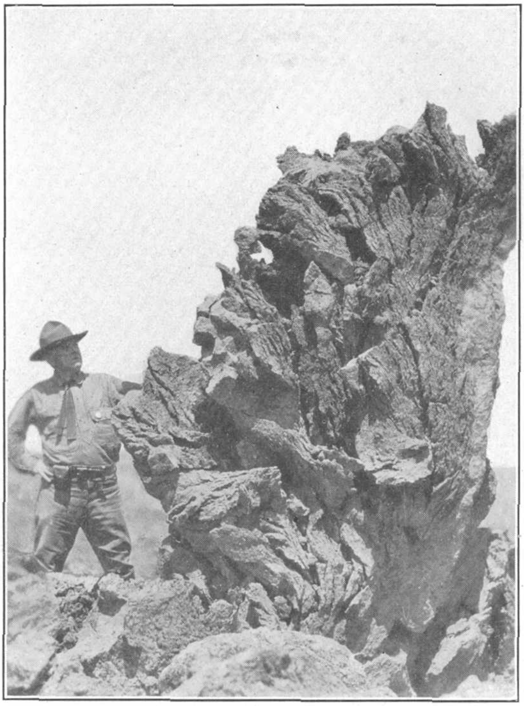
A. THE KAMOOALII LAVA FLOW OF KILAUEA

Showing typical pahoehoe and pressure dome. Photograph by H. T. Stearns.



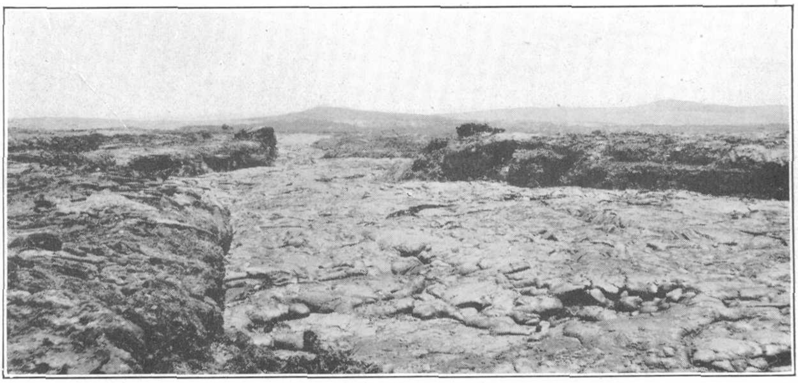
B. SPECIMEN OF PAHOEHOE FROM LAVA FLOW NEAR PAKANAKA HILL

Shows the spherical vesicles characteristic of pahoehoe. About seven-eighths natural size.



A. AA LAVA OF THE KEAMOKU LAVA FLOW FROM MAUNA LOA, ABOUT 6 MILES SOUTHWEST OF VOLCANO HOUSE

Photograph by Thomas Boles; used by courtesy of National Park Service.



B. AN ANCIENT AA CHANNEL PARTLY FILLED WITH A RECENT PAHOEHOE FLOW ON THE SOUTHWEST SLOPE OF KILAUEA

The cones of Puu Kolekole and Ulaula appear in the background. Photograph by H. T. Stearns.

should be "dead" lava; its vesicles are deformed and its gases largely replaced by air, with the result that the iron of the glass is extremely oxidized at high temperature even at the moment of solidification, in those cases like aa lava flows, where the porous paste has been stirred in the open. The swift and long Hawaiian flows are pahoehoe at the source and aa below, as might be expected. The substance of the epimagma, as defined above, will always solidify as aa if released to flow. The substance of the pyromagma will always solidify as pahoehoe if chilled before its gas discharge is finished. If its gas discharge is restrained by pressure under surface construction of tubes and heavy shells, lava may flow slowly as pahoehoe for many miles, having sluggish gas release in equilibrium with the pahoehoe condition of solidification. The beds of open lava rivers and the bottoms of the lava lakes are accumulations of crust and granules of semiconsolidation, ever added to and never melted, and this is the substance which gives to the aa flows of history their extraordinary jumbled, brecciated, dirty, and variously rusty appearance, the paste being often rolled into balls, and the whole mass appearing old, burnt, and clinkery even at the instant of consolidation. Aa flows like cheese, without inflation; pahoehoe flows like slag, but with balloon inflation swelling its lobes as it advances.

The writer finds additional evidence, from a field study of lava flows in the Hawaiian Islands and other places in the world, that aa does not have a higher gas content than pahoehoe. If aa has a higher gas content than pahoehoe then aa should form at or near the great fountains that have played from fissures on the top of Mauna Loa. It is admitted by all observers that the lava ejected from these fountains has a tremendous gas content, and this is substantiated by the fact that the fountains play 600 feet in the air, and by the abundance of pumice and frothy pahoehoe near by. The crust of much of the pahoehoe near the source of the fountains is thread-lace scoria light enough to float on water, entirely different from aa. During the Maunaiki flow of 1920 from Kilauea and the lava flow of 1880–81 from Mauna Loa molten pahoehoe and aa were alternately extruded from the vents. It is possible, therefore, for both aa and pahoehoe to form under the earth's crust. However, so far as the writer knows, no one has ever described a stream of aa on the surface changing into pahoehoe. The fact that a pahoehoe stream, as it gets farther from its source, can change into aa indicates that aa is due to the destruction of an equilibrium of some essential factors that can not be restored. Field evidence indicates that these factors are amorphous glassiness, gas, and heat.

Pahoehoe is discharged from a vent with an amount of gas which is more or less in solution at the temperature of extrusion. As the flow moves forward the temperature falls, crystallization begins, and gas is expelled. If the lava flow continues long enough for these processes to be effective, aa is formed.

The reason that many observers of a lava flow think that aa has the higher gas content is probably because in an aa flow the temperature is lower, crystallization has progressed further, and the gas that is left is being rapidly expelled from solution. The spinosity of aa is doubtless caused by the gas escaping from the somewhat viscous aa and carrying out with it a stringer of the doughy mass. Thus, as the gas content decreases and the temperature falls, pahoehoe passes through the stages described into aa, and with further cooling and crystallization the remaining gas is expelled from solution and the flow becomes a mass of moving clinkers.

DRIBLET OR SPATTER

The clots of lava that make up the spatter type of cone are called driblet or spatter. These clots are thrown out by lava fountains (see pl. 16, *A*) and are usually very glassy and scoriaceous. They differ from cinders in that they fall in a viscous or molten condition and tend to stick together and build up a solid cone of spatter around the vent. (See pl. 16, *B*.) Some of the spatter is red from oxidation, but black unoxidized spatter is not uncommon.

CINDERS

The vesicular ejecta formed by fountains that throw out lava with a higher gas content than that which makes the driblet cone are called cinders. The fountains are more explosive and hence hurl the lava higher and blow it into small pieces. Thus cinders cool in the air and usually fall in a solid state and build incoherent cones. The formation of vesicles is due to the sudden liberation of the gas when extruded. Usually cinders have a glassy skin on part of their surface, which may or may not have a bread-crust form. Cinders are heavier than pumice. Bombs are normally found associated with cinders.

SCORIA AND PUMICE

The crust of pahoehoe lava is commonly cellular as a result of escaping gases and in places becomes frothy enough to be called scoriaceous. A fragment of this crust is called a piece of scoria. Sometimes cinders are called scoria, but the term " scoria " should be limited to the frothy crust of a lava flow.

Pumice may develop from fountains in the same manner as cinders, except that it is usually formed by fountains that have a greater explosive force, due to a higher gas content of the lava rising in the conduit. However, pumice and cinders may be present in the same cone—in fact, pumice, cinders, and spatter can all be formed at the same vent. The writer has seen many vents on Mauna Loa that began their life as huge fountains that produced pumice. Gradually, as the gas spent itself, cinders were formed, and as the fountains became smaller they produced spatter. Pumice differs from cinders in that it is light enough to float on water. Widespread deposits of pumice are formed by great explosions and are not the product of lava fountains.

Dana[84] describes the pumice underlying the ash of 1790 at Kilauea as being thread-lace scoria. According to him the vesicles make up 98 to 99 per cent of the pumice of this particular bed. Pumice is a characteristic product of the fountains of Mauna Loa, and the thickness of the deposit underlying the ash of 1790 at Kilauea indicates that the fountains at Halemaumau also must have produced large quantities of it in the past. The writer found the ground covered with pumice a short distance from the rim after the fountain of July 19, 1924, began to play. Fragments of pumice 1 inch long and a quarter of an inch thick were carried by the wind upward 1,200 feet from the fountains in the bottom of the pit and dropped on the rim of Halemaumau. Pumice often drifts with the wind for miles from the high fountains of Mauna Loa. The writer suggests that the term "thread-lace scoria" be limited to the pumiceous crust of the pahoehoe flows of which the vesicles amount to 95 per cent or more of the mass. Crusts 2 inches thick of olive-drab thread-lace scoria occur on some of the pahoehoe flows near the vents on Mauna Loa.

PELE'S HAIR AND PELE'S TEARS

Threads of volcanic glass that look like spun glass are called Pele's hair. They are formed in large quantities during fountaining at Halemaumau and are often carried 5 or 10 miles by the wind. Usually, the higher the fountains play the more Pele's hair is produced. It is formed by the tearing apart of pieces of molten lava as they are ejected into the air. It receives its name from Pele, the Hawaiian goddess of volcanoes. On the ends of some of the threads there are little droplets of glassy lava, which are called Pele's tears. Perret[85] has published some admirable illustrations of Pele's hair and tears.

LAVA STALACTITES AND STALAGMITES

In many of the lava tubes or tunnels that have served as subterranean drainage channels for pahoehoe lava stalactites and stalagmites are found. The stalactites are formed by liquid lava dripping from the roof of the tube as the hot lava drains away. On the floor of the tube under each stalactite are usually found stalagmites which have been formed from the drip of the stalactites. Stalactites and stalagmites are probably also formed after the lava has drained out of the tubes by a secondary reheating process which has been

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[84] Dana, J. D., op. cit. p. 163.

[85] Perret, F. A., Some Kilauea ejectamenta: Am. Jour. Sci., 4th ser., vol. 35, pp. 611–618, 1913.

described by Jaggar[86] as "a product of melting in the fabric of the porous rock due to infiltration of air and surface combustion of lean gases, producing a rise in temperature and secondary oxidations after the caverns were broken but still hot and their lava streams had dwindled."

Remarkable lava stalactites, some of which are 4 feet long, can be seen in the tube on Maunaiki, the source cone of one of the flows of 1920 from Kilauea. Many of the stalactites are hollow and are unusually long and straight. They are coated with gypsum crystals deposited from the hot vapors which still issue from the tube. Some of them have wormlike ends. (See pl. 17.) Not far from Maunaiki, suspended from the roof of a cave at the source of the Kamooalii lava flow, are numerous lava stalactites with clusters of drops of lava at their ends. (See pl. 17.) They are thickly coated with sulphate crystals. On the floor of the cave under the stalactites are remarkable stalagmites, which represent the accumulation of molten lava, drop by drop. A few of them are 18 inches high. Some of the individual droplets are hollow as a result of rapid gas inflation at the time they cooled. Some of the stalagmites have grown unsymmetrically and have produced fantastic forms. A few specimens from this cave are illustrated in Plate 18. This cave is remarkable also for the wide sheets of gypsum that once coated its roof but have since partly peeled off so that they now hang as curtains.[87]

BOMBS

There are two general classes of bombs—bread-crust and rotational bombs. The latter occur only rarely on the cones of Kilauea and Mauna Loa.

Most bread-crust bombs are formed by a clot of liquid lava being thrown into the air by fountains or by explosions of any sort to such a height that a skin has time to form on the clot before it drops to earth. As cooling progresses, this skin is broken open as the gases in the molten interior of the clot expand. The effect is similar to the cracking of bread crust by the expansion of the gases in the dough during baking. In cross section, the bomb is usually more or less vesicular, with the cells increasing in size outward from the center like those in a loaf of bread. The crust of a bomb of this kind is dense, and the outer surface is usually checked or cracked. Bombs of this type have a magmatic origin. They can be found in the ash of 1790 on Kilauea, on some of the adnate cones on Mauna Loa and Kilauea, and on some of the tuff cones along the Kau coast, especially Puu Hou.

[86] Jaggar, T. A., jr., Hawaiian Volcano Obs. Bull., vol. 9, pp. 139, 157, 1921.

[87] For details see Finch, R. H., and Emerson, O. H., The formation of sulphate stalactites in lava tubes: Hawaiian Volcano Obs. Bull., vol. 12, p. 13, 1924.

Bread-crust bombs of another variety occur at Kilauea. During the explosive eruption of May, 1924, blocks of rocks weighing from a few ounces to 15 tons were thrown out. No traces of magmatic ejecta were found in the explosion débris. However, some of the projectiles were portions of fills of wall cracks and other intrusive bodies that had not completely cooled at the time of the explosions, for some of the intrusives were exposed in the walls of the pit afterward. Fragments of these hot bodies were hurled out during the explosions and when cold they exhibited bread-crust checking on the surface. The checking on these blocks can be explained as caused by the sudden chilling of a thin skin over a cooling and expanding rock.

Rotational or spiral bombs have a magmatic origin. They are formed by pieces of viscous, more or less gas-free lava being hurled through the air with a spiral motion from the fire fountains. The spiral motion causes the bomb to develop earlike projections on the ends of its axis of rotation. (See pl. 19, *A*.) As the middle portion of the clot of lava is the part that is heaviest and best able to withstand the friction in passing through the air, the ears are commonly bent backward during the descent. Parallel lines on the surface of the bomb are the result of its motion. The interior of a bomb of this kind is usually solid. Many beautiful illustrations and a detailed account of both types of bombs from Idaho are given by Russell.[88] Rotational bombs were found on only one cone in the Kau District, although a careful search was made for them on all the cones examined. This cone is the northernmost one of the Kamakaia Hills.

At the same Kamakaia cone on which the rotational bombs were found occurs another product of fountaining called lava ribbons.[89] One ribbon measured 7½ inches in length, three-eighths of an inch in width, and one-eighth of an inch in thickness. It consisted of dense glassy lava with one side smooth and the other side corrugated. Another measured 5⅛ inches in length, a quarter of an inch to 1⅛ inches in width, and less than one-eighth of an inch in thickness. (See pl. 19, *B*.) Several others were found of like size and shape, and all were slightly twisted. Their ends are smooth and appear to be broken off squarely. These fractured ends are glazed, a fact which indicates that they were broken while the lava inside was slightly viscous. The ribbons, it is believed, once formed the extended portions of the ears of the spiral bombs. They seem to have

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[88] Russell, I. C., Geology and water resources of the Snake River Plains of Idaho: U. S. Geol. Survey Bull. 199, 1902.

[89] These are the German "bandformige Bomben." For a detailed discussion of bombs see Reck, Hans, Physiographische Studie über vulkanische Bomben: Zeitschr. Vulkanologie Ergänzungsband, 1914–15.

been separated while the bombs were in the air, for none of them was found near the bombs. One bomb was found with a projecting ear 2 inches long, the outer 1⅛ inches being a portion of a lava ribbon. The ribbons are not abundant, although the writer had no trouble in collecting half a dozen fine specimens.

ELLIPSOIDAL LAVA

The lava of the Kau District contains structural features of two other types that are sometimes confused with bombs. They may be classed as ellipsoidal lava and from their outward appearance might be called subaerial pillow lava.

While aa lava is flowing in an open channel, portions of the confining banks are sometimes torn away or undermined so that fragments of already cooled lava are carried downstream. These blocks, while being floated along somewhat in the manner of a water-logged block of wood in a river, become smeared over with lava and corraded until they become spherical. They come to rest in and on the aa lava when it solidifies, and, because of their rounded shape in a bristling field of aa, they are very conspicuous. An example is shown in Plate 20, *A*. The largest of them weigh from 5 to 10 tons, and in places several of them are found together. These balls are also formed by a portion of viscous aa being rolled along until it is rounded by corrasion. They are figured and described by Dana[90] as bombs and are called by the French "bombes de roulement."

Ellipsoidal lava of the other type may or may not be formed by the explosive action of the magma. Examples of it are common along the Great Crack, the source of the lava flow of 1823 from Kilauea, in the Old Crack near Pahala, and along fissures on Mauna Loa. They are more or less spherical balls of lava varying in diameter from a few inches to 3 feet. Some of them are perfectly spheroidal. On Plate 9, *A*, is shown one that is 3¼ inches in diameter collected from the wall of the Great Crack. They are formed in three ways:

1. In Plate 9, *B*, is given a cross section of the one illustrated in Plate 9, *A*. This section shows the rind, or skin, and the core of the ball. The flow of 1823 is a feldspar-olivine basalt, and, as the illustration shows, the interior and the skin are from the same magma. The core, however, is more vesicular and has larger phenocrysts. The lava flow of 1823 was accompanied by fountains that threw clots of lava into the air. The fact that these clots are scattered and can be found 200 feet from the vent indicates that the activity was violent but spasmodic along the whole length of the crack. As no spatter cones exist along the crack, it is probable that the fountaining was never continuous in any one spot. During the

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[90] Dana, J. D., Manual of geology, 4th ed., p. 287, 1894.

fountaining some of the clots must have fallen back into the crack filled with hot lava, for the crack is in places 20 feet wide. These clots, being viscous, were heavier than the rising gas-impregnated magma and sank into it in the same manner as fragments of crust founder in the lava lake of Halemaumau. In sinking they grew by accretion into spherical masses and were floated up again by the rising magma. Some of them were caught on the edge of the fissure, where they are exposed to-day. This seems to be the most tenable hypothesis for their origin, for no true bombs occur along the crack, and these ellipsoids are not found lying detached on the ground.

2. Scattered among these balls of lava along the Great Crack and in outward appearance identical with them are balls that when broken open reveal bits of foreign aa. These fragments must have fallen from the wall of the fissure and acquired a skin while being floated up. Many such balls measure a foot or more in diameter and when broken open are found to contain several pieces of loose aa held together by the outside skin. The included fragments show no signs of fusion. At 20 feet below the surface of the crack there is exposed in some places a 5 to 8 foot bed of red aa made up of the usual loose fragments. Beds like these doubtless supplied the material for the cores of these balls. Other balls were found to contain angular blocks of dense, weathered pahoehoe that were torn or shaken from the wall, coated over, and floated up by the rising magma in the same way as those just described.

3. Projecting portions of the walls of the fissure were also coated over during the eruption and now form parts of spheroids. No fusion effect was shown on the walls of the fissure or on the inclusions, hence the temperature of the country rock was sufficiently low to chill the adjacent magma with comparative rapidity.

Examination of the ellipsoids at other fissures mentioned showed that they originated in the same ways. Plate 20, *B*, shows ellipsoidal lava along a fissure near the summit of Mauna Loa.

EXPLOSION BLOCKS

Blocks resulting from the explosions of 1790 and 1924 and from prehistoric eruptions can be seen in the vicinity of Halemaumau. They are also common on portions of the rim of Mokuaweoweo and near a few other vents in the Kau District. Many of these blocks reach a large size and weigh 15 tons or more. On Plate 20, *C*, is shown a 10-ton block hurled out of Halemaumau during the morning of May 18, 1924. This block is a portion of the rock wall of Halemaumau, as no magmatic ejecta accompanied the explosions of May, 1924. Such rocks, therefore, differ from true bombs in that they do not originate from the magma. These are described by Johnston-Lavis [91] as accessory ejecta.

In some volcanic regions the blocks consist of sedimentary rock derived from the underlying platform, as, for instance, the limestone blocks at Vesuvius. The writer found a few fragments of shell breccia that had been blown out by a small explosion along the Great Crack immediately after the eruption of 1823. Such fragments are named accidental ejecta by Johnston-Lavis. Sometimes both blocks and bombs are blown out during the same explosion. This occurred during the explosion of 1790 at Kilauea.

LAPILLI

Volcanic explosions are accompanied by the deposition of more or less fine material about the size of a pea. This material often accumulates in beds of considerable thickness and as lenses in the finer material, its form depending upon the direction of the wind at the time of the explosions. This material is called lapilli (plural of Latin lapillus, "little stone"). It may be derived either from the explosion of magma or from the comminution of the wall rock of the crater, or both. The origin of the lapilli is often difficult to determine, because the material of the crater walls has usually the same composition as the magmatic ejecta. However, the two varieties can generally be distinguished by careful study. The small bits of exploded magma are similar to bits of pumice or scoria, whereas the fragments of wall rock are generally denser and show variations in texture, color, and composition depending upon the particular character of the lava bed from which the fragments originated. Many beds of lapilli originating from the wall rock contain red, black, blue, and gray fragments all mixed together.

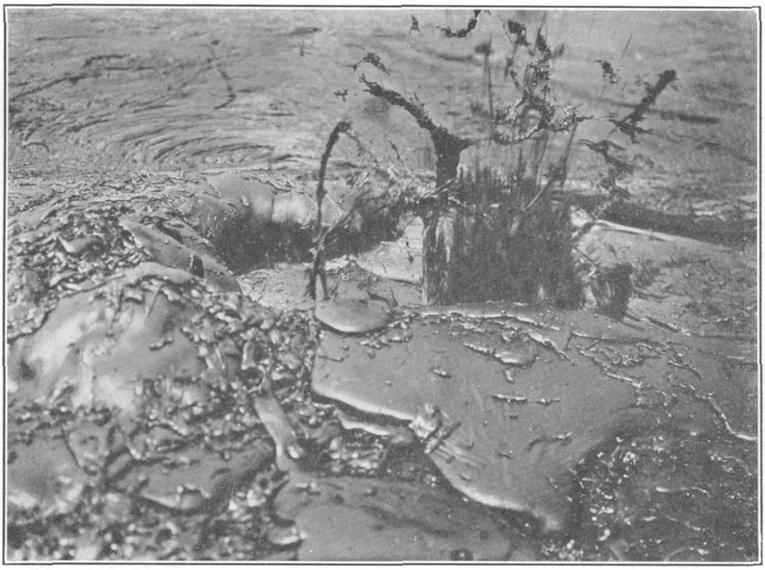
VOLCANIC SAND

The material 1 to 2 millimeters in diameter that results from a volcanic explosion is called volcanic sand. Beds of it are sometimes exposed in the explosion cones formed by lava flowing into the sea. According to the terminology of Johnston-Lavis, fine particles of wall rock would be accessory ejecta, the grains of olivine or basalt glass essential ejecta, and the seashore sand accidental ejecta.

VOLCANIC ASH

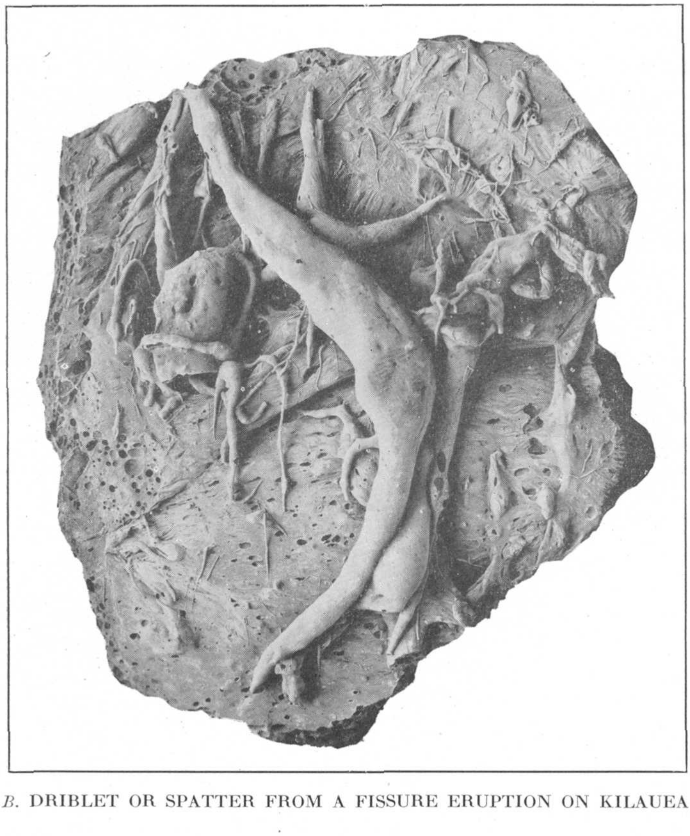
The fine material of a volcanic explosion is called ash. It is of two types. One kind originates as the dust accompanying the explosion of a magma, and the other is rock flour resulting from the pulverization of the wall rock of a volcanic vent by explosion.

[91] Johnston-Lavis, H. J., On the fragmentary ejecta of volcanoes: Geologists Assoc. London Proc., vol. 9, pp. 421-432, 1887.

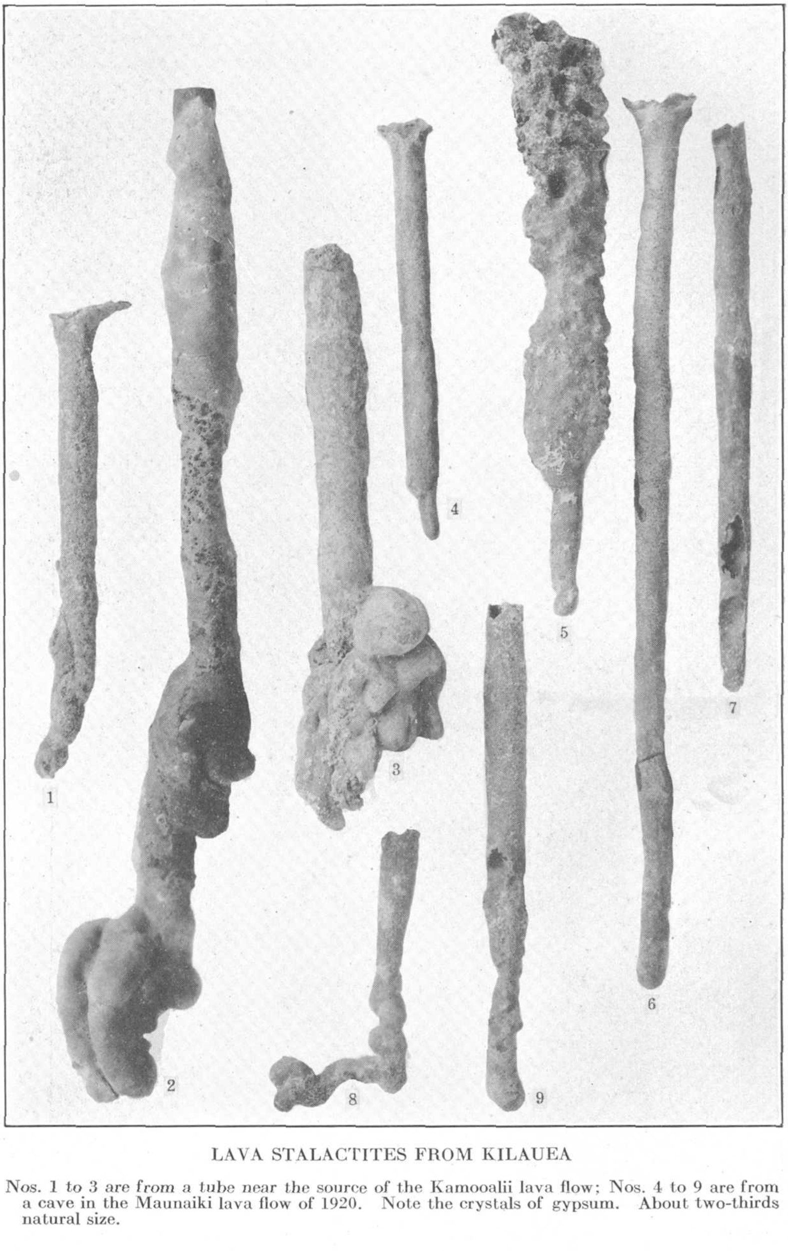


A. A LAVA FOUNTAIN THROWING OUT SPATTER WHILE MAKING A DRIBLET CONE

Photograph by T. A. Jaggar, jr.

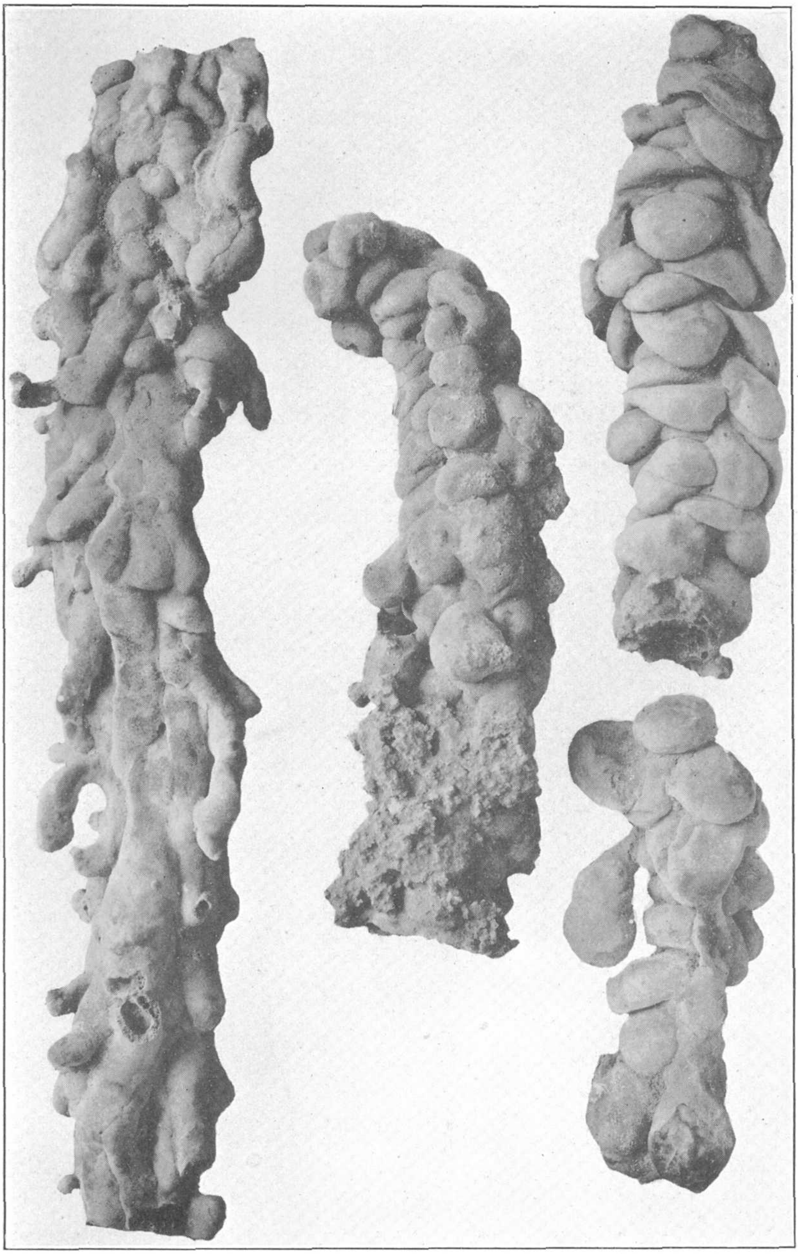


B. DRIBLET OR SPATTER FROM A FISSURE ERUPTION ON KILAUEA

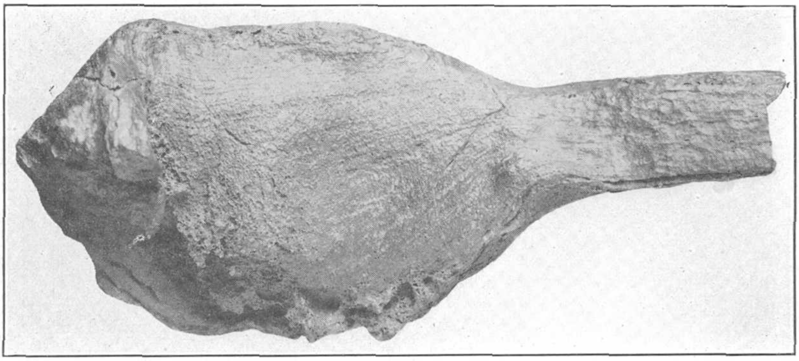


LAVA STALACTITES FROM KILAUEA

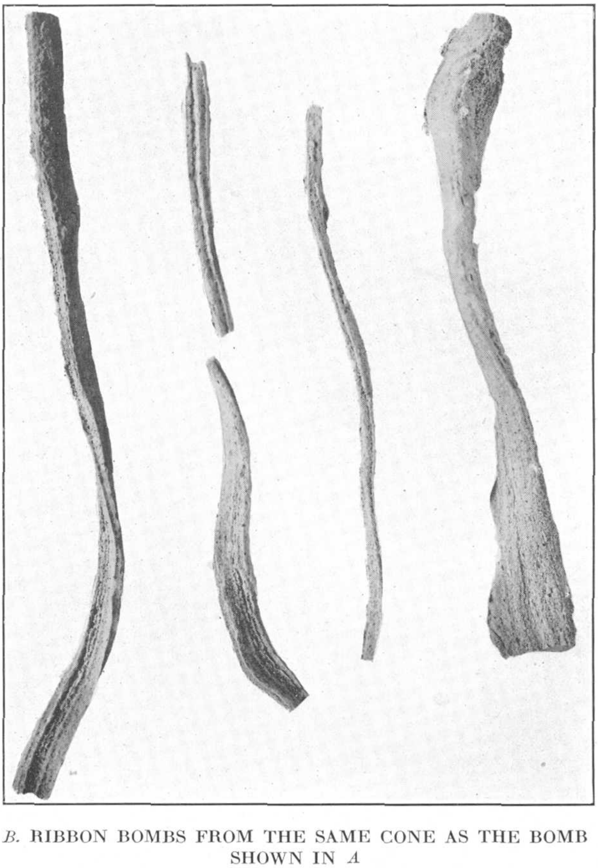
Nos. 1 to 3 are from a tube near the source of the Kamooalii lava flow; Nos. 4 to 9 are from a cave in the Maunaiki lava flow of 1920. Note the crystals of gypsum. About two-thirds natural size.



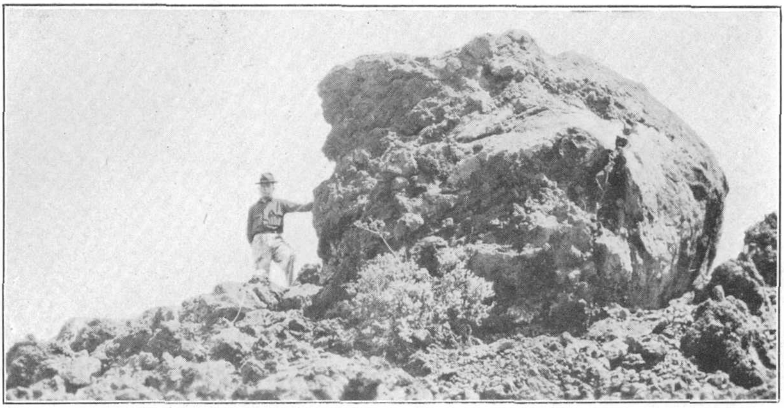
LAVA STALAGMITES FROM THE SAME TUBE AS STALACTITES NOS. 1 TO 3, PLATE 17



A. ROTATIONAL BOMB WITH AN "EAR" ON EACH END, FROM ONE OF THE CONES NEAR THE KAMAKAIA HILLS ON KILAUEA

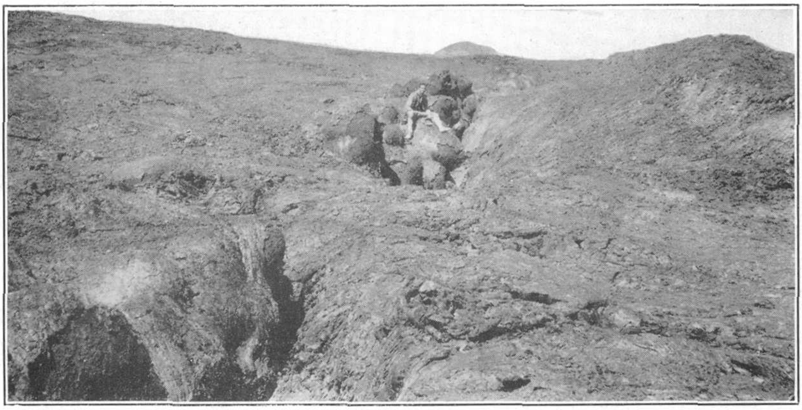


B. RIBBON BOMBS FROM THE SAME CONE AS THE BOMB SHOWN IN *A*



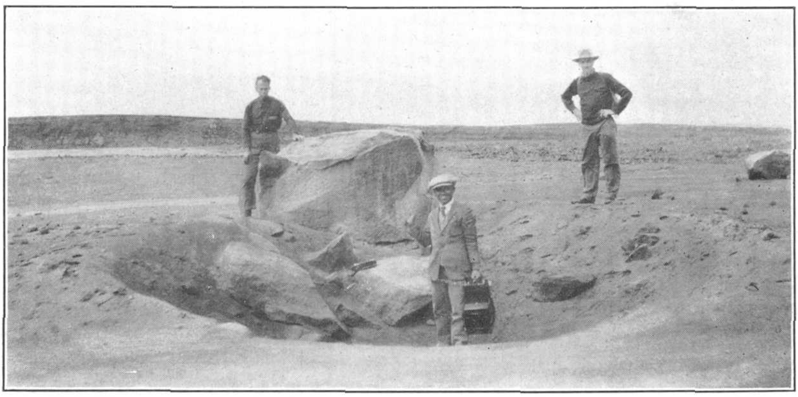
A. A "BOMBE DE ROULEMENT" ON THE KEAMOKU FLOW FROM MAUNA LOA

Near the Volcano Road about 6 miles southwest of Volcano House. Photograph by Thomas Boles; used by courtesy of the National Park Service.



B. A FISSURE ON THE NORTHEAST SIDE OF MAUNA LOA NEAR MOKUAWEOWEO

Shows ball lava lining the walls. Photograph taken August 22, 1924, by H. T. Stearns.



C. A 10-TON ROCK 3,500 FEET FROM CENTER OF HALEMAUMAU

Hurled out about 11.15 a. m. May 18, 1924. Photograph by H. T. Stearns.

AIRPLANE VIEW OF THE SOUTHWEST RIFT ZONE OF KILAUEA

The cracks end in the background at the rim of the Kilauea caldera. Width of view about half a mile. Photograph by Air Corps, War Department, November 9, 1923.

The former can usually be distinguished from the latter under the microscope because it consists of glass and many of the fragments show concave surfaces representing portions of the containing wall of a gas vesicle in the viscous magma that exploded.[92]

Often when a lava flow enters water it will explode and build up cones of fragmental material in which there is usually some ash. The color of this ash ranges from gray to black. Deposits of ash are called tuff, and the cones formed by explosions tuff cones. When basaltic tuff is altered by weathering into a more or less consolidated rock it is called palagonite.[93]

Most of the ash in the widespread ash deposits in the Kau District, such as form the ash beds in the Ninole and Pahala formations, consists of volcanic glass and its decomposition products. The ash as a whole has originated from magmatic explosions rather than from the comminution of the wall rock of a volcanic vent. The evenness of its distribution is due to its distance from the source and deposition from an atmosphere laden with fine ash.

VOLCANIC DUST

Dust may arise from a crater when no lava is in sight. Dust clouds from Halemaumau are usual during a collapse of the perilith [94] following a rapid sinking of the lava column. The dust is caused by the comminution of fragments of wall rock by avalanches. It often rises thousands of feet into the air and is carried miles by the trade winds. When deposited it resembles volcanic ash in every respect. The quantity of dust deposited in this way is of course negligible as compared with the dust or ash made during an explosion.

MUD FLOWS

During some volcanic explosions mud flows result from heavy rains accompanying falling ash. They have occurred at many volcanoes, especially Vesuvius, but there have been none in the Kau District. The disastrous landslide in 1868 in Wood Valley has been incorrectly called a mud flow.

GASES AND CHEMICAL DEPOSITS

The gases from Mauna Loa and Kilauea are carbon dioxide (CO_2), carbon monoxide (CO), hydrogen gas (H_2), nitrogen gas (N_2), argon (A), sulphur dioxide (SO_2), sulphur gas (S_2), chlorine gas

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[92] Pirsson, L. V., The microscopical characteristics of volcanic tuffs: Am. Jour. Sci., 4th ser., vol. 40, p. 191, 1915.

[93] Dana, J. D., Characteristics of volcanoes, p. 7, 1890.

[94] The perilith is the confining wall of a volcanic system, the older rock which bounds a live crater or a fissure, or system of cracks, either at the surface or deep down. Jaggar, T. A., jr., Seismometric investigation of the Hawaiian lava column: Seismol. Soc. America Bull., vol. 10, p. 164, 1920.

(Cl_2), water vapor (H_2O), and traces of fluorine gas (F_2).[95] Perret [96] thinks that the gases have a more elemental composition before oxidation. Fumaroles are vents from which volcanic gases, chiefly steam, are given forth and around which little or no sulphur is deposited. Solfataras are vents from which sulphur and its compounds are exhaled and around which sulphur deposits accumulate.

Fumaroles are scattered along the major rift zones of Kilauea and Mauna Loa, in the flows that have not yet cooled, and in and about the Kilauea caldera and Mokuaweoweo. Solfataras are much less common. One large sulphur bank, a deposit around a solfatara, occurs a few feet west of the Volcano Hotel. Others occur on the floor of Mokuaweoweo. The writer saw one form in the bottom of Halemaumau in July, 1924, just before the rise of the lava. The deposits around fumaroles and solfataras are chemical deposits. Crystalline and amorphous sulphur predominate. Chlorides and sulphates of iron, magnesium, calcium, etc., are also commonly present.

TYPES OF CONES

The cones of the Kau District can be classed in four general types—lava cones, driblet or spatter cones, cinder cones, and tuff cones.

LAVA CONES

Lava cones are much less numerous than those of any other type. They can be defined as smooth, low domes of bedded basalt that may or may not have a few intercalated ash beds. In many of them a crater is found on the top, although in some there is no sign of the place of issue of the lava. To this group belongs the great, massive dome of Mauna Loa and the smaller dome of Kilauea. Two other examples occur in the district—Puu Pahoehoe, on Mauna Loa near the Ainapo trail at 13,300 feet above sea level, and Maunaiki, on the southeast slope of Kilauea. The former, as its names implies, consists solely of pahoehoe. It was built over a fissure extending from the junction of the Crater of Pohaku Hanalei and Mokuaweoweo, and it is only 50 feet higher than the general level of flows near by. There is no crater on the top, but a small driblet heap about 1½ feet high on the fissure marks the source of the lava for this cone.

Maunaiki, the lava cone on the southwest slope of Kilauea, is particularly interesting because many people watched its growth in 1920. It originated over a fissure radial to Halemaumau and rises about 80 feet above the adjacent country. As the slope of the region and the

[95] Shepherd, E. S., The composition of the gases of Kilauea: Bull. Hawaiian Volcano Obs., vol. 7, pp. 94–97, 1919; Two gas collections from Mauna Loa: Idem, vol. 8, pp. 65–67, 1920.

[96] Perret, F. A., The ascent of lava: Am. Jour. Sci., 4th ser., vol. 36, pp. 605–608, 1913.

direction of the rift are toward the southwest, the cone is symmetrical only along the southwest-northeast axis. There are two small depressions on the top, one a crater on the west side and the other a collapsed lava tube on the east side. Maunaiki covers an area of about 1 square mile and consists for the most part of pahoehoe. If this cone had not been observed in the making no one would have surmised that it was built over a fissure half a mile long. During the eruption a large mass of solid aa tore away from the cone and slid down the southwest slope on the viscous lava for about 600 feet.

Ahuaumi, a quarter of a mile east of the Kahuku escarpment and about 4½ miles north of Kalae, on Mauna Loa, may also belong to this type. It is not shown as a cone on the map because only the topography suggests that it is a cone. Considerable ash covers all but the very top of it and adds to the difficulty of determining its origin.

The dome-shaped mass of lava on the floor of the Kilauea caldera with Halemaumau at its top is also a lava cone. Another lava cone that is much more symmetrical than those described is called Kane Nui o Hamo and is about 3 miles east of the Kau boundary in the Puna District. (See pl. 23.) It rises 282 feet above the surrounding country and has a crater in its summit 207 feet deep. (See pl. 1.)

Two kinds of miniature secondary domes associated with lava flows may be described with this group of lava cones. The more common one is the dome-shaped heap of pahoehoe that forms over a tube. Apparently it owes its origin to the clogging of a lava tube at the lower extremity, so that the lava is forced out of a hole in the roof of the tube. Domes reaching a height of 30 to 40 feet are in places formed in this manner. Numerous examples of this type occur on the upper slopes of Mauna Loa. Domes of similar appearance are also formed where an advancing margin of a pahoehoe flow becomes obstructed.

The other kind of these miniature domes is formed by the lava being forced out through the cracks in the top of a lava pressure ridge or dome formed by the warping of the solidified crust of a lava flow. Such pressure-dome driblets are very common on pahoehoe flows. (See pl. 24, *A*.)

It is quite evident from these descriptions that lava cones consist, for the most part, of pahoehoe. This, however, is to be expected, for it is essential to their formation that the lava well out quietly instead of being projected into the air as fountains. Many similar cones occur in the Snake River Plains of Idaho, and they also consist of a series of pahoehoe flows 10 to 30 feet thick. It is impossible, from the data available, to say definitely whether the quiet welling out of a pahoehoe flow is due to a high or a low gas content. Field evidence would seem to indicate that the quiet welling out of pahoehoe flows in the formation of a cone occurs when a magma with a relatively high gas content but with the gas practically all in solution arrives at the conduit.

DRIBLET CONES

Driblet or spatter cones are the most common type of cone on Kilauea. As the name implies, they are made up of the driblet or spatter of lava fountains. The fountain, while playing, hurls out clots of lava of various sizes, which fall around the vent and gradually build up a cone. When it falls, the lava is usually sufficiently plastic to run down the slope of the cone. Large clots are not projected as high as the smaller ones, hence they are more liquid when they alight. The large ones frequently shatter into several smaller pieces owing to the impact and soon become attached to the sides of the cone. The finer material is thrown higher, and consequently it generally solidifies in the air, forming cinders. Because the cinders are lighter, they fall chiefly around the periphery of the cone. If the finer material predominates a cinder cone is built, and if the spatter predominates a driblet cone is built. Cones can be found that represent all stages intermediate between typical cinder cones and typical driblet cones.

Driblet cones in the Kau District range in height from a few inches to 200 feet and in area from a square foot to a half a square mile. These cones are steeper in profile than the lava cones and have a more rugged profile than the cinder cones. When newly formed, they are generally black, although the throat or crater, the former site of the lava fountain, is a brilliant red. The craters in the tops of driblet cones are usually small, and few are left more than 20 to 30 feet deep. Weathering changes the black color of the cones to red or yellow. The rugged profile may change to a smooth profile because of the crumbly nature of the scoriaceous spatter.

True rotational and bread-crust bombs are rarely found on driblet cones, and the only bombs found in Kau associated with spatter material were on cones intermediate between cinder and driblet cones.

Driblet cones on Mauna Loa.—On Mauna Loa and its slopes cinder cones or cones of the type intermediate between cinder cones and driblet cones predominate. However, a few driblet cones occur near the Kahuku ranch—namely, Puu o Kahuku, Kamakapaa, Puu Poo Pueo, Puu Poopaa, Puu Kanikani, and several unnamed heaps south of the ranch on the east side of Pali o Kulani. (See pl. 1.) Some of these are of intermediate type. On the top of Mauna Loa there are a few driblet cones, such as Puu Ai, the Beehive, and some unnamed ones, along the fissures from which issued the lava flows of 1887, 1907, and 1916.

Driblet cones on Kilauea.—On Kilauea the following are driblet cones: Puu Koae, Cone Craters, some of the Kamakaia Hills, Cone Peak, Puu Kou, Red Cones, Puu Ulaula, Puu Kolekole, Lava Plastered Cones, and numerous other small unnamed cones in the Kau Desert.

Puu Kou, about 2 miles southwest of Kamakaia Peak, is an interesting variation of the driblet cone. (See pl. 1.) Its surface is made up of smooth pahoehoe that has welled out of the small orifice at the top. (See pl. 24, *B*.) It is a symmetrical cone about 70 feet high, steeper at the top, and indented on the summit by a pit 1 foot in diameter. Field evidence indicates that a fountain built up a driblet cone and that during the final phase of its activity pahoehoe was poured out, completely covering the driblet cone. This cone is therefore intermediate between the lava dome and the driblet cone.

Driblet spires.—Two types of miniature driblet cones occur, driblet spires and hornitos. The driblet spire is a spinelike cone a few inches to 2 feet in diameter and 2 to 12 feet high. Several of these which formed near Halemaumau and have since disappeared have been described by Dana.[97] A few driblet spires still exist in the Kau District. Madame Pele, a driblet spire about 6 feet high, stands on the Kamooalii flow northeast of Kamakaia Peak. (See pl. 25, *A*.) It is remarkable because of its resemblance to the human figure. Another spire about 8 feet high was built over a fissure in the Kilauea lava flow of 1868 near the Ponohohoa Chasms. Driblet spires are produced by the vertical piling up of lava clots ejected from a blow hole at their base. Because of their instability many of them are destroyed soon after they are formed.

Hornitos.—Driblet cones of another miniature type, called hornitos, are formed over lava tubes. They are low cones formed by fountains due to the sudden liberation of gas in confined rivers of pahoehoe lava. Fountains often result when a small cave-in takes place over a tube filled with molten lava in which the gas has been accumulating under pressure. Sometimes the pressure is sufficient to break open the roof of the tube with a small explosion.

CINDER CONES

Cinder cones are very common on Mauna Loa, and a few occur on Kilauea. They can be distinguished from other cones by the cindery, scoriaceous, or pumiceous character of the material of which they are made. In general the material is fragmental and is not stuck together as in the driblet cones. They are formed by pyro-

[97] Dana, J. D., Characteristics of volcanoes, pp. 71, 85, 1890.

explosions that eject material of a more frothy nature and usually in a more violent manner than those that form the driblet cones. The ejecta generally cool in the air and retain their shape upon falling. Bread-crust and spiral bombs are found in some cinder cones. Cinders are distinguished from pumice by the fact that the pumice will float on water and the cinders will not. Both types of material are often found in the same cone, although some cones on Mauna Loa consist entirely of pumice. The pumice cones are generally not quite so steep as the other cinder cones.

Cinder cones range in height from 5 to 200 feet and in area from a few square feet to half a square mile. When recently formed they range from black to red and often show brilliant blotches of color from fumarole or steam effects. The pumice cones are normally khaki-colored and have a satiny luster in bright sunlight.

The most characteristic feature of these cones is their smooth, rounded, generally symmetrical outlines. In places the cones are made up of several heaps, the blast having been affected by the wind or changing its angle of projection. Sometimes compound cones of this type are formed by the union of two or more lava fountains. Upon weathering and the oxidation of the iron, the cinder cones change from brilliant red or black to deep red, yellow, or brown. They have slopes of 25° to 40° and hence differ from lava cones, which have slopes of only 2° to 10°. To the practiced eye the smooth, regular outlines of the cinder cone will distinguish it at great distances from a driblet or lava cone.

Cinder cones on Mauna Loa.—On Mauna Loa the following cones belong to this class: Puu o Keokeo, Keau, Kapoalaala, Ihuanu, Halepohaha, Pahualalu, Akihi, Puu o Lokuana, Ohohia, Ohialele, Laula, Homaha, Pualehua, Puu Kuhua, Leau, Kulani, Kiipu, Ulaula, and about 200 unnamed cones on the two rift zones. Many of these cones consist of pumice. Puu o Keokeo, on the southwest rift zone of Mauna Loa, is one of the largest of this type. It covers nearly half a square mile and rises about 250 feet above the surrounding region. It is compound and was evidently formed by several fountains playing near one another. The cone appears yellowish brown from a distance, but close examination shows that the southwestern part is brilliant red. The red part is known locally as Maula, from the Hawaiian word for red. Several depressions on the summit occur in a line, indicating that the cone was formed over a crack. In the northern pit there existed, for a time at least, a lake of molten lava. There is field evidence that indicates that Puu o Keokeo was not formed during one eruption but has been built by different eruptions. It opened on the south side in 1907 and was the source of a flow that was accompanied by pyro-explosions. An excellent view of the source of the lava flows of 1887, 1907, and

1916 can be obtained from the top of this cone, and also an excellent view of the portion of the southwest rift of Mauna Loa that extends northeastward from Puu o Keokeo into Mokuaweoweo. This rift zone is thickly studded with cones and fissures and in several places contains active steam vents.

Cinder cones on Kilauea.—There are only a few cinder cones on Kilauea, and all of these consist of cinders with very little associated pumice. They include several of the Kamakaia Hills, Yellow Cone, and Cinder Hills. The two large cones due northeast of Kamakaia in the Kamakaia Hills are the finest examples of cinder cones on Kilauea. They are very symmetrical, smooth in profile, with bowl-shaped depressions in their tops. (See pl. 25, *B*.) They are similar in every way to many of the cinder cones scattered over the Columbia Plateau, in the Northwestern States, although many of those in the Columbia Plateau are higher.

Bread-crust bombs can be found on most of the Kamakaia cinder cones, but spiral bombs with projecting ears were found on only one of them.

TUFF CONES

Tuff cones in the Kau District are limited to the seacoast. Some of their tops now protrude through later flows which have extended the land into the sea. Not one of these cones is more than 1½ miles inland. In general, they consist of lava clots, bombs, cinders, pumice, lapilli, and volcanic sand. Foreign débris, comprising such material as sea sand, bits of coral, shells, and pebbles blown up from the sea bottom by an explosion, is also included. In most places the material is bedded, and generally it is well laminated and sorted by gravity. Puu Moo, 5 miles east of the village of Pahala, is exceptional because only the lower 10 to 15 feet exposed consists of tuff and cinders. This material is overlain by 10 to 15 feet of laminated driblet lava in layers 3 to 4 inches thick, with an upper layer 2 to 3 feet thick consisting of coarser spatter and ball-shaped bombs. Surmounting the driblet lava is a bed of dense lava 3 feet thick. All the beds exhibit normal cone structure and dip away from the crater. The cone is partly buried by later lavas, but doubtless the entire lower part consists of normal tuff. A cone of this type probably began its history as a tuff cone characteristic of a lava flow entering the sea, but as it continued to grow it sealed out the sea water. Then, as the lava continued flowing, probably in a tube under considerable head, it formed a fountain until the explosive force spent itself. On the cessation of the explosive phase, the lava quietly overflowed the cone, thus forming the dense uppermost bed.

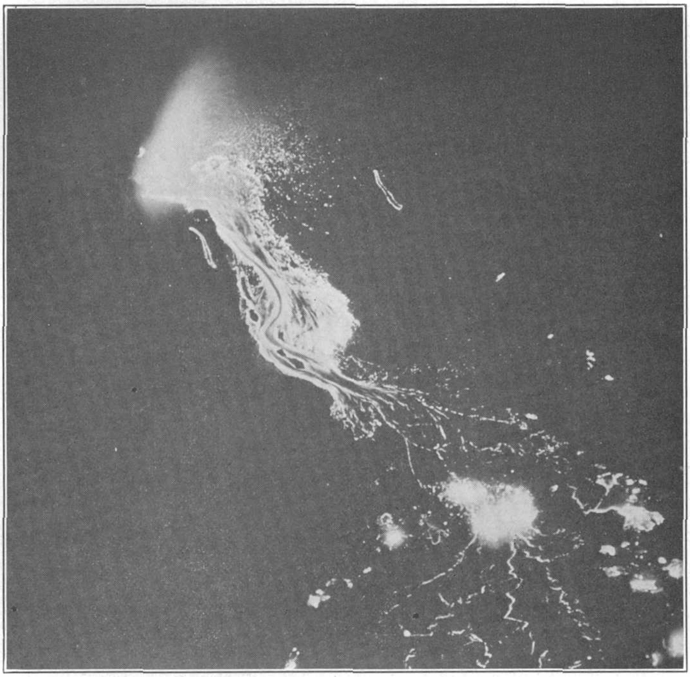
Tuff cones are usually formed where the feeding channel of an aa flow or the main tube of a pahoehoe flow discharges into the sea.

They rarely form where the margin of the flow enters the water, because the lava does not arrive fast enough to form a capping dome to retain the steam and other gases that cause the explosions. Some large flows have entered the sea without building up cones, but this is exceptional in the Kau District. In some places where it appears as if a lava flow on entering the sea did not build a tuff cone, a careful study shows that a cone was built up but was destroyed in a very short time. The sand from destroyed cones is washed on shore and forms a sand beach. The beach at Punaluu is of this type.

When a river of aa lava enters the sea it may build a cone on both sides of it, the moving lava keeping the two cones separated. This may lead to the mistaken idea that the cones are older than the lava, and that the lava separating them is of later date. A fine example of this condition is at Puu Hou, 4 miles northwest of Kalae, where a cone was built up on each side of a lava channel by the lava flow of 1868 from Mauna Loa. This cone is shown in Plate 7, *A*. The larger of the two cones is being rapidly eroded by the sea. The typical quaquaversal dips of the beds surrounding the center of the explosions are clearly shown in the photograph.

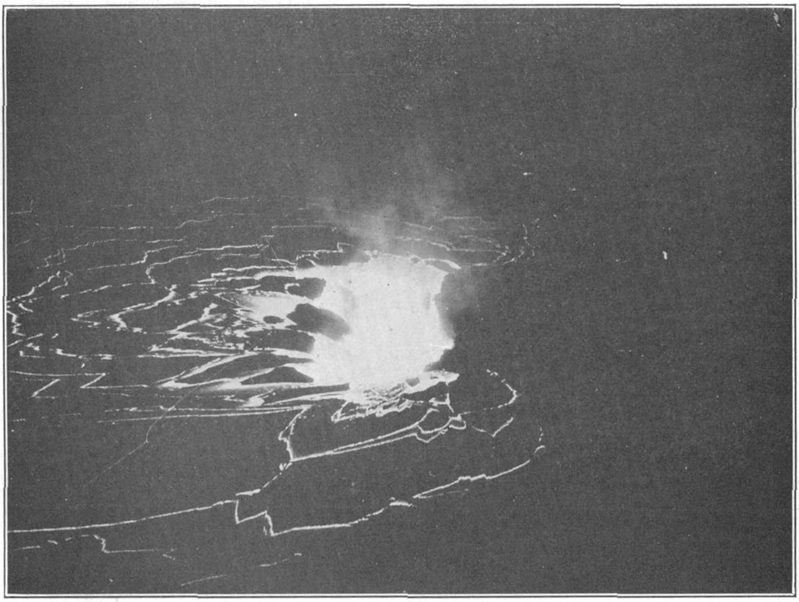
Waipouli, near the windmill 2 miles northeast of Kaalualu, is an exception to the general type but is classed with tuff cones because it owes its origin to the lava flowing into the sea. (See pl. 1.) It is a crater 30 to 40 feet deep and 50 feet in diameter. Around its rim are large blocks of lava weighing 10 to 20 tons, smeared over with lava. The walls of the crater are also smeared in the same way. There is no doubt that this crater formed over a tube, because Waipouli Well is blasted down to the tube and obtains its water supply from it. A few hundred feet north of the windmill there is a cave-in exposing a tube 50 feet across and 20 to 30 feet high, with a roof 25 feet thick. The tube evidently became plugged by the solidifying of the lava at the end of it, out at sea. The gas and lava accumulated in the tube until sufficient pressure developed to blow a hole in the roof. Then the lava flowed out of the opening made by the explosion. The large blocks of lava on the rim are probably portions of the roof that were blown out and later smeared over with lava. There is no tuff deposit around this crater, and the field evidence indicates that this explosion took place after the lava had built out the land to about the present shore line. This crater would therefore be classed as intermediate between those formed over lava tubes and those formed by lava flowing into the sea.

The following cones, listed from east to west along the coast, belong to the class of tuff cones formed by lava flows entering the sea: Na Puu o na' Elemakule, Puu Moo, Puu Pili, Kamehame, Puehu, Waipouli, Puu o Mahana, Puu o Haupu, Puu Hou, Puu Waimanalo,



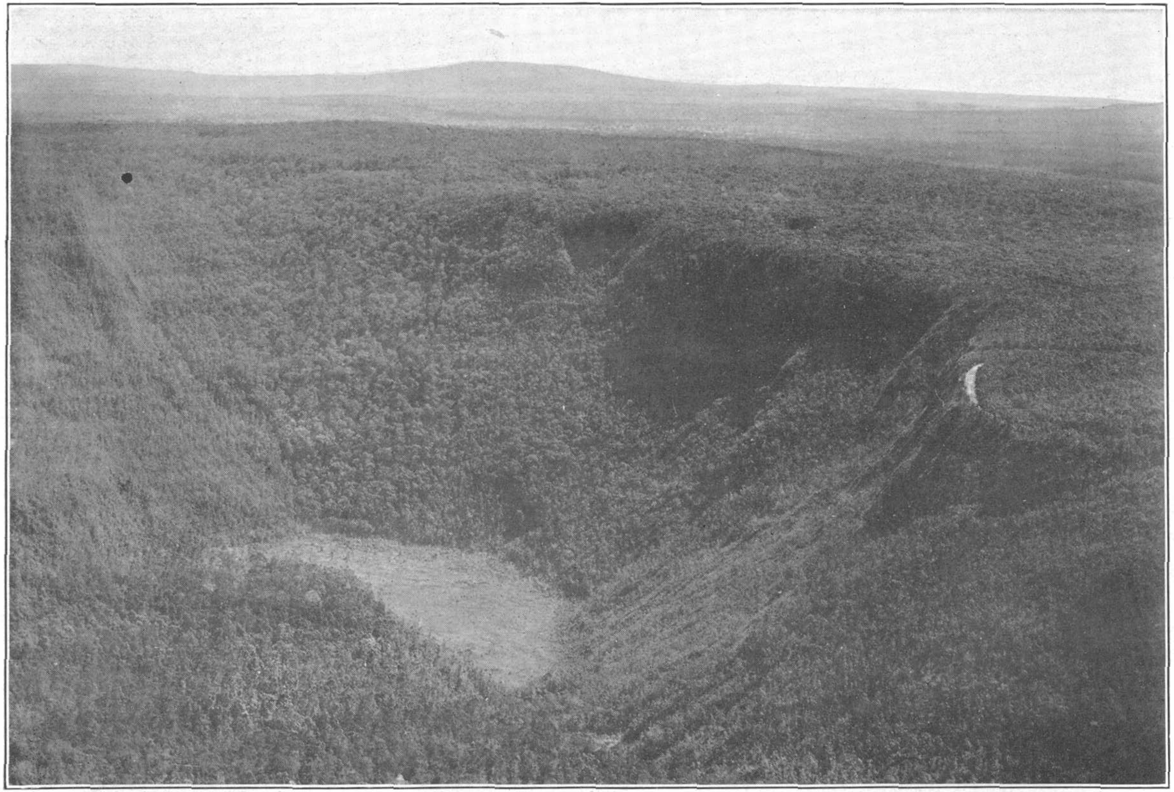
A. A NIGHT VIEW OF THE 200-FOOT LAVA OR FIRE FOUNTAIN PLAYING IN THE BOTTOM OF HALEMAUMAU

Photograph by O. H. Emerson, July, 1924.



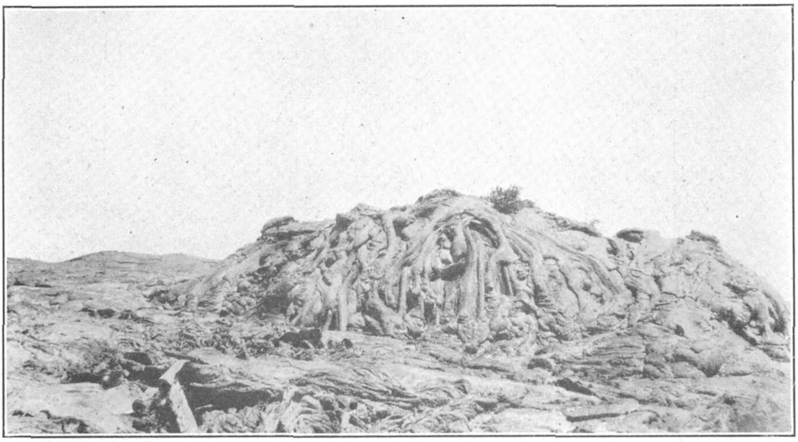
B. A NIGHT VIEW OF MOLTEN LAVA CASCADING INTO A SINK HOLE OR INLET IN HALEMAUMAU

Photograph by R. H. Finch.



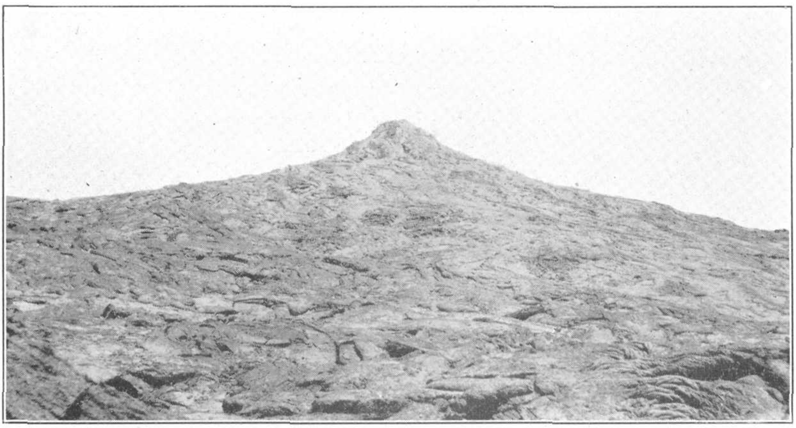
AIRPLANE VIEW OF THE PIT CRATER OF KILAUEA IKI

Lava of 1832 and 1868 on the floor; lava dome of Kani Nui o Hamo in the background. Photograph by Air Corps, War Department, November 9, 1923.



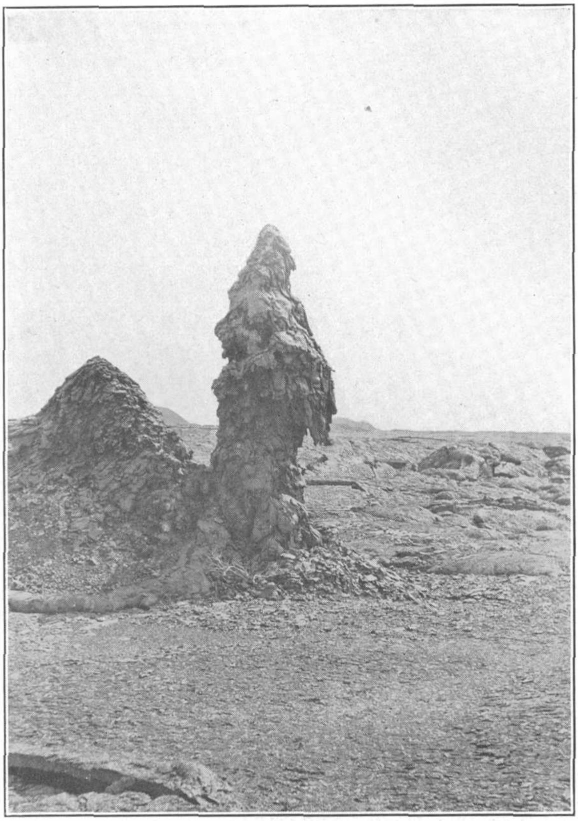
A. PRESSURE-DOME DRIBLET ON A PREHISTORIC LAVA FLOW NEAR PUU KOU ON KILAUEA

Photograph taken August 8, 1924, by H. T. Stearns.



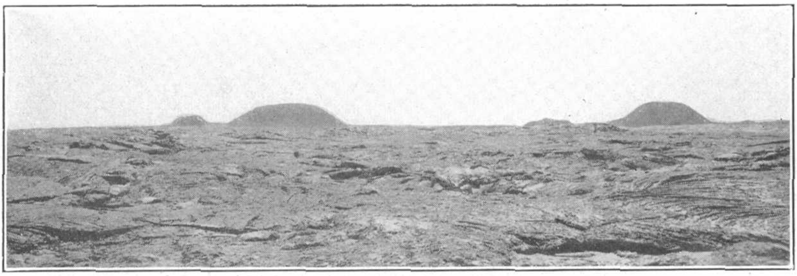
B. PUU KOU, A PREHISTORIC CONE OF PAHOEHOE IN THE KAU DESERT ON KILAUEA

Photograph taken August 8, 1924, by H. T. Stearns.



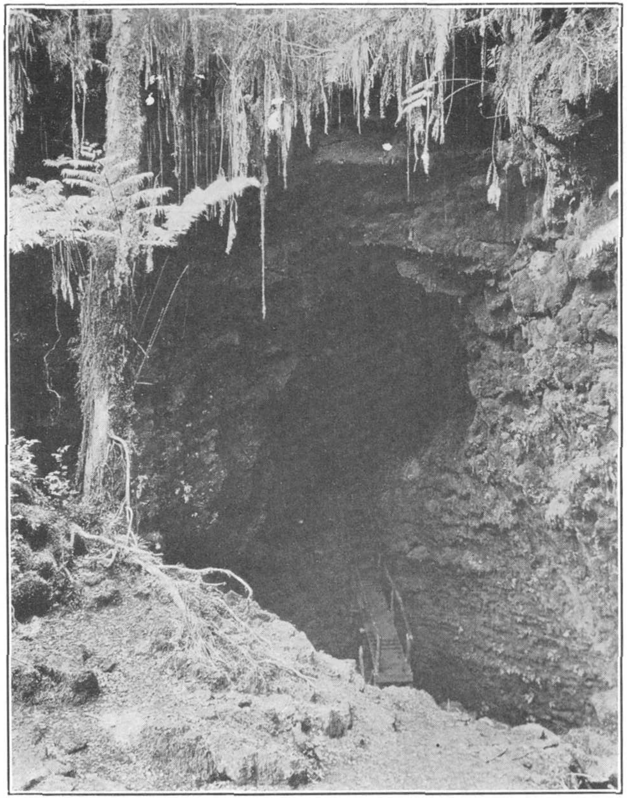
A. MADAME PELE, A DRIBLET SPIRE NORTHEAST OF THE KAMAKAIA HILLS ON KILAUEA

Photograph by W. O. Clark.



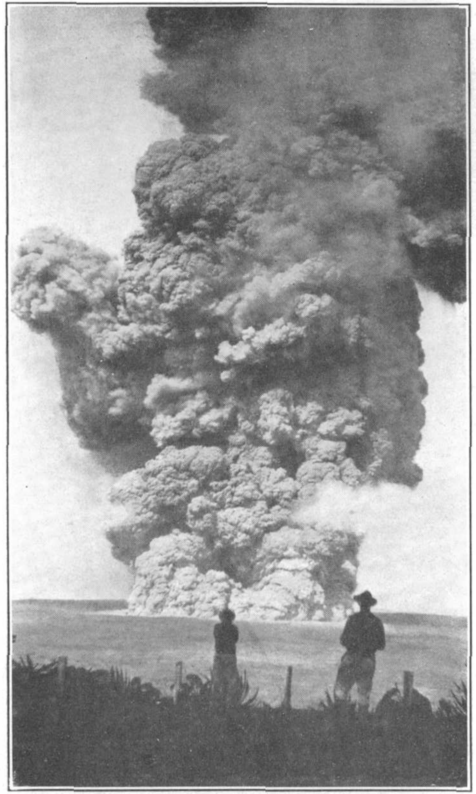
B. VIEW LOOKING SOUTHWEST TOWARD THE KAMAKAIA CINDER CONES IN THE SOUTHWEST RIFT ZONE OF KILAUEA

Photograph by H. T. Stearns.



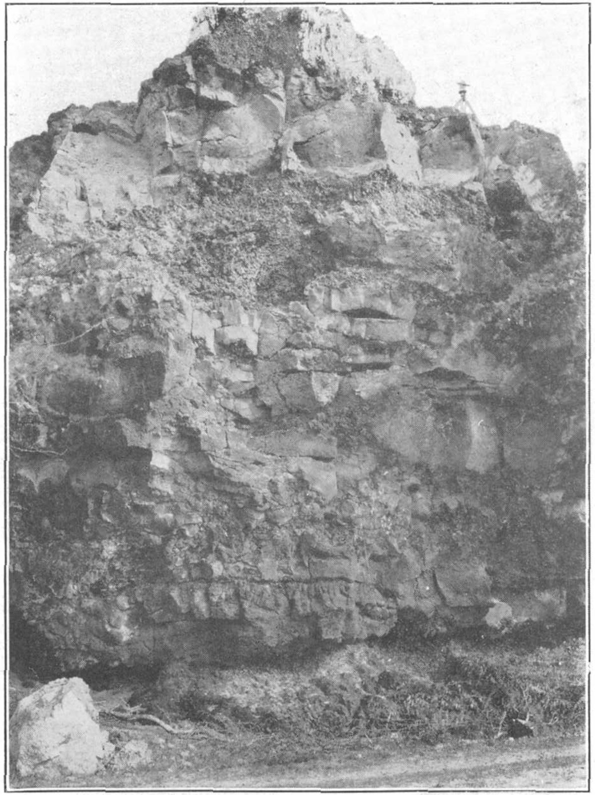
A. THURSTON LAVA TUBE, IN THE FIRST TWIN CRATER ON ROAD FROM VOLCANO HOUSE TO HALEMAUMAU

Photograph by Theodore Kelsey.



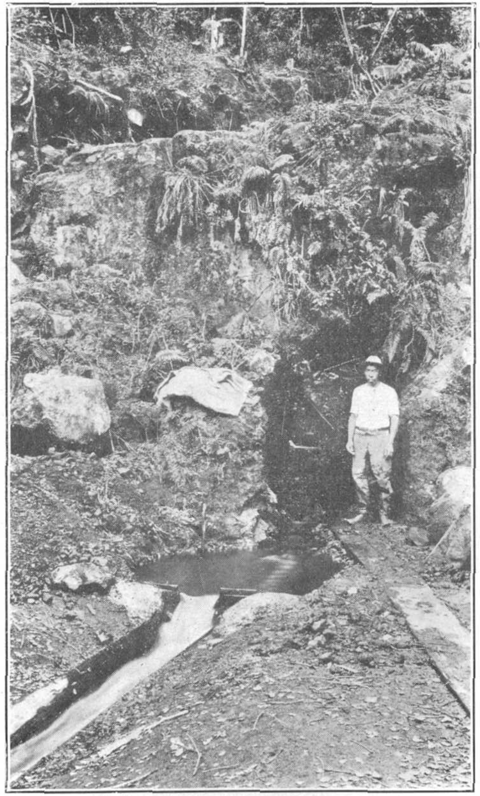
B. CAULIFLOWER EXPLOSION CLOUD AT HALEMAUMAU

11,500 feet high and rising at the rate of 13 feet a second. View taken at 8.18 a. m. May 22, 1924, from the Hawaiian Volcano Observatory, 2.1 miles northeast of Halemaumau, by H. T. Stearns.



A. VIEW OF CLIFF EXPOSING BOTH AA AND PAHOEHOE BASALTIC FLOWS

Note the beds of clinkery aa, the tubes in the pahoehoe, and the general porous condition of the mass. Photograph by C. K. Wentworth.



B. ENTRANCE TO MUDFLOW TUNNEL NO. 2, AT THE HEAD OF WOOD VALLEY

Photograph by W. O. Clark.

Puu Kaimuuwala, Kahakahakea, Puuki Hill, Na Puu a Pele, and several smaller hills that have been partly buried by later flows. (See pls. 1 and 2.)

PIT CRATERS

Pit craters occur on both Kilauea and Mauna Loa. As the name implies, they are not craters on the tops of cones, but pits in a more or less smooth plain. There is no sharp line of differentiation between a pit crater and the crater on the top of the cone, and both may have the same origin and the same appearance. Pit craters usually originate as the result of the stoping and fluxing action of the magma surging at a particular place along a crack. With the later subsidence of the lava, collapse occurs and frequently develops a roughly spherical pit, which may reach a depth of several hundred feet. The magma may or may not reach the surface. Devil's Throat, about 4 miles southeast of Volcano House, has a measured depth of 250 feet and an opening at the surface less than 50 feet in diameter. This opening has been enlarged by earthquakes, for the writer found evidence that the earthquakes of May, 1924, had shaken down several blocks from the periphery of the rim. As there is no spatter around the rim, and as the rim does not stand in relief to the adjacent plain, it appears that this pit crater was the result of the stoping action of magma that never quite reached the surface. It is only 800 feet from a large driblet cone, and the writer is inclined to believe that the magma welled up in a fissure, surged and stoped at perhaps several places, and finally reached the surface where it built the driblet cone. Then, with the subsidence of the lava, a cavern was left, the roof of which fell in, and the pit resulted.

The larger pit craters, some of which have a diameter of a mile, are probably formed by lava lakes, similar to the lake of Halemaumau. The process of fluxing and stoping is the same, but it is probably accumulative over a greater length of time. The lava, as shown by Jaggar,[98] enters the pit of Halemaumau through numerous small fissure inlets. The lakes may exist for months at a time, during which there is considerable fluctuation of the surface accompanied by occasional avalanches of the perilith. Many of the blocks of the avalanches sink into the lake and are finally digested by the magma. Such activity continued for years gradually increases the size of the orifice. Then, during periods of rapid subsidence, circular faulting of the perilith occurs, and the pit rapidly increases in size. If no overflow of the pit takes place, a typical pit crater is

[98] Jaggar, T. A., jr., Volcanologic investigations at Kilauea: Am. Jour. Sci., 4th ser., vol. 44, p. 173, 1917.

formed. If there is overflow at different times, as at Halemaumau, a lava cone will be built up with a pit crater on its summit.

Sometimes, while a driblet cone is being built, there is considerable stoping of the walls of the vent, and when the lava subsides a pit crater is developed in the top of the cone. Cone Craters, 4 miles southwest of Halemaumau, are examples of the type intermediate between a driblet cone and pit crater. The higher driblet cone of the two craters appears to have been built up during an explosive phase that followed a period of quiescence, because two pit craters were developed near by but with no spatter around them. (See pl. 1.)

Pit craters may also be formed by explosions. The crater Halemaumau was enlarged by explosion and collapse during May, 1924, from 2,000 feet to 3,400 feet in diameter. Sometimes, as at Halemaumau in 1790 and again in 1924, both stoping and explosions may enlarge the crater. The pit crater Alae, in Puna not far from the Kau line, and the pit crater Lua Poai, near the Kahuku ranch, were formed in the same way.

Pits similar in all respects to pit craters except that they are not formed over a vent are caused by the collapse of lava tubes. In some places, as at the west entrance of the Thurston lava tube, a combination will result from collapse at a vent aided by the caving in of the roof of a lava tube which was made during the stage of cone building at the vent. In this pit, called First Twin Crater, it is possible to descend for a short distance into the vent caused by the stoping and from the same pit enter the Thurston lava tube. The tube is above the floor of the pit, showing that it could not have been the cause of the crater. (See pl. 26, *A*.)

When the roof over a stoped-out void collapses, and the ground surface involved remains practically intact, although lowered to a level below the adjacent region, a circular fault basin results. The depression on the east side of Pauahi Crater, 4½ miles southeast of Volcano House, is an example of such a basin. (See pl. 1.) There are all gradations between pit craters and circular fault basins; and, as the depressions so formed are not necessarily circular (see depressions west of Heake Crater, pl. 1), it is evident that there are also gradations from pit craters through circular fault basins to fault basins of irregular shape.

On Mauna Loa the pit craters include the crater of Pohaku Hanalei, Lua Poholo, Lua Palalauhala, Lua Poai, Lua Puali, two unnamed pits in the same group, and a few other unnamed ones on the high slopes of the mountain.

The pit craters on Kilauea in the Kau District include Pit Craters (near the north Cone Crater), Pauahi, Devils Throat, Puhimau, Lua Manu, Keanakakoi, Kilauea Iki, Twin Craters, Kokoolau, Heake Crater, and Kalua Iki.

VOLCANIC PROCESSES

FISSURE ERUPTIONS

GENERAL CHARACTER

The hypomagma of the Hawaiian Islands exists in a great mosaic of fissures, which are expressed on the surface in definite relatively narrow rift systems that are arranged in a more or less geometric pattern. This is the fundamental concept of volcanism in Hawaii, for the extravasation of the lava, the surface accumulations, explosions, and all other volcanic phenomena are controlled directly or indirectly by the ancient rift complexes.

A great deal has been written about the rise of the magma through vertical tubes reaching from the magma reservoir to the surface, especially in volcanoes of the so-called "central vent type," of which the volcanoes of Hawaii are frequently cited as examples. This conception of the feeding tube is giving way before the overwhelming evidence in favor of fissure control. As Jaggar[99] has so aptly expressed it:

> The ultimate control of the pressure in all volcanoes appears to lie in the age-long rise of the magma through larger fissure systems, the orifices of which are also adjusted by accumulation, and the phenomena of eruption and eruptive interval are affected by the mechanism of the edifice, the action of the rock tide, and the periodic or occasional astrophysical stress which deform the globe and react upon its shell.

Jaggar, after living many years on the rim of the crater of Kilauea, where the lava column of Halemaumau has been constantly watched, found that the old textbook definition of a rising and falling liquid would not stand the test of modern experimental observation. He found that the lava column of Kilauea narrowed rapidly, funnelwise, with depth, instead of the reverse condition which has long been the accepted idea. He defines the lava column as follows:[1]

> A lava column is a more or less mobile vitreous silicate magma, at high temperature and pressure, charged with gases in solution, the whole being confined within the bounding wall, the perilith, and possessing or securing continuously or spasmodically an orifice or orifices of gas release on the surface of the rock crust of the globe. It is the actuating medium of volcanic action or eruption within a volcanic system, and the effective unit in any volcanic land is the system and not the mere tumulus, "volcano," or orifice. All available evidence indicates that ordinarily a volcanic system occupies a rift

[99] Jaggar, T. A., jr., Seismometric investigation of the Hawaiian lava column: Seismol. Soc. America Bull., vol. 10, p. 161, 1920.

[1] Idem, p. 170.

complex. The individual orifices are commonly concentrically clogged with congealed lava and ejecta built up so as to mask the rifts.

Considerable evidence has been gathered from a study of the live magma by Jaggar to support this definition. In the following pages the writer presents, as a result of an areal study of the rift zones of Kilauea and Mauna Loa, surface criteria that prove the existence of definite fissure systems.

KILAUEA RIFTS

SOUTHWEST RIFT

The southwest rift of Kilauea is a zone 2 to 3 miles wide that extends from the Kilauea caldera southwest to Palima Point. (See pl. 1.) It is described in the section on faults as a fissured area forming a shallow graben, which increases in depth toward the caldera. For its entire length this rift has been the scene of many lava outpourings, fountains, and explosions. Near the caldera of Kilauea this rift is rent with fissures. (See pl. 21.) On the geologic map are shown fissures that have poured out lava and have not yet been buried. Since the advent of white men this rift system has been the source of three lava flows—those of 1823, 1868, and 1920. The lava flow of 1921 in the floor of the caldera also issued from a fissure in this system. The notable prehistoric lava flows that issued from fissures along this rift are the Kamooalii, Kamakaia, Kolekole, Ulaula, Red, Lava Plastered, Yellow, and Kou flows. The sources of these lava flows are shown on Plate 1. The flows that have come from the southwest rift zone consist of aa and pahoehoe in about equal amounts. The surface phenomena accompanying these fissure eruptions vary directly with the amount of gas discharged and the fluidity of the magma. In general the fissure eruptions fall into five different classes, and one of each group will be described.

Quiet eruptions of very fluid lava.—The quiet welling out from a fissure of a highly fluid lava accompanied by only a little fountaining is best exemplified by the lava flow of 1823. The lava welled out of a crack that is now 2 to 30 feet wide for a length of 6 miles and flowed into the sea. The maximum width of the crack before the collapse probably did not exceed 10 feet. The present width is doubtless due to the collapse after the subsidence of the magma. The flow is a frothy pahoehoe, changing near the sea to aa. It ranges in thickness from a few inches to about 1 foot near the Great Crack, but near the sea it is 3 to 5 feet thick. A magma as highly charged with gases as the frothy texture of the lava indicates must have been relatively very fluid. There are no cones along the crack, although lava spatter here and there along it is evidence that fountaining was violent, spasmodic, and short lived along the entire fissure. The eruption is said to have lasted only a few days.[2] The lava issued almost simultaneously for a distance of 6 miles, a condition not conducive to localized fountaining or to the forming of cones.

To this type of fissure eruption belong the eruption that took place in prehistoric time from the old crack near Pahala, one at Ponohohoa, one near Puu Kou, one near Red Cones, and a few other unnamed fissures shown on Plate 1.

Quiet eruptions of viscous lava.—Fine examples of the quiet pouring out from a fissure of a viscous lava occurred in 1920. At this time massive pahoehoe lava issued from five different fissures on the southwest rift. So quietly did the eruptions occur that one of them escaped observation until accidentally discovered by a topographer of the United States Geological Survey several months later.

The pahoehoe of such eruptions, in welling out from the cracks, seldom leaves either driblet spire or elongated crater to mark the fissure. For instance, the dome of Maunaiki (see pl. 1) gives no surface indication of the fissure that supplied it, and had its formation not been witnessed the location of the fissure would have been impossible to determine. This process of a cone masking its own fissure with lava is probably typical of some large volcanoes that are supposed to have only a central orifice. Many of the lava domes of the Columbia Plateau in the United States, which no longer show any signs of fissures, were doubtless formed in this manner.

On some of the small patches of the lava of 1920 there are tiny spatter cones 1 to 2 feet in diameter on the site of the buried fissures. However, as these often form over lava tubes, they are not always evidence of fissure eruptions.

This type of quiet viscous outflow of lava from a fissure tends to form domes if continued long at any place. It does not occur in the Kau District as often as the eruption that builds up driblet and cinder cones. The lava flows in the southwest rift that belong to this class are the lava patches of 1868 with their driblet spires, two late prehistoric patches near Ponohohoa Chasms, Puu Kou, and the Kamooalii flow.

Moderately explosive eruptions.—The moderately explosive type is the most common of all fissure eruptions on the southwest rift zone. It is accompanied by the fountaining of lava, which builds up a line of driblet cones from a few feet to 100 feet high along the crack. These driblet cones frequently mask the fissure but can usually be correlated with one another because of the individual characteristics

[2] Ellis, William, Journal, p. 200, Honolulu, Hawaiian Gazette Co., 1917 reprint of 1827 edition.)

of each line of driblet cones. Even where later lava flows have isolated cones belonging to one fissure eruption, they can be correlated. The cones usually occur at the head of the flow, and the craters in their summits are often partly connected along the line of the fissure. The sides of driblet cones are frequently breached by deep channels through which the lava flowed. The channels do not necessarily prove that all of the lava that was discharged from the fissure flowed in them, for lava often escapes from under the base of the cone.

To the moderately explosive eruptions belong the fissure eruptions marked by Puu Kolekole, Puu Ulaula, Lava Plastered Cones, Red Cones, the inland line of Kamakaia cones, Puu Koae, Cone Crater, two lines of unnamed cones partly buried by later flows between Cone Crater and the Kilauea caldera, Cone Peak, and the fissure of 1921 in the floor of the Kilauea caldera. Many other cones were probably formed at one time in this zone but are now buried.

Highly explosive eruptions.—A fissure eruption of a moderately fluid lava accompanied by fountaining several hundred feet high is marked at the end of its activity by a line of cinder cones. Apparently, when the lava is very fluid the cone produced by fountaining of this type is a pumice cone. No predominantly pumice cones were found on the southwest rift zone of Kilauea.

The explosive fountaining of lava that forms the basaltic cinder cones of a fissure eruption should not be confused with such gigantic explosions as occurred at Katmai, Alaska, in 1912, or at Krakatoa, in the Dutch East Indies, in 1883. These great explosions blew off tops of volcanic mountains, sent cauliflower clouds of ash and steam miles into the air, threw out broken rock, and buried the adjacent regions under thick deposits of ash. The explosions that form basaltic cinder cones are due to magmatic frothing, which causes fountains of liquid lava that play only a few hundred feet in the air. Their activity is always localized, so that the resulting product of the fountain is only a heap of cinders or pumice and never a widespread ash deposit. These explosions form the so-called fire fountains of Hawaii. (See pl. 22, *A*.) Jaggar has suggested the name pyro-explosion for an eruption of this kind, to differentiate it from a true volcanic explosion. The pyro-explosion differs from the Strombolian phase of eruption (intermittent mild explosions) only by its continuity.

Cinder cones formed by pyro-explosions along a fissure are seen at many places in the United States. Hundreds of smooth conical heaps of red cinders are scattered over the San Francisco Peaks region in Arizona, the Snake River Plains of Idaho, and elsewhere. They seem to be common in most regions of basaltic outbursts, but they are very scarce on the southwest rift of Kilauea. A fissure of this type of extrusion is usually buried by the accompanying cinders and lava.

The Cinder Hills, Yellow Cone, and the seaward line of the Kamakaia Hills belong to this class. The Kamakaia group is unusual because the fissure connecting the cones is still visible. This fissure is from 2 to 20 feet wide, its width depending upon the amount of collapse following the subsidence of the lava. Evidence that the collapse was later than the formation of the cones is afforded by the linear depression running through the cinder cones. The fissure is exposed for only 1 mile, the extremities being covered by later lava flows. After the first explosions, when the cinder cones were built, there was a period of quiet outflow during which pahoehoe welled out at Kamakaia Peak and several smaller cones near by. Considerable lava flowed from this fissure and built up a platform, which now stands in relief above all the other flows resulting from fissure eruptions on the southwest rift. Before activity ceased along the rift, an explosion occurred between the two northeastern cones that scattered essential and accessory ejecta for several hundred feet from the fissure. The fragments torn from the wall of the vent are completely glazed, indicating high temperature and perhaps burning gases during the explosion. The walls of the fissure show no signs of fusion. Wind-blown sand, baked red by the lava, is exposed in the walls 3 to 5 feet below the surface. The presence of this buried wind-blown sand, which originated from Kilauea ash, is evidence that there was more than one explosion of Kilauea before 1924. The lavas of Kamakaia are themselves overlain by ash. The Kamakaia fissure eruption is similar to many in Iceland, described by Thoroddsen, and to one in Idaho, described by the writer.[3]

Crater chains.—Chains of pit craters along fissures do not occur in the southwest rift zone, although Cone Crater and its two associated pit craters form an incipient crater chain. An isolated pit crater was found on the Ponohohoa Chasm fissure.

SOUTHEAST RIFT

The southeast rift of Kilauea appears to be a part of the Kea rift system. After extending about 5 miles from Kilauea, it curves to the northeast. This curve is probably due to the combination of two rifts—a southeast Kea rift and a northeast Puna rift. The southeast rift seems to belong to the old Kea rift system, whereas the Puna rift appears to have been induced by coastal faulting on the south slope of Kilauea.

[3] Stearns, H. T., The Craters of the Moon National Monument, Idaho: Idaho Bur. Mines and Geology Bull. 13, 1928.

The southeast rift zone is about 4 miles long and is marked near the summit of Kilauea by a graben which dies out toward the southeast. (See pl. 1.) The caldera of Kilauea is formed at the intersection of the rift-zone grabens. Only about 3 miles of the southeast-northeast rift lies in the Kau District, and the description of the types of fissures in the zone is limited to this area.

Quiet eruptions.—No evidences of fissure eruptions of the quiet type accompanied by very fluid lava were noted in the district. A low dome on the Kau-Puna line, on which are the Twin Craters, was formed by a quiet fissure eruption accompanied by viscous lava. Kane Nui o Hamo, a short distance to the east of the Kau line in Puna, is a fine example of a dome formed by the quiet outflow of viscous lava. (See pl. 23.)

Moderately explosive eruptions.—A small line of driblet cones on the edge of Kokoolau Crater, an unnamed driblet cone south of the Devils Throat, the fissure of 1832 near Kilauea Iki, and the fissure of 1868 on the wall of Kilauea Iki were formed by the moderately explosive type of fissure eruption. The fissure of 1832 probably belongs to the southwest rift, although it is on the east side of Kilauea. The fissure eruptions of 1832 and 1868 are both interesting. The former issued more than 200 feet above the present floor of the Kilauea caldera and cascaded down into the caldera and also into Kilauea Iki. (See pl. 1.) The latter broke out of the talus several hundred feet above the floor of Kilauea Iki in a series of small fountains and poured down into it. Prior to this flow Kilauea Iki had been covered with vegetation. (See pl. 23.) When lava burst from the walls of Kilauea Iki in April, 1868, the pit of Halemaumau was an active lake of fire. The fact that lava broke out over 200 feet above the surface of the open lava lake of Halemaumau is evidence that disproves the old idea that the mountain flanks were rent asunder by the pressure of the lava in the lake, an idea that has often been used as the explanation of the rifts on the side of Kilauea. Furthermore, it is definite proof that the lava supplying Halemaumau exists in a rift complex that is not controlled by hydrostatic laws. Frequently lava will break out of a fissure in the walls of Halemaumau and flow down into the bottom of the pit. During times of subsidence in Halemaumau, the lava drains down through the old fissure inlets, reversing the process of extrusion. A view of one of these inlets draining the lava lake of Halemaumau is shown on Plate 22, *B*.

Highly explosive eruptions.—Cinder cones, the surface indication of fissure eruptions of the highly explosive type, do not occur on the southeast rift zone in the Kau District. They are common, however, in the adjacent district of Puna.

Crater chains.—For some unknown reason the crater-chain type of fissure eruption has prevailed on the southeast rift. The lava seems to have risen in fissures and stoped and fluxed large caverns at many places, causing pit craters of various sizes. In some places, as at the Devils Throat, the lava probably did not reach the surface, but in others it was active at the surface for a considerable time.

Pauahi, Heake, Devils Throat, Kokoolau, Puhimau, and Lua Manu form a crater chain easily accessible by the Cockett trail from Volcano House. They were doubtless not all formed at the same time. Kilauea Iki, Keanakakoi, Twin Craters, and Kalua Iki also belong to this type.

MAUNA LOA RIFTS

SOUTHWEST RIFT

The southwest rift zone of Mauna Loa is only a mile wide where it leaves Mokuaweoweo, the summit caldera, but widens out from the vicinity of Puu o Keokeo to the sea. (See pl. 1.) It is 35 miles long from Mokuaweoweo to the sea, but it can be traced some distance northeastward from the caldera toward Mauna Kea.

Quiet eruptions.—The quiet type of fissure eruption rarely occurs on Mauna Loa. The quiet discharge of very fluid lava from a fissure has not taken place on that part of Mauna Loa which lies in the Kau District. Two examples of the quiet effusion of viscous lava were found in the southwest rift zone. In 1907 lava broke out in four different places along a fissure in Kipuka Kepunoi, 1½ to 2 miles above the Volcano Road near the Kahuku ranch. It welled out in this kipuka as massive pahoehoe that covered the fissure in the same way as the lava flow of 1920 on Kilauea. This flow issued at less than 3,000 feet above sea level, whereas the main flow was extruded at an altitude of about 6,000 feet. The quiet welling out at the lower vents was probably due to the tapping of the lower-level lavas while the gas-charged upper part was being discharged at a higher level.

The other example is Puu Pahoehoe, formed by a fissure eruption on a fault concentric to the main crater of Mokuaweoweo. Massive pahoehoe issued from the fault and built up an elongated ridge. A crack with a few tiny spatter cones indicates the line of the fissure vent.

Ahuaumi, a small hill south of the Kahuku ranch, also may be of this type, but because no definite evidence could be found to indicate that it was a vent, it has not been shown on Plate 1 as a source of lava.

Moderately explosive eruptions.—Driblet cones formed by the moderately explosive type of fissure eruption are not as common on Mauna Loa as on Kilauea, a fact which indicates a difference in gas content in the respective magmas at the time of extrusion. The Beehive and two associated driblet cones occur on a fissure extending southward from the crater of Pohaku Hanalei, on the summit of Mauna Loa. An unnamed fissure eruption on the talus of the northeast wall of the main crater 50 feet above the floor of Mokuaweoweo that is supposed to have occurred in 1855 also belongs to this class.

Driblet cones, however, become more and more common with decrease in altitude on Mauna Loa. The fissures of 1887, 1907, and 1916 are marked with them. Puu Poo Pueo, Puu Kanikani, and all the cones formed by prehistoric fissure eruptions south of them belong to this class. A few driblet cones occur also on the fissure of 1868. The fissure of Puu Poo Pueo has been the source of considerable lava. The fissure eruption that was the source of a Kamehame flow 1 mile north of Ahuaumi belongs to this group. Lava from this vent is shown on Plate 1, with a tongue extending over the Kahuku fault scarp. The fact that this tongue does not extend to the bottom of the scarp is due to the scaling of the flow from the cliff. The fault scarp was formed prior to this lava flow.

Highly explosive eruptions.—Fountains several hundred feet high, often playing so close together as to form a curtain of fire, constitute the usual type of fissure eruption on Mauna Loa. They result from the arrival at the surface of a fluid magma highly charged with gas. Frequently the whole gamut of volcanic products from lava to the frothiest pumice results from such an eruption. Jaggar[4] and Wood[5] have published excellent accounts of this type of eruption. If the pyro-explosions are localized, large cones, such as Akihi, Puu o Lokuana, Pahualalu, Halepohaha, Ihuanu, Kapoalaala, Keau, and Puu o Keokeo result. Puu o Keokeo is a complex cone resulting from several fountains playing at the same time and at different times. These cones consist chiefly of pumice but include some cinders. Thirty-five large cones of this type exist between Puu o Keokeo and the summit and mark the sites of numerous fissure eruptions.

Frequently, especially near the summit of a cone, a fissure will open and pyro-explosions will extend the entire length of the crack, building up levees of pumice 2 to 10 feet high along both sides of it. This is admirably shown by practically all the recent eruptions near Mokuaweoweo and also by the fissures at the source of the lava flow of 1868 on Mauna Loa. The pumice from the fountains is often carried by the wind for miles. There are over 200 pumice cones 10

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[4] Jaggar, T. A., jr., The outbreak of Mauna Loa, Hawaii, 1914: Am. Jour. Sci., 4th ser., vol. 39, pp. 167–172, 1915; Lava flow from Mauna Loa, 1916: Idem, vol. 43, pp. 255–288, 1917.

[5] Wood, H. O., Notes on the 1916 eruption of Mauna Loa: Jour. Geology, vol. 25, pp. 322–336, 467–488, 1917.

to 20 feet high along fissures on the southwest rift. Few of the fissures over which they have formed exceed 3 feet in width where exposed.

A remarkable fissure eruption of this type occurred on the top of Mauna Loa. The fissure is the most prominent one on the summit and has been active at various times. In one period of activity fountains played not only along the fissure on the floor of Mokuaweoweo but also on the rim. The fissure crosses the floor and passes up a 50-foot fault scarp to the south lunate platform and thence up the vertical 350-foot wall of the caldera and on down the southwest slope of Mauna Loa. Fountains played simultaneously on the floor of Mokuaweoweo, on the south lunate platform, and 350 feet higher up on the rim. (See pl. 3.) The fissure in the caldera wall is filled with lava, and there is a small cone on the edge of the rim 350 feet higher than a cone directly below it. The flow from the fissure above formed a vertical cascade to the floor below for a distance of half a mile. An observer standing on the cone at 13,600 feet above sea level and looking down 350 feet to the cone below is profoundly impressed with the violation of the hydrostatic laws of liquids by a gas-charged fluid lava. This remarkable fissure eruption affords striking evidence of the buoyant effect of gases in a heavy basaltic magma.

Crater chains.—The pit craters of Lua Hou, Lua Hohonu, and Pohaku Hanalei, near the caldera of Mokuaweoweo, are the finest crater chains found on Mauna Loa. The great caldera itself is made up of a succession of such pits. The five easily accessible pit craters south of the Kahuku ranch form another chain. Three small pit craters near the same ranch, formed in 1868, also make a crater chain.

NORTHEAST RIFT

The northeast rift is composed of two units. One unit is the extension of the southwest rift toward Mauna Kea. The other unit extends N. 75° E. and has been the chief scene of activity. The former is outside of the Kau District and will not be discussed here. The latter is only 16 miles long and is not comparable in the number of cones or fissures to the southwest rift. However, it has all the characteristics of the southwest rift. It is marked by numerous red cinder and pumice cones and fissures bordered with pumice and pumiceous spatter. Many of these fissures, which are 1 to 3 feet wide, extend continuously for a mile or more. In places, as along the Volcano House trail, they form several parallel fissures from which frothy pahoehoe has issued. (See pl. 20, *B*.) No crater chains occur on this rift, the eruptions having been mostly pyroexplosive.

The portion of Mauna Loa outside of the Kau District was not searched for rift zones. It is suspected that a rift now nearly buried connects the summit of Hualalai with the summit of Mauna Loa, for a line of cinder cones extends toward Mauna Loa from the summit of Hualalai.

CONCLUSIONS REGARDING FISSURE ERUPTIONS

It is evident from the foregoing descriptions of the types of fissure eruptions that the variations in them are due primarily to differences in the gas content of the magma. The fluidity of a magma is largely dependent upon the amount of gas it contains. If the magma is supercharged with gas, it tends to form cinder cones, and if there are no large amounts of excess gas it tends to well out quietly and form lava domes. Sometimes the explosive force of the magma may be dissipated by reason of the great length of the fissure from which it is discharged. Hence the wide variations observed in the surface features resulting from a fissure eruption do not as a rule signify any great differences in the mechanism of the processes of extrusion.

The preservation of the fissure from which the lava was extruded depends upon various factors, chief among which is the extent of the collapse that follows the subsidence of the magma. The collapse that followed the lava flow of 1823 on Kilauea widened and deepened the fissure considerably. Frequently, as at the time of the Kilauea flow of 1868, there is no collapse, the lava solidifying in the cracks all the way to the surface. Topography also determines whether the fissure remains visible. On the steep slopes of Mauna Loa the upper part of the fissure is always left open, because of the draining out of lava at lower altitudes at the cessation of activity. The absence of a visible fissure and the presence of only one cone, however, can not be taken as proof that there was no fissure eruption. The fissure may be covered by later lava flows, and the cones remain as kipukas. Or the lava may break out at different places along a fissure, and the patches of lava and their cones are completely separated from one another.

The region between the two rift zones of Mauna Loa and Kilauea in the Kau District was carefully searched for sources of lava, but none were found. The conclusion is inevitable that the magma is confined in definite permanent fissure zones from the magma reservoir to the surface. When lava rises into Halemaumau or Mokuaweoweo it doubtless rises also in the fissures along the entire rift zone but to different heights. The fissure eruption may or may not cause a subsidence of the lava in the central pit.

In a reconnaissance of Mauna Kea two kinds of cones were found—cinder cones, similar to those on Mauna Loa, and tuff cones. The tuff cones were not formed by lava flowing into water, like those in the Kau District, nor by pyro-explosions, but by true magmatic explosions. The tuff cones are scattered on the slopes of Mauna Kea and do not lie like the cinder cones in definite rift zones. It appears, therefore, that when conditions are satisfactory for a true volcanic explosion, the explosive force is able to rend the rocks directly above the magma chamber and form a cone, regardless of the location of rift zones. In the pyro-explosion, however, the magma rises to the surface through preexisting fissures and is unable to rend the crust asunder between the rift zones. It is therefore essential in the study of a basaltic dome to distinguish the true explosion tuff cones from the pyro-explosion cinder and driblet cones, in order to determine the fundamental rift complex. This method is particularly productive of good results in studying the Hawaiian lava cones but would probably be of little value in studying a structurally weak cone like Vesuvius, which consists largely of ash.

As the welling out of magma along preexisting fissures is characteristic of basaltic extrusions, the probable seat of most eruptions is at the intersection of two or more fissures. Furthermore, because the intersection is the center of greatest activity, the growth of the dome or cone will reach its maximum at this place, and the frequent extrusion of lava will tend to mask the feeding rifts. However, when the central vent ceases superfluent discharges, the features of the rift zones, no longer buried by flows from the central vent, become more prominent if activity continues. This stage has been reached by both Kilauea and Mauna Loa. The volcanic processes and rift systems in the Kau District are similar to those in the great basalt plateaus of the world, except that in Hawaii large domes have been built instead of plains. The Snake River basalt plateau, in Idaho, lies in a region underlain by various types of rocks, which may be largely sedimentary and which as a rule contain many structural lines of weakness. The zones of movement in the complex underlying the plateau are probably wider than similar zones under Hawaii. Also, under this plateau the zone of movement is likely to shift as a result of continental adjustments that do not affect the Hawaiian Islands, because these islands are built up from the bottom of the Pacific Ocean. In the Snake River Plains it has been the migratory character of the volcanic rifts that has caused the basalt extruded to spread out over a wide area, forming a plain, rather than to remain stationary and build one or more lava domes. In Hawaii the permanency of the rifts has caused great domes to be built.

The fact that profound seaward slip faults bring magma to the surface indicates that at depths of 3 to 4 miles there must be potentially fluid lava or large rifts filled with magma. The width of an active fissure rarely exceeds 5 feet and may be less. Large volumes of lava seem to have no difficulty in finding their way to the surface through narrow fissures. Exposures on Oahu and on Hawaii indicate that these feeders do not widen downward, at least in the first 4,000 feet. In fact, they may extend to the source of lava with essentially the same width.

The slight extent to which the confining walls are metamorphosed during a fissure eruption in Hawaii is remarkable. None of them show signs of glazing or fusion at the surface. Dikes that were examined show only a thin film of glass along their edges that seem to have resulted from the sudden chilling of the lava in the dike.

RELATION OF FISSURE VENTS TO GROUND WATER

It is difficult for many geologists who are working in areas where basaltic dikes are numerous to reconstruct the details of the original topography of such areas. For this reason the surface features that characterize the fissure vents of the Hawaiian volcanoes are here described in detail. Moreover, knowledge of the way in which such features are formed enables one to interpret the underground structure over wide areas of basalt in the United States where cones are numerous and where erosion has not proceeded far.

The interpretation of the pattern of the dike feeders as indicated by surface features is of great economic importance in the development of ground water. Large bodies of perched ground water in the northern part of the island of Hawaii and on the island of Oahu are due to polyhedral blocks of very permeable basalt inclosed by impermeable diabase dikes. If erosion has not proceeded too far, these dikes of dense basalt have direct connection with the lines of cinder and driblet cones, such as occur in the rift zones in the Kau District, described in detail above.

It has been shown that with only a few exceptions the dike systems in the Kau District are limited to the rift zones of Kilauea and Mauna Loa. All the tunneling for water in this district has been done in ash beds, and the water obtained owes its presence at high levels to the impermeability of the ash beds upon which it is perched. The most successful procedure in recovering this perched water has been to tunnel along a contour of the mountain, or, in other words, along the strike of the ash bed, a short distance from the surface. To obtain perched water from the dike systems in the Kau District, however, an entirely different method would be necessary. The most economical and best procedure would be to drive tunnels into either Mauna Loa or Kilauea at right angles to the direction of the rift zones. The location of a tunnel to recover perched ground water of this type would have to be determined by two factors—the lowest level at which the water would be valuable for fluming sugar cane to the mills and the distance away from the rift zone.

The conditions in the Kau District are adverse to the development of perched water in the dike systems, chiefly because the intake area of the dike systems or the rift-zone areas all lie in arid or semi-arid regions; consequently, it is doubtful if sufficient water would be developed to justify the cost of tunneling. Furthermore, the rift zones in the Kau District are the sites of numerous eruptions at the present time and are traversed by numerous active faults. If a tunnel were driven into such an active zone it would be always in danger of destruction by the forces of volcanism.

VOLCANIC EXPLOSIONS

TYPES OF EXPLOSIONS

Volcanic explosions differ greatly in magnitude and origin. In volcanic treatises Kilauea and Mauna Loa are usually cited as volcanoes characterized by magmatic extrusions without explosions. Explosions of five distinct kinds occur at these two volcanoes, however—magmatic explosions, pyro-explosions, littoral explosions, submarine explosions, and phreatic explosions.

Volcanic explosions which throw out fluid and incandescent magmatic or essential ejecta [6] from a vent and which are caused primarily by the expansion or explosive forces of juvenile gases are called magmatic explosions. Such explosions may or may not be accompanied by resurgent and vadose volatile matter.

Daly [7] cites the carbon dioxide set free in the assimilation of Mesozoic limestone in the Vesuvian lava column as a type of resurgent gas. A Vesuvian phase of eruption occurs when a volcano has a violent magmatic explosion. The great eruptions of Vesuvius in A. D. 79 and 1906 are familiar examples of magmatic explosions. Most magmatic explosions hurl out not only essential ejecta but also accessory ejecta torn from the throat of the volcano. During the explosion of Vesuvius in 1906 blocks of limestone, accidental ejecta, were also extruded.

[6] The writer follows H. J. Johnston-Lavis in his terminology of ejecta (On the fragmentary ejecta of volcanoes: Geologists Assoc. London Proc., vol. 9, pp. 421–422, 1887). He defines them as follows: Essential ejecta are materials that issue in a fluid state and consist either of the volatile constituents or of the magma in which these were contained that produced the particular emission. Accessory ejecta consist of the older volcanic materials of the same vent torn away, expelled, and mixed with the essential ejecta of an eruption. Accidental ejecta consist of either volcanic materials from other centers or sedimentary or other rocks of the subvolcanic platform, also torn out, expelled, and mixed with the essential and accessory ejecta.

[7] Daly, R. A., Igneous rocks and their origin, p. 285, 1914.

The common eruption of the Hawaiian volcanoes is characterized by "fire fountains," or pyro-explosions, which are usually accompanied and followed by lava flows. Pyro-explosions throw out fluid and incandescent magmatic ejecta and hence are a variety of magmatic explosions. However, they are different from the usual magmatic explosions in that they practically never bring out accessory or accidental ejecta and seldom hurl ejecta over 500 feet into the air. Thus, a pyro-explosion is vastly different from the magmatic explosions that occurred at Krakatoa in 1883 and at Katmai in 1912, which sent cauliflower clouds 8 miles or more into the air.

An explosion caused by lava flowing into the sea could be called a littoral explosion, because it is always confined to the shore. The deposits formed by littoral explosions are always of small area and form tuff cones. These deposits are recognized by the presence of sea sand and shells among the ejecta.

Submarine eruptions have occurred in the ocean adjacent to the island of Hawaii, but, so far as is known, not in historic time. However, Kapoho cone, in the Puna District, appears to have been built as a result of a submarine explosion at some time in the prehistoric past.

Another type of volcanic explosion that occurs in Hawaii is the phreatic explosion, defined by Suess as an explosion not accompanied by fluid or essential ejecta. The fragmental deposits of phreatic explosions contain no magmatic or essential ejecta such as bombs, cinders, pumice, or ash, unless they were accidentally picked up from an older fragmental deposit of magmatic origin and redeposited with the other accessory ejecta. Phreatic explosions are primarily steam explosions at relatively low temperature as compared with the magmatic type. The classic example of a crater formed by a phreatic explosion is the Rieskessel, in the Ries District, Germany. This depression has been described by Branco [8] and others. The great eruption in 1888 at Bandaisan, Japan, has been explained by Sekiya and Kikuchi [9] as a phreatic explosion.

Because of the ash deposits on the rim of the Kilauea caldera it was early recognized that Kilauea had had explosive phases in the past. One such explosion occurred in 1790, just before the advent of the missionaries. This explosion, which was fatal to a whole company of Keoua's army, is recorded by Dibble.[10] That the explosion of 1790 was accompanied by fluent and incandescent lava is shown by the occurrence of bombs in the deposits; hence it was a magmatic explosion. No record of other explosions is found in the

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[8] Branco, W., Das vulcanische Vorries und seine Beziehungen zum vulcanischen Riese bei Nördlingen: K. preuss. Akad. Wiss. physikal. Abh., pp. 3–182, Berlin, 1902.

[9] Sekiya, S., and Kikuchi, J., Tokyo Coll. Sci. Jour., vol. 3, p. 106, 1889.

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

history of these volcanoes until May, 1924, when Kilauea once again hurled out huge quantities of ashes and rocks. The explosion was phreatic, as has been explained elsewhere by the writer.[11]

EXPLOSIONS AT KILAUEA

PHREATIC EXPLOSIONS

Until the explosion of 1924 no phreatic explosions were known at Kilauea. The writer, however, has visited and mapped three other phreatic explosive vents on the flanks of Kilauea—one at Alae Crater and two on the Great Crack—and others may exist in the unexplored forested slopes in Puna.

PREHISTORIC PHREATIC EXPLOSION

Alae Crater, Puna District.—The phreatic explosion at Alae Crater must have been similar in many respects to the explosion of 1924 at Halemaumau. The explosion was probably short-lived and, together with the collapse following it, produced a pit over 100 feet deep in the east side of the crater floor and a terrace in the thick lava fill that formed the crater floor prior to the explosion. The débris consists entirely of accessory ejecta, ranging from fine dust to blocks 3 feet in diameter. Six inches of lapilli were deposited around the rim of the crater. The blocks are almost entirely limited to a sector extending westward from the crater rim for about half a mile. This must have been due to a blast in that direction. The explosion débris is overlain on the northwest rim by some later lava that was extruded from a fissure on the rim and flowed into the crater. The lava of 1840, in the bottom of Alae Crater, is not covered with any accessory lapilli, hence the ejecta overlying the lava outbreak on the rim were doubtless deposited during the explosion of 1790 of Kilauea. Thus the stratigraphic position of the Alae ejecta indicates that they originated from an explosion antedating the eruption of 1790. The many fountains that have played in and about the crater since the phreatic explosion have deposited considerable pumice on the exposures of the explosion débris near the crater.

HISTORIC PHREATIC EXPLOSIONS

Explosions at the Great Crack in 1823.—Phreatic explosions occurred at two separate vents in the Kau Desert, about 16 miles southwest of the Kilauea caldera, on the southwest rift zone, in March, 1823. The location of the vents is shown on Plate 1. Both explosions occurred along the Great Crack, a fissure about 10 miles

[11] Stearns, H. T., The explosive phase of Kilauea Volcano, Hawaii, in 1924: Bull. volcanologique, vol. 2, pp. 193–209, 1925.

long and 5 to 25 feet wide, from which the Keaiwa flow of 1823 issued.

The explosion that occurred at vent No. 1[12] was small, for it threw out only a few accessory ejecta, most of which are less than 4 inches in diameter. It slightly enlarged the Great Crack. The explosion débris is scattered within a radius of 150 feet from the vent.

The explosion at vent No. 2 was considerably more violent, blocks as much as 1 foot in diameter being hurled 200 feet from the vent. The largest blocks lie within a radius of 50 feet, and both blocks and lapilli are predominant on the southeast side of the vent. The average depth of the débris near the vent is only 3 inches. The Great Crack was enlarged by the explosion, and the vent is now 15 feet wide, 30 feet long, and 20 feet deep. The blocks from this explosion fell on the lava of 1823, and practically everywhere smashed through the frothy crust of the flow after it had cooled. In one place, however, a block was found attached to the crust, indicating that some of the lava was still viscous. The explosion must have taken place within a few hours after the extrusion of the lava.

A study of the gray, brown, red, and black ejecta torn from the walls of this vent leads to some interesting conclusions. None of the blocks examined showed any secondary reheating effects, such as bread-crusting and glazing of the surfaces. No essential ejecta were discovered in the megascopic examination of the projectiles. The typical pumice of a magmatic explosion was missing. However, among the accessory ejecta, the writer found several small fragments of limestone consisting of brecciated shells and coral, which were torn from the walls below and blown out by the explosion. These fragments are the first accidental ejecta found on Kilauea or Mauna Loa.

The interpretation of these limestone ejecta also leads to some interesting conclusions. The vent is 280 feet above sea level and a little over half a mile from the sea. The presence of limestone among the ejecta demonstrates that a buried coral reef lies under this area. The area therefore must have been reclaimed from the sea by lava flows. As such reclamation is a common event on Kilauea and Mauna Loa, these ejecta should not necessarily be interpreted as part of a limestone platform extending under the island, as has been suggested by some earlier writers.

The presence of the accidental ejecta seems to show that the explosion originated at least 280 feet below the surface. Moreover, the absence of essential ejecta indicates that it was a phreatic

[12] This explosion vent was discovered by W. O. Clark Nov. 26, 1920.

explosion. The sequence of events is believed to have been somewhat as follows: The explosion probably began with the subsidence of the magma below sea level in the fissure, after the period of extravasation. The fissure became closed during the collapse that followed this subsidence. Evidence of this collapse is afforded by the many small grabens along the Great Crack. The rocks traversed by the fissure are filled with cracks, tubes, and other openings, so that it was relatively easy for ground water to enter the fissure. This water moved downward, became heated, and was converted into steam. Then this steam rose and escaped at different places along the Great Crack, as recorded by Ellis,[13] who visited the crack shortly after the flow had ceased. However, in at least two places at or below sea level sufficient water was converted suddenly into steam to cause an explosion, which had sufficient force to reopen the fissure and hurl out tons of débris. Field evidence indicates that the explosion ceased after a single blast. The crack was evidently opened wide enough for the steam to dissipate itself without further violence.

Explosions at Halemaumau in 1924.—During May, 1924, many phreatic explosions occurred at Kilauea. These have been described in detail by the writer[14] in another paper, hence only a brief summary will be given here.

The height of the molten lava in Halemaumau has fluctuated rapidly for two months prior to its disappearance from view on February 21, 1924. On the date of its disappearance the bottom of the pit was 380 feet below the northeast rim station. Until April 29 Halemaumau continued to be a fuming empty pit, in practically the same condition as it was on February 21. On the night of April 22 pronounced cracking and faulting of the ground began at Kapoho, 30 miles east of Kilauea. It probably resulted from collapse accompanying the downward drainage of the magma in the northeast rift of Kilauea. On April 29 the bottom of Halemaumau began to drop, accompanied by avalanches from the walls of the pit. By the end of the first week in May the bottom of Halemaumau was over 700 feet below the rim,[15] ample evidence that the lava column of Kilauea was rapidly sinking. By May 10 large clouds of dust rose from the pit, as avalanching went on unabated, and during the night of May 10–11 a small explosion occurred which threw out rocks. Small explosions occurred on May 12 and continued at frequent intervals with increasing violence until they reached a maximum on May 18. Some of the

[13] Ellis, William, Journal (reprint of 1827 edition). Honolulu, Hawaiian Gazette Co., 1917.

[14] Stearns, H. T., The explosive phase of Kilauea Volcano, Hawaii, in 1924: Bull. volcanologique, vol. 2, pp. 193–209, 1925.

[15] Hawaiian Volcano Obs. Bull., vol. 12, p. 39, 1924.

cauliflower explosion clouds that were caused by these explosions are estimated to have reached a height of over 4 miles. (See pl. 26, *B*.) Explosions continued at more or less regular intervals with decreasing intensity until May 27, when the pit returned to a condition of steaming, avalanching, and dust-making, similar to that of the period before May 11.

During May 3,961 local earthquakes and 1 teleseism were registered at the observatory. Lightning and heavy downpours of rain frequently accompanied the explosions. No magmatic or essential ejecta, pumice, cinders, or Pele's hair were thrown out during the explosions. The projectiles consisted entirely of blocks of rock torn from the throat of Halemaumau or old talus débris. The fine material consisted entirely of pulverized rock, as no ash could be found even by a microscopic examination.

The explosions were low-temperature steam explosions, and as no magmatic ejecta accompanied them they were phreatic explosions.[16]

MAGMATIC EXPLOSIONS

The following description of magmatic explosions is limited to explosions that were violent enough to bring out accessory or accidental ejecta. It does not, therefore, include the pyro explosions that form the fire fountains of Hawaii, which accompany practically all eruptions of Kilauea and Mauna Loa, and it does not include explosions caused by lava flows entering the sea, a type also common on Hawaii.

PREHISTORIC MAGMATIC EXPLOSIONS

Kapoho Crater, Puna District.—Kapoho Crater is 2 miles southwest of Cape Kumukahi, the eastern point of Hawaii, on the Puna rift of Kilauea. It is a well-defined cone three-quarters of a mile long from north to south and half a mile wide. It rises 448 feet above sea level and about 350 feet above the plain near by. The town of Kapoho (Hawaiian, " sunken in ") is on the northern base of the cone. The topography of the cone is shown in Figure 4. Before it was modified by later eruptions the crater consisted entirely of beds of tuff and pumice, which are now consolidated. In these beds are numerous accessory ejecta weighing as much as a ton, or more.

The history of this cone is more complicated than that of most of the cones on Kilauea. It evidently owes its origin to a submarine eruption, the rising magma exploding and forming a tuff cone in the same way as tuff cones are formed when lava explodes upon entering the sea. It is reasonable to suppose from its relation to the coast that it was built up as an island before the lava built out Cape Kumukahi (East Point), although no exposures were found that

[16] See also articles on these explosions by Jaggar and Finch cited in the bibliography on pp. 37–38.

would prove this statement. Since its formation erosion has furrowed the slopes of the cone and scalloped its rim. The débris from the streams on the inside slopes partly filled the old crater, and only one of the original depressions remains at the present time. This erosion interval was long enough for a layer of soil and an ash layer 6 to 10 inches thick to form on the surface of the cone. The presence of this soil layer makes the cone correlative in age with the earliest Kamehame flows and younger than many of the surrounding volcanic cones and flows.

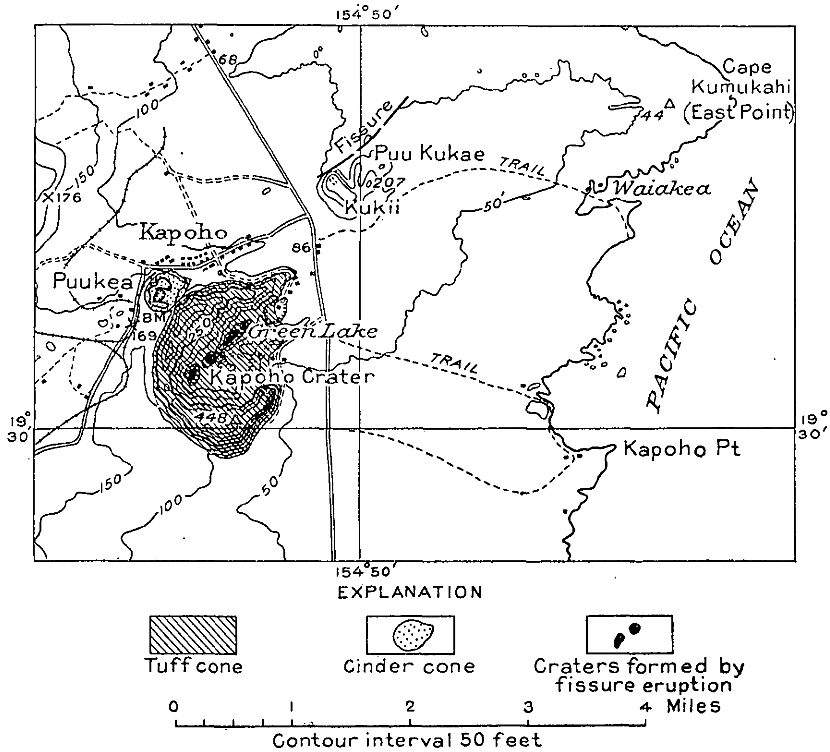


FIGURE 4.—Map of Kapoho cone, Puna District, Hawaii

After the long period of quiescence indicated by the soil layer, four lava fountains played from a fissure in the bottom of the crater of this old cone. These fountains laid down a layer of cinders 5 to 15 feet thick around their vents, and the northeastern lava jet was accompanied by a small lava flow that solidified near its source. The collapse that followed the cessation of the pyro-explosions produced three well-defined pits, which are shown in Figure 4. Small accessory ejecta occur in the beds of cinders deposited by these pyro-explosions, among which was found a piece of slightly baked clay that was probably picked up from the sediments deposited on the floor of the crater during the erosion interval. It is probable that a lake occupied the ancient explosion crater and that this clay was a deposit in the bottom of it. In the largest of the three pits formed by the last eruptive phase there is at present a small shallow pond called Green Lake. On November 11, 1924, when the temperature of the air was 82° F., the water of this lake had a temperature of 81° F. It is therefore not thermal in character, but comprises the drainage and seepage of the ancient tuff cone. Doubtless débris washed into the old crater from the surrounding walls has made this pit sufficiently impervious to hold water. It is used for a local water supply and is reported never to go dry. The symmetry of Kapoho Crater is broken on the northwest side of the outer slopes by Puukea, a later cinder cone similar to others along the rift zone. Kapoho Crater is the only cone of its type now preserved on Kilauea.

Kamakaia fissure explosion.—Immediately after the extravasation of lava from the Kamakaia fissure in the southwest rift zone of Kilauea, an explosion took place 1,200 feet northwest of the base of the highest cinder cone along the trough of the fissure. The date of the eruption is unknown. The amount of weathering of the lava indicates that this eruption took place in the Recent epoch but probably several centuries before the advent of white men. The fissure at the place where the explosion occurred is 25 feet wide and 5 to 10 feet deep and is now nearly filled with wind-blown sand. The explosion hurled out lava clots and fragments of the fissure walls. None of the ejecta exceed 1 foot in diameter, and their distribution is limited to an area with a radius of 50 feet from the explosion vent. Fine lapilli 2 to 3 millimeters in diameter occur 300 feet from the source, but this material may have been drifted by winds to that distance since the time of the explosion.

The presence of essential ejecta among the débris indicates the magmatic origin of the explosion. Typical bombs and scoria are missing, the essential ejecta consisting entirely of lava clots such as accompany pyro-explosions. It is possible that the clots were thrown out during the closing scenes of the explosion. The accessory ejecta present are unusual in that they are completely glazed. This fact indicates that they must have been partly re-fused during the explosion and hence do not owe their glazed surfaces to melting by ascending lava when in place prior to the blast. The glazing is less than 1 millimeter thick and not similar to the bread-crusting of accessory ejecta, for each fragment feels and looks as if it were varnished. The fused surfaces indicate clearly that burning gases, presumably chiefly hydrogen, accompanied and probably caused the explosion.

Early explosions at Kilauea caldera.—Until a few years ago an ash bed was exposed in the base of Uwekahuna Bluff, but it has been buried by lava. According to Powers,[17] only 17 feet of the ash bed was exposed. It consisted of yellow ash with some rock fragments 1 to 2 inches in diameter, lava droplets, thread-lace scoria, and a few bombs 6 inches in length. The bombs indicate a magmatic explosion at Kilauea early in its history.

The region surrounding the Kilauea caldera is covered with a deposit of ash, lapilli, and bombs that ranges from about 2 feet to more than 30 feet in thickness. The sections of ash that exceed 5 feet are limited to the south rim of the caldera, as the prevailing winds are northeasterly. In Plate 28 an attempt has been made to represent the ash by contour lines from measurements made by the writer in 1924 and by Powers near the pit, where the flow of 1921 altered exposures. So many factors, such as direction of wind, amount of rain, localized explosion blasts, and lava flows, have affected the thickness of the ash at any particular place that the map only approximates the original form of the deposit. The ash is usually found in the depressions in the lava flows, and in many places the high parts of the flows are bare. The thicknesses given in the figure represent as nearly as possible the average depth for each locality. For a long time the ash deposit around Kilauea was supposed to have resulted from the eruption of 1790. Powers[18] has shown that this ash represents at least two explosive phases separated by some time interval, because the Keamoku flow, a late prehistoric flow from Mauna Loa, overlies and is overlain by thin deposits of ash.

Before considering the map, a few facts regarding the present climatic conditions at Kilauea and their effects on the deposition of ash should be noted. A belt of country extending from Kilauea Iki around the north side of the rim to the military camp has a precipitation of about 80 inches a year and is covered with a dense growth of semitropical vegetation. Around the rim in both directions from these points the precipitation decreases rapidly until the lowest portion of the rim is reached on the southwest, where the annual rainfall probably does not exceed 10 inches. Consequently this southwestern portion of the rim is a barren ash desert practically devoid of vegetation. The prevailing trade winds pass over the northeast side of the volcanic dome and drop their moisture. Thus it is a common experience to be standing in a fine mist at the Volcano House and see a cloud of dust rise from the southwest rim caused by the same wind a few minutes after it has passed over the floor of the caldera. It is probable, therefore, that the thickness of

[17] Powers, Sidney, Explosive ejectamenta of Kilauea: Am. Jour. Sci., 4th ser., vol. 41, p. 230, 1916.

[18] Idem, p. 238.

the ash varies according to its location with regard to wind and rain. Further, when it rains on the southwest rim, cloudbursts frequently result, cutting deep gullies into the ash and washing away considerable portions of it. Moreover, when an explosion occurred in the crater, in 1924, the prevailing northeast winds almost invariably bent the cauliflower explosion cloud toward the southwest; hence there was usually a greater deposition of ash in that direction. Directed blasts during any series of explosions tend to cause an accumulation of débris in special directions and sectors.

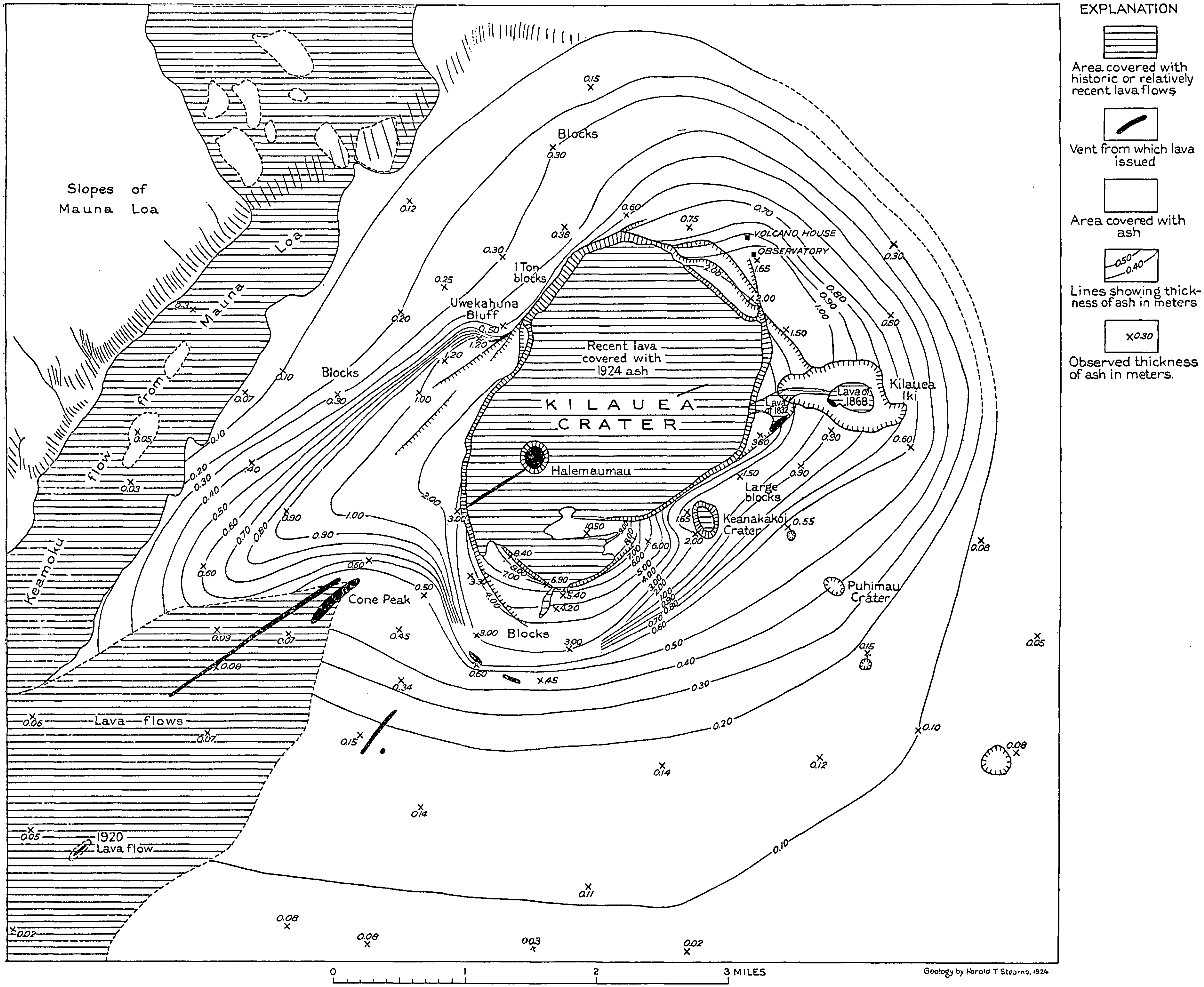
These numerous conditions of deposition give a wide variation in the thickness of the ash around Kilauea. The complexity is made greater also because lava flows have buried the ash in places.

Therefore the representation of the ash deposit together with its interpretation must be general.

The contour map of the ash deposits (pl. 28) shows a few facts regarding the distribution of the ash. First, there is a great thickness of ash on the south rim; second, there is an abrupt thinning a very short distance south of the rim; third, there is an unusual piling up of ash southwest of Halemaumau with an abrupt decrease in thickness in the region southwest of Cone Peak, and also there is an abrupt variation near Uwekahuna Bluff; fourth, there is a piling up of ash near Waldron Ledge. The following explanations of these peculiarities are offered:

1. The great thickness of ash on the south rim is an accumulation of the débris from many explosions, large and small, from Kilauea. Its thickness is due primarily to its location, which is above the level of the lava flows on the floor of the caldera and yet low enough and near enough to the explosion vents to receive a large amount of ash. Moreover, it also lies in the leeward side of the vent in the belt of prevailing winds. The explosion of 1924 deposited fully twenty times as much ash on this section of the rim as it did on Uwekahuna Bluff, north of the vent. During the feebler explosions the south rim received ash when none reached Uwekahuna Bluff.

2. The abrupt change of thickness from 10 feet to 1 or 2 feet within a quarter of a mile near the south rim of the caldera can not be adequately explained by variations in the effects of wind and rain alone. In this region a line of driblet cones marks the line of a fissure eruption parallel to the concentric faults that bound the caldera. (See pl. 28.) The writer believes that a lava flow poured out of this fissure after the deposition of most of the ash, for there are exposures of a flow in the ash southwest of the fissure vent, although no lava flow is interstratified with the thick deposits of ash in the adjacent caldera rim.



MAP SHOWING DISTRIBUTION AND THICKNESS OF ASH DEPOSITS AROUND KILAUEA CALDERA

3. The unusual piling up of ash on the rim southwest of Halemaumau and the abrupt change of thickness in the region southwest of Cone Peak are probably due to two or more causes. Uwekahuna Bluff, a vertical escarpment 500 feet above the floor of the caldera, limits the deposition because of its higher altitude. Moreover, when the trade winds strike the cliff they rebound with an eddying effect and move southwestward. Therefore, a dust-laden explosion cloud, when carried southwest of the crater by the wind, would tend to deposit most of its load just southwest of the place of the eddies created by Uwekahuna Bluff. This condition, combined with the effects of the differences of altitude of the two places, would cause an appreciable change in deposition from the top of Uwekahuna Bluff to the lower fault terrace, a quarter of a mile to the southwest. Moreover, Uwekahuna Bluff receives more rain than the region a quarter of a mile southwest of it, and undoubtedly some of the ash has been washed down from it to the lower country. At the present time several gullies drain southwestward from the bluff. Winds also have probably blown considerable ash from the high portions of the northern rim.

These factors and that of directed explosion blasts fully account for the piling up of ash in this locality. They do not, however, explain the change in thickness of ash near Cone Peak. As the area just southwest of Cone Peak is not subject to any apparent climatic conditions different from those of the region bordering it on either side, another cause must function. In this area also are found fissures (pl. 28) which have sent streams of lava southwestward. These flows are much more exposed than those in the adjacent country, hence it is concluded that they have buried some of the ash beds, although no exposures showing the ash passing under these lava beds have been found. It is possible that as new cracks are formed such an exposure may be revealed.

4. The piling up of ash near Waldron Ledge in a direction opposite to that of the trade winds can be explained by either a directed blast or a vent situated near by. Both Powers [19] and the writer favor the latter explanation. An artificial exposure near the Volcano Observatory showed tree molds that did not extend downward through the entire thickness of the ash. This indicates that vegetation was growing on a bed of ash, a condition which is interpreted as evidence that there have been at least two epochs of deposition at this locality. In the same artificial exposure Jaggar [20] counted six different vegetable

[19] Powers, Sidney, op. cit., p. 235.

[20] Personal communication. The writer did not have an opportunity to see this artificial exposure before it was destroyed.

horizons. The thickness of ash on the eastern rim implies the location of a vent a quarter to half a mile southwest of Waldron Ledge. Further, the thinning of the ash toward Kilauea Iki and Keanakakoi indicates that these craters did not have explosions of any magnitude.

If the causes of these variations in thickness of the ash are interpreted correctly, then the sites of most of the explosions must have been in the general vicinity of the present Halemaumau.

The burial of the ash by lava flows at different times and the six vegetable horizons in the ash at the exposure near the Volcano Observatory lead to the conclusion that the ash deposit at the surface represents not less than six different explosive epochs in the history of Kilauea before 1790. Moreover, as these lava flows are probably recent, compared with the basal members of the thick ash beds south of Kilauea, there have probably been in recent geologic time many explosive phases of Kilauea. Because the ejecta are both essential and accessory, it must be concluded that both magmatic and phreatic explosions have occurred at Kilauea at more or less frequent intervals. This conclusion is further supported by the presence of at least two known ash beds separated by lava flows in Uwekahuna Bluff. These beds indicate explosive phases in Kilauea's history before the formation of the caldera.

The writer therefore concludes from the data at hand that the Kilauea caldera existed prior to the surface ash deposits, and that the deposition of ash has continued throughout a great length of time, during which a few old fault blocks have disappeared into the depression; some new ones have been formed, and many of them have moved.

HISTORIC MAGMATIC EXPLOSIONS

Explosions at Kilauea in 1790.—The explosive phase of 1790 has been described by Dana, Hitchcock, Brigham, Perret, Powers, and others, hence only a brief summary of the events will be given in this paper. Sometime about 1790 a series of explosions took place that killed a number of Hawaiians who happened to be passing near Kilauea. As no white men were then on the island, the details of the eruptions are based on statements of the natives gathered by Rev. Joseph Goodrich after an interval of many years. The explosions must have been considerably more violent than those in 1924, for blocks 1 to 2 feet in diameter can be found a mile from the rim of Kilauea. During one of the explosions of 1924 only one block nearly 1 foot in diameter was hurled 5,000 feet from the center of Halemaumau, and most of the blocks fell within 3,000 feet. Some of the explosion clouds during 1924 reached a height of 3 to 4 miles, so that explosions violent enough to throw many large blocks 1 to 2 miles from the Kilauea rim probably sent clouds over 5 miles into the air.

The arrangement of the blocks around Kilauea seems to indicate that the center of the explosions was a little north or northeast of the present Halemaumau, or nearer Uwekahuna Bluff. The explosion brought out with it essential as well as accessory ejecta, so that there is no doubt regarding the magmatic character of the explosion. Perret[21] has given some beautiful illustrations of bombs from the ash of 1790.

Archibald Menzies, a member of Vancouver's expedition, while ascending Mauna Loa in February, 1794, from Kapapala, made the following note in his journal: "We had the volcano Kilauea to our right most part of this day, and in the forenoon the smoke and ashes arising from it made the air very thick, which at times proved very tormenting to our eyes." [22]

This statement has been interpreted as meaning that explosions occurred at Kilauea in 1794, but with the information gained during the explosions in May, 1924, it can be interpreted in another way. The explosions of 1924 deposited considerable fine ash over the Kau Desert, especially southeast of Kapapala; and, at the present time, whenever there is a week or more of dry weather followed by a windy day, huge clouds of dust are picked up from the southern rim of Kilauea, and blown toward Kapapala. The writer spent several weeks near Kapapala during the summer of 1924 and experienced many days in that region when the dust "proved very tormenting" to his eyes.

Had anyone experienced such a dust storm without being fully acquainted with the actual conditions at Kilauea, he might easily have concluded that an explosion had taken place at Kilauea. One day in June, 1924, 20 miles southwest of Kilauea, during just such a storm, a stranger inquired of the writer if Kilauea was in eruption. The fact that Menzies does not mention any other eruption later in his journal seems to indicate that the "smoke and ashes" were only dust clouds caused by a windy day.

EXPLOSIONS ON MAUNA LOA

Prehistoric explosions near Mokuaweoweo.—While making a reconnaissance of the top of Mauna Loa in August, 1924, the writer found explosion débris in a kipuka at an altitude of 12,200 feet on the new Ainapo trail, about 1 mile from the rim of Mokuaweoweo. The largest block weighed about 50 pounds, and there was very little ash associated with it. In the kipuka there were also numerous frag-

[21] Perret, F. A., Some Kilauean ejectamenta: Am. Jour. Sci., 4th ser., vol. 35, pp. 611–618, 1913.

[22] Hitchcock, C. H., Hawaii and its volcanoes, p. 72, 1909.

ments of fresh pumice. This pumice, however, resulted from recent pyro-explosions at Mokuaweóweo, for it also occurs on the later lava surrounding the kipuka. The fact that all the ejecta were of the accessory type indicated that the explosion was phreatic.

The débris from another explosion from Mokuaweoweo was observed by Wilkes, who had his camp on it, and later by Alexander [23] and others. The distribution of the explosion débris, as shown on Plate 3, indicates that there were either two explosion vents or two directed explosion blasts from one vent. The latter alternative is more probable than the former, because the ejecta appear to be of about the same age and located in sectors nearly opposite to each other. The vent was probably situated a little nearer the west rim than the east. All the débris is of the accessory type, although fresh pumice from the recent fountains occurs on top. The fact that very little fine material lies on the lava beds surrounding the area suggests that the explosion was short lived. Moreover, this lack of material is not due to burial by later flows, for the actual thinning of the débris outward from the vent can be traced in the field. The blocks range from a few inches to 3 feet in diameter. The writer is inclined to believe that the ejecta represent one big explosion with two branches, a common occurrence during the explosions of 1924 at Kilauea. Smaller explosions may have followed and deposited débris on the old floor of Mokuaweoweo. It is impossible at the present time to find any explosion débris on the floor because of burial by later lava flows. A few isolated ejecta in some of the cracks between fault blocks on the northwest rim have been found.

Prehistoric explosions at Lua Poai.—A phreatic explosion took place during the deposition of the Pahala ash [24] at Lua Poai, a pit crater 290 feet deep and 1,000 feet in diameter 1 mile south of the Kahuku ranch. (See pl. 1.) This crater is the largest one of the five in the line of pit craters extending from Kahuku ranch toward the sea. The distribution of the explosion débris is unknown, for it is overlain by 10 feet of yellow Pahala ash. The ejecta are exposed only on the west side of the crater, the other slopes being grass covered. The largest blocks weigh about 1 ton. Measurements with a hand level indicate that there is 32 feet of ash on the rim, but only a small portion, 1 to 5 feet of the section came from this crater. The explosion débris from the crater is underlain by about 20 feet of ash from other sources. The yellow ash is the upper member of the Pahala basalt, and hence this explosion must have taken place in late Pahala (Pleistocene?) time. This Lua

[23] Alexander, J. M., On the summit crater of Mount Loa in October, 1885: Am. Jour. Sci., 3d ser., vol. 30, p. 35, 1888.

[24] Personal communication from W. O. Clark, Pahala, Hawaii, who first noted the deposits.

Poai explosion is probably accounted for by ground water, because the bottom of the crater is not more than 1,600 feet above the water table.

The other pit craters in this crater chain may also have been sites of explosions, but at the present time they are covered with Pahala ash and vegetation. Lua Palalauhala, the most northern of the chain, shows no explosion blocks in an exposure on its rim, but it does show a dark-colored ash in the section which corresponds in part at least to the ash deposited by the explosion at Lua Poai.

Magmatic explosions.—No traces of magmatic explosions were discovered on Mauna Loa, but it is possible that in the future the débris of some may be discovered on its slopes. Near Hilo there are several magmatic explosion cones, but these are considered parts of the Mauna Kea system.

CAUSE OF EXPLOSIONS

For years it was thought that all the ash around Kilauea resulted from the explosion of 1790, and that only one explosion had occurred at Mauna Loa. It is evident from the foregoing descriptions that explosions are not uncommon at either volcano, and that two if not more have occurred within historic times and passed by unobserved. The occurrence of phreatic explosions, so far as the writer is aware, has never been recognized previously at Kilauea and Mauna Loa. In May, 1924, a series of explosions occurred which are now generally agreed to have been due to ground water.

The water tables in Hawaii are of two types—the perched water table, in which water is retained at a high level by an impervious ash bed or by a dike system, and the normal water table. Because of the permeable condition of the lava beds, water soon moves downward almost to sea level. This condition undoubtedly allows sea water to find its way under the island. The ground water of Hawaii occurs as a low dome-shaped lens resting upon salt water and gradually mixing with it both by slow assimilation under the island and by springs flowing into the sea near the shore, at or about tide level.

Through this dome of ground water the lava must rise after it has receded below sea level. During most of the history of Mauna Loa the lava could not have receded far below the water table for any length of time, or phreatic explosions would probably have been more frequent. Unless the magma recedes below the water table and remains below long enough for the rocks to become cooled in the conduit, water will not collect in the fissures above the magma. With the rocks cooled, water can enter the crevices and move downward. In this downward course it will eventually reach a zone of hot rock, where it will be converted into steam, and thereupon it will rise and be discharged through the vents on the surface. Some of the steam on its way upward may condense and pass downward again and become reheated. As the magma rises the rocks above it are heated, and the level at which water can enter the fissure zone is raised.

If the magma rises slowly, the water in the fissure will be quietly dissipated as steam, and the water table will be forced to recede from the walls of the fissure. If the magma rises rapidly, if the supply of ground water is plentiful, and if the vent is for any reason choked with débris, an explosion will result.

Phreatic explosions may lead to magmatic explosions. If the magma is rising rapidly in the conduit, owing to causes at present unknown, and if the phreatic explosions within a short time blow away several thousand feet of rock above the magma, the sudden lifting of the load and the accompanying release of pressure on the magma might easily cause rapid gas expansion and gas-bubble convection. Once the convection was started it would tend to be accelerated by causing the magma column to froth and thereby decreasing the pressure. In this way a phreatic explosion might be followed immediately by a magmatic explosion.

The hypothesis given above is set forth as a possibility for future investigation. It certainly does not explain all magmatic eruptions, and in the explosions in May, 1924, at Kilauea, this order of events did not take place. However, the fact that the magma did not reach the surface until at least 70 days after the explosion began indicates that the magma rose very slowly. Moreover, as the vent above was deepened gradually by engulfment [25] the requirements of the hypothesis were not fulfilled, and it was not, therefore, a test case.

Explosions play an important part in the history of any oceanic basaltic volcano. To judge from the history of Oshima and other basaltic volcanoes that form small islands off the coast of Japan, explosions have occurred frequently there, and many of them were phreatic. With the growth in height of a continuously active oceanic basaltic volcano there is a proportionate increase in the distance the lava column has to fall before ground water can affect it, hence phreatic explosions should be less frequent. It is interesting to note that Oshima Volcano, in Tokyo Bay, is about 2,200 feet high and that phreatic explosions occur there at frequent intervals. Kilauea is about 4,000 feet high, and phreatic explosions are less frequent there than at Oshima. Mauna Loa is 13,675 feet high, and phreatic explosions there are separated by long intervals of time. There are, however, other factors than height that influence the frequency of phreatic explosions in basaltic volcanoes. Chief among these are the

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[25] Jaggar, T. A., jr., Plus and minus volcanicity: Washington Acad. Sci. Jour., vol. 15, p. 416, 1925.

size and shape of the lava conduit and the continuity of activity at the summit crater.

It should be noted further that the lava fountains on Kilauea are much less violent than those on Mauna Loa. It appears that the intensity of pyro-explosions increases with the height of a basaltic cone. As the cone reaches heights like that of Mauna Loa, phreatic explosions dwindle into insignificance compared with pyro-explosions.

The facts above set forth suggest a rough order of explosions varying with the height and age of a basaltic volcano. At first, phreatic explosions occur frequently, but as the cone increases in height they decrease in number, whereas the intensity of pyro-explosions increases. This order of events can be deranged at any time by abnormal behavior of the magma in the conduit, such as a subsidence to unusual depths or long periods of quiescence.

The part played by explosions and ground water, however, should not be overrated as compared with ordinary activity and lava flows at a basaltic lava volcano. As Jaggar [26] has said, "Explosive eruption at a lava volcano is a secondary phenomenon, and primary volcanism may be fundamentally dependent on hydrogen and other deep gases."

PETROLOGY

PETROGRAPHY

The rocks of the Kau District were first studied intensively in the field by L. F. Noble in 1920, and the microscopic determinations were made by Whitman Cross. Noble discussed these determinations in an unpublished report submitted to the United States Geological Survey in July, 1920, a large portion of which has already been quoted by Washington.[27] The petrography has been revised in the light of the recent detailed geologic mapping by the writer.

NINOLE BASALT

In view of the small area and small thickness of its exposures, the Ninole basalt is best represented in the collection. However, the exposures of this basalt reveal only an insignificant part of the lava flows composing the Ninole formation, and the specimens collected are a still more insignificant part of the rocks exposed. Any conclusions drawn from them must therefore be tentative only and should be considered a starting point for the future specialist. Moreover, the microscopic determinations of the rocks point out only relative differences, and the final solution of the problem of magmatic

[26] Jaggar, T. A., jr., Activity of Kilauea Volcano: Science, new ser., vol. 60, Suppl., p. xii, Sept. 5, 1924.

[27] Washington, H. S., Petrology of the Hawaiian Islands, II, Hualalai and Mauna Loa: Am. Jour. Sci., 5th ser., vol. 6, pp. 100–126, 1923.

differentiation, if it has taken place, lies in the hands of the chemist. These facts should be kept in mind in reading the following discussion of the petrography, chemistry, and magmatic differentiation.

W. O. Clark states that when he and Noble began field work in the Kau District they collected specimens of the Ninole basalt only from massive beds, thinking that these beds would yield the most significant results. Later, as Clark became more familiar with the geology, he was convinced that any of the rock types of the Pahala or Kamehame basalts could be duplicated in the Ninole basalt and that the sampling method first used had overemphasized one type of rock. With this in mind he collected a series of specimens from the face of Puu Enuhe as nearly as possible 100 feet apart, regardless of the type of lava or the thickness of the bed. The results were as he had surmised, for a microscopic examination showed no appreciable predominance of any type of basalt in these specimens as compared with the other series.

Analyses show all gradations from ophitic olivine basalts (analysis 1, Table 1, p. 163) through aphyric labradorite basalts (analysis 2, Table 1) to feldspar phyric basalts.[28] Microscopic determinations on 23 specimens indicate that the variation in composition is not quite as great as among the specimens of the Kamehame formation, but this is probably due to the small number of specimens. The writer, like Clark, is confident, after reviewing the microscopic determinations, that any specimen of one series of flows could be duplicated from any other series of flows. However, of the 25 specimens from the Ninole basalt, more than half fall into two closely related types—aphyric olivine-free labradorite basalts with excess silica and feldspar phyric labradorite basalts with little or no normative olivine.

Megascopically, most of the Ninole lava beds are not only lighter in color and finer in texture than the Kamehame, but they are less strongly characterized by distinct olivine crystals. Some determinable olivine, however, is generally visible under the microscope. The presence or absence of large amounts of olivine in a basalt has been shown by Bowen and Andersen [29] to depend upon conditions of cooling; hence it is not a distinguishing characteristic. The light color of a basalt is ordinarily due to a relatively complete crystallization, whereas the darker lavas are likely to have a ferritic and partly glassy base. Cross has suggested that Ninole lavas are probably less

[28] The writer follows Washington's nomenclature (Petrology of the Hawaiian Islands, I, Kohala and Mauna Kea, Hawaii: Am. Jour. Sci., 5th ser., vol. 5, pp. 465–502, 1923), because it seems to be the most easily understood.

[29] Bowen, N. L., and Andersen, Olaf, The binary system $MgO-SiO_2$: Am. Jour. Sci., 4th ser., vol. 37, p. 499, 1914.

mafic—a fact which would also account for the difference in color—but this does not appear to hold true in the few analyses made.

The following petrographic descriptions by Whitman Cross [30] show the character of a few of the specimens examined from this formation:

No. 85. Southeast side of Puu Enuhe Ridge at an altitude of 1,050 feet. (See pl. 1.) Megascopic: A light-gray felsitic rock with subordinate porous texture. Pores minute, elongated, and irregularly distributed with a few larger ones. There are minute pale-green olivine and white feldspar specks as the only recognizable constituents. Apparently the rock is holocrystalline. Microscopic: The rock is holocrystalline. Augite and olivine are developed in grains and clusters, contrasting with the dominant mass, which is a typical basaltic aggregate of plagioclase microlites with minute crystals of augite, olivine, and magnetite between them. There is seriate gradation from the smaller to the larger grains of all the silicates. Olivine is probably very subordinate in the groundmass. Quantitative determination is very difficult and tedious. Minerals are fresh and there is no glass.

No. 87. Southeast side of Puu Enuhe at an altitude of 1,450 feet. (See pl. 1.) Megascopic: Bluish gray with red in parts. The main color is due to the rusty lining of round pores and to tarnished olivine. Pores occupy nearly 50 per cent of the space, are nearly round, and are 1 millimeter or less in size. Olivine is abundantly distributed in crystals, some of them larger than the pores, lustrous and tarnished. Microscopic: The abundant olivine crystals are characterized by the presence of ferritic trichites, well worthy of study and illustration. They are variably developed in abundance and form within irregular areas sharply defined by fractures. Some are quite irregular, while others appeared to be cleavage planes. The olivine may be 40 per cent of the rock. The rest is a common basaltic mixture of plagioclase, microlite, and augite grains with ferritic base and perhaps some glass. The rock is much poorer in plagioclase than any other of the collection.

No. 90. Southeast side of Puu Enuhe, at an altitude of 1,600 feet. (See pl. 1.) Megascopic: Ash-gray; irregular porous texture. Large pores up to 2 centimeters in diameter, with rusty walls irregularly distributed. They grade down to minute, more nearly round pores. The mass of the rock has few notable crystals. Microscopic: Mainly ophitic mass of plagioclase, augite, magnetite, and residual glass with ferritic material. Olivine and augite in few larger crystals in clusters. Olivine also in the groundmass.

No. 92. Southeast side of Puu Enuhe, at an altitude of 1,790 feet. (See pl. 1.) Megascopic: Light bluish gray, with subordinate and irregular pores. Mass mainly aphanitic, but contains few pale-green olivine grains or groups, a few reaching 1 millimeter in diameter. Microscopic: Very fine-grained plagioclase microlites with interstitial magnetite, augite, and ferrite. Fluidal structure subordinate. Many small phenocrysts of olivine. A marked distinction between the larger crystals and groundmass.

No. 25. Massive bed of basalt above ash at Kaumaikeohu Spring, at an altitude of 2,780 feet. (See pl. 1.) Megascopic: Hand lens shows some olivine, and the plagioclase of the ophitic mass is distinct. Microscopic: Texture ophitic, with plagioclase, augite, olivine, and magnetite well developed. Olivine

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[30] Letter to N. C. Grover dated June 30, 1921.

is the richer but seldom occurs in phenocrysts. No microlite groundmass or base; rare ferritic glass wedges. Olivine unusually abundant in this type. [See analysis of this specimen, Table 1, No. 2.]

No. 34. Nine-tenths of a mile northwest of Naalehu, at an altitude of 1,300 feet. (See pl. 1.) Megascopic: Bluish gray, aphyric, few round pores, 5 centimeters or less. Microscopic: Similar to Nos. 26 and 27. Hypersthene distinct in aggregates. Olivine not abundant. [The analysis of this specimen is shown in Table 1, No. 1.]

All the Ninole beds occur on the Loa Ridge and hence were derived from only one source, whereas the later lavas originated on both Kilauea and Mauna Loa. Chemical analyses show that probably no andesites occur in the district, although many rocks are close to andesite.

PAHALA BASALT

The 16 specimens from the Pahala basalt on Kilauea and Mauna Loa that were examined microscopically range in composition from picrite basalts to feldspar phyric basalts. On the whole these rocks are very similar to the lavas of the Ninole basalt and like them do not invariably have prominent olivine crystals. The range in types is practically identical with that of the Ninole rocks, but a larger number of them appear to be a little more mafic than most of the specimens from the Ninole basalt.

A few of the specimens from the Pahala basalt are described by Cross [31] as follows:

No. 24. Half a mile west of Pahala, at an altitude of 800 feet. (See pl. 1.) Megascopic: Irregularly vesicular. Greenish spots, 1 millimeter or less in diameter, are aggregates of mineral grains containing usually much more augite than olivine. These spots are free from plagioclase. Microscopic: Ophitic, very fine grained; few small olivine phenocrysts.

No. 26. One mile northwest of Middle Moaula Camp, at an altitude of 1,950 feet. (See pl. 1.) Megascopic: Aphyric vesicular, about 25 per cent of space occupied by round pores, 1 millimeter. Microscopic: Ophitic relation of plagioclase and augite. Olivine in small phenocrysts abundant. Hypersthene occurs in the few aggregates in larger crystals than augite. Magnetite and ferritic glass in angular spaces.

No. 28. Same locality as No. 26. Megascopic: Vesicular, round to oblong pores 1 to 5 millimeters; iridescent olivine phenocrysts distinct, not abundant. Microscopic: The mass of rock is of unusual character. There are some relatively large crystals of plagioclase, augite, and olivine, with a connected base of ferritic material containing minute grains of augite and plagioclase microlites. The relatively large grains are still very small, so the rock as a whole has an unusually fine grain.

No. 16. Lowest bed exposed in Kahuku Pali, on trail 3½ miles northwest of Kalae. (See pl. 1.) Megascopic: Olivine-rich basalt, very vesicular, pores about one-third of the mass. Olivine perhaps about one-half of the rock portion. Pores are round, are irregular with reddish walls, varying from less

[31] Letter to N. C. Grover dated June 30, 1921.

than 1 millimeter to 3 or 4 millimeters. Olivine brilliant, iridescent, reaching 0.5 millimeter in diameter. Rock resembles No. 19 as to the abundant development of olivine and relation to pores. Microscopic: Aside from the fresh and well-crystallized olivine, the mass consists mainly of plumose or rude spherulitic, bundles of augite prisms which are curving and branching of rough outline, and are embedded in opaque ferritic material. This is, no doubt, in part magnetite, but there are no distinct crystal grains of that mineral except as rare inclusions in olivine. Plagioclase microlites are much less abundant than augite; they are in some places forced into general parallelism with the augite, but they are more commonly irregularly placed, as if older than the augite. The rock is a very mafic basalt well deserving chemical analysis. It is unlike any other of the collection.

KAMEHAME BASALT

Among the Kamehame lavas also are found representatives of all types from picrite basalts to feldspar phyric basalts. Specimen 9 was identified by Cross as being an augite andesite containing hypersthene (?). The geologic horizon of this specimen was uncertain at the time it was collected by Noble, and the rock was considered by him the least mafic of all specimens collected. After a microscopic determination Noble described it as probably Ninole, possibly Pahala, certainly not Kamehame. This critical specimen, which would have given the Ninole basalt the greatest range in composition had its assignment to the Ninole been correct, has now been proved to belong to the Kamehame beds. Clark, who was with Noble at the time he collected the specimen, took the writer to the lava tube from which it was obtained, and after a careful study of its relations to Pakanaka Hill both decided it could belong only to the Kamehame basalt. Hence the greatest known range in composition seems to occur in the Kamehame lavas. However, as the writer has already said, this specimen probably could be duplicated in the other formations if a sufficiently large number of specimens were collected.

Cross's descriptions [32] of a few of the specimens from this formation are as follows:

No. 35. Seven-tenths of a mile north of Naalehu, at an altitude of 1,150 feet. (See pl. 1.) Megascopic: Olivine-bearing augite andesite; vesicular pores from 1 centimeter to less than 1 millimeter, of irregular shape and distribution. Porphyritic from development of spots 3 millimeters in diameter or less, which are mostly aggregates of several feldspathic crystals, some of only one crystal. Microscopic: Phenocrysts are mainly plagioclase but with some of augite greater than olivine. Groundmass microlitic; plagioclase very well developed crystals arranged to express flow structure; augite in grains and with subordinate development in prisms (=microphenocrysts). Olivine is rare unless developed among the small grains, which seem more likely to be augite. Magnetite de-

[32] Letter to N. C. Grover dated June 30, 1921.

velops into individual grains like augite. No glass or ferritic base. [An analysis of this specimen is given in Table 1, No. 3.]

No. 13. Side of road half a mile west of Waiohinu. (See pl. 1.) Megascopic: Dark bluish gray, mainly aphyric, vesicular; vesicles irregularly distributed, round to oblong, 1 to 6 millimeters. With lens a few small phenocrysts of olivine. Mass apparently finely crystalline under the lens. Microscopic: Much ferritic black interstitial material, probably olivine-poor; careful search necessary in finding any small crystals.

19. About 1½ miles northwest of Hilea. Megascopic: Olivine-rich dark-gray vesicular rock, pores about 50 per cent, 1 to 4 millimeters. Olivine crystals abundant between pores, often projecting into them. Olivine tarnished, glistening, very abundant. Microscopic: Olivine constitutes nearly one-half of the rock mass; the rest is ophitic, with plagioclase more abundant than augite. Irregularly distributed ferritic base and subordinate magnetite in distinct grains. [An analysis of this specimen is given in Table 1, No. 4.]

No. 9. About 1¾ miles north of Hilea. (See pl. 1.) Megascopic: Dark ash-gray aphanitic rock, vesicular, with minute pores irregularly distributed. Some areas contain many minute vesicles and seem like inclusions, especially as there are irregularly large pores on the seeming borders of these areas. There are no phenocrysts, and with the lens there are recognized only minute glistening crystal specks. Microscopic: The rock is apparently olivine-free, or at least very poor in olivine. It is unusually fine grained, requiring high power of the microscope for its best study. The main constituents are plagioclase, augite, magnetite, and an undetermined yellowish-green mineral. A bright-yellow prismatic mineral resembling rutile is apparently the same mineral found in No. 2. There is a lighter, pale-smoky residual glass. A rude estimation of composition gives plagioclase about 40 per cent, magnetite about 15 per cent, augite and the undetermined mineral each about 20 per cent. The augite is pale, light green in minute grains, and rare rude prisms. The undetermined mineral is of variably strong yellowish green, sometimes with the brilliancy of epidote. It occurs partly in grains, partly in rude prisms, both being more or less cloudy. There is an indistinct cross structure resembling that of altered melilite, but it is not that mineral; it resembles an alteration product, but the rock is so fresh otherwise that I doubt its secondary character. If an alteration product, I think it comes from a rhombic pyroxene. The rock is hardly a basalt, but chemical analysis would be necessary to ascertain its true chemical relations.

A review of the determinations of the Kamehame rocks shows that, although they fairly represent all types, there is a slight tendency for them to be more mafic than either the Pahala or pre-Pahala. Certainly picrite basalts are common among them. The prehistoric flow that is broken by the Waiohinu fault is probably the richest in olivine of all the basalts in the Kau District. As compared with the Pahala and Ninole lavas, the most distinctive features of these rocks lie in the greater amount of unindividualized ferritic material in the groundmass and the darker color.

CHEMICAL ANALYSES

TABLE 1.—*Analyses of lavas from Mauna Loa* [a]

	1	2	3	4	5	6	7	8
SiO_2	49.24	48.60	49.24	45.97	49.27	52.65	51.90	52.30
Al_2O_3	12.72	10.75	13.51	5.98	9.38	12.12	11.69	11.84
Fe_2O_3	4.27	3.92	3.86	5.86	1.28	2.19	2.24	2.06
FeO	8.44	9.38	8.88	7.39	10.31	8.87	8.84	9.03
MgO	7.10	9.80	5.90	23.55	17.74	7.43	7.37	7.15
CaO	9.74	10.38	10.44	6.47	7.46	10.12	9.87	10.60
Na_2O	1.87	2.54	2.40	1.50	1.80	2.25	2.07	2.47
K_2O	.28	.34	.46	.42	.42	.35	.41	.49
H_2O+	1.57	.22	.70	.64	.12	.24	.31	.15
H_2O-	1.15	.06	.47	.04	.06	.07	.04	.03
CO_2	None.	None.	None.	None.	(b)	(b)	(b)	(b)
TiO_2	3.40	3.37	3.70	1.75	2.58	3.52	4.89	3.98
P_2O_5	.08	.18	.17	.21	.26	.25	.28	.28
MnO	.10	.05	.12	.11	.09	.11	.11	.10
	99.96	99.59	99.85	99.89	100.77	100.17	100.02	100.48
Specific gravity at temperature stated	--------	--------	--------	--------	[c] 3.094 24°	[c] 2.955 24°	[c] 2.838 21°	2.874 24°

Norms

	1	2	3	4	5	6	7	8
Q	8.28	--------	5.10	--------	--------	7.98	9.96	6.42
Or	1.67	2.22	2.78	2.78	2.22	2.22	2.22	2.78
Ab	15.72	21.48	21.68	12.58	13.62	18.86	17.82	20.96
An	25.58	16.96	24.46	8.34	20.29	21.96	18.63	19.74
Di	17.57	27.15	20.67	17.25	15.14	21.10	22.95	24.91
Hy	15.20	18.35	12.19	19.62	22.88	17.24	14.00	14.19
Ol	--------	1.25	--------	26.34	20.35	--------	--------	--------
Mt	6.26	5.57	5.57	8.58	3.25	3.25	3.25	3.02
Il	6.54	6.38	6.99	3.34	2.89	6.69	9.27	7.60
Ap	.34	.34	.67	.67	.34	.67	.67	.67

[a] Washington, H. S., Am. Jour. Sci., 5th ser., vol. 6, pp. 113, 115, 122, 1923.
[b] Not determined.
[c] Determined with the pycnometer on the rock powder.

1. Aphyric labradorite basalt, III.4''.4''.5. Clover Hill, near Naalehu, Kau, Mauna Loa. Ninole basalt. R. K. Bailey, analyst. No. 34, Plate 2.
2. Ophitic olivine basalt, III''.5.3.''5. Kamaikeohu Spring, Kau, Mauna Loa. Ninole basalt. R. K. Bailey, analyst. No. 25, Plate 2.
3. Feldspar phyric basalt, III.(4)5.''4.(4)5. Naalehu, Kau, Mauna Loa. Kamahame basalt. R. K. Bailey, analyst. No. 35, Plate 2.
4. Chrysophyric picrite basalt, IV.(1)2.3.1(2).(1)2. Makanao Valley, Kau, Mauna Loa. R. K. Bailey, analyst. No. 19, Plate 2. Kamehame basalt.
5. Picrite basalt, (III)IV.(2).2.1(2).2. Flow of 1868, Mauna Loa. H. S. Washington, analyst.
6. Aphyric andesine basalt, III.4''.''4.(4)5. Pahoehoe of 1880–81, near Hilo, Mauna Loa. H. S. Washington, analyst.
7. Aphyric andesine basalt, III.4''4.(4)5. Aa of 1887, Mauna Loa. H. S. Washington, analyst.
8. Aphyric andesine basalt, III.4(5).3(4).(4)5. Aa of 1919, Alika flow, Mauna Loa. H. S. Washington, analyst.

Analyses 1 to 4 were made by the Geological Survey especially for this investigation. They were published in advance by Washington, and the interpretation of formations to which they belong has since been revised by the writer. No. 2 is listed by Washington as pre-Pahala (?). Field work has established it as belonging to the Ninole basalt. No. 3, listed by Washington as Pahala, has since been determined as belonging to the Kamehame basalt; hence, Washington's conclusions regarding this specimen should be revised accordingly. Unfortunately, owing to this revision in the geologic assignment of this specimen, there is no analysis of a specimen representing the Pahala lavas.

The results of these analyses are discussed under the heading "Petrography." A detailed chemical discussion was presented by Washington in the article cited. Many other analyses of Kamehame rocks from Mokuaweoweo and elsewhere on Mauna Loa are given by Dana,[33] Cross,[34] and others. The walls of Mokuaweoweo were carefully examined by the writer for Pahala ash, but none was found; hence, the lavas exposed there are doubtless Kamehame.

TABLE 2.—*Analyses of lavas from Kilauea* [a]

	1	2	3	4	5	6	7	8
SiO_2	51.06	51.77	46.59	46.50	50.07	49.74	50.32	50.63
Al_2O_3	12.91	13.54	7.69	9.37	13.32	12.36	12.83	13.08
Fe_2O_3	1.33	.75	2.20	2.47	1.92	1.64	1.74	1.09
FeO	9.63	9.63	10.46	10.79	9.28	10.08	9.93	10.10
MgO	8.09	7.33	21.79	21.00	8.01	8.83	7.39	7.44
CaO	11.03	10.57	7.41	6.25	10.64	10.88	11.06	11.38
Na_2O	1.92	2.18	1.33	1.52	2.16	2.45	2.38	2.36
K_2O	.43	.45	.28	.22	.45	.55	.41	.47
H_2O+	.16	.16	.37	.14	.49	.17	.33	.15
H_2O-	.06	.05	.04	.03	.22	.05	.05	.08
TiO_2	3.59	4.01	1.83	1.70	2.70	2.49	3.10	3.33
ZrO_2	None.	(b)	None.	(b)	None.	Trace.	(b)	(b)
P_2O_5	.22	.26	.11	.10	.26	.41	.30	.33
Cl	-------	-------	-------	-------	.08	.10	.04	(b)
S	None.	(b)	None.	(b)	.11	.04	(b)	(b)
Cr_2O_3	None.	(b)	.13	(b)	.05	.04	(b)	(b)
V_2O_3	-------	-------	-------	-------	None.	.02	(b)	(b)
MnO	.16	.15	.18	.11	.16	.14	.10	.12
NiO	-------	-------	.12	(b)	.04	.05	(b)	(b)
BaO	None.	(b)	None.	(b)	None.	Trace.	(b)	(b)
SrO	-------	-------	None.	(b)	Trace.	.07	(b)	(b)
MoO_3	-------	-------	-------	-------	Trace.	.01	(b)	(b)
	100.59	100.85	100.53	100.20	99.97	100.08	99.98	100.56
Specific gravity at temperature stated	3.009 24°	2.896 24°	3.001 -------	3.031 24°	------- -------	2.851 -------	[c] 2.956 24°	[c] 2.859 24°

Norms

	1	2	3	4	5	6	7	8
Q	3.78	5.16	-------	-------	2.16	-------	2.04	4.80
Or	2.78	2.78	1.67	1.12	2.78	3.34	2.22	2.78
Ab	16.24	18.34	11.00	13.10	18.34	20.96	20.44	21.13
An	25.02	25.85	14.46	18.07	25.30	30.85	23.07	23.63
Di	22.31	20.08	17.05	9.76	20.83	24.78	24.23	25.69
Hy	21.38	18.96	18.23	20.62	21.06	17.00	18.43	12.67
Ol	-------	-------	30.49	30.35	-------	4.67	-------	-------
Mt	1.86	1.16	3.25	3.48	2.78	2.32	2.55	1.62
Il	6.84	7.60	3.50	3.19	5.17	4.71	5.93	6.38
Ap	.67	.67	.34	.34	.67	1.01	.67	.67

[a] Washington, H. S., Am. Jour. Sci., 5th ser., vol. 6, pp. 342–343, 346–347, 351–352, 1923.
[b] Not determined.
[c] Determined with the pycnometer on the rock powder.

1. Labradorite basalt, III."5.4.4(5). Flow in crater wall, Kilauea, H. S. Washington, analyst.
2. Labradorite basalt, III."5.4.4(5). Dike in crater wall, Kilauea. H. S. Washington, analyst.
3. Chrysophyric picrite basalt, IV.1(2).2. Below Uwekahuna, crater wall, Kilauea. George Steiger, analyst. Daly, R. A., Jour. Geology, vol. 19, p. 293, 1911.
4. Chrysophyric picrite basalt, "IV.1(2).3.1(2).2. Old flow, west of Kamakaia, Kau Desert, Kilauea, H. S. Washington, analyst.
5. Labradorite basalt (pahoehoe), III.5.4.(4)5. Lava of 1894 (?), floor of crater, Kilauea. J. B. Ferguson, analyst. Day, A. L., and Shepherd, E. S., Geol. Soc. America Bull., vol. 24, p. 586, 1913.
6. Labradorite basalt, III.5.3(4).4. Dipped from crater, 1911, Halemaumau, Kilauea. J. B. Ferguson, analyst. Day, A. L., and Shepherd, E. S., op. cit., p. 586. Specific gravity by C. E. Tilley, Min. Mag., vol. 19, p. 279, 1922.
7. Labradorite basalt (aa), III.5."4.(4)5. Flow of 1920, Maunaiki, Kilauea. H. S. Washington, analyst.
8. Labradorite basalt (pahoehoe), III.(4)5."4.(4)5. Flow of 1920, Maunaiki, Kilauea. H. S. Washington, analyst.

[33] Dana, J. D., Characteristics of volcanoes, p. 348, 1890.

[34] Cross, Whitman, Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, p. 48, 1915.

All the specimens in Table 2 belong to the Kamehame basalt and are therefore representative of only the upper crust of the dome of Kilauea. Washington in the paper cited describes the specimens in detail. Other analyses of Kilauea lavas have been published by Cross, Dana, Day, and Shepherd. (See list of papers on pp. 36–41.)

MAGMATIC DIFFERENTIATION

Regarding magmatic differentiation the writer can do no better than quote here the conclusions reached by Cross,[35] with which he is in accord:

1. It does not seem probable that there has been any noteworthy differentiation in the main reservoir beneath the Hawaiian district. It being supposed that some volcanoes are much younger than others, the recent ones appear to have presented the same variety of basaltic types during their main activity.

2. During the active growth of each volcano the lavas presented a moderate variability in composition without detected system of variation. The processes of differentiation were too frequently interrupted to permit strongly pronounced results.

3. With decreasing eruptive activity and possibly attendant contraction and limitation of lava chambers, a higher degree of differentiation was accomplished and is shown by more salic and correspondingly more femic lavas than those of earlier date.

4. In the long period of parasitic or subsidiary eruptions conditions were favorable to extensive differentiation. This may be due to a localization of smaller magmatic chambers or to lengthened intervals of quiet.

5. The processes of this differentiation are still problems for investigation. To me they appear to have acted mainly upon the liquid magma. Movement, under gravity, of crystal particles may have played a part.

It is interesting to note that apparently there has been an evolution from alkalic to femic extrusions from the Ninole to the Kamehame lava flows. This evolution may be more apparent than real, for the Kamehame specimens examined show a greater variation than the Ninole or Pahala specimens. Conclusions of any sort must be tentative, however, in view of the small number of flows that are represented. To judge from the thickness and area of flows in the Kau District, it would take at least 30,000 lava flows to build Mauna Loa from sea level to its present height of 13,675 feet. There are exposed in the Kau District hundreds of lava flows ranging in age from Tertiary (?) to the present time that await a careful petrographic study. This study must be supplemented by many chemical analyses before any definite conclusions can be reached.

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[35] Cross, Whitman, Lavas of Hawaii and their relations: U. S. Geol. Survey Prof. Paper 88, p. 93, 1915.

Part II.—WATER RESOURCES

By William O. Clark and Harold T. Stearns

CLIMATE

TEMPERATURE

The eight main islands of the Hawaiian group lie between latitudes 18° 56′ and 22° 14′ north, and the island of Hawaii is due west of Mexico City. However, the climate of the islands is semitropical rather than tropical. It is stated that, owing to the drift of Bering Sea waters to this region, the temperature of the surrounding waters is about 10° lower than that of other regions of equal latitude. Both Honolulu and Hilo stations are practically at sea level; Pahala has an altitude of 850 feet.

Temperature (°F.) at Honolulu, Hilo, and Pahala [a]

Station	Mean in January	Mean in August	Mean annual	Absolute maximum	Absolute minimum
Honolulu	70.5	78.1	74.4	87	56
Hilo	69.7	74.8	72.1	91	51
Pahala	68.4	73.7	71.1	96	50

[a] U. S. Weather Bureau, Summary of climatological data, Hawaiian section, 1918.

The highest temperature on record anywhere in the islands is 97°. This temperature was recorded only at Aiea and at Wailua Mill, both on the island of Oahu. The lowest temperature varies widely with the altitude. The lowest recorded by the Weather Bureau is 25° F. at Humuula, on the island of Hawaii, 6,685 feet above sea level. Both Mauna Kea and Mauna Loa are frequently snow-capped. Occasionally snow falls on Mauna Kea (White Mountain) in midsummer, as it did on the night of July 20, 1924.

In the Kau District, as in many other places in the islands, the warmest part of the day is likely to occur before 10 o'clock in the morning, as after that time clouds are likely to form, giving protection from the sun for the rest of the day, and the temperature is also reduced by the sea breeze, which comes in about 9 o'clock.

The Hawaiian Islands lie in the belt of the northeasterly trade winds. These winds are extremely persistent throughout most of the year. They are, however, occasionally interrupted during the winter months by southwesterly winds. These winds do not usually persist for more than two or three days at a time in the Kau District. Usually good strong breezes blow throughout the warmer part of the day.

The land mass of the island of Hawaii is large enough to permit a well-marked land and sea breeze. During the middle of the day the trade winds are steady and strong, but in the early morning and about sundown they are usually very quiet. Strong winds at night are rare, but there is usually a gentle "mauka" breeze (breeze from the mountain), which is sufficiently cool to render the nights refreshing and to make sleeping under a blanket comfortable. In the four years which the writer (Clark) has spent at Pahala there have been few nights when a blanket was not necessary for comfort. Cool nights are also characteristic at Hilo. The days may be very hot on account of the high humidity, but after sundown the mountain breeze is refreshing and at times a little chilly.

PRECIPITATION

The many local influences, resulting from the size, shape, and trend of the individual islands, their mountains of widely varying elevations, nearness or relative remoteness from the sea, their canyons, plateaus, plains, their abrupt palis, rising from valleys or the sea, in conjunction with the prevailing trade winds or, as in the Kona districts of Hawaii, the dominant southwesterly wind, all combine to complicate the study of Hawaiian climatology, especially rainfall.[1]

DISTRIBUTION RELATIVE TO SLOPES AND ALTITUDE

Altitude, topography, and slope all have a profound effect on rainfall. As the islands lie in the belt of the northeasterly trade winds and rise to considerable altitudes the windward or northeasterly slopes are very rainy where they are not in some way protected by local topography or wind direction. The same causes that make the windward slopes wet in general render the lee or southwestern slopes abnormally dry. The rainfall increases rapidly with altitude up to a certain height, and then rapidly decreases with a further increase of altitude. The altitude of heaviest rainfall varies greatly with the total height of the mountain slope up which the wind is driven. For instance, the heaviest rainfall on Kauai occurs on Mount Waialeale, the summit, at an altitude of 5,080 feet. The rainfall there probably averages between 475 and 500 inches a year; and in 1920, according to the United States Weather Bureau, it was 549 inches. Also on West Maui the greatest rainfall is at the summit. At the Puu Kukui station, at an altitude of 5,000 feet, the Weather Bureau record of 1920 shows a rainfall of 402 inches. This station and Mount Waialeale are among the rainiest places in the world.

On the Hilo coast of the island of Hawaii, on the slopes of Mauna Kea, it is surprising to find the rainiest belt lying at an altitude of only about 1,200 feet, whereas on the windward slope

[1] Dangerfield, L. H., Summary of climatological data for the United States, Hawaiian section, p. 3, U. S. Weather Bureau, 1918.

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of the Kohala Mountains the area of heaviest rainfall reaches an altitude of about 3,500 feet, and possible reaches the summit, which is 5,505 feet above sea level. It is not altogether apparent why the belt of heaviest rainfall should lie at so low an altitude on the Hilo coast. It may be due in part to the fact that both Mauna Kea and Mauna Loa are high enough to pierce through the entire thickness of the trade winds and into the belt of the westerly winds. At the tops of these great peaks (each nearly 14,000 feet above sea level) the temperature falls below freezing almost every night in the year. The cold air flows down the slopes, probably tending to decrease the thickness of the belt of trade winds and, mingling with these winds, carries low temperatures, particularly at night, to a relatively low altitude. At any rate it seems to be a fact that it rains more often at night in the region about Hilo than at any other place in the islands.

Apparently the heaviest precipitation on East Maui, on the windward slopes of Haleakala, occurs at an altitude of about 4,000 feet. The summit of Haleakala is somewhat more than 10,000 feet above sea level.

AREAL DISTRIBUTION

The rainfall of the islands is very irregularly distributed. Places only a few miles apart may have totally different rainfall conditions. This extreme localization is due chiefly to a difference in altitude and location with reference to the leeward or windward side of the island. However, there are some very striking differences between places on the same side of the island and of the same altitude. On Kauai the rainfall on the summit of Mount Waialeale (altitude 5,080 feet) averages between 475 and 500 inches a year, whereas on the leeward side the Weather Bureau records show an average annual rainfall of only 22.66 inches at Kekaha (altitude 8 feet), 22.21 inches at Waiwa (35 feet), 23.23 inches at Makaweli (140 feet), and 15.81 inches at Pali Trail (850 feet). All these places are within 15 miles of Mount Waialeale. On West Maui the differences are only a little less striking; Puu Kukui (altitude 5,000 feet) has an annual rainfall between 370 and 400 inches, and Olawalu (altitude 15 feet), about 7 miles distant, only 8.08 inches.

On the island of Hawaii the extremes are less, though possibly even more striking in character. There are two distinct areas of maxima on the windward slopes, and these areas lie at very different altitudes. One of these areas probably lies along the crest of the Kohala Mountains, the highest peak of which is 5,505 feet above sea level. Rain-gage stations at the highest altitudes in this area show the highest precipitation. Alakahe, 3,870 feet above sea level, has an average annual rainfall of 204 inches; Kawainui, at an altitude of 4,080 feet, has an average of 277 inches. These are the highest stations for which records are available in these mountains, but the rainfall may be even higher on the crest of the ridge.

The other area of maximum rainfall occurs on the Hilo coast at an altitude of about 1,200 feet. Here the records show that Hakalau and Honomu (both at 1,200 feet) have an average annual rainfall, respectively, of 273 and 257 inches. Records from stations of both higher and lower altitudes show less rainfall.

In the Puna District, where the winds pass over the low Puna Ridge, extending from Kilauea to the eastern point of the island, the maximum rainfall occurs at a higher level. So far as records show, it probably reaches a maximum about Glenwood, which is at an altitude of 2,300 feet and has an average annual rainfall of 228 inches. The Volcano House, on the rim of the crater of Kilauea at an altitude of 4,000 feet, has an average annual rainfall of only 84 inches.

There is also a wide variation in the amount of rainfall at sea level on the windward coast of Hawaii. At Hilo (altitude 40 feet) the average annual rainfall is 139 inches, whereas at Paauilo (altitude 400 feet) it is only 27 inches. At a near-by place in Paauilo (Notley), at an altitude of 750 feet, the rainfall is given as 75 inches.

The westward slopes of the island of Hawaii are not so dry as might be expected as a result of the trade winds being interrupted by the high mountains. In the lee of these mountains the winds are prevailingly from the southwest and give both North Kona and South Kona a fairly moist climate. The rainfall at Kealakekua (altitude 1,450 feet) averages 62 inches a year.

In the Kau District there is considerable variation in the rainfall, but the limits are not as wide as those of many other areas in the islands. The following table gives a summary of all records available in the district:

Average annual rainfall at stations in Kau District to 1925

[Station numbers refer to location on pl. 2]

No.	Station	Altitude	Length of record	Years of record	Average annual rainfall	Source of records
		Feet	*Years*		*Inches*	
1	Hilea	320	35	1885–1925	37.90	U. S. Weather Bureau.
2	Honuapo	25	10	1895–1907	29.73	Do.
3	Kapapala ranch	2,150	39	1886–1925	58.10	Do.
4	Kau	1,850	8	1905–1913	57.74	Do.
5	Keaa Homesteads	1,680	4	1901–1906	43.69	Do.
6	Kiolakaa	1,000	12	1914–1925	57.90	Do.
7	Keaiwa	1,650	10		74.35	Hawaiian Agricultural Co.
8-a	Moaula Gulch	1,950	10		88.79	Do.
8-b	Moaula Station	550	[a] 3	1921–1925	58.92	U. S. Weather Bureau.
9	Mauna Anu	6,600(?)	4	1922–1925	164.99	Do.
10	Mountain House	3,060	4		107.08	Hutchinson Sugar Plantation Co.
11	Naalehu	673	35	1890–1925	44.81	U. S. Weather Bureau.
12	do	1,250	3	1896–1900	47.33	Do.
13	do	1,740	2	1898–1900	73.19	Do.
14	Pahala	835	34	1892–1925	42.86	Do.
15	Pahumimi	5,140	4	1922–1925	141.74	Do.
16	Volcano House	4,000	16	1899–1916	83.57	Do.
17	Volcano Observatory	3,984	13	1913–1925	103.78	Do.

[a] 1921, 1923, 1924; other years incomplete.

As shown in the following tables, the years 1919 and 1925 were very dry throughout the Kau District, and 1923 was excessively wet. During 1920, 1921, and 1924 the rainfall varied from below to above normal at different stations. In all probability if the entire Kau District were considered as a unit, the rainfall for these years was about normal.

Monthly and annual rainfall, in inches, at stations on Hawaii, 1919–1925

Hilea

Month	1919	1920	1921	1922	1923	1924	1925	Normal
January	0.58	3.99	15.69	5.41	16.35	0.44	2.42	3.72
February	.11	.90	3.56	7.81	11.59	.64	2.92	4.12
March	1.76	5.61	4.02	3.87	10.88	8.64	5.84	5.09
April	1.04	1.16	1.61	2.12	18.92	10.99	.53	2.83
May	1.43	2.30	2.50	.88	1.43	2.64	1.19	1.79
June	.96	.74	.22	1.22	.36	1.00	1.00	1.04
July	1.14	.37	.43	.69	.50	1.55	3.39	1.75
August	1.04	1.73	1.48	.75	3.06	1.27	.61	2.81
September	3.95	1.00	.64	2.68	5.20	1.82	.97	2.03
October	7.40	2.24	2.38	2.94	.88	6.68	4.79	2.95
November	4.45	.48	1.02	1.96	1.63	6.39	1.41	5.22
December	2.08	7.75	2.42	2.30	6.47	4.55	2.38	4.55
Annual	25.94	28.27	36.07	32.63	77.27	46.71	27.45	37.90

Normal based on 35 years' record.

Kapapala ranch

Month	1919	1920	1921	1922	1923	1924	1925	Normal
January	1.45	10.32	28.54	6.21	29.05	1.00	7.29	6.28
February	.00	5.06	5.95	8.62	18.69	1.79	1.64	6.94
March	7.15	8.25	3.97	7.92	16.52	17.29	6.12	8.15
April	1.28	3.64	2.32	4.22	25.42	18.06	1.19	4.00
May	5.24	6.53	5.72	1.25	1.99	5.99	2.15	3.61
June	1.76	1.77	.00	.89	.86	3.54	1.72	1.71
July	1.57	.74	1.51	1.35	.81	2.08	2.78	2.76
August	5.23	5.75	1.36	1.78	5.92	2.62	1.20	3.58
September	2.54	.46	1.00	--------	10.57	1.84	2.79	3.66
October	2.19	6.49	11.41	4.30	2.37	5.62	6.71	4.31
November	4.97	1.48	1.42	7.14	2.37	3.18	1.68	7.14
December	2.02	17.72	3.08	1.69	11.18	3.84	2.26	5.96
Annual	35.40	68.21	66.28	--------	125.75	66.85	37.53	58.10

Normal based on 39 years' record.

Kiolakaa

Month	1919	1920	1921	1922	1923	1924	1925	Normal
January	1.86	5.51	14.85	6.09	15.83	1.08	2.28	8.86
February	.77	2.99	5.19	10.39	7.27	1.59	1.54	5.36
March	1.78	6.64	4.50	2.54	10.81	4.41	6.03	5.98
April	3.13	2.04	2.29	2.18	15.55	12.61	1.55	4.94
May	3.30	3.08	3.78	2.31	3.38	3.89	1.42	3.17
June	4.00	2.01	1.25	1.28	2.67	2.45	4.41	2.84
July	.91	1.19	1.46	2.92	.61	3.78	2.83	2.53
August	3.10	2.56	3.89	1.98	4.35	2.29	3.50	3.21
September	4.60	3.83	2.71	3.08	3.96	3.65	2.26	3.02
October	6.58	3.87	3.57	4.86	1.84	5.31	3.88	4.70
November	6.27	1.03	2.32	3.32	3.22	8.35	3.03	5.89
December	3.47	7.34	2.90	4.07	7.00	3.50	4.47	7.40
Annual	39.77	40.79	48.71	45.02	76.49	52.91	37.20	57.90

Normal based on 12 years' record.

Monthly and annual rainfall, in inches, at stations on Hawaii, 1919–1925—Continued

Mauna Anu

Month	1922	1923	1924	1925
January	15.00	30.60	0.00	0.32
February	6.00	20.80	.24	1.64
March	3.80	30.00	19.80	2.16
April	(a)	32.20	12.60	.82
May	3.80	7.00	.46	2.10
June	(a)	(a)	2.52	1.22
July	7.40	(a)	.78	2.42
August	17.40	15.00	.16	1.66
September	(a)	39.00	.72	2.70
October	9.20	47.60	3.64	4.30
November	9.00	(a)	10.34	(a)
December	7.20	28.98	3.64	1.66
Annual	78.80	251.18	54.90	21.00

[a] Included in figure for following month.

Moaula

Month	1921	1922	1923	1924	1925
January	16.16	5.66	20.62	0.21	4.57
February	2.84	7.38	14.66	.46	2.78
March	2.43	2.55	11.09	14.61	7.06
April	2.08	2.55	18.11	11.71	.23
May	3.97	.19	1.99	3.15	.90
June	.00	.41	.24	1.27	1.10
July	.20	.10	.45	.90	1.47
August	1.45	.63	2.82	1.04	1.05
September	.35	---	3.70	1.95	.65
October	4.28	---	.09	6.17	2.72
November	1.51	4.15	.96	7.09	---
December	1.63	1.80	11.76	4.80	.38
Annual	36.90	---	86.49	53.36	---

Naalehu

Month	1919	1920	1921	1922	1923	1924	1925	Normal
January	1.07	4.09	16.42	6.98	14.57	0.67	1.38	5.40
February	.12	1.34	4.00	10.43	7.97	.66	.74	4.99
March	1.24	4.87	3.18	2.57	9.59	4.51	7.37	5.60
April	1.94	1.55	1.64	1.49	17.34	13.00	.81	3.10
May	1.43	3.52	2.08	.07	2.14	2.93	.51	2.08
June	1.18	1.01	.45	.61	1.20	1.43	2.13	1.52
July	.32	.82	.92	2.69	.42	2.61	1.51	2.13
August	.66	.78	2.97	1.06	4.16	1.88	1.72	3.69
September	3.19	2.36	2.11	2.16	4.58	4.39	2.24	2.71
October	5.44	2.37	1.68	4.58	1.34	5.66	3.31	3.46
November	4.41	.55	1.08	2.75	2.08	8.47	2.93	5.54
December	3.99	6.70	2.54	2.74	7.22	4.82	3.56	4.59
Annual	24.99	29.96	39.07	38.73	72.61	51.03	28.21	44.81

Normal based on 35 years' record.

Pahala

January	0.68	8.07	16.61	6.73	19.60	0.31	4.87	4.94
February	.02	1.53	2.65	5.93	13.14	.69	1.99	5.47
March	3.79	6.93	3.09	3.57	11.27	10.93	5.98	6.00
April	.27	1.70	1.05	1.77	17.29	15.77	.38	2.79
May	1.73	4.15	3.67	.44	1.13	3.15	1.32	2.21
June	.82	1.19	.10	.84	.42	2.23	1.11	1.00
July	1.41	.76	.59	.29	.57	1.12	2.17	1.30
August	4.45	1.73	1.17	.81	2.83	.88	1.32	3.28
September	2.22	.59	.54	2.20	5.72	1.75	.80	2.17
October	4.94	4.08	7.34	1.83	.17	7.73	3.95	2.89
November	4.27	1.03	1.38	2.89	1.12	6.54	1.40	6.32
December	3.17	11.41	2.46	3.04	10.07	4.23	.40	4.49
Annual	27.77	43.17	40.65	30.34	83.33	55.33	25.69	42.86

Normal based on 34 years' record.

Monthly and annual rainfall, in inches, at stations on Hawaii, 1919–1925—Continued

Pahuamimi

Month	1922	1923	1924	1925
January	14.60	31.00	0.00	1.84
February	5.00	21.80	.12	2.26
March	3.60	29.00	14.20	1.40
April	([a])	19.60	6.40	.46
May	3.20	7.00	.12	.80
June	([a])	([a])	2.84	.14
July	5.20	([a])	.32	.86
August	16.80	15.00	.06	.44
September	([a])	39.60	.14	1.84
October	8.60	17.20	1.46	2.50
November	9.40	([a])	4.54	3.46
December	7.60	28.74	1.46	.28
Annual	74.00	208.94	31.66	16.28

[a] Included in figure for following month.

Volcano Observatory

Month	1919	1920	1921	1922	1923	1924	1925	Normal
January	3.92	8.48	43.96	16.93	26.23	0.78	9.59	14.23
February	3.27	2.11	3.73	15.78	14.26	3.85	.96	8.06
March	8.52	9.12	2.19	28.13	20.66	10.41	18.40	11.50
April	3.90	3.31	7.63	9.38	27.60	13.27	7.32	8.65
May	2.54	2.66	5.32	3.45	4.33	6.83	2.92	5.52
June	2.99	2.57	1.52	1.28	4.14	1.39	4.88	4.26
July	3.95	3.91	4.25	3.69	3.93	4.74	2.49	7.59
August	5.36	3.66	5.10	4.45	7.19	3.58	9.69	6.28
September	5.72	4.71	5.16	6.14	8.82	2.82	2.55	6.29
October	4.62	7.51	11.37	4.50	7.55	8.22	5.16	6.97
November	3.62	6.74	10.80	6.74	3.14	9.61	5.98	13.41
December	4.14	14.84	6.47	2.34	14.65	4.42	2.41	10.82
Annual	52.55	69.62	107.50	102.81	142.50	69.92	72.35	103.58

Normal based on 13 years' record.

SOME HEAVY RAINFALL RECORDS

The following table, compiled from the records of the United States Weather Bureau, serves to show the volume of some of the exceptionally heavy downpours:

Heavy rains in the Hawaiian Islands

Island	Station	Rainfall in 24 hours (inches)	Date
Hawaii	Honomu	31.95	Feb. 20, 1918
Do	Hakalau	26.40	Feb. 19, 1918
Do	Olaa (Kurtistown)	20.10	Dec. 16, 1918
Do	Houuapo	13.88	Apr. 26, 1923
Do	Pakaikou	23.00	Apr. 27, 1915
Kauai	Halaula	22.00	Sept. 27, 1914
Maui	Hana	[a] 28.20	Apr. 27, 1915
Do	Honomanu Valley	21.02	Mar. 11, 1909
Do	Keanea Valley	21.88	Do.

[a] It has been stated to the writer that 24 inches fell here within four hours.

DISTRIBUTION IN TIME

The rainfall varies widely in different years, but there is no well-marked rainy season. Records of rainfall have been kept for a period of 39 years by the Hawaiian Agricultural Co., at Pahala, and the highest annual rainfall occurred in 1923, when the total was 83.33 inches. The lowest occurred in 1912, when the total was only 14.24 inches. The maximum is therefore nearly six times the minimum.

The graph in Figure 5, based on all available data up to and including 1918, was prepared by Lawrence H. Dangerfield, of the United States Weather Bureau, and published in the "Summary of the climatological data for the United States, Hawaiian section." In that report graphs for all the other islands are given also.

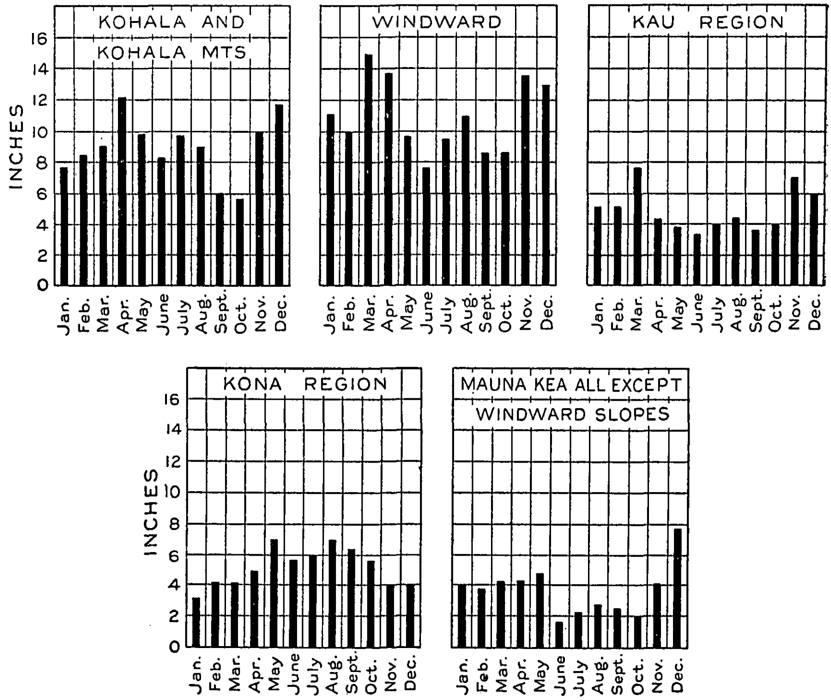


FIGURE 5.—Comparative monthly distribution of precipitation on the island of Hawaii

SURFACE WATER

The streams of the Hawaiian Islands are extremely ephemeral in their flow, as might be inferred from the irregular rainfall and the general steepness of the slopes. All the other large islands are better supplied with living streams than the island of Hawaii. Here there are vast areas with no perennial streams and in fact large areas without well-defined stream ways.

In the whole Kau District there is not a single perennial stream—indeed, there are no streams at all except those of the most ephemeral character. In general they flow only a few hours after a heavy rainfall. Within the forest belt they may continue to flow for a few days after a protracted rain, when the ground is thoroughly soaked, but it is very rare, indeed, that their waters reach the sea, though the distance from the forest belt to the sea in few places exceeds 10 miles and is in most places not more than 6 or 7 miles. Not only is the Kau District destitute of streams but there is not a perennial stream between the Wailuku River, at Hilo, and Kumakua River, near Upolu Point, by way of the Kau District, a distance of more than 200 miles. This is a very striking fact when it is remembered that the average rainfall in the forest belt is between 75 and 100 inches and in some places is more than 200 inches.

GROUND WATER

OCCURRENCE

Ground water in the Hawaiian Islands has four distinct types of occurrences—(1) the artesian water of Oahu; (2) water that is restrained and held up by a system of dikes and sills found on Oahu and West Maui and also in the Kohala Mountains of Hawaii; (3) water that is perched by ash beds in the Kau District and probably elsewhere on the island of Hawaii; (4) water of the main water table, common to all the islands alike.

The lavas of the Kau District so far as exposed are made up entirely of thin surface flows. This fact imposes certain characters upon the rocks which have an extremely important bearing on the ground water of the region.

The lavas are all exceedingly permeable. The two types of lava recognized are pahoehoe and aa. From 30 to 50 per cent or more of the volume of the pahoehoe is usually made up of gas vesicles, and in the process of cooling the whole mass is so fractured that it is very rare indeed that a 10-foot cube can be found. The average volume of blocks without fracture perhaps does not exceed 1 or 2 cubic feet. The walls of the vesicles, if not broken, are fairly impervious, for water does not regularly circulate through them. But the rocks are in many places shattered along both vertical and horizontal planes, so that the joints are more or less open. Frequently a slight creep of only a small fraction of an inch causes the walls of the broken vesicles to be no longer in perfect contact, with the result that the water circulates with little resistance along more or less wide open channels. In addition to the joints and fissures the different flows, and for that matter the different beds of the same flow, are not in tight contact, and between each two beds there remains a plane along which water can move freely. A pahoehoe flow, when extruded, crusts over immediately on the surface but continues to flow through a system of channels and tubes. It often happens that when the flow ceases the molten lava in these tubes drains out, leaving an intricate system of open tubes. These caverns may be of any diameter from a few inches to 50 or 60 feet. They interlace with one another, forming in places a very intricate pattern, and one system may be connected with another at a lower level by a hole in the floor of the upper tube. It is extremely dangerous to explore these openings unless great care is exercised. Occasionally in traversing the country a horse breaks through the thin roof of a large tube and falls in. Such systems of tubes, of which there are literally thousands in the Kau District, of course offer free passage to ground water. On the basis of observations with a plumb line, E. D. Preston concluded that Mauna Loa has very low density, and hence it must be cavernous to great depths.[2]

There are two forms of aa in every flow. One of them resembles a loose, porous slag heap from a blast furnace, and the other consists of a comparatively dense, thick-bedded rock with large, irregular vesicles and usually broken into blocks by fissures which gape as much as 2 feet. These dense portions form lenticular masses or thin beds in the general clinkery flow. Aa flows may be seen all over the district, and in most vertical sections several beds of clinkers are exposed. (See pl. 27, *A*.)

There are two groups of volcanic ash beds in the Kau district. The older ash bed, which occurs in the Ninole basalt, is usually a single bed, but locally it is divided into two or three beds with an aggregate thickness of less than 20 feet. The younger ash bed, which forms the top member of the Pahala basalt, consists in many places of more numerous beds, which have an aggregate thickness of about 55 feet. So far as explored the ash bed of the Ninole seems to be more compact and somewhat less permeable than the ash bed of the Pahala, but it has less extensive outcrops.

It is evident from the above description that all the formations in the district are permeable, the lavas so extremely permeable as to offer only a little resistance to the downward percolation of ground water and practically no resistance to its horizontal movement.

MAIN WATER TABLE

Because of the permeability of the rock most of the water that falls as rain sinks below the surface and quickly finds its way downward to a level only a little above sea level. All the evidence at hand indicates that throughout the island of Hawaii the main water table lies not far above sea level. Where the lava has been penetrated to sufficient depth the water table has been found to be generally only a foot, or at most a few feet, above sea level.

[2] Dana, J. D., Characteristics of volcanoes, p. 280, New York, 1890.

On the island of Hawaii only one deep well is known to the writer. This well is situated at the Olaa sugar mill, in the Puna District, at an altitude of about 225 feet. It encounters the water table only a foot or two above sea level. It was drilled to a depth of 450 feet, or 225 feet below sea level, and it is said to furnish a supply of water sufficient to operate the mill.

Another proof of the ease with which ground water moves through the lava rock and also of the low altitude of the main water table is found on central Maui, where there are a number of large pumping plants. All these plants draw their water from lava rock, and the water level in the pits and wells stands only about a foot or so above sea level when the pumps are not in operation. These plants belong to the Hawaiian Commercial & Sugar Co. At well No. 5, which may be taken as typical so far as occurrence and yield of ground water are concerned, there are two pits with two drilled wells in each. The pits were dug somewhat below sea level, and the water stands about a foot above sea level when the pump is not in operation. When the pump is operated at the rate of 22,000,000 gallons a day, or more than 15,000 gallons a minute (33½ second-feet), the drawdown is only 7 feet.

Lindgren [3] describes a number of wells on Molokai. Many of these wells on being pumped became so salty as to be worthless, but some of them were pumped at a rate of 1,000,000 gallons a day or more with out seriously increasing the salt content. One of these, a 14-inch well 56 feet deep, was pumped for a period of 30 days at a rate of 2,500,000 gallons a day, and the salt content rose from 19 to 64 grains to the gallon.[4]

In the Kau District, as in many other places in the Hawaiian Islands, there are numerous springs which issue near sea level. The two largest of these are at Ninole and Kawaa, southeast of Hilea. At Ninole the total discharge of the spring area above low tide is perhaps not less than 20 or 25 second-feet; at Kawaa it is probably about two-thirds of that quantity. Along the adjacent shore there is reported to be considerable fresh water coming up from the floor of the sea a few feet below low tide. At some places, particularly at Ninole, where the discharge of water is most concentrated, it is seen issuing from lava tubes. It is believed that a large percentage of wells constructed to draw water at or near sea level would prove successful, and that in general these wells would be capable of supplying large quantities of water. Of course, particularly near the seashore, there would be danger of increasing the salt content of the water if

[3] Lindgren, Waldemar, U. S. Geol. Survey Water-Supply Paper 77, 1903.
[4] Idem, p. 44.

the wells were pumped too heavily. Distance from the seashore could not be taken as an absolute guaranty against a high salt content. There might be an open connection with the sea, such as open lava tubes or clinkery aa beds, that would permit the easy entrance of sea water into the well when the water level was lowered by pumping. However, this would probably not occur in any large percentage of the wells a mile or so from the shore.

PERCHED OR HIGH-LEVEL WATER

All high-level ground water in the Kau District, so far as known, is perched. In every observed occurrence water is in lava rock overlying a bed of volcanic ash and is held up by the ash.

The ash varies a little in texture from one exposure to another, although it is of rather uniform fineness. In some places it is of a dry, mealy texture, in others it is more compact or considerably cemented as a palagonitic tuff. These differences may occur in the same bed only a few feet apart. Beds of volcanic ash occur in the Ninole, the Pahala, and the Kamehame formations. In the Kamehame they are interbedded with lavas in only two or three places about Kilauea, as far as known, though on the surface they form a thin layer over considerable areas. The ash of 1924 was spread very thinly over a rather large area, but only in the caldera is it found in sufficient thickness to be recognized as a distinct deposit. The Kamehame ash, wherever it is thick enough to form a recognizable deposit, is too coarse and too loose to hold water. In general the Ninole ash is somewhat more indurated and less permeable than the Pahala ash.

The Pahala ash in the Kau District consists of a series of widespread beds, which are in many places separated from one another by intervening lava beds. The interstratified beds generally range in thickness from a few inches to 6 or 8 feet, but locally they reach a thickness of 25 or 30 feet. On top of the hills of Ninole basalt, such as Puu Enuhe, where the whole of the Pahala ash occurs as one bed, the thickness is as much as 55 feet.

So far as known the Ninole ash is only in a few places separated into two or at the most three beds by intercalated flows. Probably the total thickness does not much exceed 15 feet. In general the slope of the Ninole ash beds is less than the general slope of the present surface, whereas the slope of the Pahala ash varies little from that of the present surface. So far as yet discovered by tunneling the direction of the ancient drainage lines of the Ninole ash beds makes an angle with the drainage of the present surface. However, it may well be that only tributary drainage has so far been encountered. The direction of the ancient drainage lines on the Pahala ash is roughly parallel to those of the present surface.

The ash beds of both formations are very erratic with respect to the character and thickness of the ash. At one place the ash may be compact and relatively impervious; at another place near by it may be of a loose, mealy consistency and so permeable as to allow water to pass readily downward through it. At one point in a tunnel the ash may be 6 or 8 feet thick, and at another point 10 feet away it may be only a few inches thick or entirely lacking. This abrupt thinning of an ash bed is doubtless due to erosion at the time the bed was exposed on the surface and before it was buried by subsequent lava flows. Also the deposition of the ash covered a considerable period of time and was accompanied by numerous lava flows, so that at one place the ash bed may consist of a number of conjoined layers, whereas at other places it is separated into two or more members by intercalated lava flows. Three tunnels have encountered the toe of such an intercalated lava flow which separated the ash bed into two members, one passing below the toe of lava and the other passing above it. The Noguchi Tunnel, one of the old tunnels with the largest mean annual discharge in the district, gets all of its water from such an intercalated bed of Ninole lava.

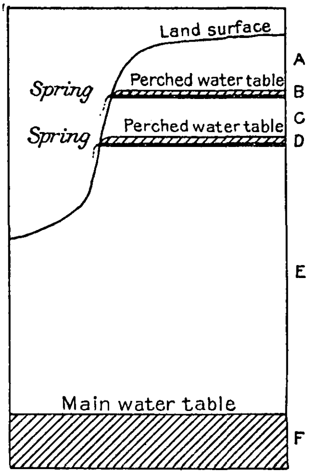


FIGURE 6.—Section at Kapapala ranch, Kau District, showing three zones of aeration (A, C, E) alternating with three zones of saturation (B, D, F). (After Meinzer)

From the structure above described it is to be expected that the bodies of perched water will be relatively small and that many may occur at the same level or on different parts of the same ash bed. Also there may be several at the same locality, lying one above another on different ash beds. Two such perched water bodies have already been discovered at the head of Wood Valley. In each place where they have been encountered the upper water body is about 100 feet above the lower one. (See fig. 6.) At one of these places an intermittent third body of perched water occurs about 100 feet above the second or 200 feet above the lower one. No development has been made at the higher level except to clear away the surface and expose the ash bed. A small spring at this artificial exposure flows except in dry weather. Doubtless with further development a little water would be found on this ash bed at all times.

The high-level ground water of the Kau District is extremely irregular in its occurrence, even on the ash beds. This is to be expected, however, from the variation in the extent of the ash, its undulating surface, and its varying permeability. The water occurs in the joints and cavities of the lava rock, in the interstices of the clinkery aa, in lava tubes, in tree molds, and along the contacts of overlapping lava flows where these overlie ash beds.

The lava rock is extremely porous, and the pores and cavities are so large and communicate with one another in such a way as to offer large storage space for water and very little resistance to its movement. Hence the perched water rapidly drains away, and the tunnels that have been driven to recover this water fluctuate greatly in their yield.

The water occurs in relatively few openings above the ash beds. Apparently throughout most of its extent the ash bed is dry, and where water is present it usually does not extend more than a few inches above the ash bed, although locally it may extend 3 or 4 feet above the ash. The depth of water on the ash bed varies with weather conditions, as does also the number of different places at which water is found along the bed.

WATER-BEARING FORMATIONS

WATER IN THE NINOLE BASALT

Water of both the main water table and the perched type is found in the Ninole formation. Wherever the Ninole rocks occur in the zone of the main water table there is an abundance of water, though possibly somewhat less than in the later formations of like position. This conclusion is based upon the fact that where Ninole rocks are exposed they are on the average somewhat more dense than those of the later formations. There also appear to be fewer lava tubes and less of the clinkery aa in them. Because of these characters of the formation, should it be found near sea level or below it, a greater quantity of water might be pumped from it without seriously increasing the salt content than could be pumped from the later formations. However, all the rocks are sufficiently permeable to yield salty water if wells are sunk far below sea level in them and pumped at a rate sufficient to lower the water table any large amount, but under present conditions there is no site where such a project is economically feasible.

The occurrence of high-level perched water in the Ninole basalt is confined to the lavas immediately overlying volcanic ash beds. These ash beds are more or less impervious and serve to prevent or at least retard the downward passage of the water, thus causing an increase of lateral movement. The quantity of water passing a given point on one of these ash beds depends on the amount of rainfall on the area above the bed, the extent of the bed draining toward the point, the relative perviousness or imperviousness of the bed, its thickness, whether it is broken by fracture, whether it has been cut through by erosion concurrent with its deposition, and whether there is an impervious ash bed directly above it.

To judge from the character of the Ninole ash and from the relatively constant yield of tunnels driven into it, the ash is probably less pervious and probably of wider unbroken extent than the Pahala ash. The only tunnels driven in the Ninole ash for which records of discharge for any considerable period are available are Noguchi tunnels Nos. 1 and 2. The discharge curves for these tunnels are given in Plate 29.

WATER IN THE PAHALA BASALT

Wherever the Pahala basalt lies below sea level or only a few feet above it water could doubtless be obtained from it in large quantities. However, as in the case of the Ninole basalt, there is no present demand for this water except where the depth to water makes pumping unfeasible. Moreover, there probably will not be a demand for it in the future, for there is little arable land or even pasture land to be served by it where the water is shallow. What was said regarding the quality and occurrence of water below the main water table in the Ninole basalt may be said with only slight modification of the water below the main water table in the Pahala basalt.

High-level perched water in the Pahala basalt occurs essentially like that in the Ninole basalt. The ash beds on the whole are more undulating, lie at steeper angles, are less continuous, and are more permeable. The tunnels following these ash beds are nowhere under very deep cover, usually less than 100 feet, and in many places not more than 25 feet. The nearness of the tunnels to the surface, where response to precipitation is rapid, largely accounts for their highly fluctuating yield. The yield increases quickly with a rain and decreases quickly when the rain is over. Discharge curves for tunnels of this type are found in Plates 29 and 30.

In the Pahala as in the Ninole basalt the water occurs in very thin streamlets on the ash. When the water is encountered, it is generally only a few inches in depth above the ash and occurs as narrow streams. For the most part it follows slight depressions in the surface of the ash or ancient buried drainage lines. The best plan to locate water is by driving tunnels along the contour of the ash beds, thus making the direction of the tunnel at right angles to the old drainage lines on the ash. Because of the narrowness of the streams of perched water, only a few feet of tunnel will be water bearing at any one place. However, where the water is following a slight sag in the ash rather than a well-defined drainage line it may occur more or less throughout a length of 50 to 100 feet of the tunnel. Many depressions in the ash are found to be entirely dry. It seems likely that these depressions were caused by the ash being originally deposited over uneven surfaces and that they represent small closed basins. They may also represent sections of old drainage channels which have been cut completely through the ash a little upstream from the point where the tunnel crosses them, and hence whatever water they may be carrying is lost at the place where they are eroded through.

WATER IN THE KAMEHAME BASALT

So far as known permanent ground water does not occur in the Kamehame basalt except where it lies at or near sea level. In many such localities large springs issue from it. The springs on the seashore at Ninole and at Kawaa Bay issue from the Kamehame basalt. The total visible discharge at Ninole is probably not less than 20 second-feet, or about 13,000,000 gallons a day. How much may be discharged somewhat below sea level is not known. At Kawaa the discharge is perhaps two-thirds that at Ninole. So far as known all the fresh water appearing along the Kau shore line issues from the Kamehame basalt. This is not strange, as the larger part of the coast line is composed of this basalt, and only minor parts consist of Pahala basalt.

WATER SUPPLIES AND PROSPECTS

CENTRAL KAU

Very little has been done in the Kau District to develop ground-water supplies from the main water table. So far as known to the writers there are only two points at which development has been attempted except for a few old "Hawaiian wells." These old wells consist merely in widening a crack near the seashore and making the water more easily accessible. Doubtless water was seen in the crack before any work was done. Probably none of these "wells" exceed 10 feet in depth. The wells at the mill and the well near the Kaalualu ranch house of the Hutchinson sugar plantation, at Honuapo, obtain water for domestic purposes and stock. At both places the water is brackish. The wells at the mill are shallow holes drilled in the bottom of a pit, which is about 20 feet deep and extends a little below sea level. The water stands only a few inches above sea level in the pit. The drilled holes have been filled to such an extent that their yield has been considerably reduced. Originally these wells furnished about 2,000 gallons a minute, or all the water that was needed at the mill. Now, however, they are used only to supplement the supply from the flumes when the flume water is insufficient to operate the mill.

The only water in the Kau District that is valuable for fluming cane is high-level perched water. Because this water occurs only in small seeps and streamlets on the ash beds and because there is only a small quantity to be had at any one place, the only feasible method of development is by tunneling. The tunnels are driven along the contour of the upper surface of the ash beds, or as nearly so as conditions will permit. The water is generally moving down the slope, at right angles to the contour along the upper surface of the ash bed. Hence a tunnel driven along the ash in this manner will intercept the largest quantity of water for a given length of tunnel. As the

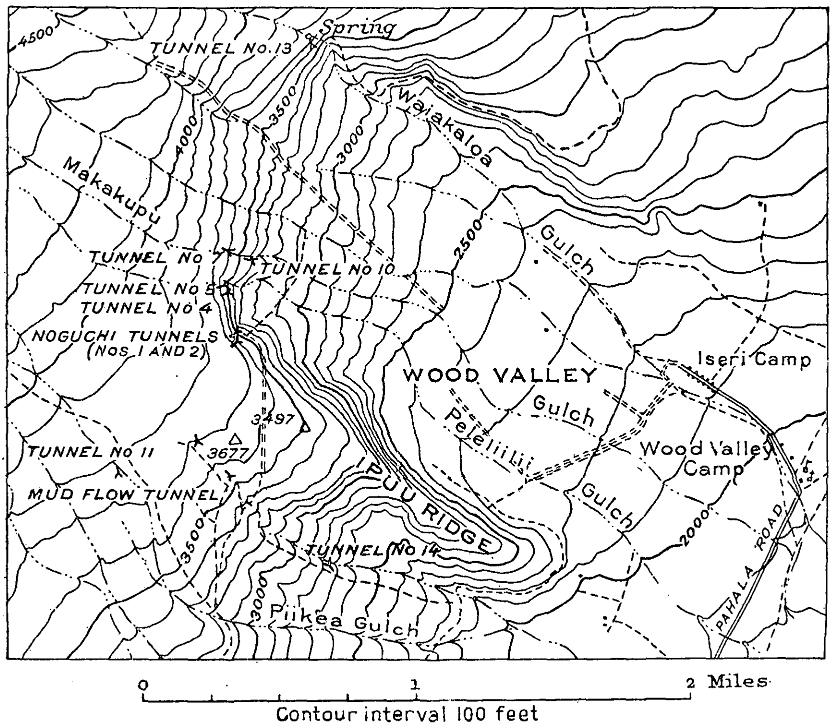
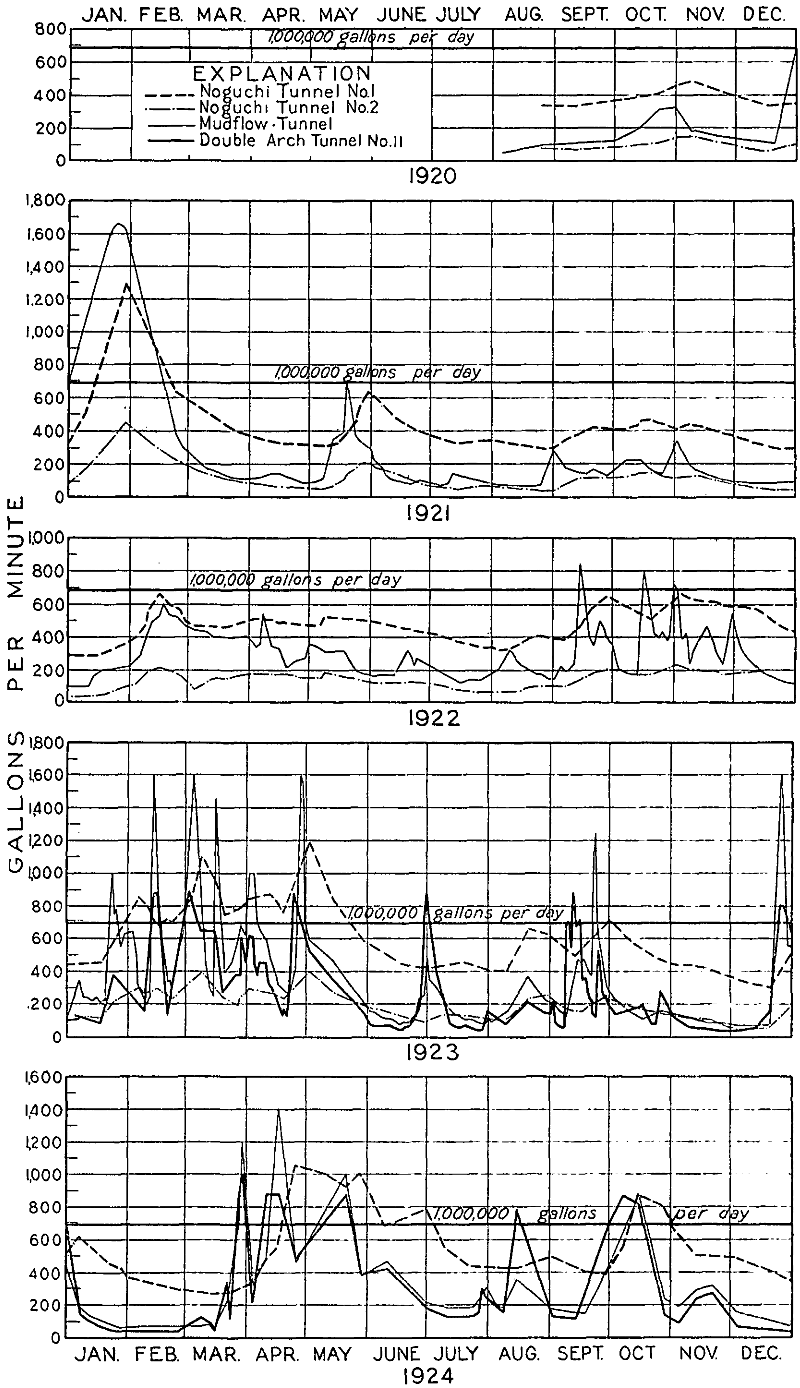


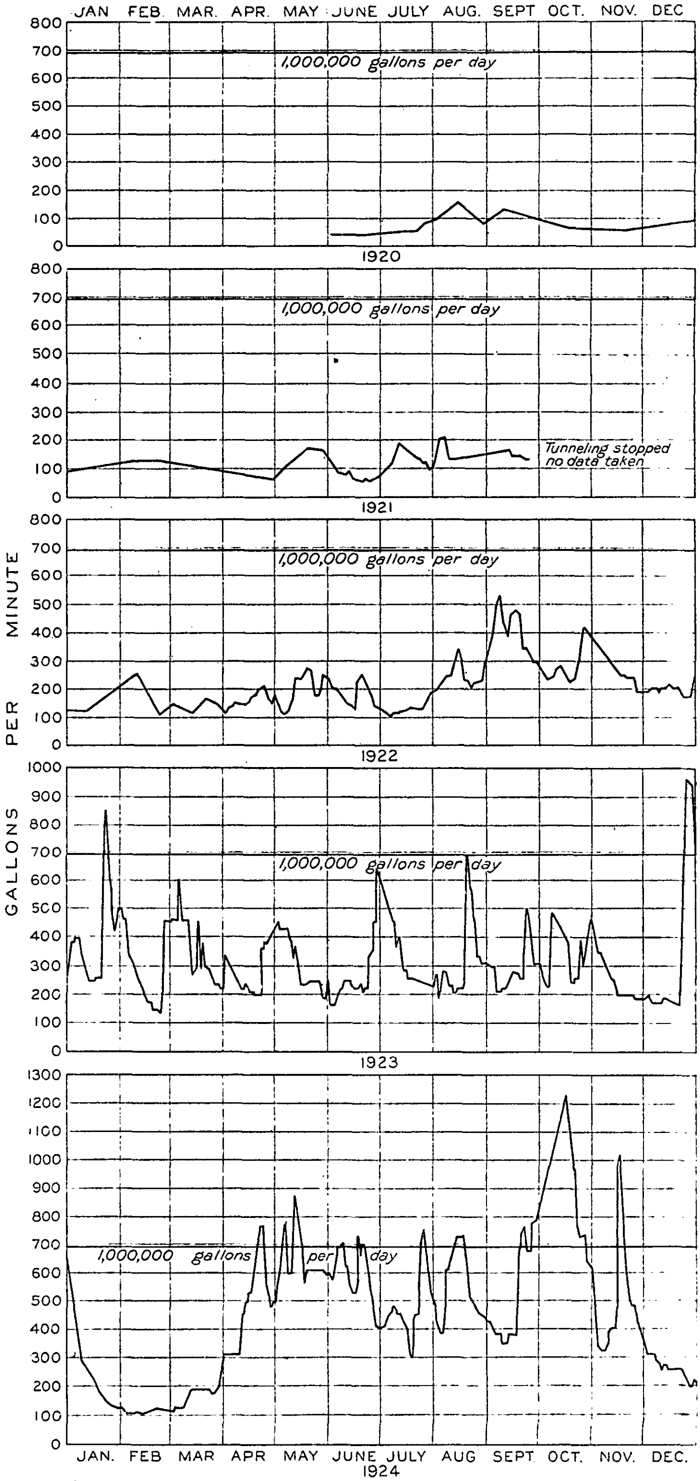
FIGURE 7.—Map of tunnels at head of Wood Valley, near Pahala

only ground water occurs on the surface of the ash bed it is necessary to keep the roof of the tunnel along the upper contact in all places. Even in this position it is possible to pass within a few feet of water without any signs of it appearing in the tunnel.

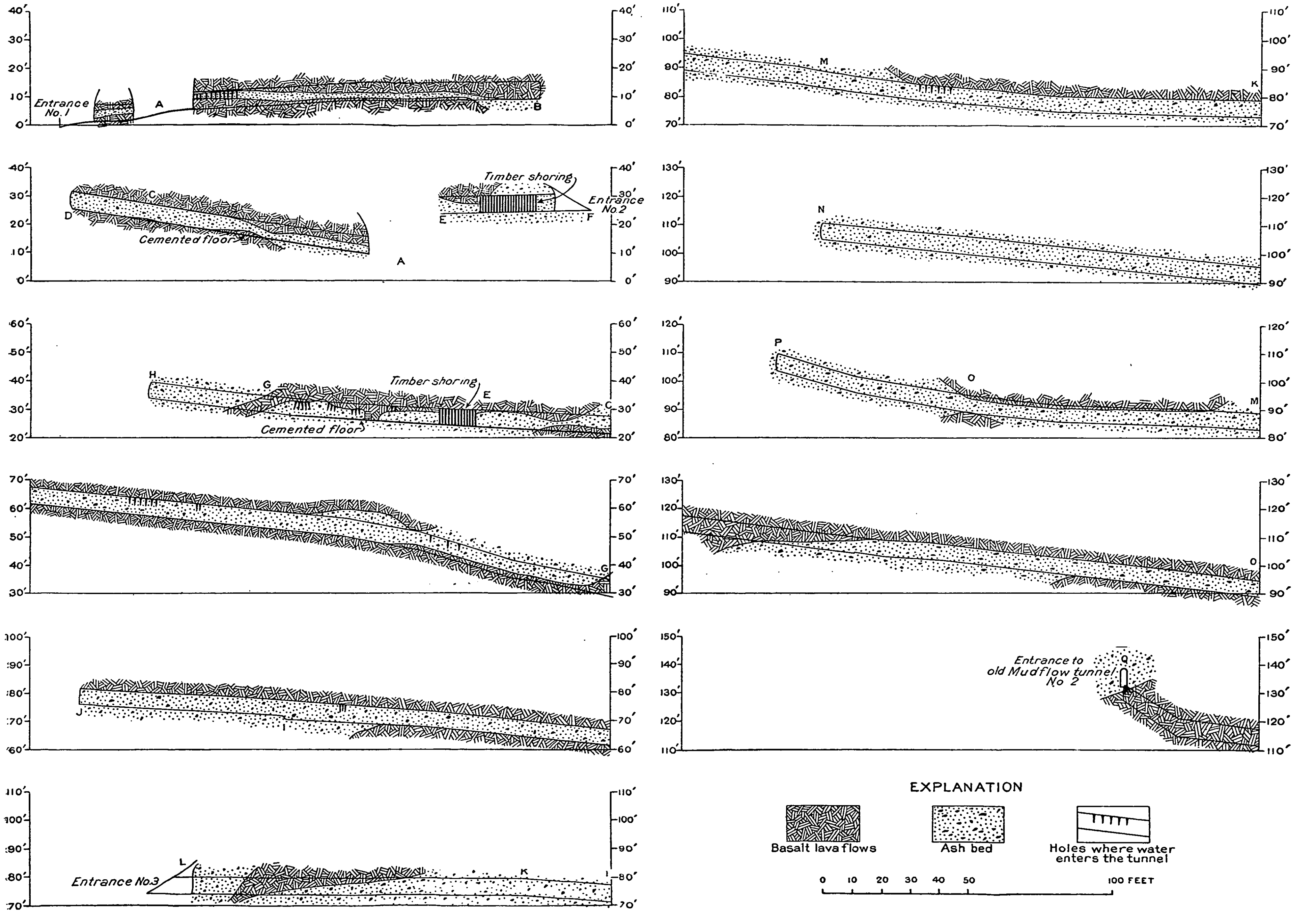
A spring was known to occur in the stream bed a short distance upstream from the mouth of one of the shallow tunnels. The tunnel was driven a little to one side of the spring and about 30 feet beyond it but gave no sign of water. A survey of the tunnel was made to locate the point at which a lateral should be driven to reach the spring. The exact line and the distance to the point at which the spring appeared on the surface were found, and a lateral was then



DISCHARGE OF SEVERAL TUNNELS OF THE HAWAIIAN AGRICULTURAL CO., PAHALA, HAWAII



DISCHARGE OF NEW MOUNTAIN HOUSE TUNNEL OF HUTCHINSON SUGAR PLANTATION CO., NAALEHU, HAWAII



LONGITUDINAL GEOLOGIC SECTION OF MUDFLOW TUNNEL OF HAWAIIAN AGRICULTURAL CO., PAHALA, HAWAII started for this point. It was driven only about 3 feet when the spring was tapped. Thus the main tunnel had passed within 3 feet of the spring without finding any water.

Because the surfaces of the ash beds are uneven the tunnels are always crooked. Thus if an ancient drainage channel is encountered the tunnel must swing up the ancient channel until it can cross the ash bed. Sometimes, when it is found that the ash bed is completely eroded away, the tunnel is driven through the rock that fills the buried channel in order to intersect the ash on the other side. All sorts of irregularities are encountered in the ash beds, just as might be expected from the fact that they were deposited on the irregular surface of a hummocky lava flow.

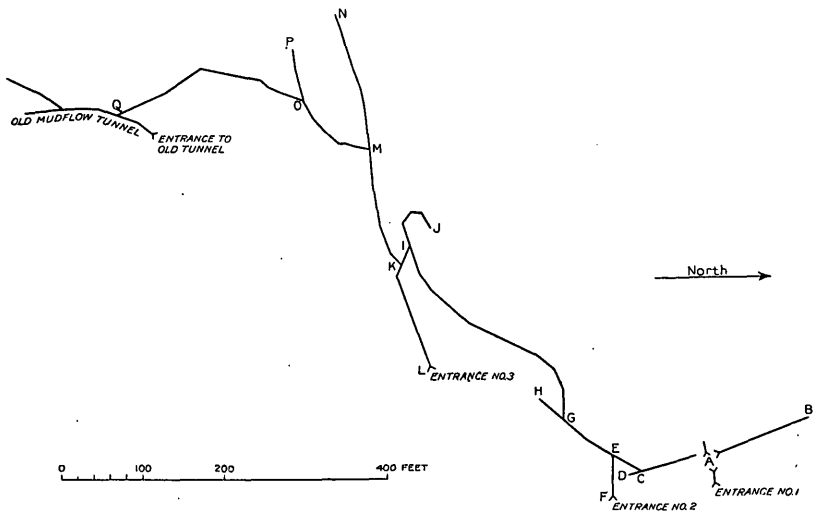


FIGURE 8.—Plan of Mudflow Tunnel, Hawaiian Agricultural Co., Pahala

In two tunnels cracked and shattered fault zones were encountered. In both of these tunnels the ash bed disappeared at the fault. One of the tunnels was abandoned, and in the other the ash was found again by the use of a peculiar aa flow as a horizon marker. Some of the cracks encountered were 6 to 8 inches wide, and a current of air entered sufficiently strong to blow out a candle. Air currents also frequently come in through lava tubes. They are often a great help in clearing the tunnel of powder fumes and in providing ventilation.

The tunnels for the most part are very crooked and have an uneven grade. Figure 7 shows the location of the tunnels near Wood Valley. The other tunnels not shown on Figure 7 are shown on Plate 1. Figure 8 shows the plan of the Mudflow Tunnel, and Plate 27, *B*, shows its entrance. Plate 31 shows a log of the tunnel. Figure 9 shows the plan of the Mountain House Tunnel. The total length of this tunnel in November, 1924, when the work on it was still in progress, was 5,375 feet. These plans are sufficient to show the irregular form of the tunnels and their general crookedness. It will be

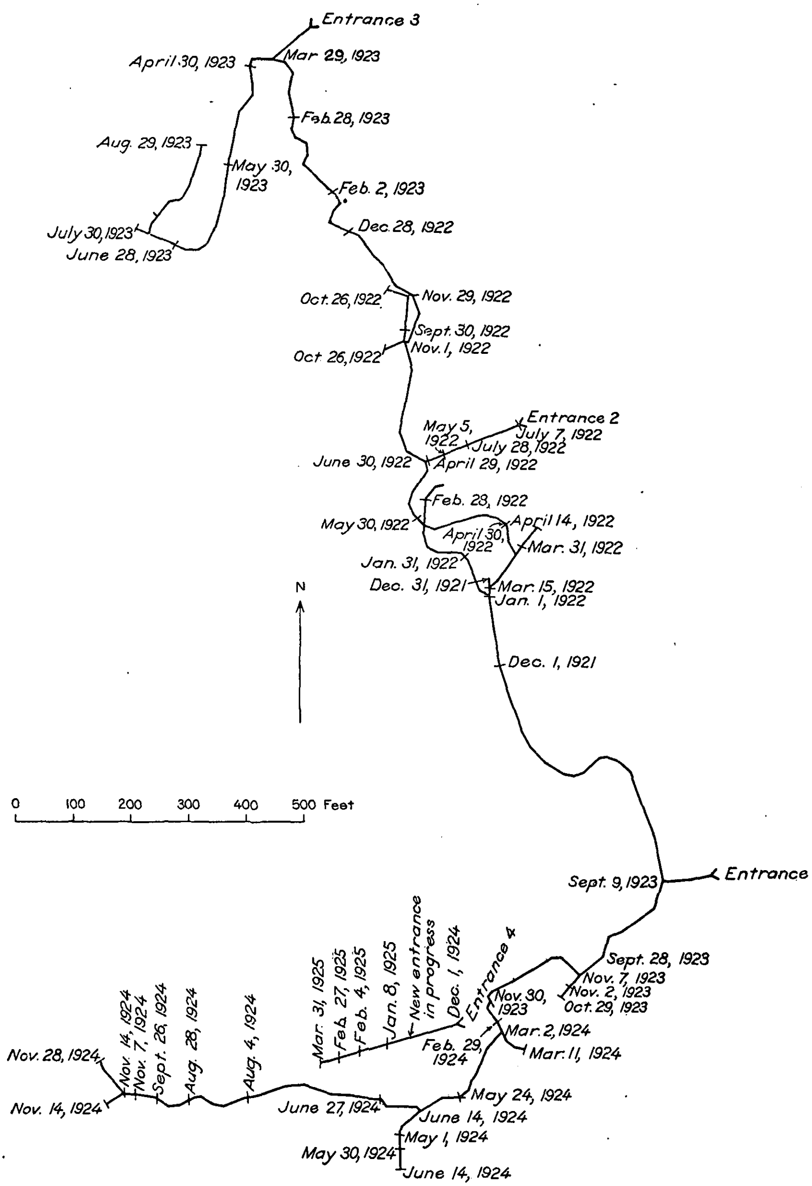


FIGURE 9.—Plan of Mountain House Tunnel, Hutchinson Sugar Plantation Co., Naalehu

noted in Figure 9 that at one place branches of the Mountain House Tunnel cross each other. One of these is at a somewhat higher level than the other. The one at the lower level was put in first and encountered a small quantity of water. The upper lateral was put in some three months later and encountered somewhat more water than the lower one. Throughout the greater part of the area covered by this tunnel there are two beds of volcanic ash, which in some places are separated by only a few feet of fine aa lava and in others join each other or are more widely separated. At some places the aa thickens, and the tunnel may follow either the upper or the lower ash bed.

The tunnels are 6 feet high and about 4 feet wide. The material excavated is transported to the dump in a wheelbarrow, or when conditions are favorable and there is sufficient water the ash is sluiced out with the water. The rock, of course, must always be carried out in a wheelbarrow. Owing to the crookedness and in some places to the steep grade of the tunnel, it is not feasible to lay track and use cars, and hence the length of haul becomes a serious matter. Although the contracts in vogue call for increasing pay with increasing depth of a tunnel it is difficult to keep workmen when the haul is more than 1,000 to 1,200 feet. In one tunnel the haul reached 1,500 feet, but this was an exception. A new entrance 500 feet long is now being driven in order to shorten this haul, so that work may proceed on the main tunnel.

In none of the tunnels has it been necessary to install blowers to clear the tunnel of powder smoke, because of the air currents entering the tunnel through the natural openings in the lava. The air currents are variable both in strength and in direction, according to the weather and the time of day. In this respect there is a marked difference between the tunnels in the Kau District and some that are being driven on Maui and Oahu. On Oahu a blower had to be installed in one tunnel about 600 feet long and with only two bends through the entire length. In the Kau District it would be difficult to install machinery of any kind in the tunnels, as all materials must be carried over long, difficult trails on pack animals, and, as a rule, a part of the way on the backs of men.

EASTERN KAU

The Kapapala and Keauhou lands of eastern Kau are used entirely for grazing. The former are occupied by the Kapapala ranch of the Hawaiian Agricultural Co., and the latter by the Keauhou ranch, belonging to Arthur M. Brown. The Volcano House, Kilauea military camp, Volcano Observatory, and several private homes are also situated in the Keauhou lands at Kilauea Crater.

The Kapapala ranch at present receives its water from a spring at the head of Wood Valley. The slopes of Mauna Loa in the Kapapala lands were carefully studied with the view of developing perched high-level water. Thick Pahala ash beds were found, but in every place where they were exposed they were coarse or open textured, and hence pervious to percolating waters. It was therefore concluded that, although the geologic structure was favorable, attempts to develop high-level water would be unsuccessful because of the permeable character of the ash beds. A few water holes were found which owe their existence to cattle puddling the ash in depressions of a lava flow. They are simply small impervious catchment basins and are dry except during rainy weather.

The Kapapala lands, in the Kau Desert, comprise mostly barren lava that is shattered by hundreds of cracks and faults. Here not only the geologic structure but the rainfall is adverse to water development. Along the coast there are a few cracks in which brackish water can be obtained, but as that region is an uninhabited desert waste it has no need for a water supply. The few fishermen who frequent the region either carry their water or drink the brackish water. Fresh water could easily be obtained by drilling a quarter of a mile inland.

The Keauhou lands are likewise situated in a region where the development of ground water is impracticable. The geologic structure appears favorable on the Mauna Loa slope, but here, as on the Kapapala lands, the interstratified ash beds are coarse in texture and allow ground water to move downward freely. The upper Keauhou ranch unit, on the Mauna Loa slope, depends entirely upon rainfall and storage tanks and except in unusually dry weather has sufficient water. The water supply for the ranch can always be increased by building additional tanks. The lower Keauhou ranch unit, called the Ainahou ranch, is situated on the eastern border of the Kau Desert, and although there are interstratified ash beds here, faulting prevents the occurrence of high-level water. The texture of the ash is coarse here also, and hence the conditions for developing high-level water are very unfavorable.

A few miles to the northeast of the Ainahou ranch, in the vicinity of Kane Nui o Hamo, there is abundant rainfall practically throughout the year, owing to the moist trade winds. The practical method of supplying water to the Ainahou ranch is to build watersheds and storage tanks on the slopes of Kane Nui o Hamo and pipe the water from them to the grass lands. This will insure a water supply throughout the year that will be limited only by the run-off area of the watersheds and the capacity of the storage tanks.

At Keauhou Beach there is brackish but fairly palatable spring water. The most practicable method of developing water for stock at this locality is to blast a well 3 feet in diameter to the water table at an altitude of about 50 feet above sea level, preferably in a swale extending back from the coast. Such a well would furnish more and fresher water than shallower wells at sea level. The equipment of the well would be above the effective level of the earthquake sea waves that so frequently sweep this coast. The well should be equipped with an automatic steel windmill and a storage tank. The wind blows continually at this place, but unless the windmill had a regulator heavy winds would destroy it.

The Volcano House and other buildings at the summit of Kilauea are all equipped with watersheds and storage tanks and, being located in a region of heavy rainfall, they rarely suffer from a shortage of water. There is no other practicable way of developing water at this locality because of unfavorable geologic structure.

KALAE OR SOUTH POINT REGION

Kalae at the present time is given over to the cattle industry, except that a little agriculture is practiced on the Kamaoa homesteads. The homesteads are supplied for both domestic use and stock with water piped from the Haao Springs, in Waiohinu Valley, several miles to the north. Shortage of water is seldom experienced except when pipes burst or get clogged. All the homesteads are equipped with small storage tanks to take care of this emergency.

The Haao Springs issue from the top of an ash bed interstratified with Pahala basalt. Their flow is unusually constant compared to that of other springs in this region, primarily owing to the width of the rainy belt above them. Examination of the springs indicates that there is probably a large quantity of ground water in the Kamehame lava flow overlying the ash bed that does not find its way to the surface at the springs but spills over the valley walls and is lost. Therefore, it is recommended that this spring be developed by a tunnel driven under the supervision of a geologist in order to increase the water resources of this region. The additional water obtained could be profitably utilized for irrigation by the homesteaders or leased to the Hutchinson plantation for fluming.

The Kaalualu ranch has successfully developed water at the ranch house at Kaalualu and at Waipouli, 2 miles northeast of the house, by blasting shallow wells to the main water table. The water in these wells rises and falls with the tide but is only slightly brackish and is palatable to both man and beast. It has been successfully used for irrigation. The water is lifted by means of windmills.

Digging for water in the South Point region, except along the coast, is not recommended. The Pahala ash beds, although thick in this region and in places interstratified, are too permeable in most places and receive too little rainfall to yield water. It is useless to dig in the ash itself for water, as is illustrated by the dry hole 35 feet deep near Lua Poai. Water, if found at all in usable quantities in this region, will occur at the surface of the ash and not below the surface.

WESTERN KAU

The Kahuku lands are devoted to stock raising by the Parker Ranch Co. The present supply of water is obtained entirely from rainfall, which is caught by watersheds and stored in tanks. Shortage of water is seldom experienced except on the lower lands. Examination of the region showed that wherever the geologic structure is favorable the ash is too pervious to hold the water up, except possibly in the Waiahuli water hole, described below. Hence, tunneling is not recommended for developing water on these lands. Moreover, most of the structural features are crossed by the shattered southwest rift of Mauna Loa, which allows a free descent of high-level water to the main water table. Several water holes due to puddling by cattle similar to those on the Kapapala and Keauhou lands were found in the Kahuku lands.

A small perennial pool known as the Waiahuli water hole is located about 5 miles northwest of the Kahuku ranch. Mr. Martinsen, manager of the ranch, said that the pool was never known to go dry, and that during a test he had taken 600 gallons from the hole in two hours. The temperature of the water on September 4, 1924, was 64° F., which was about 12° below the air temperature. The pool is an aa flow channel at an altitude of 2,400 feet in a region where the annual rainfall is about 20 inches or more. The water hole is completely surrounded by aa lava and is inaccessible to cattle. It is about 1½ feet in diameter and about 1 foot deep. The water level in the hole is reported to fluctuate about 8 inches during the year. The fact that this hole yielded water for two hours without exhausting the supply shows that it is not a mere storage basin for occasional rains but rather a spring that is fed by a body of ground water. The surface rock is a very permeable aa, but there is doubtless an underlying impervious bed that holds up the water. As no perennial water is known to occur at high levels in the Kau District except in association with ash beds, it is probable that there is an ash bed beneath the aa. As this water hole lies in the southwest rift zone of Mauna Loa, where lava flows occur frequently, it is not likely that there is any ash bed of sufficient thickness to warrant tunneling. It is also possible that this water is being fed to the water hole by the ancient aa channel acting as a drainage channel, though this is very unlikely, because the aa channels are, as a rule, extremely permeable. It is possible, however, that during one stage in the flow the channel was veneered by lava similar to the smooth, unjointed coating sometimes seen on the levees of the channels. This condition might account for this small supply of water. In either case tunneling would be impracticable.

The Waiahuli water hole is in a kipuka that is at present used as a fattening paddock by the Kahuku ranch. The cattle depend upon dew and rain for their water, and hence the paddock can not be used satisfactorily during dry spells. The construction of a 50,000-gallon storage tank in the depression about 100 feet south of the water hole is recommended. A pipe could be laid from the tank to the water hole at small cost. It will be necessary to pick (not blast) a ditch for the pipe for the upper few feet, in order to have the pipe tap the bottom of the water hole. Blasting this ditch is unadvisable because the impermeable bottom of this water hole might be cracked open and allow the water to sink. By concreting part of the water hole and leading the water to the storage tank the water now going to waste could be conserved. In case the flow would not fill the tank, a small auxiliary watershed could be built near by. Such an arrangement would supply 100 head of cattle throughout the year, which is about the number that can be fed by the grass in this kipuka.

QUANTITY OF GROUND WATER

As there is practically no development of water from the main water table in the Kau District little need be said regarding it. It is believed, however, that there is abundant fresh water near sea level. Some large springs are known along the seashore, the most notable of which are at Ninole and Kawaa.

The high-level or perched water is very much less in quantity than that of the main water table, and it is also much less steady in its flow. The number of high-level springs is extremely small, there being none except in the rainy belt and only a very few there. Less than a dozen permanent high-level springs that have a large enough discharge to be economically valuable are known in the Kau District. This seems an amazing fact when it is remembered that over a considerable area the rainfall is between 100 and 200 inches a year and is equally distributed throughout the year. The yield of all tunnels is highly variable. By far the most constant flow is that from the Noguchi tunnel, on the escarpment back of Wood Valley. However, during the period from 1920 to 1925, during which records have been kept, even this tunnel has varied in discharge from about 210 to 1,300 gallons a minute. The minimum discharge occurred in March, 1925. The character of the flow from this tunnel is seen from the curves shown in Plate 29.

The more common type of flow is represented by the curves of the Mudflow Tunnel and the Double Arch Tunnel (No. 11), also shown in Plate 29. Plate 30 shows the discharge of the Mountain House Tunnel. This is somewhat more constant in volume than the average tunnel. Work is still in progress on this tunnel. All the other curves represent tunnels now complete, though certain parts of them, except for Noguchi Tunnel, cover periods before the tunnels were complete. It will be seen from these curves that the discharge from all sources is highly erratic. Plate 32 shows a composite curve of all water developed on the Pahala plantation since 1920. The chart compares the yield of water in 1924 with that of the Noguchi Tunnel for the same year. Plate 33 shows the water developed on the Hutchinson plantation since 1920.

THERMAL WATER

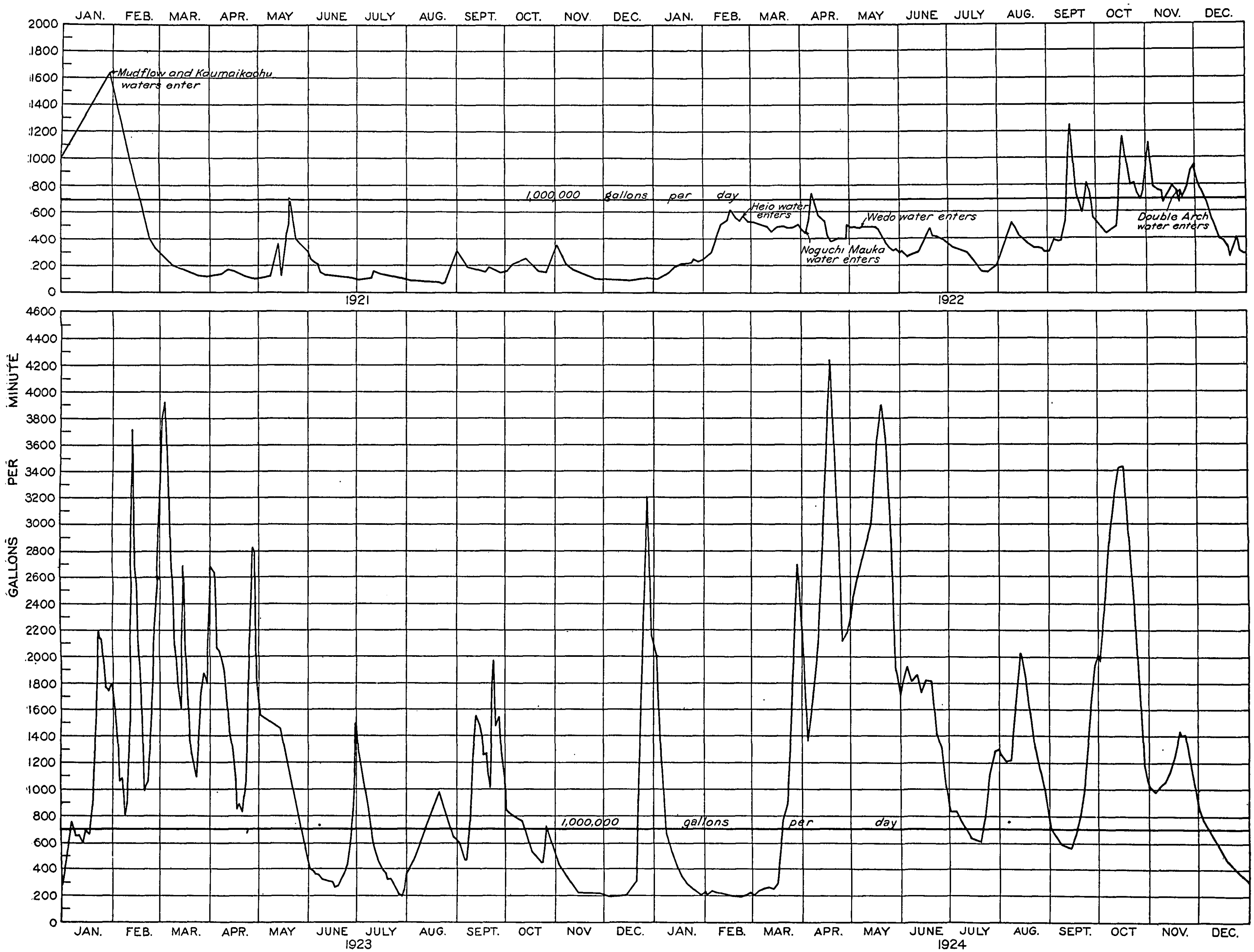
No hot springs occur in the Kau district, but there are several steam vents. Hot water condensed from steam is used to supply two bathhouses located on the north rim of Kilauea. Both are steam baths. The steam is conveyed in wooden pipes from steam cracks near by, and the wash water is supplied from rain tanks.

Pele's Bathroom, in the floor of the Kilauea caldera, is a steaming lava tube with water, caused by the condensation of the steam as it comes into contact with the cool outside air, dripping from the roof near the opening. The location of other hot caves is shown on Plate 1. Steam cracks are common on the summit and on both rift zones of Kilauea. In some places the steam condenses and gives a little water near by. Warm water occurs in a crack at Waiwelawela Point, southeast of Pahala. It is probable that if the rocks were less pervious more heated water would occur on the surface, but with the conditions as they exist, both juvenile and meteoric, hot waters usually become diluted and cooled at the main water table and never reach the surface.

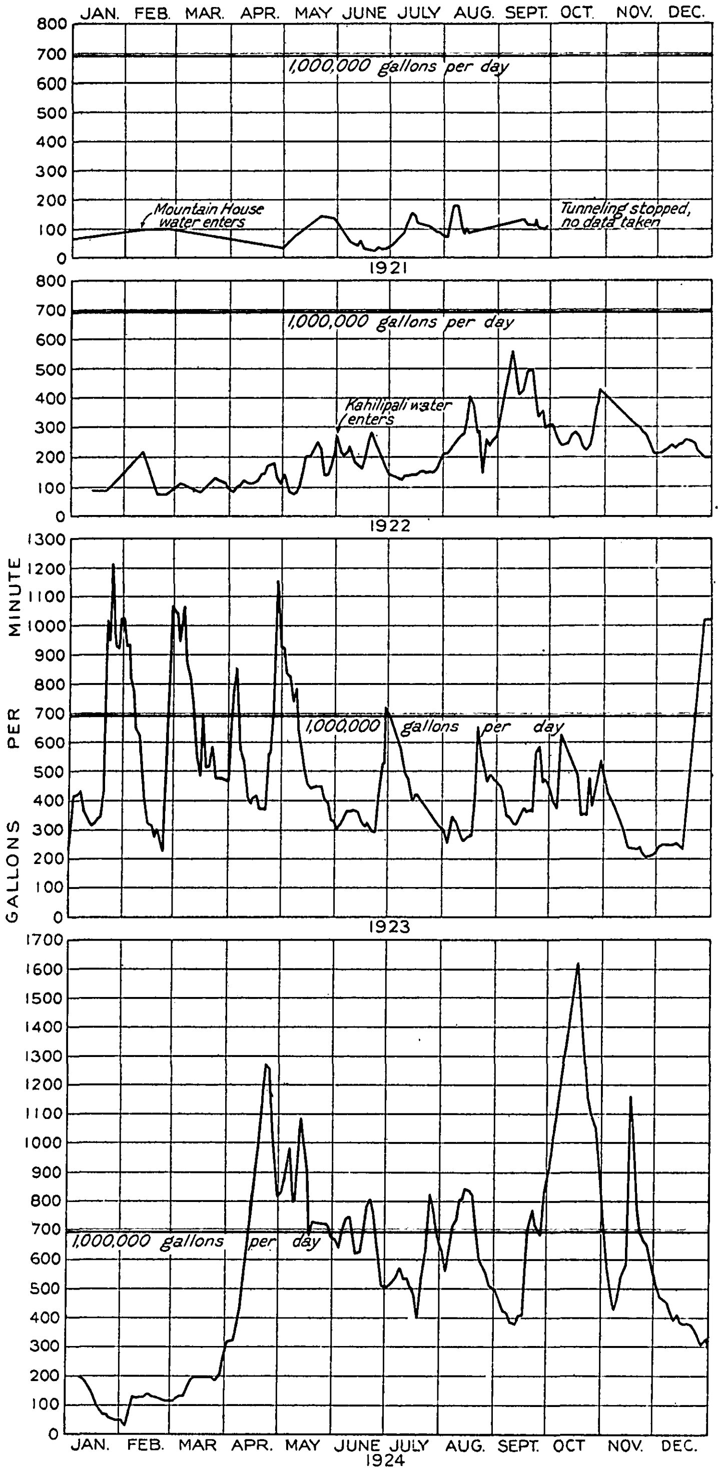
It is evident from the increased amount of steam rising from hot cracks during rainy weather that most of the water that is converted into steam by the hot rocks below is of meteoric origin. This is particularly conspicuous at Maunaiki, the cone of 1920. During dry spells no steam rises from the cracks and only at one or two places can rising heat be felt, yet after a rainy spell clouds of steam rise from many places on the Maunaiki cone. The phreatic explosions on Kilauea and Mauna Loa show that large supplies of ground water can be heated and driven off in the form of steam without actually coming into contact with the magma itself.

SUMMARY

The geologic study of the occurrence of ground water in the Kau District has shown that no perched water occurs in the basalt domes of Kilauea and Mauna Loa in the district except in association with impervious ash beds. A careful examination of the two great slag heaps of Mauna Loa and Kilauea does not make one wonder "why



TOTAL WATER DEVELOPED SINCE 1920 BY NEW TUNNELS OF HAWAIIAN AGRICULTURAL CO., PAHALA, HAWAII



TOTAL WATER DEVELOPED SINCE 1920 BY NEW TUNNELS OF HUTCHINSON SUGAR PLANTATION CO. NAALEHU, HAWAII there is not more high-level water" (a favorite question of the inhabitants), but why there is any high-level water at all. Considerable progress has been made in developing high-level water since 1920 by tunneling on ash beds, and much more water can be obtained by continuing the methods now in use. The best prospects for future development are at the Noguchi tunnel, Kaumaikeohu Spring, and Haao Springs.

It has been well established that as a rule the ash in the Ninole formation is the most impervious of all the ash beds and yields a supply of water that fluctuates the least. This regularity in yield indicates that the Ninole ash is more widespread and less interrupted by lava flows and erosion channels than the Pahala ash.

The examination of the Kahuku, Kalae, Kapapala, and Keauhou lands resulted mainly in negative evidence regarding supplies of perched ground water, but this evidence is valuable in that it should prevent waste of money in places where the conditions are unfavorable.

The water holes and cracks containing ice on the summit of Mauna Loa were mapped, and the explorer and tourist intending to make the ascent need no longer carry large supplies of water.

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